(a) (b) (c) (d)

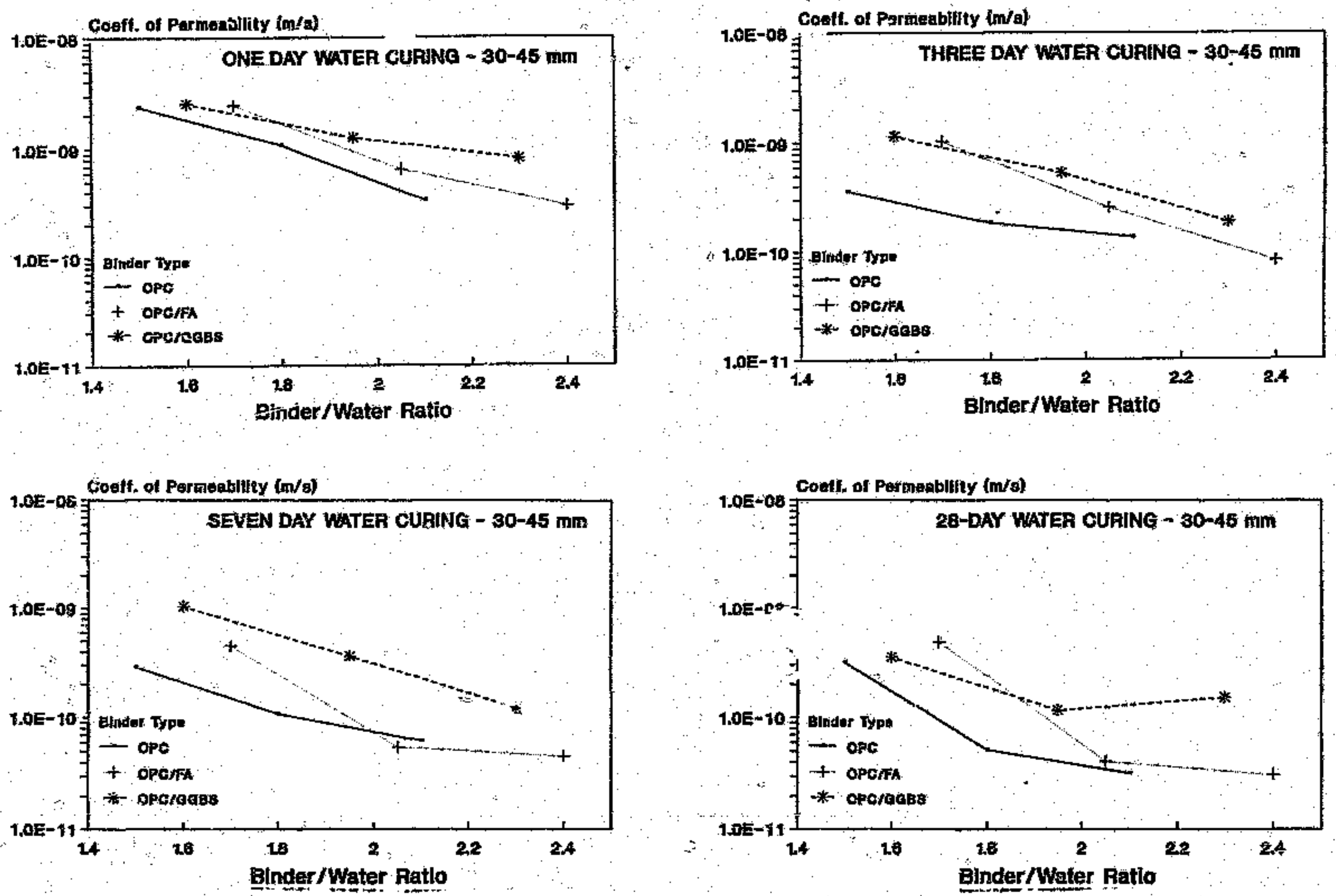

Figure 6.3 28-day oxygen permeability vs. b/w ratio for the 30-45 mm slices of the three binder type concretes.

6.2.2 Sorptivity

Figures 6.4 to 6.6 show the relationship between the water sorptivity and b/w ratio for the three binder types tested. The figures show the sorptivity measurements of the 0-15, 15-30 and 30-45 mm depths respectively, for the four curing regimes.

The results are very similar to those obtained with the oxygen permeability measurements and again show that the OPC concretes have improved surface qualities for the same b/w ratio and degree of curing. However, unlike the permeability values, the sorptivity performance of the three binder type concretes are similar for curing periods of three days and longer. This implies that, for the binders used in this study and for curing periods longer than three days, the sorptivity of the cover concrete becomes insensitive to the binder type.

A further point to note is that, for curing periods longer than three days, the sorptivity of all the concretes tested appears to become insensitive to changes in the b/w ratio.

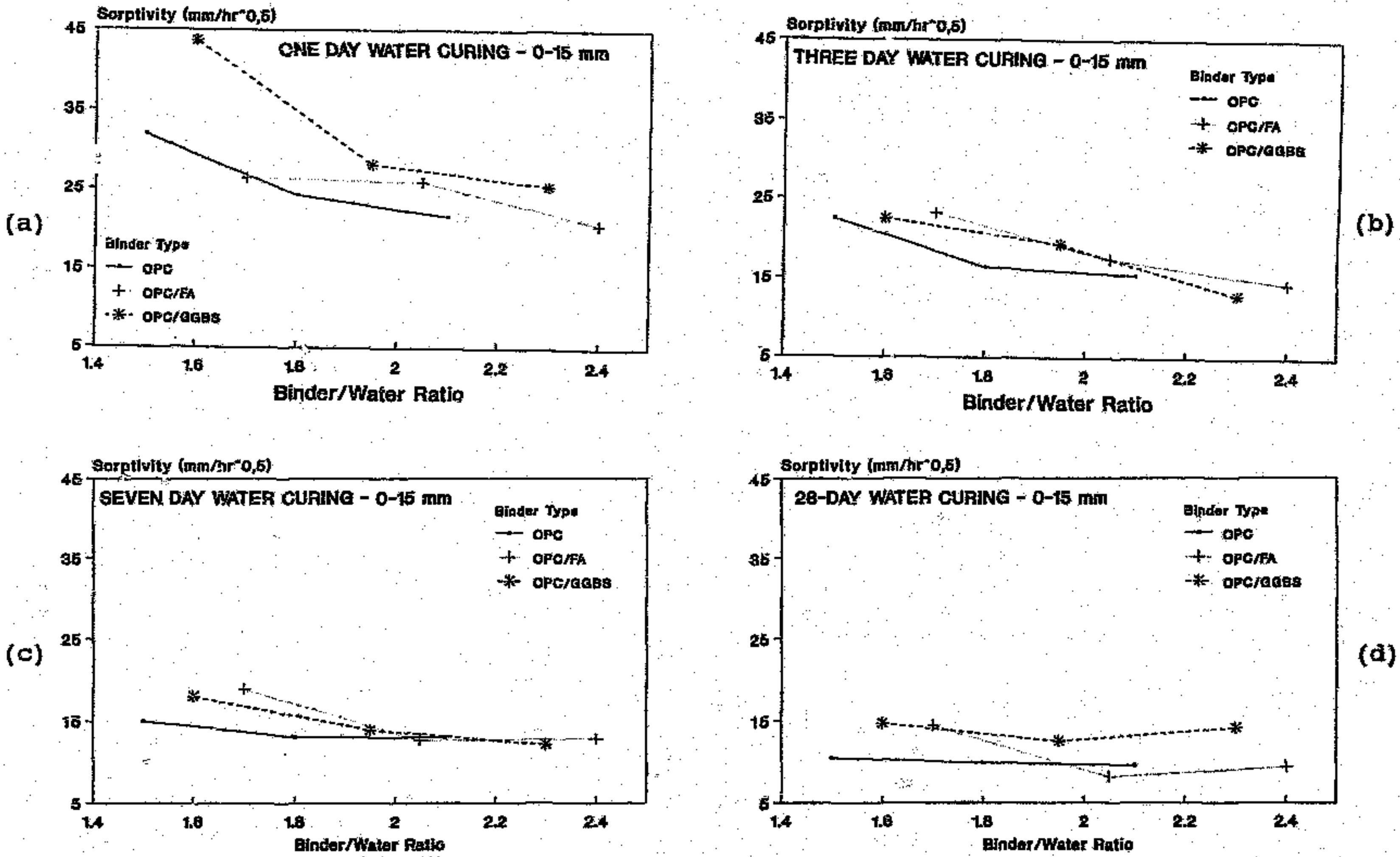

Figure 6.4 28-day water sorptivity vs. b/w ratio for the 0-15 mm slices of the three binder type concretes.

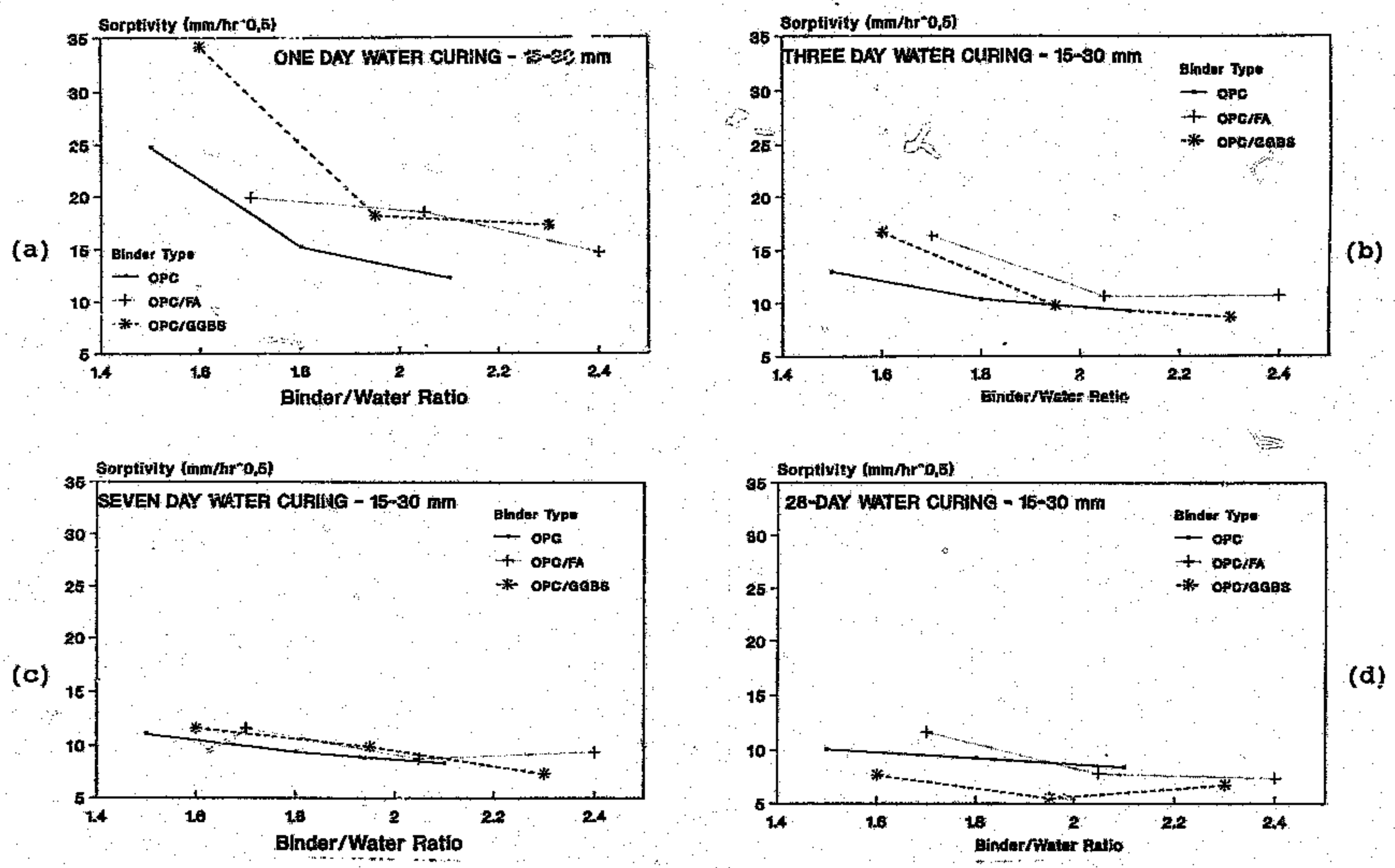

Figure 6.5 28-day water sorptivity vs. b/w ratio for the 15-30 mm slices of the three binder type concretes.

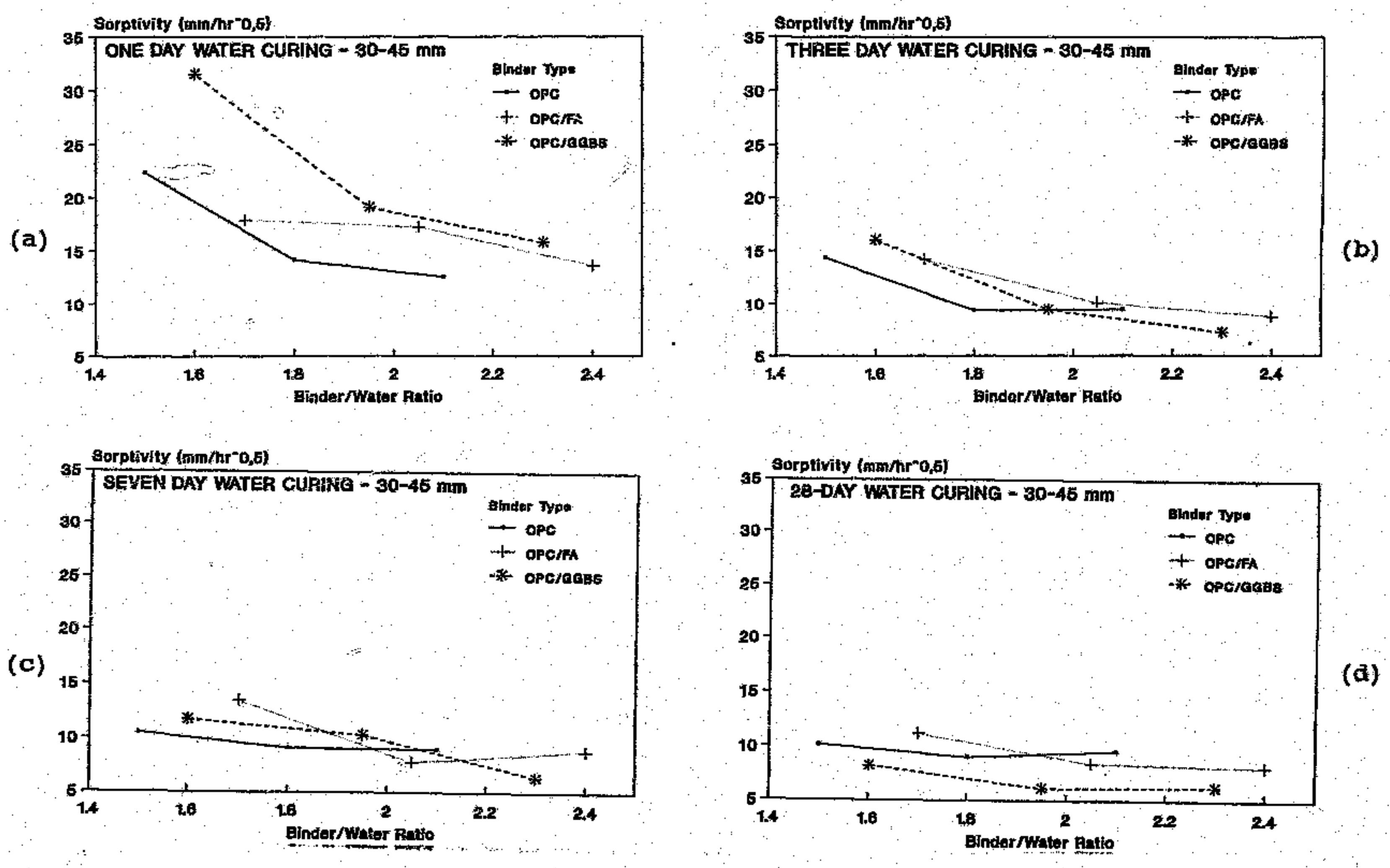

Figure 6.6 28-day water sorptivity vs. b/w ratio for the 30-45 mm slices of the three binder type concretes.

6.3 Effect of Compressive Strength on Durability Index Values

6.3.1 Permeability

Figure 6.7 shows the coefficients of permeability for the 0-15 mm slices, plotted against the 28-day, water cured compressive strengths of the concretes. The corresponding curves for the internal slices are shown in Figures 6.8 and 6.9.

These figures show that, for equal compressive strengths, the FA concretes generally show the lowest surface permeability for all the curing regimes. This is due to the pore refinement effect of the pozzolanic reaction as well as the physical, pore blocking effect associated with the fineness of this material. It is likely that the pore blocking effect plays a greater role in the improved performance of the lower strength range concretes under one day water curing conditions. The extent of hydration in the cover zone of these concretes would not have been sufficient for the pozzolanic effect to make a major contribution to reducing permeability.

The OPC concretes again show a relative insensitivity of surface permeability to compressive strength after 28 days of water curing. The comment presented earlier regarding the effect of additional curing on capillary discontinuity is also appropriate to this observation.

The GGBS concretes show results which are either greater than or simil·· to those of the OPC concretes. The reverse trend shown by the high strength GGBS concrete after 28-days of water curing appears to be anomalous and should be ignored. This trend was also noted on the curves in Figures 6.1 and 6.2 above.

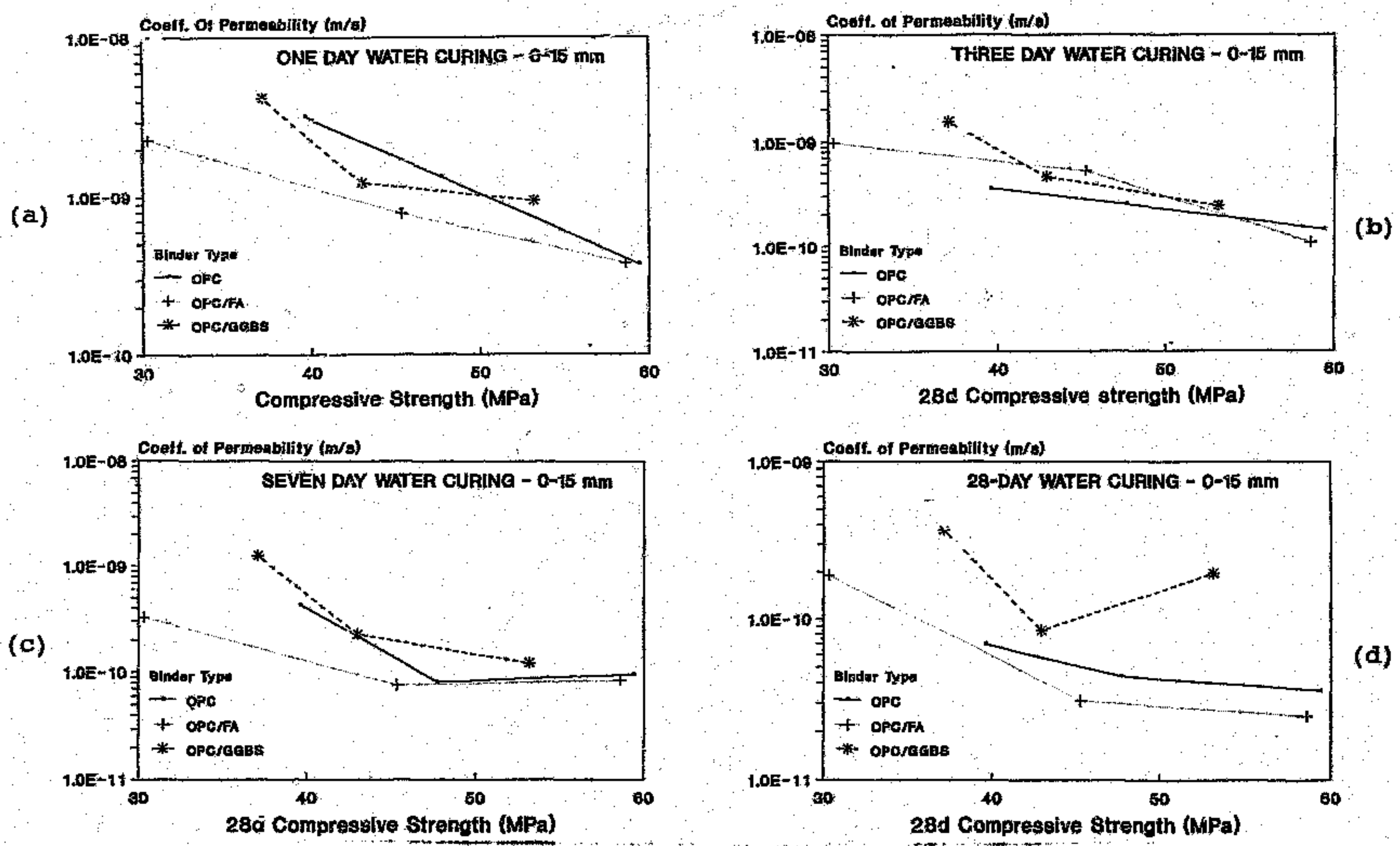

Figure 6.7 28-day oxygen permeability vs. compressive strength for the 0-15 mm slices of the three binder type concretes.

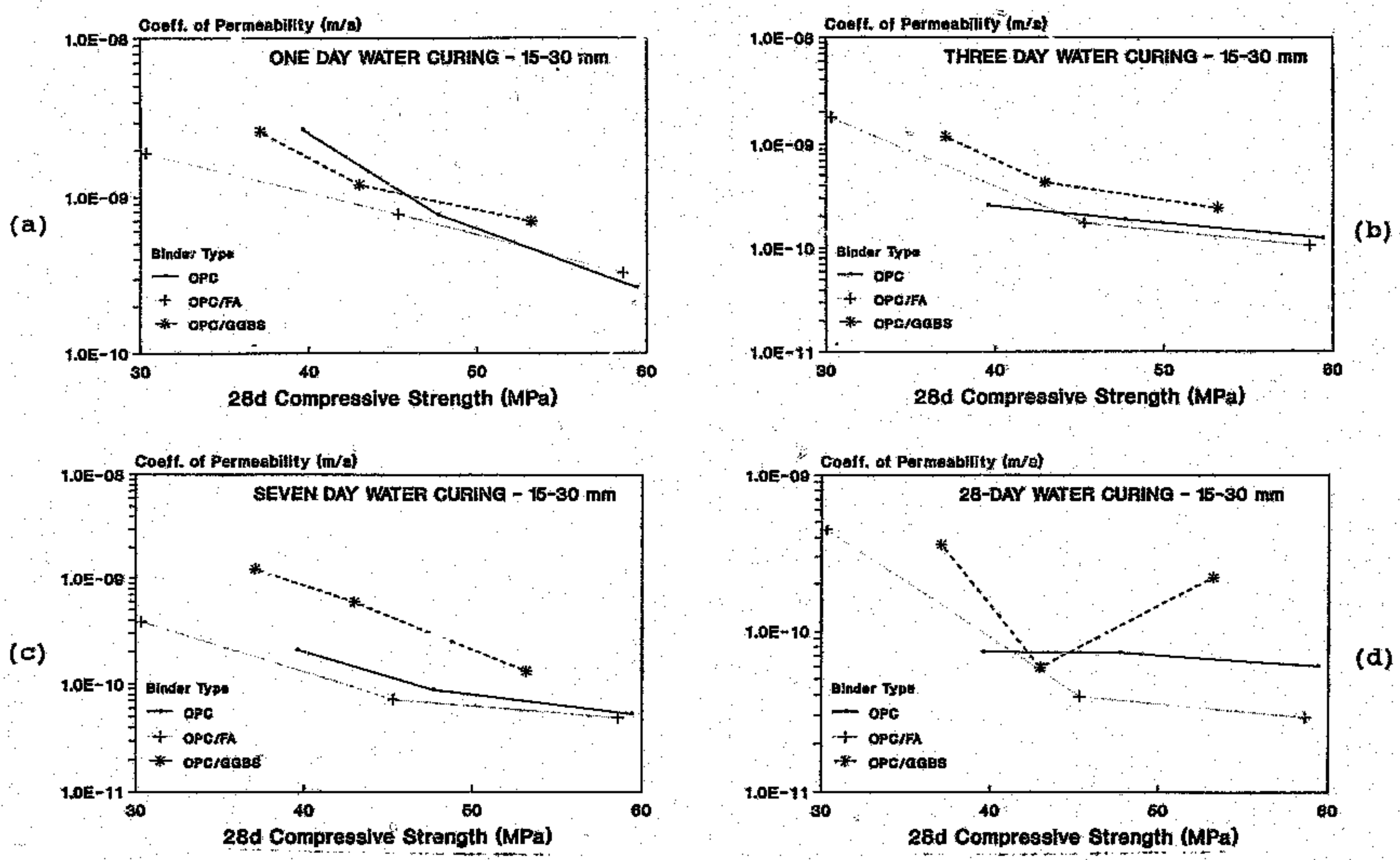

Figure 6.8 28-day oxygen permeability vs. compressive strength for the 15-30 mm slices of the three binder type concretes.

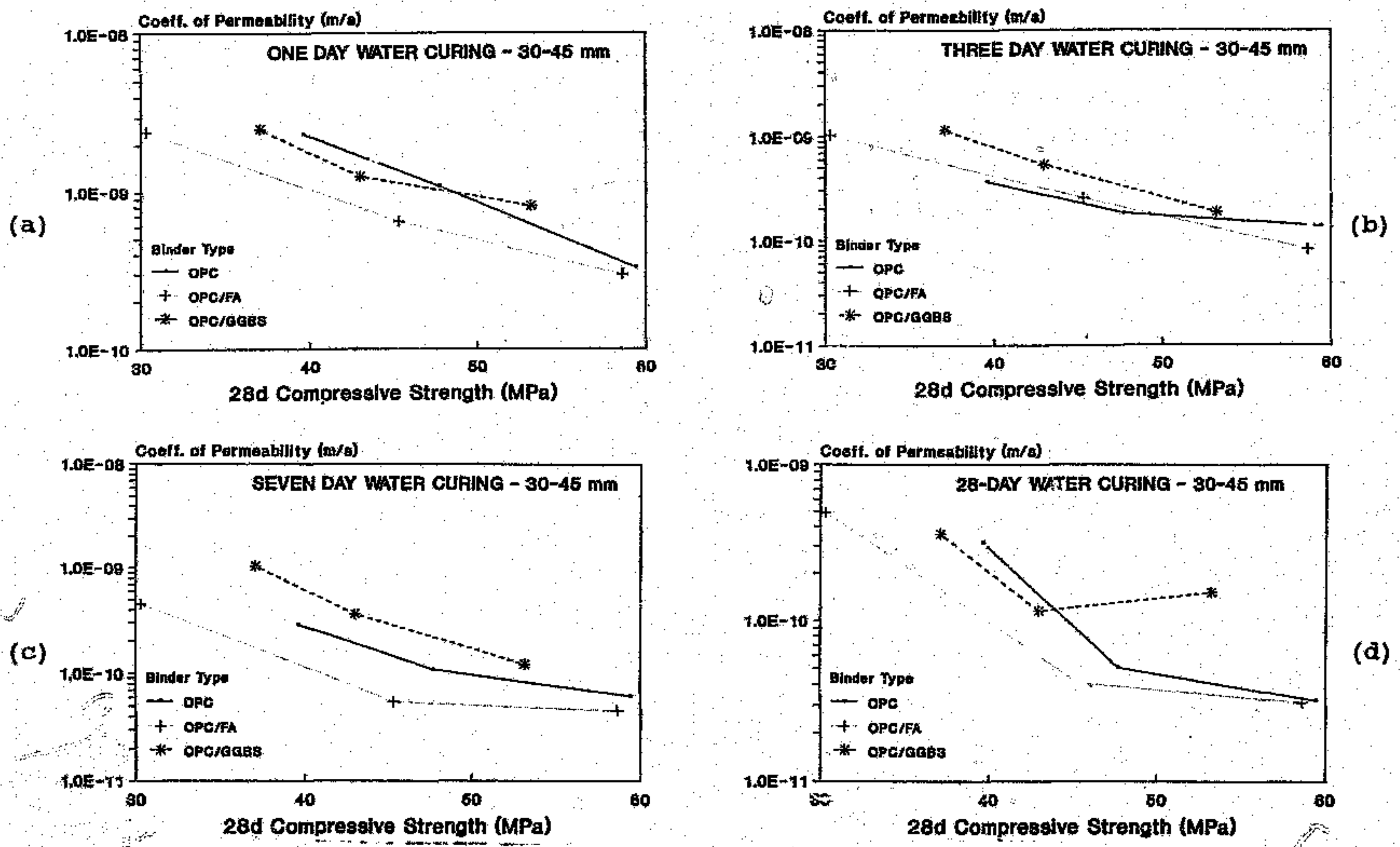

Figure 6.9 28-day oxygen permeability vs. compressive strength for the 30-45 mm slices of the three binder type concretes.

6.3.2 Sorptivity

Figure 6.10 shows the measurements of water sorptivity plotted against the 28-day, water cured compressive strengths of the concretes. The corresponding curves for the internal slices are shown in Figures 6.11 and 6.12.

It can be seen that, aside from the low strength concretes under one day of water curing, the differences in sorptivity values for the different binder type concretes are small when compared on the basis of equal compressive strengths. Also for moist curing periods of three days and longer, the curves are relatively flat, again indicating that increases in compressive strength have a small effect in decreasing the surface sorptivity of concrete.

However, the curves very clearly show the detrimental effects of poor curing at early ages on the surface properties of concrete. Poor curing effects increases in sorptivity at depths of up to 45 mm from the surface and for concretes with compressive strengths as high as 40 to 50 MPa.

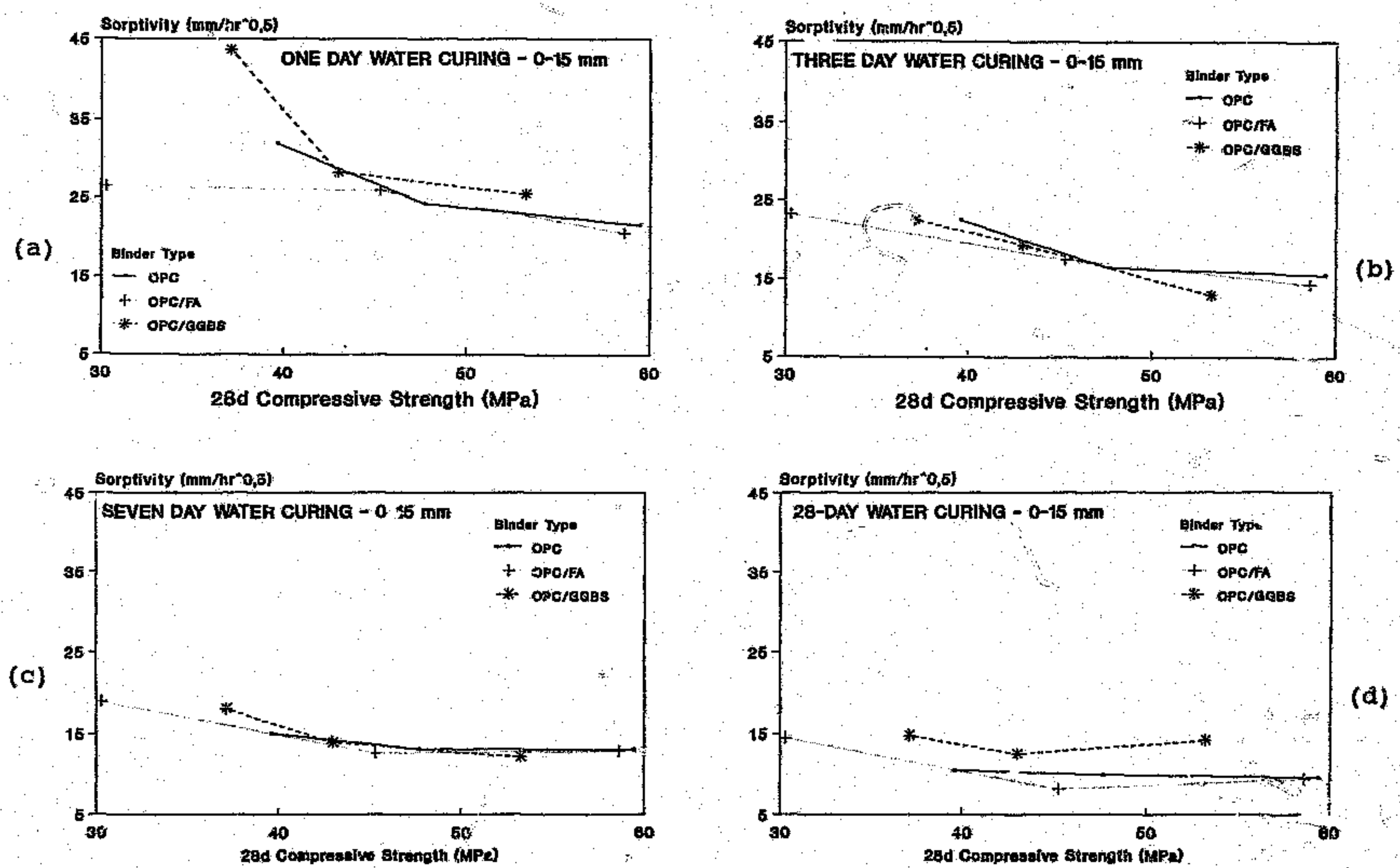

Figure 6.10 28-day water sorptivity vs. compressive strength for the 0-15 mm slices of the three binder type concretes.

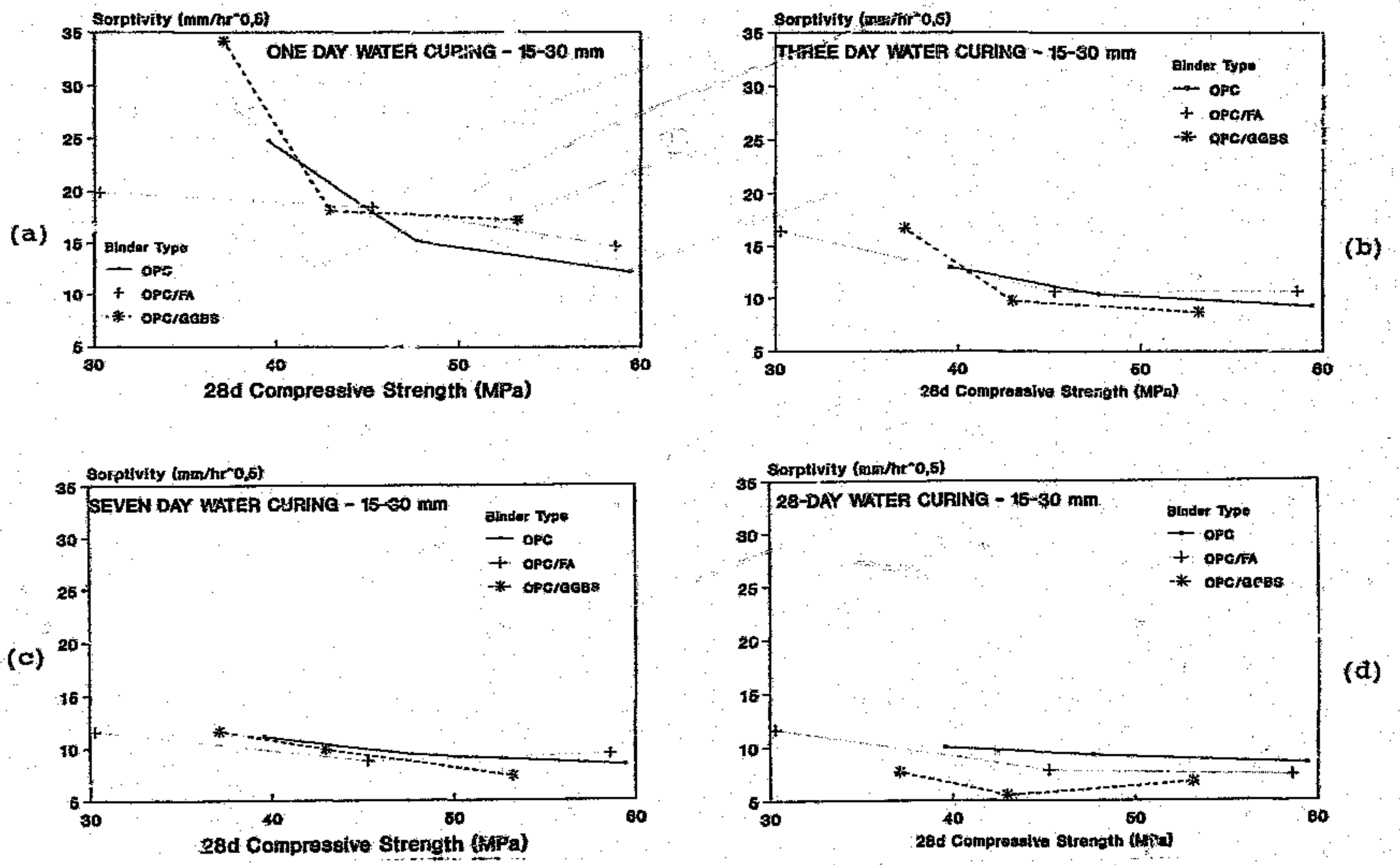

Figure 6.11 28-day water sorptivity vs. compressive strength for the 15-30 mm slices of the three binder type concretes.

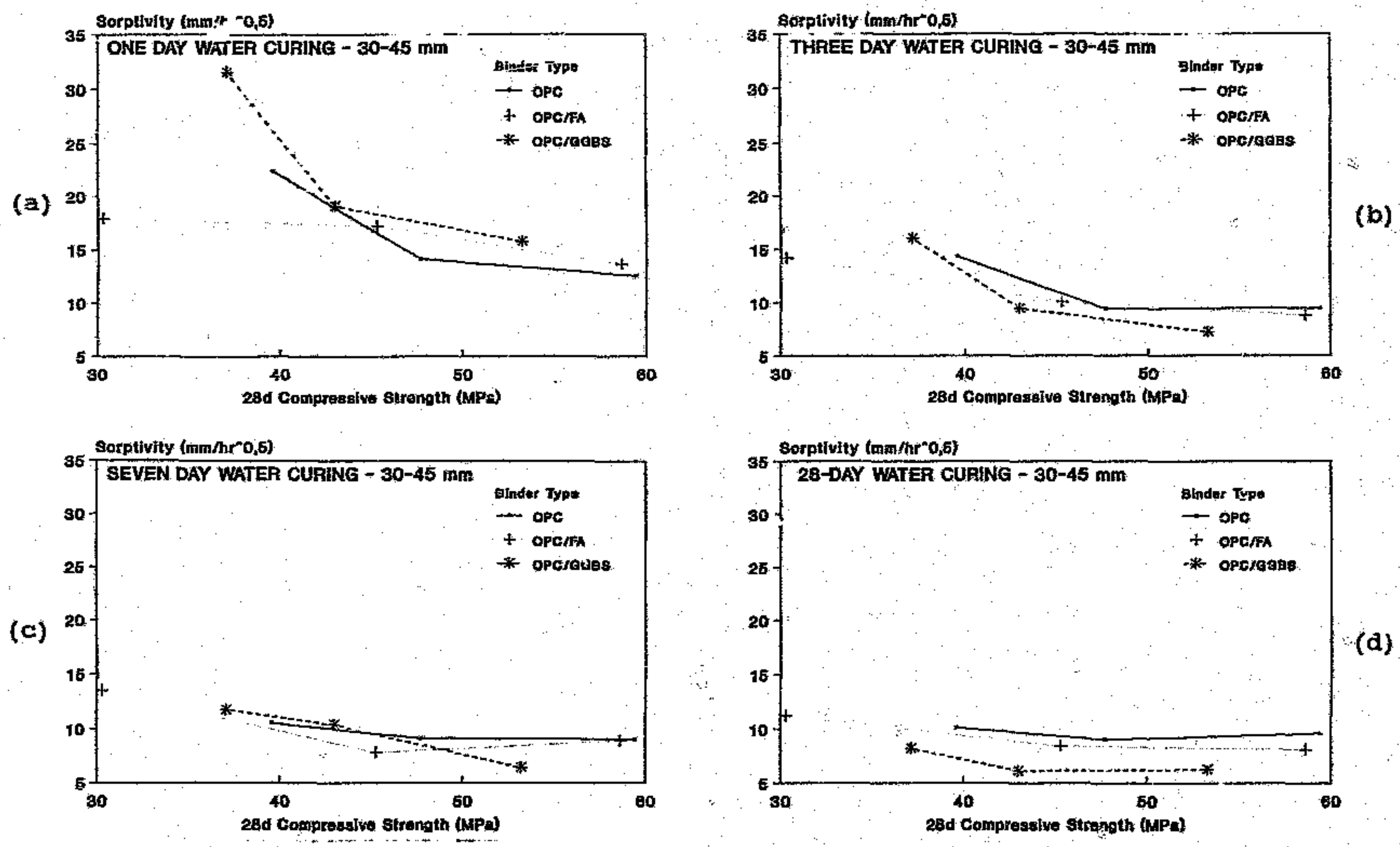

Figure 6.12 28-day water sorptivity vs. compressive strength for the 30-45 mm slices of the three binder type concretes.

6.4 Effect of Initial Curing Time on Durability Index Value

An attempt at empirically modelling the variables used in this study requires a multi variable approach, with duration of curing and depth from the drying surface as the independent variables and the durability index value as the dependent variable. However, this approach was found to be unwieldy and would have distracted from the possible usefulness of such a model. It was therefore decided to use a two-stage approach to the model:

- first develop a two-variable model describing the relationship between the duration of moist curing and the durability index value of the surface segment of the concrete (0 - 15 mm);
- develop a model describing the relationship between the durability index values of the surface and internal segments of the concrete.

6.4.1 Durability index of the surface segment

The combined form in which the results were presented in Chapter 5, in Figures 5.13 to 5.15 for example, gave an indication of the effect of the duration of moist curing in reducing the permeability and sorptivity of the concrete. As examples, Figures 6.13(a) and 6.13(b) below show these trends for the surface slices of the low strength concretes only, with the extent of moist curing shown in linear form. The figures show the permeability and sorptivity response of the concretes to changes in the duration of early moist curing.

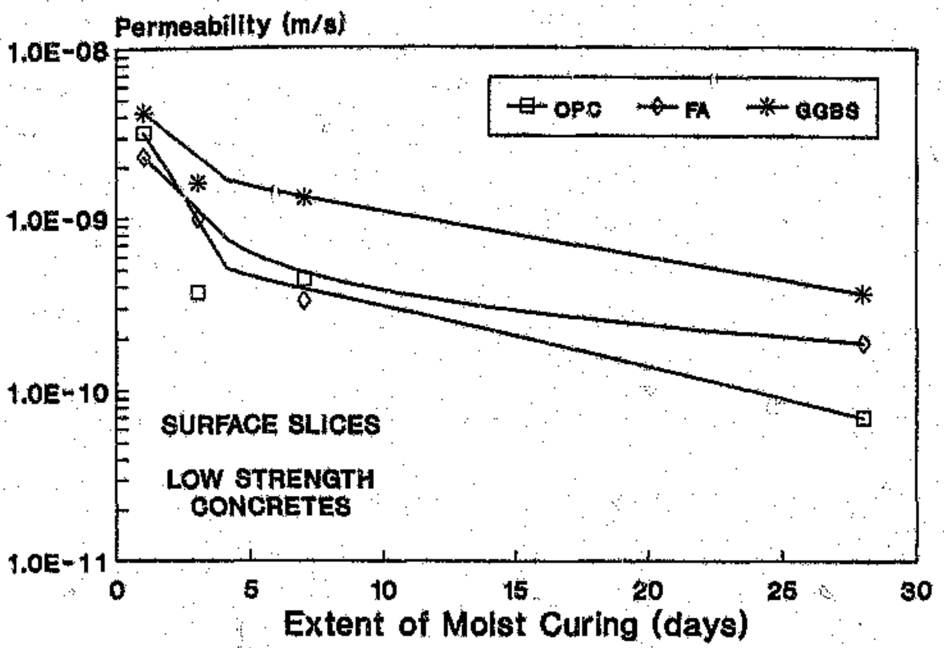

Figure 6.13(a) Trends of permeability responses of the concretes to changes in the duration of moist curing

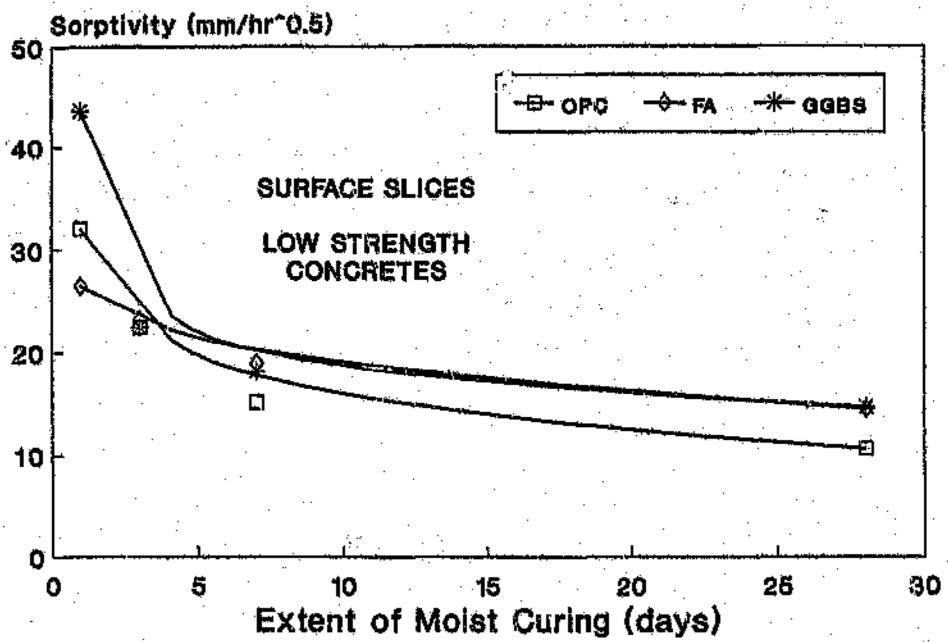

Figure 6.13(b) Trends of sorptivity responses of the concretes to changes in the duration of moist curing

All the concretes show that the durability index values decrease at a decreasing rate as the period of initial moist curing increases. Given the form of the curves shown in Figure 6.13, it was decided to develop an empirical model of the response of the concretes to duration of curing by numerically fitting a regression equation of the form:

$$D_I = A.(T_c)^B \qquad 6.1$$

Where D_I is the durability index value (permeability or sorptivity) and T_c is the duration of early moist curing. The values of A and B are constant for a particular binder type and b/w ratio.

Equation 6.1 can be re-written in linear form as:

$$\ln(D_I) = B.\ln(T_c) + \ln(A) \qquad 6.2$$

Regression analyses were carried out, in which the permeability and sorptivity results of the surface slices were fitted to Equation 6.2. The calculated values of ln(A) and B are shown in Table 6.1 for the permeability measurements and Table 6.2 for the sorptivity measurements. These tables also show the correlation coefficient for each regression analysis. It should be noted that, in all the analyses presented here, the units of permeability and sorptivity are m/s and $mm/hr^{½}$ respectively.

Table 6.1 Equation 6.2 coefficients for the permeability results of the 0-15 mm slices.

Mix Number	ln(A)	B	Correlation Coefficient
P1	-19.863	-1.060	0.949
P2	-20.765	-1.027	0.963
P3	-21.776	-0.687	0.996
F1	-19.974	-0.778	0.976
F2	-20.779	-1.052	0.958
F3	-21.817	-0.781	0.986
S1	-19.363	-0.703	0.987
S2	-20.580	-0.799	0.998
S3	-21.178	-0.606	0.752

Table 6.2 Equation 6.2 coefficients for the sorptivity results of the 0-15 mm slices.

Mix Number	ln(A)	B	Correlation Coefficient
P1	3.454	-0.340	0.994
P2	3.136	-0.264	0.989
P3	3.042	-0.239	0.996
F1	3.303	-0.185	0.993
F2	3.243	-0.348	0.999
F3	2.980	-0.226	0.988
S1	3.620	-0.316	0.940
S2	3.262	-0.248	0.953
S3	2.989	-0.159	0.657

Tables 6.1 and 6.2 that correlation coefficients greater than 0.94 were obtained for most of the concretes tested. The high strength slag concrete shows poor correlation coefficients for both the permeability and sorptivity results because of the (apparently) anomalous results obtained for the 0-15 mm slice after 28 days of curing. It was, however, decided to include this result in the analysis in order to maintain a perspective on the possible extent of deviation between measured and predicted values.

It was found that approximately linear relationships exist between the ln(A) and B coefficients and the b/w ratio of the concretes. Figures 6.14(a), 6.14(b), 6.15(a) and 6.15(b) show these relationships as well as the regression lines fitted to each relationship.

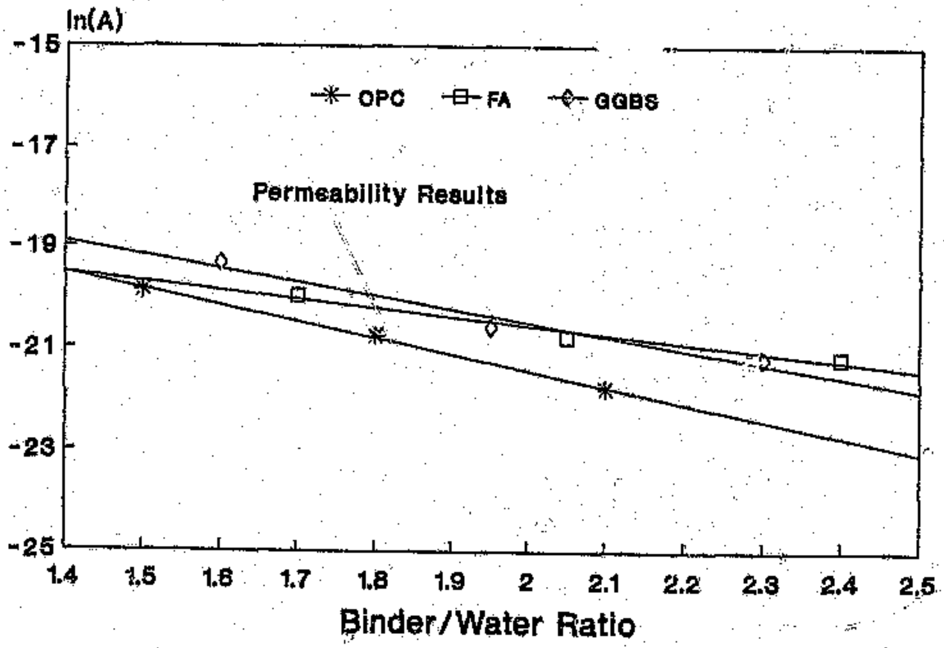

Figure 6.14(a) Relationship between the ln(A) coeff. for the permeability results, and the b/w ratio of the concrete

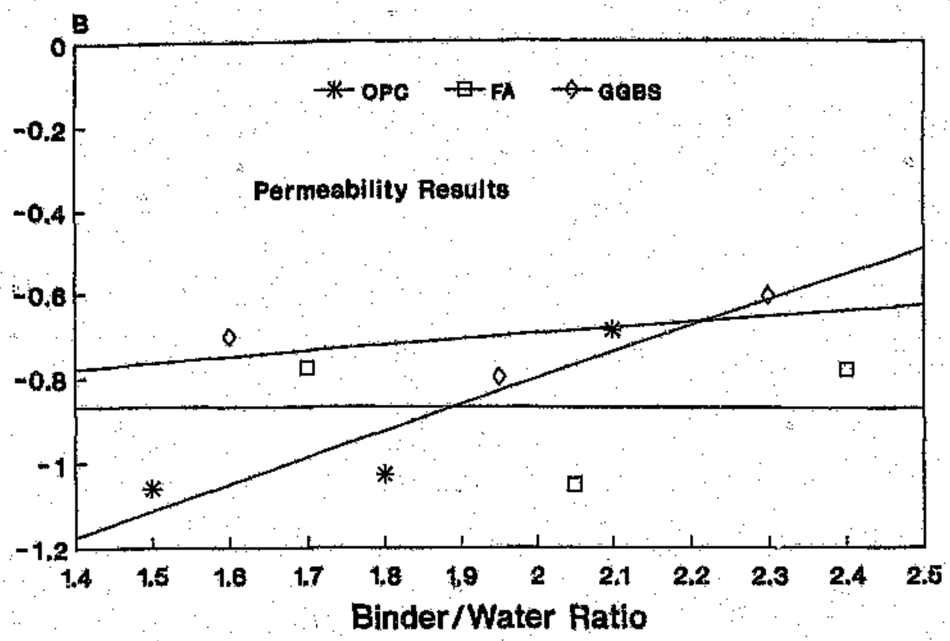

Figure 6.14(b) Relationship between the B coeff. for the permeability results, and the b/w ratio of the concrete

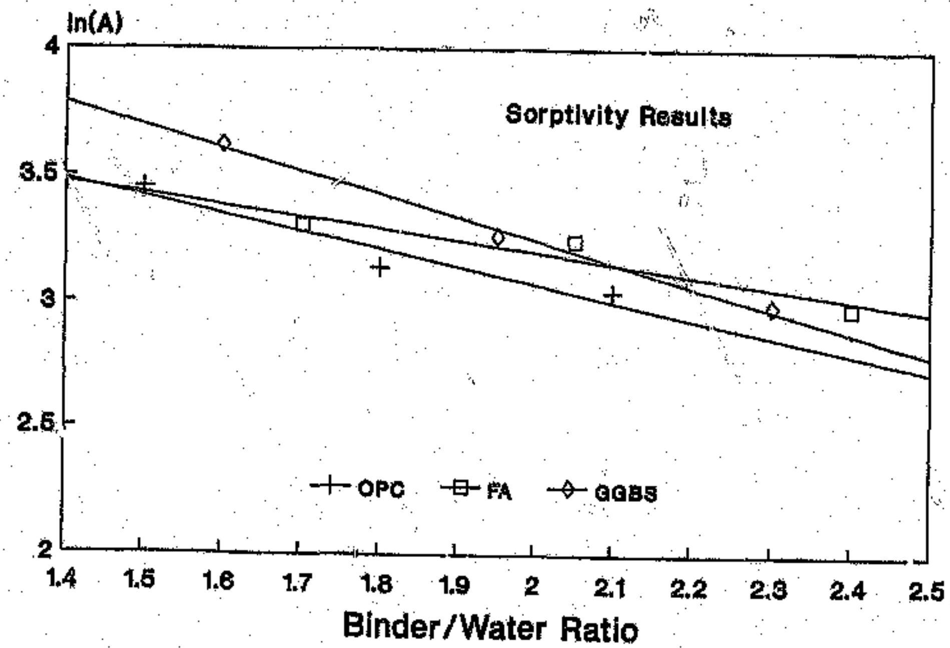

Figure 6.15(a) Relationship between the ln(A) coeff. for the sorptivity results, and the b/w ratio of the concrete

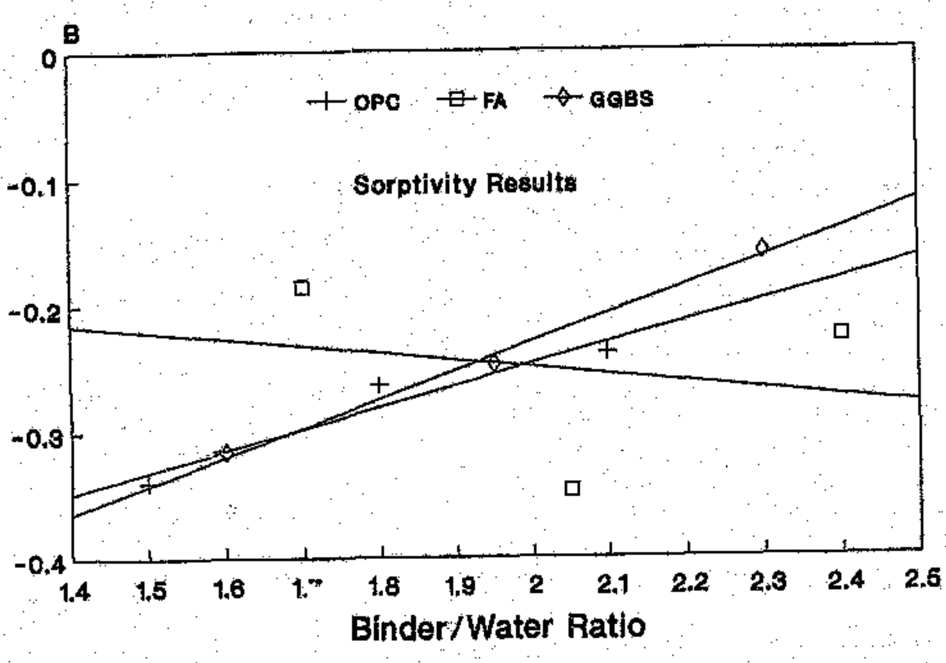

Figure 6.15(b) Relationship between the B coeff. for the sorptivity results, and the b/w ratio of the concrete

For the permeability results, the relationships between the B coefficient and the b/w ratio are not very well defined. However, the linear relationship was accepted in the interest of simplifying the model being developed.

The values of ln(A) and B could therefore be determined from the regression lines in Figures 6.14 and 6.15 based on a knowledge of the b/w ratio of the concrete. Using these regression lines, the model developed for predicting the oxygen permeability and water sorptivity of the concretes can then be expressed as follows:

Oxygen permeability:

$$\ln(k) = B_p.\ln(T_c) + \ln(A_p) \quad 6.3$$

where k is the coefficient of oxygen permeability (m/s) and T_c is the duration of early age moist curing (days). The values of A_p and B_p are determined from Equations 6.4 and 6.5 respectively.

$$\ln(A_p) = \lambda_1.(b/w) + \lambda_2 \quad 6.4$$

$$B_p = \lambda_3.(b/w) + \lambda_4 \quad 6.5$$

The values of λ_1 to λ_4 are dependent on the binder type and are presented in Table 6.3.

Table 6.3 Values of the λ_1 to λ_4 factors for use in Equations 6.4 and 6.5

Factor	Binder type:		
	OPC	70/30 OPC/FA	50/50 OPC/GGBS
λ_1	-3.188	-2.633	-2.644
λ_2	-15.062	-15.459	-15.205
λ_3	0.622	-0.0047	0.138
λ_4	-2.044	-0.861	-0.973

Hence, the model requires controllable parameters of concrete manufacture - b/w ratio, binder type and extent of curing - to predict the coefficient of permeability at 28 days.

Using "circular reasoning", a back calculation was carried out using the model developed above to determine the 28-day permeability of the surface slices of the concretes tested. This was done to determine the effect of the assumptions made in developing the models (for example, the linear relationship between the b/w ratio and the ln(A) and B coefficients). The results of the "predicted" permeability values are plotted against the corresponding measured permeability values in Figure 6.16. The overall coefficient of correlation for the relationship shown in Figure 6.16 is 0.979. This indicates that the assumptions made in developing the model were acceptable.

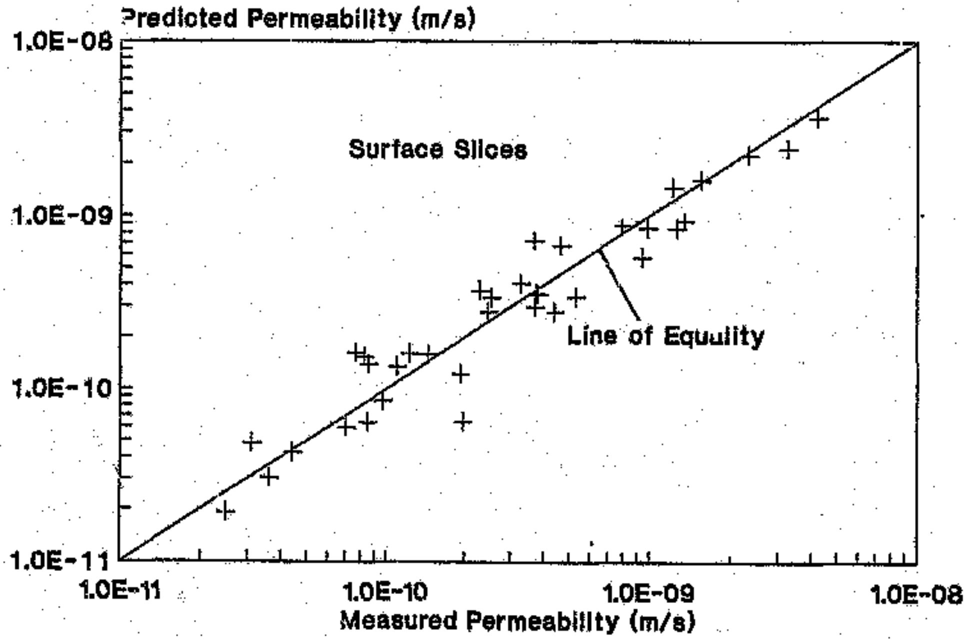

Figure 6.16 Permeability predicted using Equations 6.3 to 6.5 compared with the measured permeability values

Water sorptivity

The model developed for calculating the 28-day sorptivity is similar to that presented above for oxygen permeability. The corresponding equations take the form:

$$\ln(S) = B_s.\ln(T_c) + \ln(A_s) \qquad 6.6$$

where S is the water sorptivity (mm/hr^{½}) and T_c is the duration of early age moist curing (days). The values of A_s and B_s are determined from Equations 6.7 and 6.8 respectively.

$$\ln(A_s) = \lambda_5.(b/w) + \lambda_6 \qquad 6.7$$

$$B_s = \lambda_7.(b/w) + \lambda_8 \qquad 6.8$$

The values of λ_5 to λ_8 are presented in Table 6.3 for the various binder types.

Table 6.4 Values of the λ_5 to λ_8 factors for use in Equations 6.7 and 6.8

Factor	Binder type:		
	OPC	70/30 OPC/FA	50/50 OPC/GGBS
λ_5	-0.685	-0.461	-0.903
λ_6	4.443	4.121	5.051
λ_7	0.169	-0.585	0.224
λ_8	-0.586	-0.133	-0.678

As with the permeability model, a back calculation was carried out to show the comparison between calculated and measured sorptivity values, similar to that shown in Figure 6.16. These results are shown in Figure 6.17 below. The overall correlation coefficient of 0.957 was obtained for the results in this figure, which again shows the acceptability of the assumptions made in developing the model.

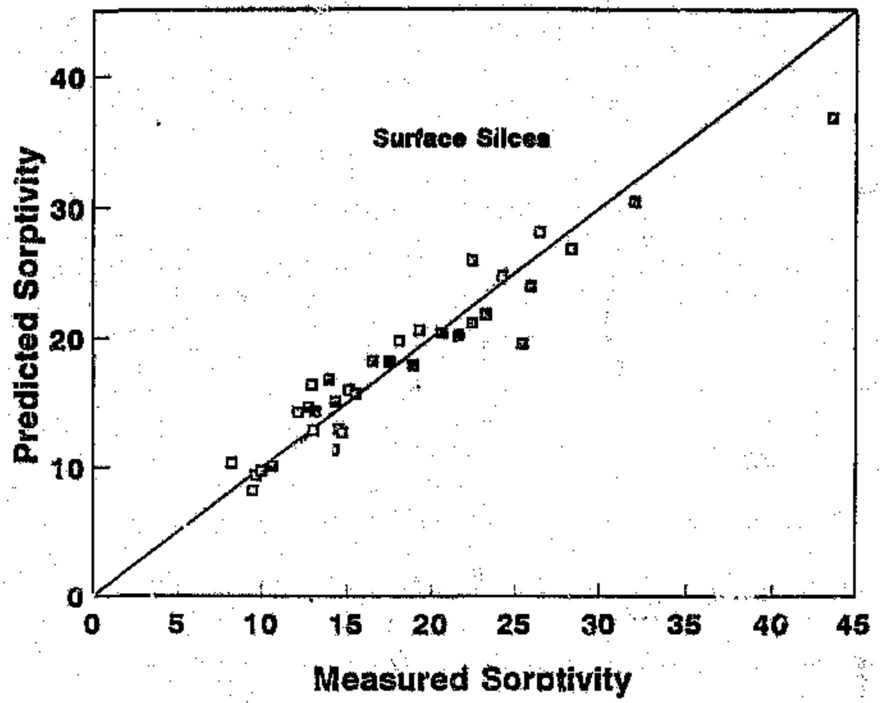

Figure 6.17 Sorptivity predicted using Equations 6.6 to 6.8 compared with the measured sorptivity values

6.4.2 Using the models to determine surface index values

Figures 6.18 and 6.19 show the relationships between b/w ratio and permeability and sorptivity respectively, based on the mathematical models developed above. A family of curves for each binder type is presented to account for the different extents of initial moist curing. The following points are noted from these curves:

Oxygen permeability (ref. Figure 6.18)

- Being a logarithmic relationship, the curves plot as straight lines on the log-linear graphs shown. However, reference to Figure 6.1, shows that the experimental relationships generally decrease at a decreasing rate with increasing b/w ratio. This trend is not reflected in the model and can be considered as a weakness of the model. Nevertheless, this does not detract from the usefulness of the model, since its prediction ability is demonstrated in Figure 6.16. Also, in view of the erratic trends noted in the curves in Figure 6.1, a refinement in the prediction ability of the model (at the cost of a more complex and unweildy model) does not appear to be warranted.

- For a given b/w ratio, the OPC concretes generally give a lower index value than the OPC/FA or OPC/GGBS concretes.
- As observed in Section 6.2.1, the model also shows that, with increasing b/w ratio, the OPC concretes become less sensitive to the extent of initial curing. This is indicated by the changing slope of the curves.
- The OPC/FA and OPC/GGBS concretes have approximately the same sensitivity to the extent of initial curing, regardless of the b/w ratio. This is shown be the approximately parallel curves for these concretes.

water sorptivity (ref. Figure 6.19)

- The OPC concretes again show generally lower index values than the OPC/FA and OPC/GGBS concretes for all b/w ratios.
- The OPC/FA concrete shows approximately the same sensitivity to the extent of initial curing regardless of the b/w ratio. Also, there is a significant improvement in surface sorptivity of the OPC/FA concretes when the b/w ratio is increased, even with 28 days of curing.

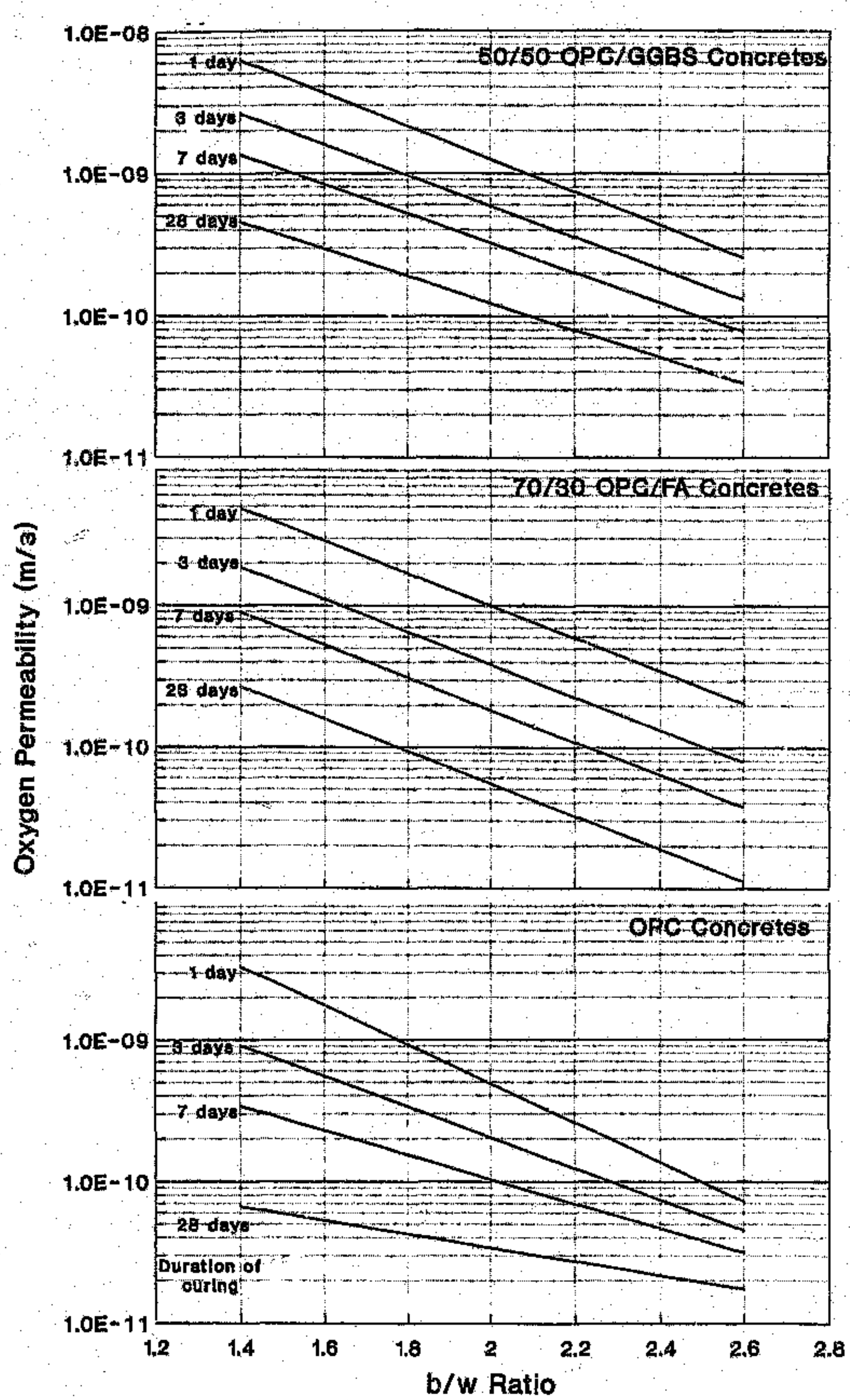

Figure 6.18 Modelled relationship between permeability and b/w ratio for the various concretes

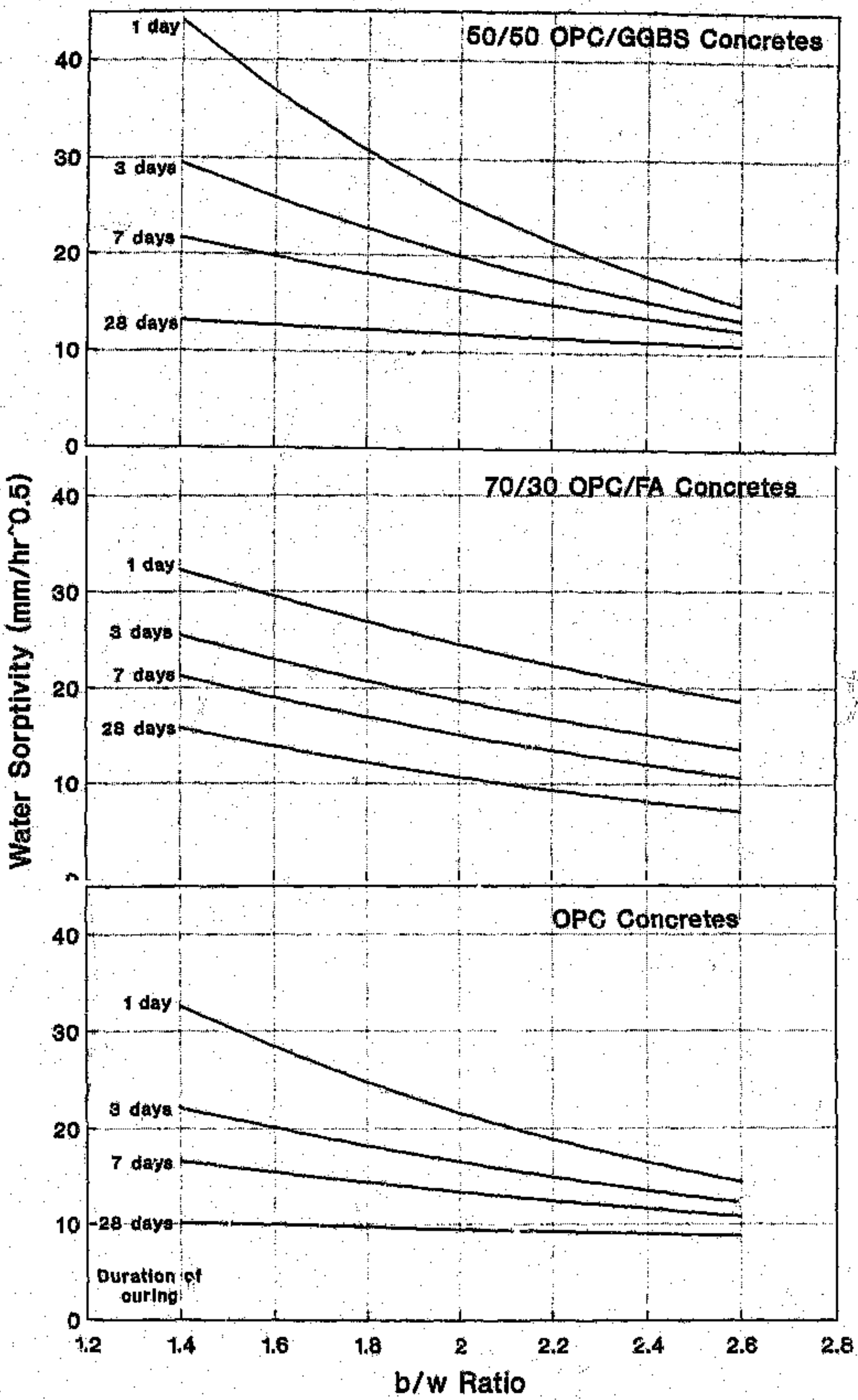

Figure 6.19 Modelled relationship between sorptivity and b/w ratio for the various concretes

- The OPC and OPC/GGBS concretes show a decreasing sensitivity to the effects of initial moist curing as the b/w ratio increases. Also, with 28 days of initial moist curing, the surface concretes become almost insensitive to variations in the b/w ratio.

6.4.3 Variation of durability index with depth from drying surface

As mentioned in Chapter 5, the variation of oxygen permeability with depth into the concrete was found to be erratic and often anomalous. A single function could therefore not be established to describe the relationship between concrete permeability and depth from the drying surface. The problem of sample thickness in relation to maximum aggregate size has prevented a clear representation of this relationship.

In the case of the sorptivity measurements, the results are much less erratic and it was possible to fit regression curves to individual sets of data relating sorptivity to the duration of curing. However, a relationship could not be established across the data sets for depths from the drying surface to account for w/b ratio or compressive strength. Hence, it was decided to present the data graphically instead of in the form of a mathematical model.

The sorptivity results of the internal slices were expressed as percentages of those obtained for the corresponding surface slices. The average percentage was then obtained for samples of the same binder type, curing condition and depth from the surface. These average values are presented in Figures 6.20 to 6.22, where depth form the surface is plotted as the average depth for the individual slices.

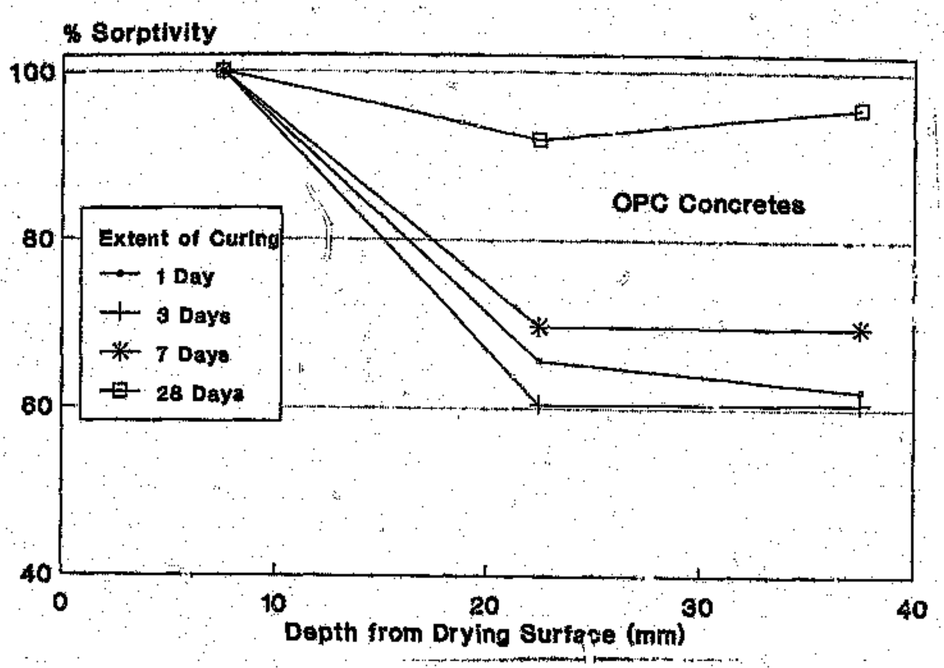

Figure 6.20 Variation of sorptivity with depth from a drying surface - OPC concretes

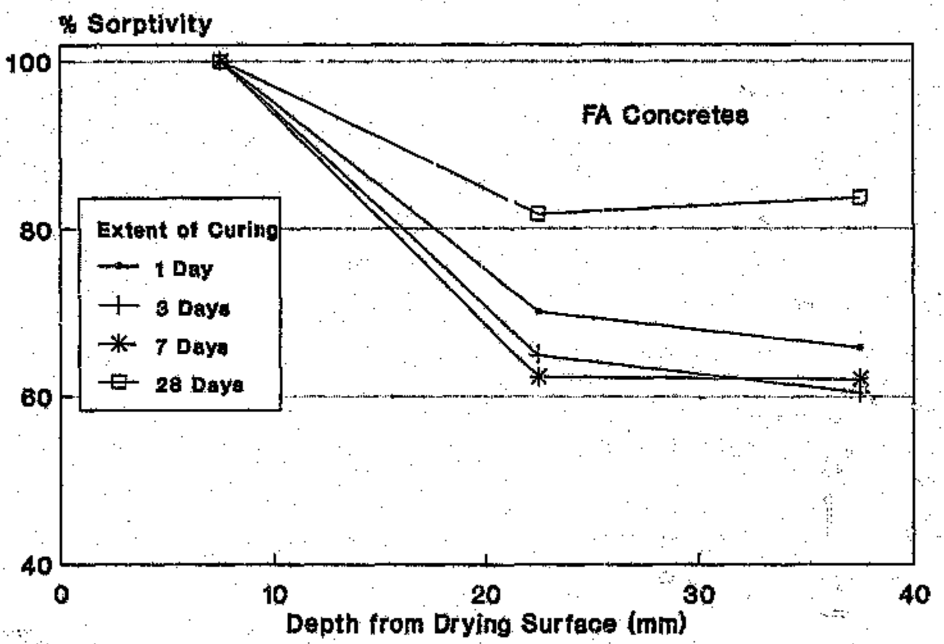

Figure 6.21 Variation of sorptivity with depth from a drying surface - FA concretes

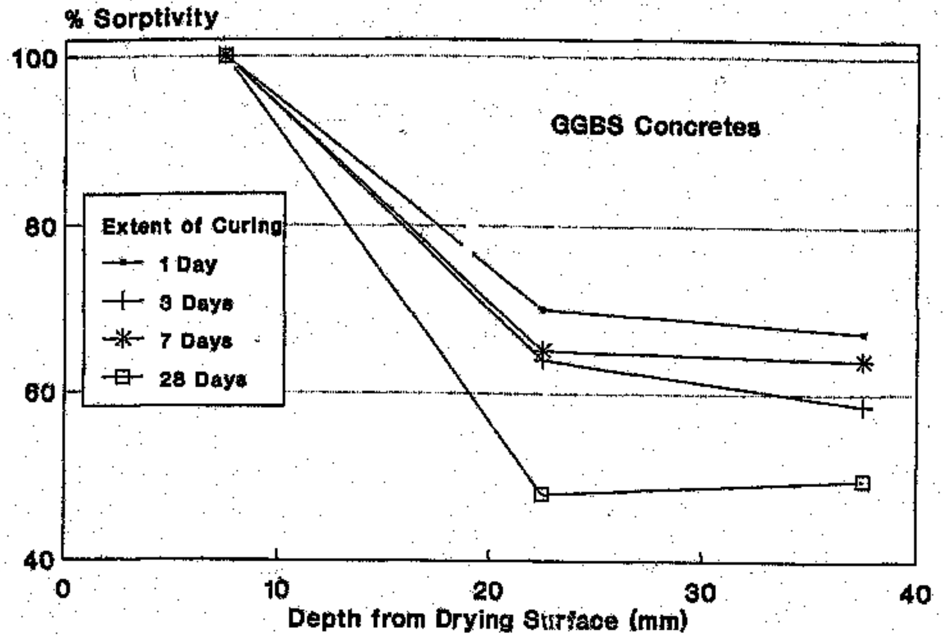

Figure 6.22 Variation of sorptivity with depth from a drying surface - GGBS concretes

The following points are noted from these curves:

- The curves show that, for curing periods up to 7 days, the sorptivity decreases rapidly to approximately 20 mm from the surface, then appears to become uniform with increasing depth.
- Both the FA and GGBS concretes show appreciable reductions in sorptivity with depth from the surface after 28 days of curing. Differences in the porosity values of the surface and internal slices were not large enough to account for this effect. The reason for this observation, as well as its implications will require further investigation.
- There is no fixed order to the percentage reduction in sorptivity to the extent of moist curing. In the case of the OPC concretes, the order of curing duration in increasing percentage reduction is: 28, 7, 1 and 3 days. In the case of

the GGBS concretes, this order becomes: 1, 7, 3 and 28 days.

Nonetheless, the curves provide useful indications of the effect of drying on the gradient of sorptivity with depth into the concrete. Having determined a sorptivity value using Equations 6.6 to 6.8, the numerical variation of sorptivity with depth into the concrete could be estimated using Figures 6.20 to 6.22.

6.5 Relating the Depth of Carbonation to Durability Index Values

Early age permeability and sorptivity measurements of the cover concrete zone serve the purpose of monitoring the effectiveness of curing procedures in developing the properties of this zone of the structure. In this context, the results are used in a relative sense and compared with corresponding results obtained in concretes treated in a standard manner (eg. water cured for 28 days). On the other hand, if these tests are to be used as durability index tests, attempts must be made to relate absolute values of permeability and sorptivity to long-term durability performance of the concrete.

This section shows the relationship between the permeability and sorptivity results, as durability index tests, and the depth of carbonation, as a durability process. An attempt is also made to quantify the effect of different binder types on this relationship.

Since most of the carbonation depths measured were less than 15 mm, it was decided to use the durability index values of the 0-15 mm slice of the samples to develop the relationships. A further reason for this decision was that the models developed above are most reliable for the surface slices.

Figures 6.23 and 6.24 show plots of the measured carbonation depths at 10 months and the 28-day oxygen permeability and sorptivity respectively. The different binder type concretes are identified separately on these curves and the regression lines for each binder type are also shown.

Figures 6.25 and 6.26 show the relationships between the 28-day durability index results and the 20 month depths of carbonation measured on the FA and GGBS concretes. The regression lines are shown on these figures as well.

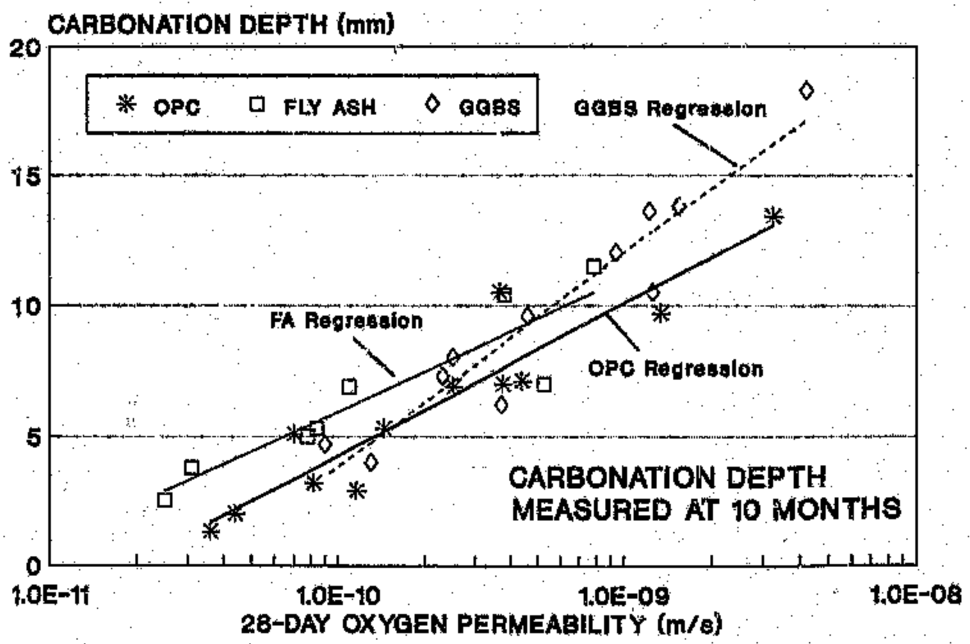

Figure 6.23 28-day surface permeability vs. 10-month carbonation for the three binder types

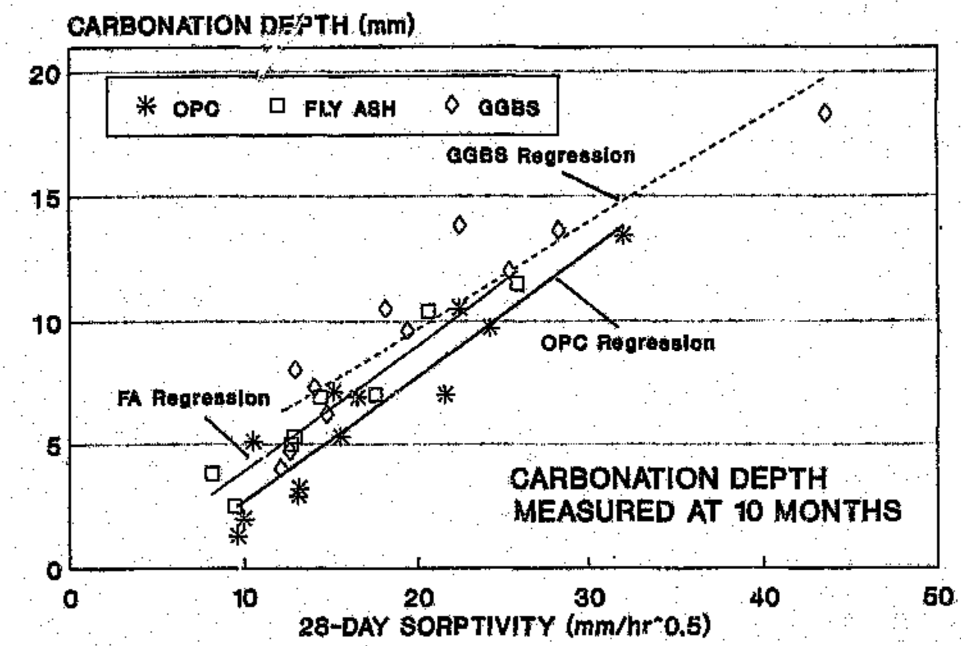

Figure 6.24 28-day surface sorptivity vs. 10-month carbonation for the three binder types

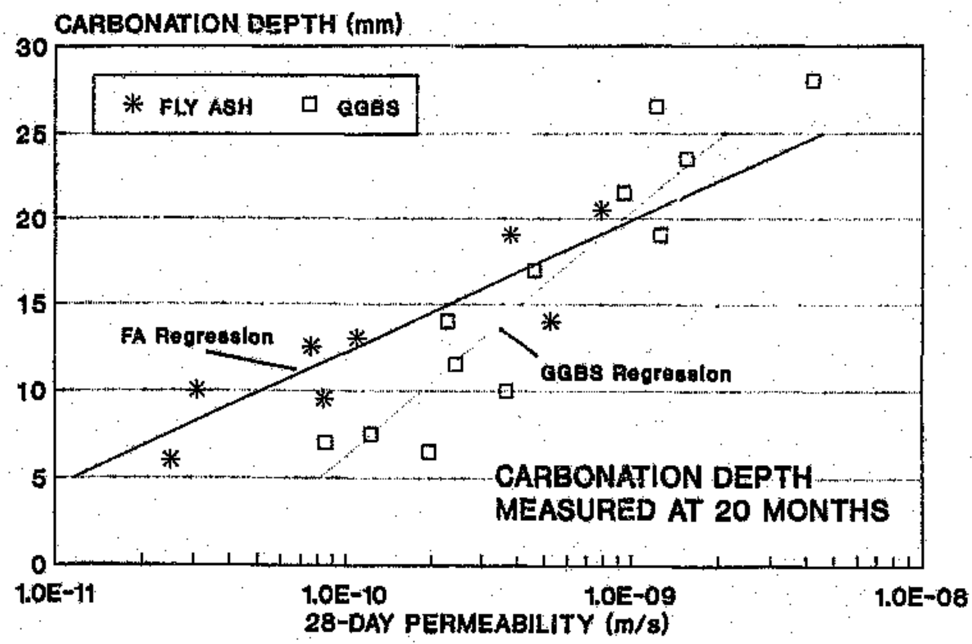

Figure 6.25 28-day surface permeability vs. 20-month carbonation for the three binder types

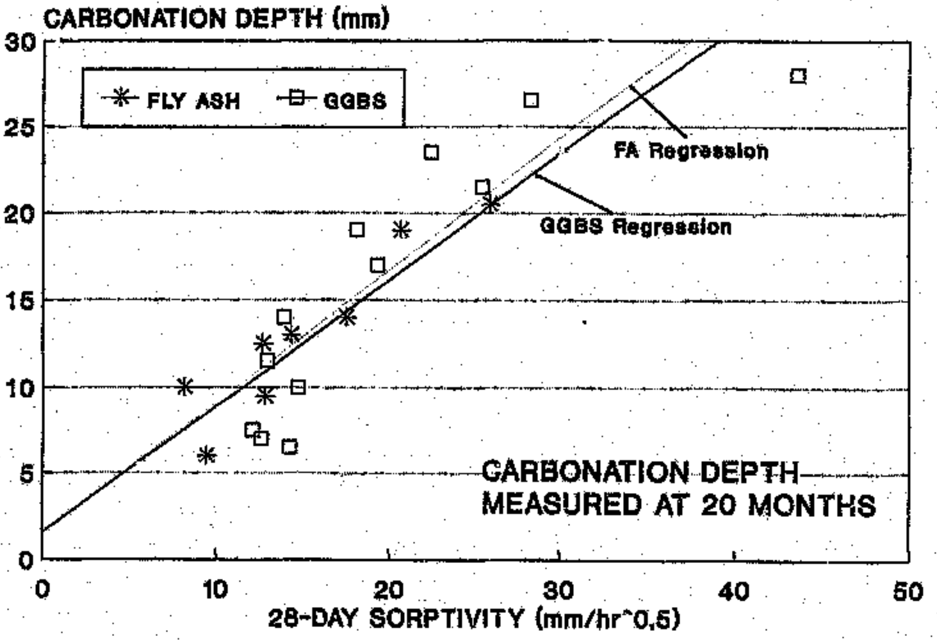

Figure 6.26 28-day surface sorptivity vs. 20-month carbonation for the three binder types

The regression lines take the forms shown in Equations 6.9 and 6.10.

For permeability:

$$x = \lambda_9 . \ln(k) + \lambda_{10} \qquad 6.9$$

for sorptivity:

$$x = \lambda_{11} . S + \lambda_{12} \qquad 6.10$$

where x is the depth of carbonation (mm), k and S are as defined before and λ_9 to λ_{12} are coefficients dependent on the binder type. The values for λ_9 to λ_{12} for both 10- and 20-month carbonation depth measurements are given in Table 6.4.

Table 6.5 Values of coefficients λ_9 to λ_{12} for use with Equations 6.9 and 6.10

Binder Type	λ_9	λ_{10}	λ_{11}	λ_{12}
	For 10-month Carbonation Depth			
OPC	2.514	62.2	0.504	-2.3
OPC/FA	2.317	59.5	0.551	-1.4
OPC/GGBS	3.558	85.7	0.434	1.0
	For 20-month Carbonation Depth			
OPC/FA	3.351	89.3	0.761	1.5
OPC/GGBS	6.162	148.1	0.727	1.6

Table 6.5 shows the correlation coefficients obtained for the regression lines shown in Figures 6.23 to 6.26.

Table 6.6 Correlation coefficients of the regression curves shown in Figures 1 and 2

	Correlation coefficient for the relationship based on:			
	O_2 Permeability		Water Sorptivity	
Binder type	10 mths	20 mths	10 mths	20 mths
100% OPC	0.940	-	0.938	-
70/30 OPC/FA	0.938	0.890	0.965	0.930
50/50 OPC/GGBS	0.954	0.936	0.924	0.866

The correlation coefficients obtained indicate that all the linear relationships developed are significant.

Figure 6.23 shows a clear trend of increasing depth of carbonation with increasing surface permeability. The following points are noted with regard to the regression lines shown:

- The FA line is approximately parallel to and shifted above the OPC line. This indicates that, for the same value of permeability, FA concretes carbonate faster than OPC concretes. This phenomenon can be ascribed to the lower calcium hydroxide content of the FA concrete presenting less reactive material to the advance of the carbonation front.
- The GGBS line is rotated with respect to the OPC line indicating that, for concretes in the high permeability range, GGBS concretes carbonate faster than OPC concretes and vice versa.

Figure 6.24 also shows a good correlation between 28-day sorptivity and the depth of carbonation. Here again, the regression line of the FA results is approximately parallel to and shifted above the OPC line. The GGBS line is rotated with respect to the OPC line but not as markedly as for the oxygen permeability relationship.

In the case of the 20-month carbonation depth measurements, the relationships shown in Figures 6.25 and 6.26, there appears to be a larger scatter in the results. This is reflected in the lower correlation coefficients obtained in the regression analysis of this data. Figure 6.25 shown that a significant difference in the slope of the regression line occurs for the FA and GGBS concretes. This figure indicates that, for equal surface permeability, FA concretes carbonate faster than GGBS concretes in the low range of surface permeability values.

On the other hand, Figure 6.26 shows an almost equal relationship between 28-day sorptivity and 20-month carbonation depth for the FA and GGBS concretes. It must be noted however, that the GGBS concretes showed a much larger scatter of results, as reflected by the lower correlation coefficient.

6.6 Relationship Between the Coefficient of Permeability and Water Sorptivity

An important advantage of the test methods developed is that the permeability and sorptivity tests are conducted using the same sample, nominally at the same age after casting. The two tests can therefore be compared directly in order to establish if a reliable relationship exists between them. If such a relationship exists, it may justifiably be argued that only one of the tests is necessary as a durability indicator.

Figure 6.27 shows a plot of the coefficient of permeability against water sorptivity for the 0-15 mm slices. The regression line shown for this data is described by the equation (S and k are as described above):

$$S = 4.924.\ln(k) + 126.2 \qquad 6.11$$

correlation coefficient = 0.893.

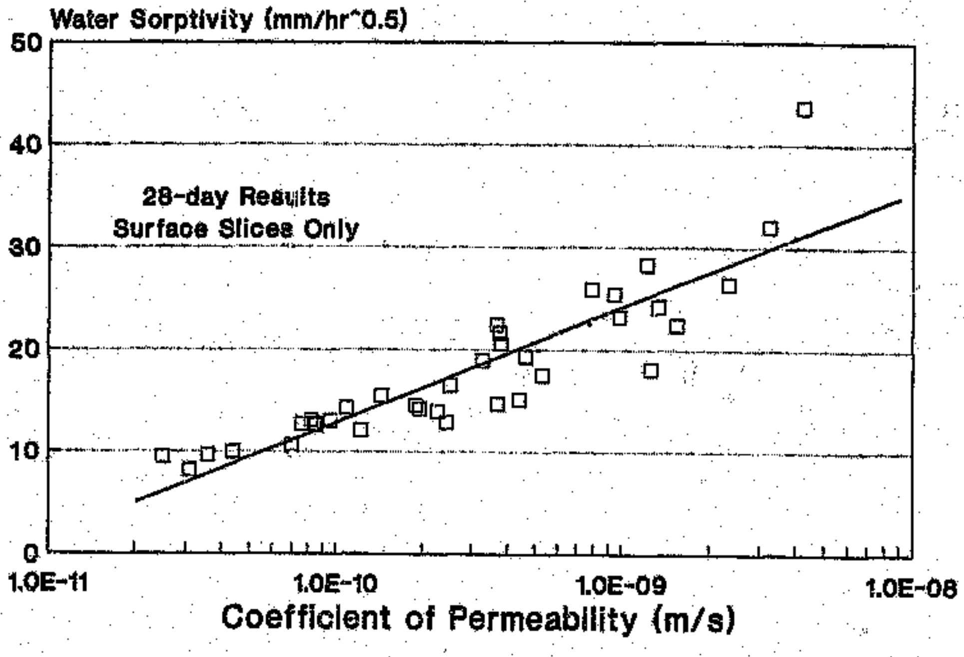

Figure 6.27 Relationship between permeability and sorptivity for the surface slices

Figure 6.28 shows the relationship between the test results of the two test methods for all the samples tested. The regression line for all the samples tested is shown on this graph together with the line obtained for the surface slices only, as shown in Figure 6.27. The overall regression line is described by the equation:

$$S = 3.965.\ln(k) + 101.3 \qquad 6.12$$

correlation coefficient = 0.747.

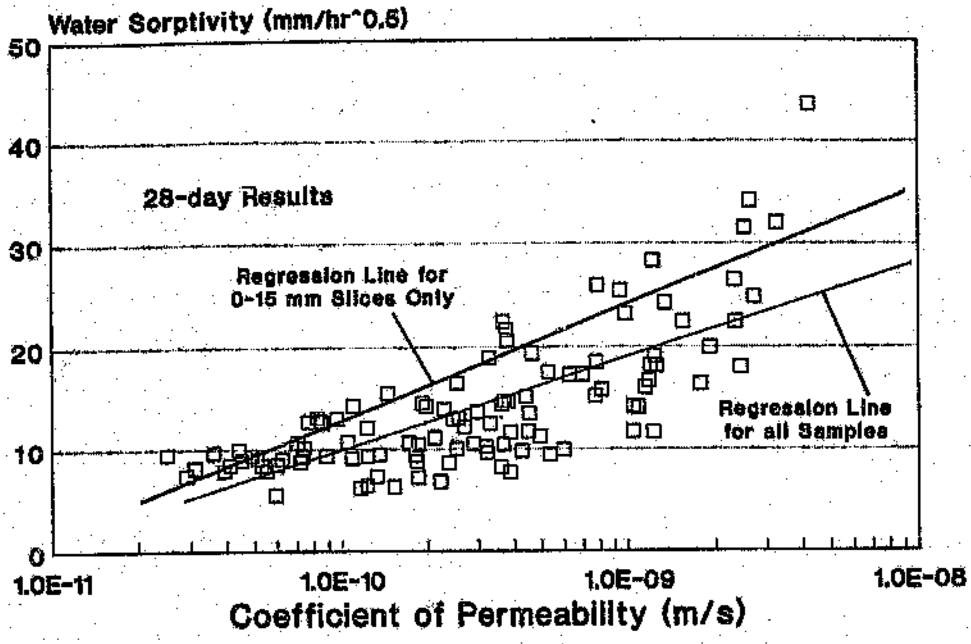

Figure 6.28 Relationship between permeability and sorptivity for all the samples tested

The following points are noted from these results:

- although fairly low, both the correlation coefficients indicate significant relationships between the two test methods because of the large number of data points used in the regression analyses;
- however, despite this, the scatter of results around the regression line for all the results appears to be unacceptably large;
- the relationship for the surface slices is considerably more significant and a much smaller scatter is noted;
- the differences in the correlation curves

indicates that, for the same value of permeability, the sorptivity of the internal concretes is lower than that of the surface concretes - the difference between the two values becomes larger as the coefficient of permeability increases;

It appears that no simple relationship exists between the coefficient of permeability and the water sorptivity of concrete. This is probably due to the fact that different mechanisms of transport are operational for driving the two fluids through concrete. It can be expected that these mechanisms are differently affected by microstructural aspects such as porosity, pore size distribution and the nature and degree of interconnection of pores.

It is felt that this study has not provided sufficient information for one of the test methods to be rejected in favour of the other, with any degree of confidence. It is likely that, depending on the nature of the expected aggressive environment, one of the tests may be a more useful index test than the other. Further research will be necessary in order to finally establish the usefulness of each of these tests as indicators of long-term durability under a wide range of aggressive environments.

6.7 General Discussion

A number of mathematical and graphical models have been developed in this chapter which are aimed at restructuring the results of this project into more usable forms for engineering application. An attempt was made to express the models in terms of controllable parameters such as b/w ratio, compressive strength and extent of curing. In some measure, successful relationships have been developed between these parameters.

However, it must be noted that these models and their relative degree of accuracy of prediction, apply only to the materials and conditions used in the laboratory investigation. Although numerical values have been determined for the various coefficients, it is unlikely that these will be applicable for other concretes in other drying environments.

The usefulness of the models is rather that they show the trends to be expected from the interaction of various parameters and, where applicable, the form of possible empirical equations describing this interaction. The analysis has also shown the relative performance of the different binder types tested.

Since most specifications and codes of practice use b/w ratio and compressive strength as parameters for controlling durability, Sections 6.2 and 6.3 show the effect of these parameters on the 28-day durability index value and, hence, the quality of the cover concrete. Such relationships allow these specifications to be used with greater confidence and reliability.

The empirical relationship developed in Section 6.4, relating the surface durability index to the extent of early-age moist curing appears to describe the results obtained with a good degree of reliability. The model is also able to account for the different response of different binder types to the degree of early moist curing.

The gradient of durability index and hence, concrete quality from a drying surface, was found to be more difficult to model. This was apparent from the erratic nature of the curves in Figures 6.18 to 6.29 as well as the poor relationship between permeability and sorptivity for these depths, as discussed in section 6.6. Further research, which includes an assessment of the durability performance of this internal zone, is required in order to address this issue.

The equations developed for predicting long-term carbonation using early-age permeability and sorptivity tests appear to be reliable in view of the relatively good correlation coefficients obtained. This holds promise for the use of these index-type tests to control durability at the construction stage. Further research must be conducted to assess the usefulness of these index tests in predicting the durability performance of concretes exposed to different drying conditions and different aggressive environments.

6.8 Conclusions

The following conclusions are drawn on the basis of results and discussions presented in this Chapter:

a) Lack of active curing during the early stages of hydration has a marked effect in increasing the permeability and sorptivity of surface concrete for all b/w ratios and strengths tested. This effect is noted for up to 45 mm below the surface of the concrete.

b) For a given curing condition and b/w ratio, OPC concretes generally give lower permeability and sorptivity values than the OPC/FA and OPC/GGBS concretes. Also, for curing periods longer than 3 days, the sorptivity of the cover concrete becomes insensitive to the binder type.

c) For equal compressive strength, the OPC/FA concretes showed the lowest surface permeability for all the early curing conditions tested. Also, for curing periods of 3 days and longer, concretes made with the different binder types show similar surface water sorptivity values. Under these curing conditions, increases in compressive strength have a small effect in decreasing the surface sorptivity of the concretes.

d) Based on the test procedure used in this investigation, the oxygen permeability and water sorptivity of the 0 to 15 mm surface segment of concrete can be predicted from the following equations:

$$\ln(D_i) = B.\ln(T_c) + \ln(A)$$

$$\ln(A) = \lambda_a.(b/w) + \lambda_b$$

$$B = \lambda_c.(b/w) + \lambda_c$$

Where D_i is the durability index (permeability or sorptivity), T_c is the duration of moist curing (days) and λ_a to λ_d are factors which depend on the binder type. For the results of this investigation, the λ factors are given in Tables 6.3 and 6.4. These equations allow the durability index values to be determined on the basis of controllable concrete parameters: b/w ratio and the duration of early-age moist curing.

e) OPC/FA and OPC/GGBS concretes show appreciable reduction in water sorptivity with depth, even after 28 days of water curing. The reason for this is unclear and will require further investigation.

f) The depth of carbonation (x) is related to the durability index values (D_i) as follows:

$$x = \lambda_s . D_i + \lambda_f$$

$$D_i = \ln(k) \text{ for permeability}$$

$$D_i = S \text{ for sorptivity}$$

λ_s and λ_f are constants.

g) For equal surface permeability or sorptivity, OPC concretes carbonate slower than OPC/FA and OPC/GGBS concretes.

h) In this investigation, it was found that the 10- and 20-month depths of carbonation of the OPC/FA and OPC/GGBS concretes could not be related to each other using the conventional square-root relationship. Further investigation is required to confirm these results and perhaps develop a more suitable relationship for the depth of carbonation over time.

i) There appears to be a linear relationship between the sorptivity and logarithm of permeability measured for the samples tested. However, the scatter of the data points is too large and the correlation coefficients too low for this relationship to be established with confidence.

CHAPTER 7

CASE STUDIES

7.1 Introduction

This chapter presents some of the projects in which the durability index test methods developed an discussed in Chapters 3 to 6, were used to address actual construction or specification problems. All the projects presented here involve the use of permeability, sorptivity and/or carbonation testing to determine the performance of in situ structures or the potential performance of proposed concrete mixes.

For various reasons, some of the clients have requested that the projects not be named in this discussion. In these cases, the project is identified by the most important parameter being tested and/or the type of structure being tested.

The following projects are discussed in this Chapter:

a) Cast-in-situ concrete culverts in Namibia: Effectiveness of curing compound.
b) Mzimkulu river incrementally launched bridge on the Natal N2.
c) Slip-formed concrete - Effect of very early exposure of concrete to drying environments.
d) Ready mixed concretes - Durability effect of proposed alternative mixing procedure.

7.2 Cast-in-situ concrete culverts in Namibia: Effectiveness of curing compound

This project involved the durability aspects of concrete to be used for cast-in-situ storm-water culverts under a road. The culverts were expected to be partly submerged in water for considerable periods during the rainy season. Analysis of the water expected to flow through the culverts gave Basson[1] leaching indices between 300 and 380. A leaching index value of 350 is considered non- to mildly aggressive while a value of 1000 is considered very highly aggressive. The values obtained placed the water in the non- to mildly aggressive category and could therefore present a slight leaching problem when in contact with concrete.

7.2.1 Concrete details

The tender documents for the project called for the use of a 70%/30% blend of OPC/FA as the binder for the concrete. However, for economic reasons, the contractor proposed to use rapid hardening portland cement (RHPC) in the following mix:

Cement content:	280 kg/m^3
Water/Cement ratio:	0.68
Admixtures:	Retarding/plasticising
Aggregate:	
Stone:	Crushed dolomite
Sand:	Blend of crushed dolomite and natural sands
Measured 7-day strength:	39.0 MPa.

A question was raised regarding the durability performance of the proposed concrete relative to the requested OPC/FA concrete. After some discussion between the contractor and the client, it was felt that, provided the concrete was adequately cured, the durability performance of the proposed mix in the given environment would be at least equivalent to that of an OPC/FA concrete.

It then became necessary to gauge the effectiveness of the contractor's proposed method of curing, which involved the use of a resin based curing compound. The proposed curing compound was reported to be approximately 5 times better than the minimum requirement of ASTM C309-81[2], currently the only test method used in South Africa for assessing the quality of curing compounds.

The curing method was assessed by testing laboratory samples of the proposed concrete for oxygen permeability and water sorptivity. Details of the test programme are given below.

7.2.2 Laboratory procedure

Sample and curing details

Nine 100 mm cubes were cast by the Portland Cement Institute (PCI) and de-moulded approximately 24 hours after casting. After de-moulding, these cubes were cured in the following manner:

i) three cubes placed in a standard water curing tank for a further 27 days;
ii) three cubes exposed to drying in the laboratory at PCI having had all six faces of each cube coated with the recommended amount (6 m^2/ℓ) of a pigmented, resin-based curing compound.
iii) three cubes exposed to drying in the laboratory at PCI, coated with the same curing compound as above

but using twice the manufacturer's recommended dosage rate (ie. 3 m^2/ℓ).

The coated samples were placed in a room where the temperature was controlled at ±23 °C. These were arranged so that free air movement was allowed around all faces of the cubes. All the samples were transported to our laboratories 28 days after they were cast.

Sample pre-treatment and testing

Upon receipt of the samples, a ±2 mm thick layer was removed from a vertical (as cast) surface of each cube. This was necessary to remove the effect of the curing compound on the test results. For each cube, a 68 mm diameter core was drilled from this surface and a 20 mm thick disk was cut from the core representing a depth of 2 to 22 mm from the surface of the sample. These disks were then pre-treated and tested for oxygen permeability and water absorption as described in Chapter 5.

7.2.3 Results and discussion

Table 7.1 presents the average of three results obtained of the oxygen permeability and water absorption tests. This table shows that the durability properties of concretes cured using the curing compound are considerably lower than that of the concretes cured for 28 days under water. However, the 28-day water cured values should be seen as "ideal", control test values which would not normally be obtainable in-situ.

It was expected that the 28-day water cured strength of this concrete would be approximately 45 MPa. These results were therefore compared to those obtained for the P2 concretes at 28 days. By setting the 28-day index values to 100% and linearly interpolating where necessary, it was possible to obtain estimates of the equivalent duration of water curing for the curing compound coated samples.

Table 7.1 Results of Oxygen permeability and water sorptivity tests

Curing Method	Average Coeff. of Permeability ($x10^{-10}$ m/s)	Average Water Sorptivity ($mm/hr^{½}$)
Water cured for 28 days	0.38	8.85
Double coat of curing compound	1.36	12.94
Single coat of curing compound	1.96	14.75

These estimates are presented in Table 7.2 below. The estimated periods of water curing provides a measure of the efficiency of the curing compound treatments. Figure 7.1, presented by Ballim et al[3], shows how the estimates were obtained.

Table 7.2 shows that the single coating of curing compound provides the same development of concrete surface properties as approximately 3 days of water curing while a double coating is equivalent to 5 days of water curing. Given that the concrete intended for use on the project will contain RHPC, it is reasonable to expect the equivalent of three days of water curing on site. The high rate of initial hydration of the RHPC means that it can tolerate shorter curing periods than plain OPC or OPC/fly ash blends, for which a minimum of 5 days of water curing is recommended[4].

Table 7.2 Equivalent water curing period of the curing compound treated samples.

Curing method	Estimated equivalent water curing period (days) based on:		Average equivalent water curing period (days)
	Permeability results	Sorptivity results	
Single coat of curing compound	3.6	2.8	3.2
Double coat of curing compound	5.2	5.2	5.2

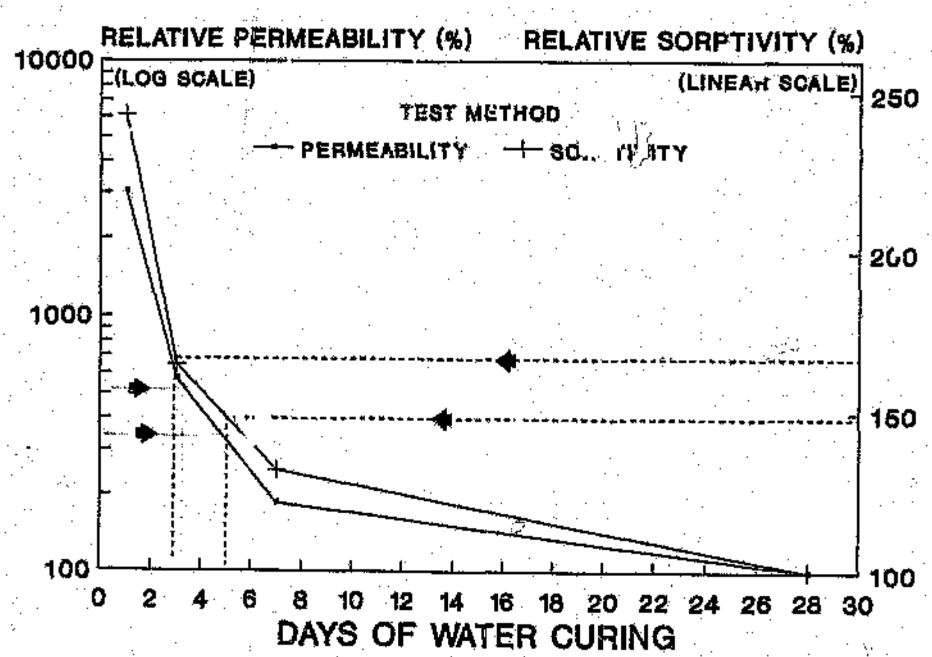

Figure 7.1 Method of estimating the equivalent water curing duration of the curing compound coated samples (after Ballim et al[3])

To give an indication of the durability implications of the results in Table 7.1, estimates of the carbonation rates for the single and double coated concretes using Figures 6.23 and 6.24 in Chapter 6. For comparison, an estimate of the carbonation rate of an OPC/fly ash concrete of the same surface permeability as the single coated concrete is also presented. These estimates are shown in Table 7.3, where the value D is the carbonation coefficient used in the square root equation relating depth of carbonation to time of exposure.

The results shown in Chapter 5 indicate that, for equal strengths, a 70/30 OPC/FA mix gives lower permeability than a plain OPC mix. However, if the plain OPC is replaced with RHPC, it can be expected that the increased fineness of the binder will result in permeability values similar to the OPC/FA mix. Hence, the comparison with the OPC/FA concrete in Table 7.3 is based on equal permeability values.

The reason for the higher rate of carbonation of the OPC/FA concrete is that it has a lower concentration of calcium hydroxide in the pore structure and the carbonation front can therefore move at a greater rate. This lower calcium hydroxide concentration derives from the lower OPC content and the fact that calcium hydroxide is consumed by the pozzolanic reaction of the fly ash.

The estimates presented in Table 7.3 were intended to give an indication of relative durability performance and were not meant to imply that an equivalent rate of carbonation should be expected in situ. The actual carbonation rate would strongly be affected by the environmental exposure conditions.

Table 7.3 Estimated rate of carbonation for the curing compound treated concretes and an equivalent OPC/fly ash concrete.

Concrete Details	D mm/(month)$^{1/2}$	Time to Carbonate to 45 mm Depth (years)
Double coat of curing compound	1.771	54
Single coat of curing compound	1.992	42
OPC/FA concrete with same 28-day permeability single coated concrete	2.214	34

7.2.4 Summary of findings

The following important points were raised by this investigation:

a. With the application of the resin-based curing compound, the proposed RHPC concrete can be expected to provide a similar degree of resistance to deterioration as the OPC/FA concrete.

b. The ASTM C309[2] test does not appear to be a reliable measure of the effectiveness of curing compounds. The curing efficiency of the compound tested is considerably lower than would be expected, given the performance of the material in the ASTM test.

c. Durability index testing of concrete, in the form of surface permeability and sorptivity, gives a direct measure of the effectiveness of a curing compound in developing the surface properties of concrete. The good agreement in the predictions of the effective duration of moist curing is encouraging from the point of view of the usefulness of these tests.

d. Some of the comparisons made in this study may require further clarification since RHPC was used as the binder in the samples. However, there is sufficient evidence to warrant further research into characterising the effectiveness of curing compounds.

7.3 Mzimkulu River Incrementally Launched Bridge on the Natal N2

The Mzimkulu river bridge at Port Shepstone forms part of the extension and upgrading of the N2 freeway on the Natal South coast. The proximity of this structure to the ocean gave rise to some concern on the part of the design engineers regarding the long term durability of the in situ concrete. The concern derived mainly as a result of the relatively short periods over which some of the concrete sections were held in the shutters - reported to be between 2 and 5 days.

The bridge deck was constructed using the incrementally launched technique and Figure 7.2 shows an early stage in the launching of one side of the deck. Figurr 7.3 shows the row of piers looking northwards across the river.

In order to quantify the extent of the problem, it was decided to undertake a series of tests measuring the potential durability of the concrete. These tests would inform a decision on whether or not it was necessary to apply a protective coating to the concrete in order to improve the long term durability.

Figure 7.2: Early stages of the bridge [illegible]

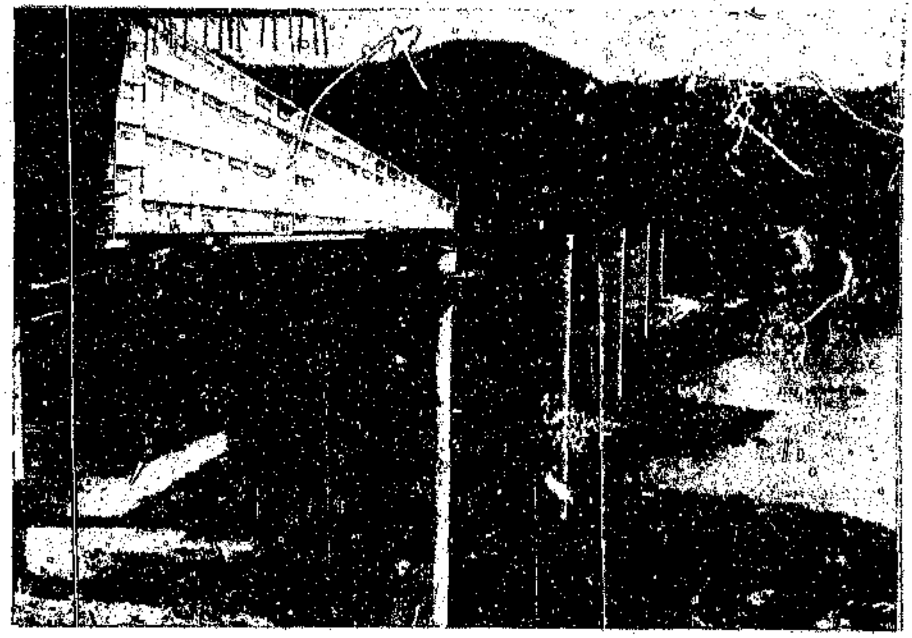

Figure 7.3: View of the piers looking Northwards across the river

Samples retrieved from the structure were tested for strength and surface oxygen permeability, water absorption and carbonation. At the time of testing,

Figure 7.2: Early stages of the bridge deck launch

Figure 7.3: View of the piers looking Northwards across the river

Samples retrieved from the structure were tested for strength and surface oxygen permeability, water absorption and carbonation. At the time of testing, concrete samples from the piers were between 6 and 24 weeks old while those from the deck were 18 days old.

7.3.1 Description of the samples

Test samples consisted of 100 mm diameter cores drilled from the structure. The lengths of the cores varied between 260 mm and 300 mm. All the cores were kept moist durir · transport by being wrapped in wet geo-fabric and placed in plastic bags. Table 7.4 gives physical details of the cores as received. The areas of concrete to be cored were selected by the resident engineers on site. Three cores were taken from each of the piers and 4 cores were taken from the web of the deck.

The concrete appeared to be of a fair quality with only a few compaction voids visible on the surface. All the cores were obtained from the pier walls and side web of the deck and therefore had off-shutter top surfaces.

Table 7.4: Physical Condition of the Cores as Received

Core Group	Location	Observations/Comments
AS 1/2/3	3 cores, 1st pier, South side	Good compaction; reinf. bar in AS3; cover depth = 47 mm.
BN 1/2/3	3 cores; 2nd pier; North side	Concrete well compacted; few small pores evenly distributed; no reinforcement present.
CS 1/2/3	3 cores; 3rd pier; South side	Larger stone size than AS, BN and ES cores; many ±1 mm pores visible on the surface; no reinforcement encountered.
CN 1/2/3	3 cores; 3rd pier; North side	As for CS samples with less surface porosity; reinforcement bars through each core; cover depths as follows: CN1 = 43 mm, CN2 and CN3 = 37 mm
ES 1/2/3	3 cores; 5th pier; South side	As for AS concrete; no steel reinforcement encountered.
IW1/2/3/4	4 cores; inland side; web of deck	Few compaction voids ranging from small to 10 mm. Approx. 2.5 days in formwork.

7.3.2 Sample Preparation

The cores received were cut into three segments: (i) 0 to 60 mm, (ii) 60 to 170 mm and (iii) 170 to 210 mm measured from the exposed surface. Where a reinforcement bar was encountered in the core, the first segment was reduced to 0 to 35 mm.

The 0 to 60 mm and 170 to 210 mm segments were cored to obtain 68 mm diameter cores. 20 mm thick test slices were then cut from these cores to represent depths of 0 to 20 mm, 20 to 40 mm and 170 to 190 mm into the concrete measured from an exposed surface. Some of the samples had to be abandoned because of the presence of reinforcement.

The two ends of the 60 to 170 mm segments were planed on a high speed facing machine to ensure that they were parallel to each other. These segments were then stored in a standard curing tank for three days before being tested for compressive strength.

7.3.3 Test methods and procedure

The three 20 mm slices obtained from each core were dried for 7 days in a ventilated oven controlled at 50 °C. These samples were then tested for oxygen permeability and water absorption as described earlier.

After the water absorption test, the 0 to 20 mm slices were broken along a diameter and the depth of carbonation was determined by spraying a 1% phenolphthalein in alcohol solution onto the broken surface.

The approximately 110 mm high core segments were tested for compressive strength in an Amsler compression testing machine with a 2000 kN capacity. A sheet of soft board was interposed between the loading platens and the ends of the test cylinders. This was done to eliminate any eccentricity which may have been introduced by the ends of the cylinders not being perfectly parallel to each other.

7.3.4 Results and Discussion

Compressive strength: Table 7.5 shows the results of the compressive strength tests carried out on the cores. The density values shown in this Table are "apparent" densities, calculated on the basis of saturated surface dry weight, measured to an accuracy of 5 g. It should be noted that no correction factors have been applied to the strength results presented in Table 7.5.

The results show that all the strengths were greater than 30 MPa. For the piers, the average strength of the concretes is 35.1 MPa with individual in the range 30.6 MPa to 39.2 MPa. The apparent density results are also fairly uniform for all the samples.

Table 7.5: Average Results of Sample density and Compressive Strength Tests

Sample group	Density (kg/m^3)	Strength (MPa)
AS	2357	33.9
BN	2393	36.5
CS	2411	34.1
CN	2392	38.1
ES	2382	32.8
IW	2403	44.5

Permeability, sorptivity and carbonation tests: Results of the oxygen permeability and water sorptivity for the various slices tested are shown in Table 7.6. The measured depths of carbonation are also shown in this table.

The results presented in Table 7.6 show that sections of the bridge have suffered reduced long term durability potentials as a result of inadequate curing. This is indicated by the higher durability index values at the surface of the samples than on the inside samples. Of particular concern are the sections represented by the AS, CS, ES and IW samples.

As an indication of the durability effect of the reduced surface quality, sample group AS showed 7.5 mm of carbonation 6 months after casting. Using the $\sqrt{t}$ relationship for the rate of carbonation and assuming that the specified 40 mm of cover depth has been satisfied, the steel in this area will be de-passivated after 14 years. This illustration assumes that carbonation will be the only action leading to de-passivation of the steel.

Table 7.6: Average Results of Oxygen Permeability Coefficier ., Water Sorptivity and Carbonation Depth Tests

Core Group	Age at test (months)	Oxygen Permeability ($x10^{-10}$ m/s) at depths:			Water Sorptivity ($mm/hr^{1/2}$) at depths:			Depth of carbonation (mm)
		0 to 20 mm	20 to 40 mm	180 mm	0 to 20 mm	20 to 40 mm	180 mm	
AS	6	11.3	4.6	0.8	17.6	8.4	7.4	7.5
BN	4	4.3	1.9	1.3	8.3	9.2	8.3	2.1
CS	2	6.4	4.5	4.2	15.0	8.8	7.7	3.5
CN	2	1.9	2.1	2.9	9.4	6.2	6.1	3.0
ES	6	18.4	8.0	1.3	6.9	10.7	8.1	3.0
IW	0.6	4.0	1.9	0.3	10.9	7.2	6.8	–

It is interesting to note the lack of relationship between the compressive strength of the internal concrete and the durability properties of the cover concrete. This again points to the retarded development of properties of the cover concrete resulting from inadequate curing.

An in-situ carbonation investigation showed that it was mainly the first lifts of some of the piers which were of particularly low quality. This was accompanied by porous surface areas at the interfaces between casting lifts. The porous areas were caused by loss of grout from the shutters.

While the surface index value for the deck web samples is not unduly high, the values obtained for the internal slices show that an increased duration of curing would improve the potential durability of the surface concrete. However, the duration of early-age curing was dictated by the deck jacking cycle, which was approximately 2.5 days. Hence, the formed surfaces of the deck were exposed to air drying 2,5 days after casting.

7.3.5 Recommendations

The following recommendations were made for improving the potential durability of the structure:

Bridge Piers
It was proposed that the first lifts of piers AS, CS, ES and be coated with a proprietary sealant which would reduce the access of gases and dissolved ions into the cover concrete. If partial coating presented a problem with regard to the aesthetics of the structure, consideration would have to be given to "concrete

coloured" coatings or colourless surface penetrant materials. Technical aspects were to be discussed with the manufacturers of these products.

It was stressed that the porous zones noted on some of the piers and in particular, at the joints between successive lifts were to be sealed and made good. It was recommended that an epoxy based mortar be used for this purpose. Again, the choice of the most appropriate sealant was to be made after consultation with the suppliers of these materials.

The depth of carbonation of the concrete was to be monitored continuously, especially on the piers cast during the investigation. The site personnel had sufficient experience with the phenolphthalein test to conduct the carbonation monitoring tests. A decision could then be made as to the need for coating on other sections of the piers on the basis of the measured rate of carbonation. It was possible that a final decision could have been taken on this aspect by the middle of 1992.

Bridge deck

It was recommended that, as a section of the deck is jacked forward, the newly exposed concrete be coated with a curing compound. This would ensure that the first 20 mm of the cover concrete develops a sufficient degree of impermeability to obviate the need for subsequent protective coating to be applied to the underside of the deck.

The application of the curing compound would possibly interfere with the dressing operation carried out by the contractor. However, where it was necessary to carry out minor repairs or when rubbing down was required, the affected area of concrete could be re-coated with curing compound after the dressing operation. It was also pointed out that cementitious coatings and repairs do not adhere to most curing compounds. If such coatings were to be applied, the requirements of the curing compound would have to be discussed with the supplier.

7.4 CASE 3: SLIP FORMED CONCRETE: EFFECT OF VERY EARLY EXPOSURE OF CONCRETE TO DRYING ENVIRONMENTS

7.4.1 Introduction

This investigation was aimed at comparing the effectiveness of a wax-based curing compound on plain OPC concrete and concrete made with blends of OPC and GGBS. The concretes tested were to be used in a slip-formed construction project and were therefore to be exposed to drying conditions at approximately 5 hours after casting. The investigation was therefore aimed at informing a decision on the use of GGBS in the concrete for this project.

Concrete samples were prepared and stored in the laboratory under three conditions:

- exposed to air drying 5 hours after casting and coated with curing compound;
- exposed to air drying 5 hours after casting - uncoated;
- water cured for entire period.

The mass change of the air dried samples was regularly monitored up to 28 days after casting. At 28 days after casting, surface segments of the concretes were tested for oxygen permeability and water sorptivity in order to determine the effectiveness of the curing compound on the different concrete types.

7.4.2 Mixes and materials

Table 7.7 below shows the mix proportions of the 5 concretes tested. Mix 1 was the plain OPC control mix and mixes 2 to 5 consisted of blends of OPC and GGBS. A 50% blend proportion was used for mixes 2, 3 and 5 while Mix 4 contained 40% GGBS. Table 1 also shows the measured slump of each mix. All the solid materials, the water reducing admixture and the white pigmented, wax based curing compound used, were the materials intended to be used in the structure.

Table 7.7: Mix proportions (kg/m^3) and slump measurements of the concretes tested

Material	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Water	170	170	170	160	165
Slagment	-	160	170	128	160
OPC	320	160	170	192	160
Vaal river sand	525	525	509	527	525
12 mm - dust Dolomite	525	525	525	525	525
19 mm Dolomite stone	975	975	975	975	975
Admixture (ml/m^3)	800	800	800	800	400
Measured slump (mm)	50	145	95	35	55

7.4.3 Laboratory procedure

Sample preparation and moisture loss measurements
Nine 100 mm cubes were cast using each of the mixes shown in Table 1. These cubes were de-moulded and exposed to their respective curing regimes in the

following manner:

(a) three cubes were de-moulded at 5 hours after casting and exposed to air drying in the laboratory;

(b) three cubes were de-moulded 5 hours after casting, coated with curing compound and exposed to air drying in the laboratory;

(c) three cubes were de-moulded after approximately 18 hours and placed in a standard water curing bath up to 28 days after casting.

The following procedure was used for the cubes exposed under conditions (a) and (b):

- At 5 hours after casting, carefully remove the side faces of the cube mould so as not to damage the surface of the concrete. This was best achieved by sliding the individual mould plates upward against the concrete surface.
- Weigh the cube on its base plate to the nearest 0.1 g.
- Immediately coat the 5 exposed surfaces of the cube with curing compound by splashing the curing compound from a standard 50 mm paint brush.
- Wipe off any excess curing compound from the base plate of the mould and weigh the cube and base plate to determine the mass of curing compound applied.
- Place the cube on the North window ledge in the laboratory exposed to sunlight during the morning only.
- Weigh the cube and base plate approximately 15 hours after casting, then remove and weigh the base plate.
- Coat the underside of the cube with curing compound and re-weigh the cube. Place the cube

back on the window ledge.

- Weigh the cube at regular intervals and, while keeping the cube in the as-cast orientation, rotate the cube with respect to the direction of sunlight at each weight determination.
- Coat a sheet of glass of known surface area with the stated amount of curing compound and expose this alongside the cubes. Weigh the glass regularly to determine the mass loss of the curing compound.

The manufacturer's specification required that the curing compound be applied at a rate of 5 m^2/ℓ. It was found that, at 5 hours after casting, the side faces of the cubes were not able to hold this amount of compound and a second coat of compound was applied after the base plate was removed on the day after casting.

As stated above, the cubes were exposed indoors to morning sunlight only. At approximately 12h30 each day, a black plastic sheet was placed over the windows so as to eliminate direct sunlight onto the cubes.

Oxygen permeability and water sorptivity tests:
At 28 days after casting, a 68 mm diameter x 25 mm thick disk was obtained from a side face of 8 of the cubes of each mix tested (3 coated, 3 uncoated and 2 water cured). These disks, representing the 0 to 25 mm surface section, were tested for oxygen permeability and water absorption as described in earlier chapters. These tests were conducted in order to monitor the effect of the different curing regimes on the development of the surface quality of the concretes. The outside face of the samples which had been coated with the curing compound was lightly rubbed with sand paper to remove approximately 1 mm of the surface.

Compressive Strength:
For each mix, one of the water cured cubes was used to obtain an indication of the 28-day compressive strength of the concrete.

7.4.4 Results and discussion

Sample moisture loss
Using the curing compound on the glass slide, it was determined that the curing compound lost approximately 90% of its mass after 6 hours of exposure in the laboratory. The mass of the compound remained stable thereafter. This correction was applied to the mass loss measurements obtained for the coated samples. Figures 7.4 and 7.5 show the average mass loss of the coated and uncoated samples respectively.

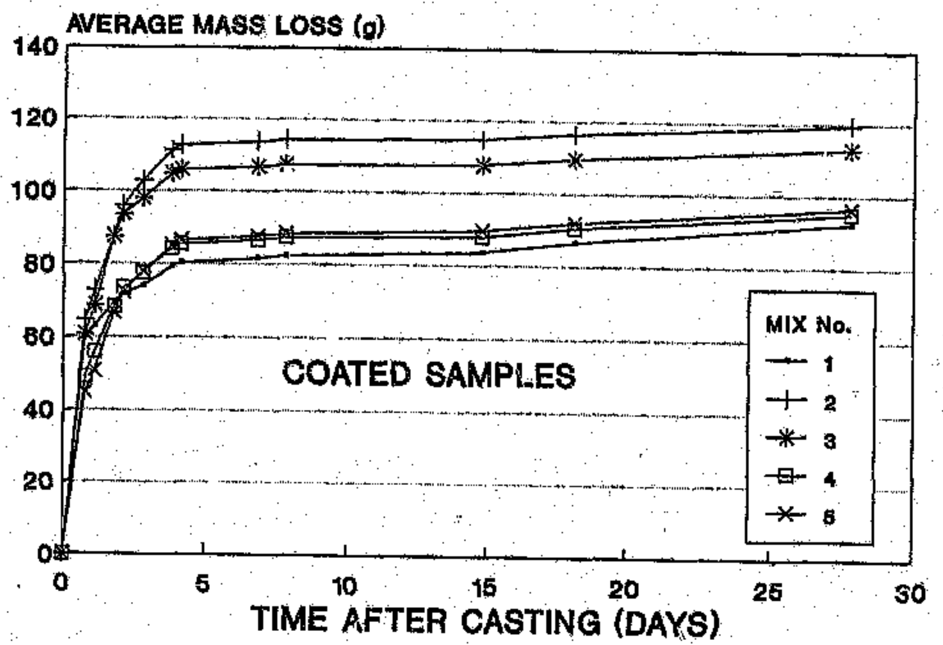

Figure 7.4: Average mass loss of the curing compound coated samples

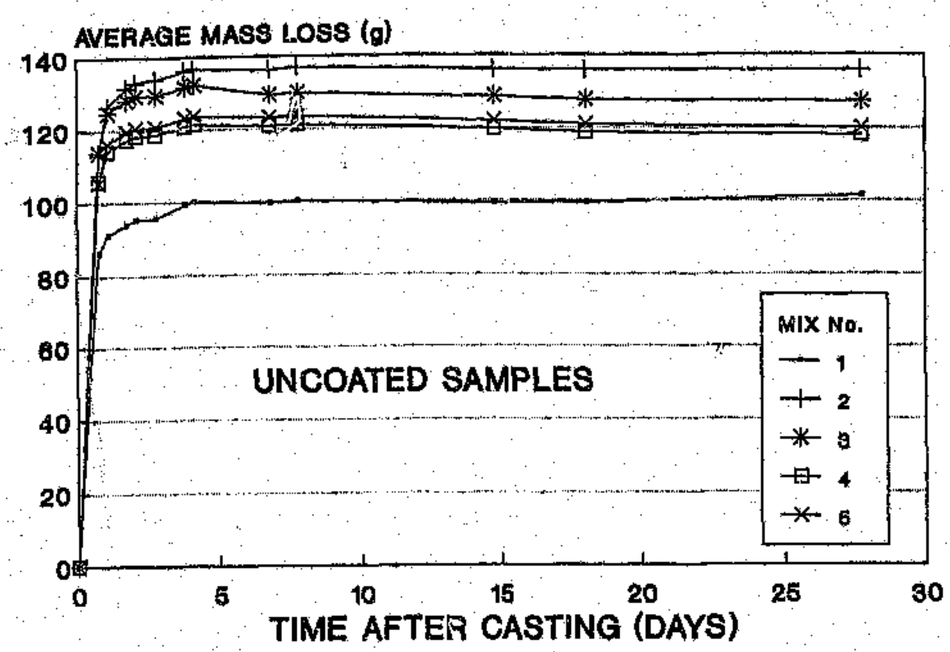

Figure 7.5: Average mass loss of the uncoated samples

These results show that:

- The effect of the curing compound is a combination of a reduction in the initial rate of moisture loss together with a reduction in the total amount of moisture lost.
- For the air dried samples, the OPC mix (Mix 1) generally showed the lowest mass loss in both the coated and uncoated conditions.
- Mixes 2 and 3 showed the highest mass loss for the coated and uncoated conditions but this may be a reflection of high slump values obtained with these mixes. There may therefore have been more moisture available to be dried off from the samples.
- GGBS mixes 4 and 5 have shown the greatest response to the curing compound than any of the other mixes. For these mixes coated with curing

compound, the initial rate of moisture loss is lower than that for the OPC concrete. Thereafter, the rate of moisture loss is similar to that of the OPC concrete. Also, the curing compound reduced the 28-day cumulative mass loss of the OPC concrete by 11.5% while the corresponding reductions for mixes 4 and 5 were 18.6% and 20.9% respectively.

Oxygen permeability and water sorptivity

The results of the oxygen permeability and water absorption measurements for the three exposure conditions are shown in Figures 7.6 and 7.7 respectively.

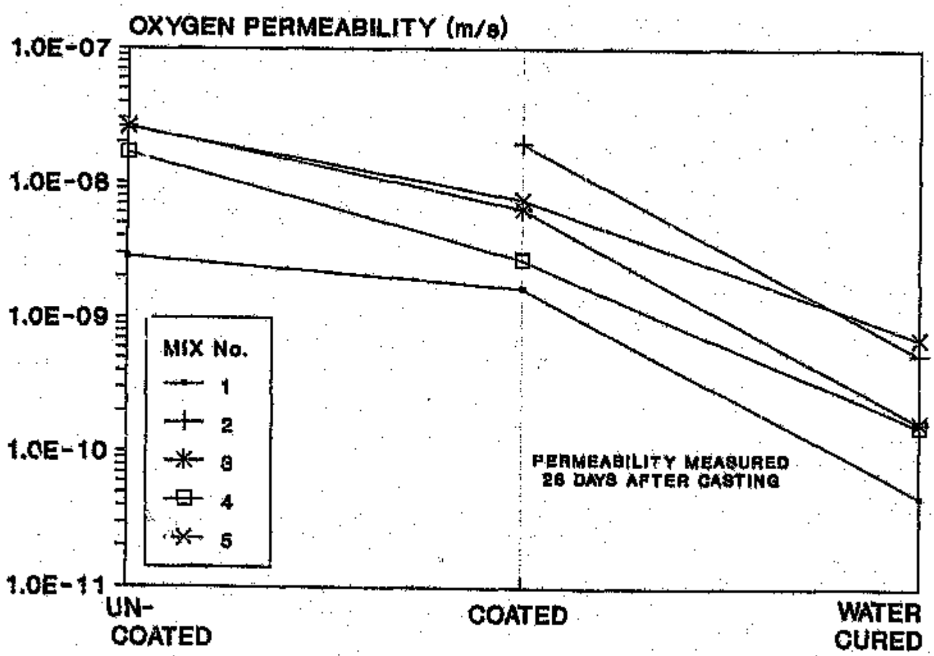

Figure 7.6: Oxygen permeability of the various concretes for the three exposure conditions

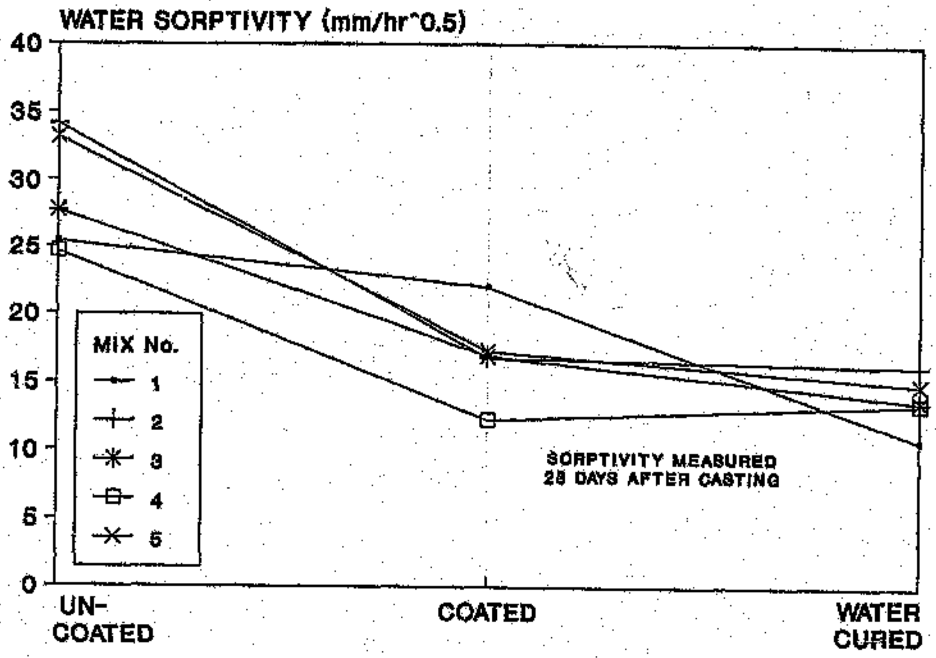

Figure 7.7: Water sorptivity of the various concretes for the three exposure conditions

From these results, it is noted that:

- The curing compound has had a greater effect in reducing the water sorptivity of the surface concrete than it has had in reducing the oxygen permeability. For the GGBS concretes, the water sorptivities of the curing compound coated sample are equivalent to those of the 28-day water cured samples.
- The water sorptivity result obtained for the coated OPC samples (Mix 1) is considered to be anomalous and requires further testing.
- The coated and water cured results for Mix 4 are similar to those of the plain OPC concrete (Mix 1). It must be noted however, that Mix 4 had a higher binder/water ratio than Mix 1.

Compressive strength

Table 7.8 shows the results of the compressive strength tests. It should be noted that each result was obta'ned using a single cube sample.

Table 7.8: Results of compressive strength tests

Mix Number	Sample Mass (g)	Compressive Strength (MPa)
1	2680	48.1
2	2670	30.1
3	2615	36.2
4	2645	43.8
5	2590	37.4

The trend of these strength results generally reflects that obtained in the results discussed above. The highest strength concretes (Mixes 1 and 4) also showed the better performance from the point of view of moisture loss and development of surface properties.

7.4.5 Conclusions

a. Upon exposure to drying conditions at very early ages, untreated GGBS concretes lose more moisture than plain OPC concretes.

b. The wax-based curing compound was more effective in reducing the moisture loss of Mixes 4 and 5 (GGBS mixes) than reducing the moisture loss of the OPC mix. This meant that these GGBS concretes had similar moisture retention characteristics as the OPC concrete under conditions where the concretes were coated with the curing compound.

c. Considering the effect of the curing compound in developing the concrete surface quality, Mix 4 showed similar properties to that obtained for the OPC mix on the basis of oxygen permeability and water sorptivity test results.

7.5 CASE 4: READY MIXED CONCRETES: DURABILITY EFFECTS OF A PROPOSED ALTERNATIVE MIXING PROCEDURE.

7.5.1 Introduction

A local ready mixed concrete supplier had identified a possible strength advantage in altering the mixing procedure of their concretes. Before implementing any changes to the production process, it was necessary to understand the effects of this new procedure on other aspects of the performance of concretes. This project was undertaken in order to quantify the effects of the new mixing procedure on the durability performance of concrete.

This concrete supplier was also considering the addition of finely ground silica "flour" to the concrete as a possible cost-saving action while maintaining the engineering performance of the concrete. A series of concretes with the silica flour additions was included for testing in the programme. These concretes were also prepared using the new mixing procedure.

In the test programme, oxygen permeability and water sorptivity were used as indexes to indicate potential durability. Both surface and internal sections of the concrete samples were tested.

7.5.2 Mixes and Sample Preparation

Table 7.9 shows the material proportions for the various mixes tested. This information was provided by the concrete supplier and the admixture referred to was denoted "P509". For each mix, six 150 mm cubes were manufactured at the factory laboratory and were delivered to our laboratories 28 days after casting. All the cube samples were water cured and were transported in a moist condition.

Series 1 concretes were mixed in the conventional manner; Series 2 concretes were prepared using the proposed new procedure; Series 3 concretes were mixed as for Series 2 and had finely ground silica flour added to the mix. Slump values for all the concretes ranged between 75 and 85 mm.

Table 7.9: Mix proportions (kg/m³) for the various mixes tested.

Mix Series	1			2			3		
Mix Number	548	549	550	551	552	553	554	555	556
Strength Grade (MPa)	20	30	40	20	30	40	20	30	40
OPC	230	300	360	215	285	340	195	255	305
Water	185	185	185	175	175	175	175	175	175
Dune Sand	299	241	190	338	279	233	337	279	233
19 mm Stone	1120	1120	1120	1120	1120	1120	1120	1120	1120
Coarse Sand	520	520	520	520	520	520	520	520	520
Admix. (mℓ)	460	600	720	430	570	680	390	510	610
Si Flour	-	-	-	-	-	-	20	30	35
w/c Ratio	0.80	0.62	0.51	0.81	0.61	0.51	0.90	0.67	0.57

Concrete strengths were determined at the factory laboratory and reported as shown in Table 7.10 for both 7- and 28-day strengths. These results were obtained using 150 mm cubes as well.

Table 7.10: 7- and 28-day compressive strength results

Mix Number	Compressive Strength (MPa)	
	At 7 days	At 28 Days
548	25.0	35.0
549	34.0	39.0
550	43.0	48.0
551	26.0	30.0
552	35.0	41.5
553	45.0	51.0
554	21.0	23.5
555	30.0	36.5
556	36.0	43.0

Upon receipt of the cube samples, a 68 mm diameter core was drilled into a cast face of three cubes of each mix. From each of the cores, two disc samples were cut representing depths of 0 to 20 mm and 40 to 60 mm into the concrete. These discs were cut using a high speed, continuous rim diamond grit blade. Hence, for each mix, three 20 mm thick surface samples and three 20 mm thick internal samples were obtained. The samples were then tested for oxygen permeability and water absorption.

7.5.3 Results and Discussion

Table 7.11 shows the results of oxygen permeability and water sorptivity tests carried out on the disk samples. The table shows the individual and average results obtained for the two parameters on the surface slices (0-20 mm) and internal slices (40-60 mm). In this Table, an asterisk (*) indicates that the result was discarded. In order to provide a basis for comparing the results, Figures 7.8 and 7.9 show the permeability and sorptivity results for the surface and internal slices respectively, as percentages of that obtained with the corresponding conventionally mixed samples.

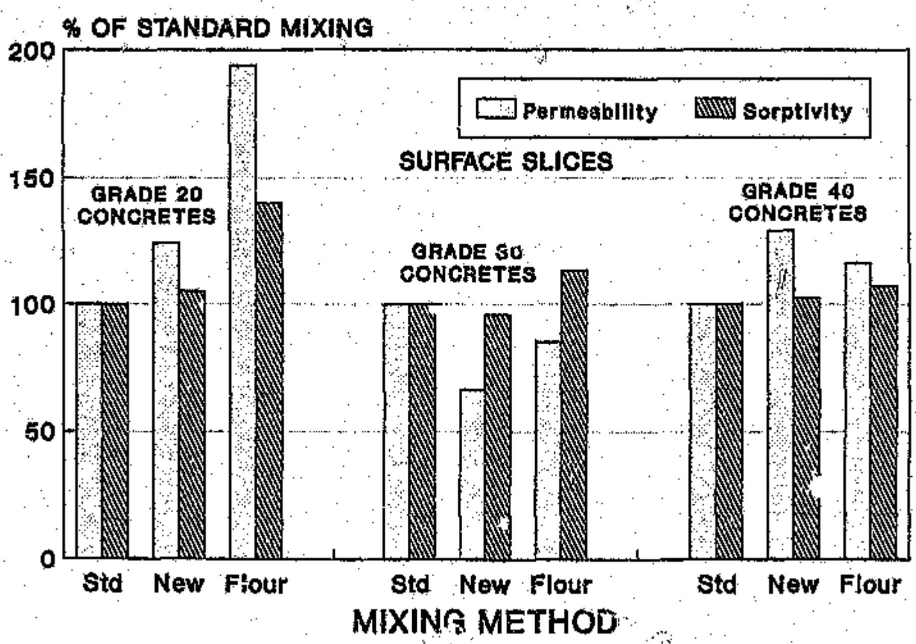

Figure 7.8 Relative values of permeability and sorptivity for the surface slices

Table 7.11: Permeability and sorptivity results for all the concretes tested

		0-20 mm Slice		40-60 mm Slice	
Str. Grade	Mix No.	Permblty 10^{-11} m/s	Srptvty mm/hr^{½}	Permblty 10^{-11} m/s	Srptvty mm/hr^{½}
20 MPa	548	7.37 5.86 6.68	9.13 9.05 9.23	11.10 7.80 6.95	10.50 8.06 9.74
	Ave	6.64	9.14	8.62	9.43
	551	7.99 7.82 8.84	9.74 8.00 11.11	9.76 7.90 9.22	8.83 10.55 8.08
	Ave	8.22	9.62	8.96	9.15
	554	16.30 11.90 10.40	13.33 12.95 11.15	15.50 20.90 8.39	10.39 10.52 8.84
	Ave	12.87	12.48	14.93	9.92
30 MPa	549	6.73 5.92 7.34	10.87 7.08 7.59	7.88 9.65 *	9.45 10.28 *
	Ave	6.66	8.51	8.77	9.87
	552	4.56 4.64 4.07	8.12 9.65 6.71	6.82 * 5.20	9.56 9.47 9.07
	Ave	4.42	8.16	6.01	9.37
	555	6.31 4.85 5.87	9.08 9.98 9.82	4.87 7.37 *	8.71 8.14 8.76
	Ave	5.68	9.63	6.12	8.54
40 MPa	550	4.32 4.20 5.33	9.49 10.07 11.51	8.61 5.70 7.20	10.17 8.50 10.60
	Ave	4.62	10.36	7.17	9.76
	553	5.53 6.53 5.89	10.90 11.10 9.81	5.22 5.62 5.68	9.14 8.50 9.81
	Ave	5.98	10.60	5.51	9.15
	556	6.16 4.60 5.37	11.86 10.58 10.93	* 6.67 5.85	10.31 9.21 8.76
	Ave	5.38	11.12	6.26	9.43

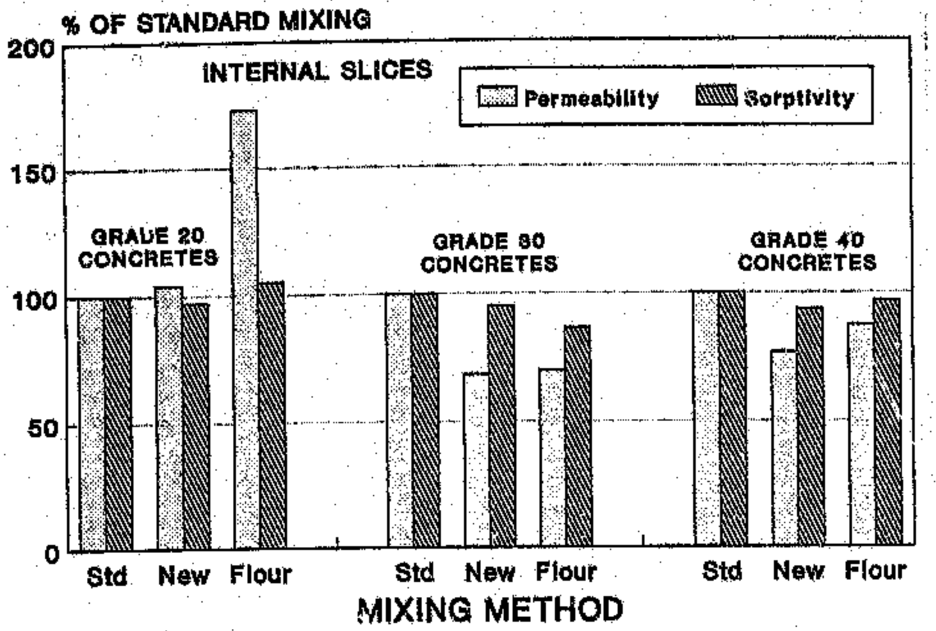

Figure 7.9: Relative values of permeability and sorptivity for the internal slices

Permeability

These results show that surface slices were generally slightly less permeable than internal slices. This is a reflection of the fact that the concretes were well cured and the surface concrete was allowed to develop a similar state of hydration to that of the internal concrete. Since the surface concrete contains a layer of high cement content, this has caused slightly improved air permeability properties.

The addition of silica flour to the mix caused increased permeability only at the Gı .de 20 concrete level. However,as shown in Table 7.10 above, this concrete had a considerably lower compressive strength than the concretes mixed using the conventional (Std.) and the new methods. Figure 7.10 shows a relationship between average oxygen permeability and compressive strength for the concretes tested in this project. Although poorly defined, a relationship of decreasing permeability with increasing compressive strength is apparent, being more sensitive for the lower strength concretes. Part of the observed increased permeability for the Grade 20 Si flour mix could be explained by the reduced strength of this concrete.

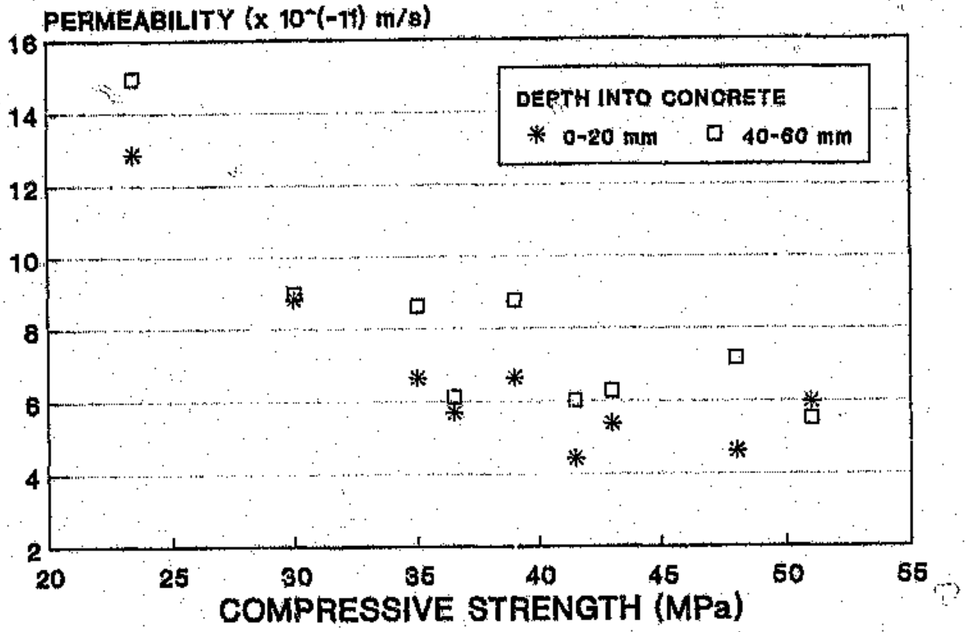

Figure 7.10: Relationship between strength and oxygen permeability for the concretes tested

Considering that the difference between good and poor quality concrete, as measured by permeability, can be of the order of 10^3 to 10^4 times, it can be said that the concretes tested showed similar permeability values (ignoring the Grade 20, Si flour mix). This means that the new mixing method has had little effect on the oxygen permeability of the concretes under good curing conditions.

Water sorptivity

In comparison with oxygen permeability, water sorptivity measures a different mode of fluid transport through concrete. The difference between the performance of the surface and internal slices is therefore not as clearly defined as in the case of the permeability results.

As with the permeability results, the Grade 20 Si Flour mix shows considerably higher sorptivity than the corresponding conventional and new-method mixes. However, the results are generally similar for the for the different mix processes.

7.5.4 General discussion

Given the strength levels, the concretes tested have shown good performance from the point of view of permeability and sorptivity. An important factor contributing to this observation is the good curing condition to which these concretes had been subjected. The extent of curing was sufficient to ensure that the surface concrete developed to a similar quality to that of the internal concrete. Also, as noted in Chapter 6, after an extended period of initial water curing, the durability index values of surface concrete becomes insensitive to changes in compressive strength.

As noted above, the results show that the new mixing procedures gives the same and often improved permeability and sorptivity performance as the conventional mixing procedure. However, since the new mixing method and Si flour concretes have lower cement contents than the corresponding conventionally mixed concretes, equivalent permeability and sorptivity values could mean lower durability performance. The concretes with the lower cement contents would produce proportionately less calcium hydroxide upon hydration and would therefore show a higher rate of carbonation in a given environment. For the same permeability and sorptivity values, the concretes with lower calcium hydroxide contents generally show higher rates of carbonation rates.

Although no test results are available, a similar effect would be encountered in a marine environment where chloride penetration presents the main durability problem. Given two concretes with the same accessibility for chlorides, the concrete with the lower cement content will have a lower ability to bind chlorides. The lower cement content concrete would therefore have a greater amount of free chlorides for the same amount of total chlorides diffused into both concretes. Hence, the de-passivation of reinforcement would occur earlier in the lower cement content concrete.

7.5.5 Conclusions

The following conclusions are drawn on the basis of the results and discussion presented above:

a. All the concretes were well cured as evidenced by the similar oxygen permeability and water sorptivity results obtained for the surface and internal segments tested.

b. Altering the mixing procedure has had a negligible effect on the oxygen permeability and water sorptivity of well cured concretes relative to the conventional mixing procedure.

c. Replacing a portion of the cement with "silica flour" and mixing using the new method, has also had a negligible effect on the measured durability index values. It is believed that the high index results obtained with the Grade 20 silica flour concrete is a reflection of the high porosity of this concrete resulting from its high w/b ratio. It is unlikely that the addition of silica flour to the mix would, on its own, result in an inferior pore structure.

d. The lower cement content of the concretes made with the new mixing method and the silica flour concretes may mean that these concretes will be less durable in service than the conventionally mixed concretes. Further testing will be necessary to establish this influence.

List of References

1. Basson, J.J. *Deterioration of concrete in aggressive waters*. Portland Cement Institute, Midrand, South Africa. 1989.

2. American Society for Testing Materials. *Specification for liquid membrane forming compounds for curing concrete*. ASTM C309-81.

3. Ballim, Y, Taylor, P and Macdonald, H.K. A preliminary assessment of the effectiveness of a liquid membrane-forming curing compound. *Concrete Beton*. Number 66, January 1993.

4. Concrete Society of S.A. *Concrete curing: Description, method and control*. CSSA, Midrand, South Africa. 1991.

CHAPTER 8

GENERAL CONCLUSIONS

8.1 Introduction

In this Chapter, an attempt is made to draw together the important observations, conclusions and trends noted in Chapters 1 to 7. Possible areas for future research in the field of concrete curing and durability are also identified and, where possible, suggestions are made as to the form that such research may take.

The conclusions presented below are divided into those relating to the test methods and those relating to the performance of the concretes tested. Finally, a section is presented on the future research needs.

8.2 Test Methods

a. In relation to many of the durability index test apparatuses developed, the falling head permeameter and water sorptivity tests developed in this project have the advantages of low cost, simple construction and ease of use. These considerations satisfy an important objective in the development of the tests: namely that the test methods be suitable for use in an on-site laboratory.

b. Good correlations have been obtained between the actual results of these tests and the results predicted by the theoretical equations.

c. The oxygen permeability and water sorptivity test methods are sufficiently sensitive to detect the effects of variations in moist curing on the pore structure of surface concrete, at various depths into the concrete. This means that the tests could be used to monitor the quality of in situ surface concrete.

d. The test methods are sensitive to the moisture condition of the samples at the time of testing. Care is required in standardising the method of pre-conditioning the samples before testing. Contrary to other reported results, it was found that oxygen permeability measurements are not sensitive to variations in the aggregate size to sample thickness ratio for as cast samples. For samples cut from larger specimens, variations in oxygen permeability with sample thickness appear to depend on the bleeding characteristics of the concrete.

8.3 The Performance of Concretes Tested

a. Increasing the duration of curing has a significant effect in reducing the durability index values of the surface zone of concrete made with each of the three binder types used. The decrease in index values is most significant for curing periods from 1 to 7 days. Thereafter, only small decreases in these parameters are observed with increasing durations of curing.

b. The effect of drying in limiting the development of low durability index values, was noted at depths of up to 45 mm.

c. For a given curing condition and b/w ratio, OPC concretes generally give lower permeability and sorptivity values than the OPC/FA and OPC/GGBS concretes. Also, for curing periods longer than 3 days, the sorptivity of the cover concrete becomes insensitive to the binder type.

d. For equal compressive strength, the OPC/FA concretes showed the lowest surface permeability for all the early curing conditions tested. For curing periods longer than 3 days, increases in compressive strength have a small effect in decreasing the surface sorptivity of the concretes.

e. The results show that a particular durability index level can be achieved either by extending the duration of curing of a low strength concrete or decreasing the w/b ratio of a poorly cured concrete. In choosing one of these options to improve the surface quality of the concrete, economic parameters related to particular projects must be considered.

f. The oxygen permeability and water sorptivity of the 0 to 15 mm surface segment of concrete can be predicted from the following equations:

$$D_i = A.(T_c)^B$$

$$\ln(A) = \lambda_a.(b/w) + \lambda_b$$

$$B = \lambda_c.(b/w) + \lambda_c$$

Where D_i is the durability index (permeability or sorptivity), T_c is the duration of moist curing (days) and λ_a to λ_d are factors which depend on the binder type. These equations allow the durability index values to be determined on the basis of controllable concrete parameters: b/w ratio and the duration of early-age moist curing.

g. The depth of carbonation (x) is related to the durability index values (D_i) as follows:

$$x = \lambda_e . D_i + \lambda_f$$

$$D_i = \ln(k) \ for\ permeability$$

$$D_i = S \ for\ sorptivity$$

λ_e and λ_f are constants.

h. For equal surface permeability or sorptivity, OPC concretes carbonate slower than OPC/FA and OPC/GGBS concretes.

i. There appears to be a linear relationship between the sorptivity and logarithm of permeability measured for the samples tested. However, the scatter of the data points is too large and the correlation coefficients too low for this relationship to be established with confidence.

8.4 Future Research Directions

a. Further research is required in order to establish the effect of drying history on durability index measurements of samples made using a wide range of concrete types. This may involve more fundamental studies of concrete microstructure, volume and distribution of porosity and microscopic examinations of the extent of damage caused by different drying methods. such studies will be necessary before firm recommendations can be made as to the "standard" pre-conditioning method to be adopted.

b. Research should be focused at quantifying the effect of curing conditions and environments which are different from those used in this investigation. In particular, the effects of in situ outdoor environments, as well as the different curing methods commonly used in Southern Africa, should be quantified with a view to facilitating specification and control of concrete curing.

c. The relationship between the early age durability index value of a particular concrete and its resistance to deterioration in various aggressive environments must be studied further. The present investigation has considered the rate of carbonation as a durability process. Future studies should consider deterioration processes such as sulphate attack, chloride ingress and soft water attack to cover the main mechanisms of concrete deterioration.

APPENDIX

Table A1: Compressive strength of OPC concretes at 28 days

Mix No.	Sample No.	Sample Mass (g)	Failure Stress (MPa)	Average Strength (MPa)
P1	1 2 3	2530 2545 2550	39.0 39.6 40.4	39.6
P2	1 2 3	2510 2510 2500	46.9 48.9 47.4	47.7
P3	1 2 3	2535 2520 2520	58.4 60.9 59.0	59.4

Table A2: Compressive strength of OPC concretes at 10 months

Mix No.	Sample No.	Sample Mass (g)	Failure Stress (MPa)	Average Strength (MPa)
P1	1 2 3	2540 2520 2515	53.2 52.4 52.5	52.7
P2	1 2 3	2515 2520 2520	64.4 70.5 67.0	67.3
P3	1 2 3	2560 2550 2560	79.6 79.1 80.0	79.6

Table A3: Compressive strength of FA concretes at 28 days

Mix No.	Sample No.	Sample Mass (g)	Failure Stress (MPa)	Average Strength (MPa)
F1	1 2 3	2510 2515 2540	30.2 31.4 32.3	31.3
F2	1 2 3	2500 2500 2520	44.7 45.2 45.9	45.3
F3	1 2 3	2530 2530 2560	58.8 59.1 57.9	58.6

Table A4: Compressive strength of FA concretes at 10 months

Mix No.	Sample No.	Sample Mass (g)	Failure Stress (MPa)	Average Strength (MPa)
F1	1 2 3	No results available		
F2	1 2 3	2520 2540 2535	71.3 74.0 74.6	73.3
F3	1 2 3	2525 2530 2550	87.5 88.5 92.5	89.5

Table A5: Compressive strength of GGBS concretes at 28 days

Mix No.	Sample No.	Sample Mass (g)	Failure Stress (MPa)	Average Strength (MPa)
S1	1 2 3	2530 2560 2510	37.4 37.3 36.6	37.1
S2	1 2 3	2500 2515 2505	39.4 39.6 39.0	39.4
S3	1 2 3	2510 2520 2540	51.7 53.2 54.8	53.2

Table A6: Compressive strength of GGBS concretes at 10 months

Mix No.	Sample No.	Sample Mass (g)	Failure Stress (MPa)	Average Strength (MPa)
S1	1 2 3	2460 2540 2490	53.4 49.7 53.2	52.1
S2	1 2 3	2540 2530 2540	63.5 65.9 61.9	63.7
S3	1 2 3	2550 2550 2540	83.7 74.8 81.6	80.0

Table A7(a): 28-day oxygen permeability ($x10^{-10}$ m/s) for the P1 (OPC) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	28 36	23 31	38 9
Average	32	27	23
3	4.4 2.9	2.2 2.9	2.4 4.8
Average	3.7	2.6	3.6
7	5.8 3.0	2.1 2.2	2.0 3.8
Average	4.4	2.1	2.9
28	0.85 0.55	0.74 *	3.3 3.1
Average	0.7	0.74	3.2

* = result discarded

Table A7(b): 28-day oxygen permeability ($x10^{-10}$ m/s) for the P2 (OPC) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	11 15	7.8 7.6	10 11
Average	13	7.7	11
3	2.3 2.8	1.8 1.9	1.7 1.9
Average	2.5	1.9	1.8
7	0.70 0.94	0.90 0.86	1.0 1.1
Average	0.82	0.88	1.1
28	0.36 0.52	0.57 0.88	0.54 0.48
Average	0.44	0.73	0.51

Table A7(c): 28-day oxygen permeability ($x10^{-10}$ m/s) for the P3 (OPC) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	3.0 4.4	2.3 3.0	2.9 3.6
Average	3.7	2.7	3.3
3	1.5 1.4	1.2 *	1.6 1.1
Average	1.4	1.2	1.4
7	1.2 0.76	0.59 0.47	* 0.62
Average	0.96	0.53	0.62
28	0.36 0.36	* 0.6	0.32 *
Average	0.36	0.6	0.32

* = result discarded

Table A8(a): 28-day oxygen permeability (x10^{-10} m/s) for the F1 (OPC/FA) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	39 16 15	31 17 9	40 9 *
Average	23	19	24
3	9.1 5.8 14	19 26 7	19 8.2 3.7
Average	9.8	18	10
7	3.9 3.5 2.3	5.7 3.5 2.4	6.6 4.9 2.1
Average	3.3	3.9	4.5
28	1.0 2.8 –	1.5 7.4 –	2.2 7.6 –
Average	1.9	4.5	4.9

Table A8(b): 28-day oxygen permeability ($\times 10^{-10}$ m/s) for the F2 (OPC/FA) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	7.4 8.3	9.7 5.8	7.3 5.5
Average	7.9	7.7	6.4
3	7.2 3.4	1.9 1.5	3.4 1.6
Average	5.3	1.7	2.5
7	0.77 0.75	0.81 0.62	0.55 *
Average	0.76	0.72	0.55
28	* 0.31	0.35 0.43	* 0.41
Average	0.31	0.39	0.41

Table A8(c): 28-day oxygen permeability ($\times 10^{-10}$ m/s) for the F3 (OPC/FA) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	3.6 3.9	2.9 3.6	2.9 3.0
Average	3.8	3.3	3.0
3	1.2 0.94	0.93 1.2	0.84 0.81
Average	1.1	1.0	0.82
7	1.1 0.52	0.60 0.38	0.47 0.43
Average	0.84	0.49	0.45
28	0.21 0.29	0.31 0.26	0.31 0.30
Average	0.25	0.29	0.31

Table A9(a): 28-day oxygen permeability ($x10^{-10}$ m/s) for the S1 (OPC/GGBS) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	44 40	27 26	25 *
Average	42	26	25
3	18 13	13 10	* 11.5
Average	16	12	11.5
7	15 10	13 12	11 10
Average	13	12	10
28	3.7 3.6	4.3 2.9	4.1 3.0
Average	3.7	3.6	3.6

Table A9(b): 28-day oxygen permeability ($x10^{-10}$ m/s) for the S2 (OPC/GGBS) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	15 8.9	14 10	15 10
Average	12	12	12
3	5.3 3.9	4.6 3.9	4.3 6.3
Average	4.61	4.2	5.3
7	1.9 2.6	4.9 7.1	4.3 3.0
Average	2.3	6.0	3.7
28	1.0 0.69	0.70 0.48	1.1 1.2
Average	0.85	0.59	1.2

Table A9(c): 28-day oxygen permeability ($x10^{-10}$ m/s) for the S3 (OPC/GGBS) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	10 8.6	7.1 6.7	6.9 9.3
Average	9.4	6.9	8.1
3	2.2 2.7	2.7 2.0	1.7 2.0
Average	2.4	2.4	1.9
7	1.2 1.2	0.96 1.7	1.0 1.4
Average	1.2	1.3	1.2
28	1.9 2	2.6 1.8	2.1 0.97
Average	2	2.2	1.5

Table A10(a): 10-month oxygen permeability ($\times 10^{-10}$ m/s) for the P1 (OPC) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	41 21 11	22 17 13	20 17 15
Average	24	18	17
3	5.0 6.0 5.7	4.7 6.3 5.0	4.7 6.4 4.1
Average	5.5	5.3	5.1
7	3.7 * 3.0	2.4 3.4 3.5	3.5 2.8 2.8
Average	3.4	3.1	3.0
28	1.3 1.7 1.1	1.1 1.8 0.96	1.1 * 0.92
Average	1.4	1.3	0.99

Table A10(b): 10-month oxygen permeability ($x10^{-10}$ m/s) for the P2 (OPC) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	12 9.2 7.4	8.65 8.25 6.9	10 9.4 9.3
Average	9.6	7.9	9.7
3	3.6 3.1 2.8	4.1 2.0 2.4	4.4 2.1 3.4
Average	3.2	2.8	3.3
7	1.2 1.2 1.4	1.6 1.6 1.9	3.6 2.1 3.0
Average	1.3	1.7	2.9
28	1.1 0.52 0.67	0.64 1.0 0.92	0.63 0.95 0.77
Average	0.77	0.86	0.78

Table A10(c): 10-month oxygen permeability ($\times 10^{-10}$ m/s) for the P3 (OPC) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	9.3 7.4 8.2	9.1 9.3 7.8	10 9.7 12
Average	8.3	8.7	10.8
3	5.2 3.0 1.1	6.5 3.3 2.6	* 3.9 3.5
Average	3.1	4.2	3.7
7	2.2 1.6 1.4	1.1 1.1 2.3	1.2 2.1 1.6
Average	1.7	1.5	1.6
28	0.56 0.68 *	0.93 0.54 0.77	0.69 0.84 0.68
Average	0.62	0.75	0.74

Table A11(a): 10-month oxygen permeability ($x10^{-10}$ m/s) for the F1 (OPC/FA) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	* * 21	25 20 15	18 22 17
Average	21	20	19
3	14 13 18	14 15 16	14 16 20
Average	15	15	17
7	6.5 5.4 11	8.0 5.7 *	8.7 5.4 4.4
Average	7.7	6.8	6.2
28	4.9 8.3 8.8	7.0 11 12	8.0 8.8 12
Average	7.3	9.9	9.5

Table A11(b): 10-month oxygen permeability ($\times 10^{-10}$ m/s) for the F2 (OPC/FA) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	12 10 11	14 11 9.2	14 10 8.4
Average	11	12	11
3	3.1 3.4 2.7	2.6 2.8 3.4	3.3 2.6 3.5
Average	3.1	2.9	3.1
7	2.4 1.5 5.2	1.9 1.3 1.3	1.6 1.9 1.5
Average	3.0	1.5	1.7
28	0.49 0.54 0.41	0.44 0.61 0.50	0.45 0.82 0.40
Average	0.48	0.52	0.56

Table A11(c): 10-month oxygen permeability ($\times 10^{-10}$ m/s) for the F3 (OPC/FA) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	4.4 5.7 4.8	4.5 4.9 4.1	4.8 5.5 4.4
Average	4.9	4.5	4.9
3	2.3 1.6 1.3	1.5 1.5 1.8	1.5 1.2 1.8
Average	1.7	1.6	1.5
7	0.81 0.91 0.73	0.61 0.63 0.58	0.76 0.57 0.71
Average	0.82	0.61	0.68
28	0.38 0.37 0.38	0.27 0.26 0.38	0.29 0.34 0.35
Average	0.38	0.30	0.33

Table A12(a): 10-month oxygen permeability ($x10^{-10}$ m/s) for the S1 (OPC/GGBS) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	85 * 57	63 31 36	65 30 39
Average	71	43	44
3	44 16 8.7	11 26 9.6	11 50 14
Average	23	15	25
7	6.2 5.2 7.2	4.1 3.6 7.1	8.9 5.8 7.4
Average	6.2	4.9	7.4
28	7.6 8.4 2.8	4.3 5.8 3.8	3.4 3.8 6.3
Average	6.3	4.7	4.5

Table A12(b): 10-month oxygen permeability ($x10^{-17}$ m/s) for the S2 (OPC/GGBS) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	21 13 11	13.9 12.4 8.7	21 12 7.3
Average	15	11.7	13
3	5.2 4.9 4	3.0 4.6 6.3	5.8 4.8 7.2
Average	4.7	4.6	5.7
7	2.5 2.1 2.4	6.5 3.3 2.1	9.6 6.1 2.8
Average	2.3	3.9	6.2
28	4.5 1.2 3.0	1.3 4.6 1.4	2.4 4.9 2.2
Average	2.9	2.4	3.2

Table A12(c): 10-month oxygen permeability ($x10^{-10}$ m/s) for the S3 (OPC/GGBS) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	8.1 11 11	9.0 8.1 9.8	8.4 6.6 7.5
Average	9.9	8.9	7.5
3	2.3 2.6 1.9	2.4 3.0 2.2	2.4 1.6 2.7
Average	2.3	2.5	2.2
7	1.7 1.3 1.4	* 1.4 1.3	2.2 2.2 1.1
Average	1.5	1.4	1.8
28	1.0 1.5 2.9	1.0 1.5 1.8	* 0.78 1.2
Average	1.8	1.4	0.98

Table A13(a) : 28-day water sorptivity (mm/hr^{½}) of the P1 (OPC) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	31.9 32.1	25.2 24.4	25.2 19.6
Average	32.0	24.8	22.4
3	23.9 20.9	11.9 14.1	13.5 15.2
Average	22.4	13.0	14.4
7	15.9 14.3	10.8 11.3	10.0 11.1
Average	15.1	11.1	10.5
28	10.8 10.3	9.8 10.3	11.2 9.2
Average	10.6	10.1	10.2

Table A13(b): 28-day water sorptivity (mm/hr^{½}) of the P2 (OPC) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	24.5 24.0	16.1 14.4	11.4 16.9
Average	24.2	15.2	14.1
3	17.5 15.4	10.4 10.4	8.8 9.9
Average	16.5	10.4	9.4
7	13.0 13.2	9.4 9.3	9.2 9.0
Average	13.1	9.4	9.1
28	9.9 10.0	8.9 9.7	9.0 9.1
Average	10.0	9.3	9.1

Table A13(c): 28-day water sorptivity (mm/hr$^{1/2}$) of the P3 (OPC) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	21.5 21.6	12.4 12.1	12.1 13.0
Average	21.6	12.2	12.5
3	15.6 15.4	7.4 11.2	9.5 9.4
Average	15.5	9.3	9.5
7	12.9 13.2	7.8 8.9	9.4 8.7
Average	13.0	8.4	9.1
28	10.3 8.9	8.3 8.6	9.9 9.4
Average	9.6	8.5	9.6

Table A14(a): 28-day water sorptivity (mm/hr$^{1/2}$) of the F1 (OPC/FA) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	27.0 24.7 27.6	24.2 18.8 16.6	20.1 15.3 *
Average	26.4	19.9	18.0
3	22.0 22.2 25.3	14.5 16.5 18.3	14.6 14.1 13.9
Average	23.2	16.4	14.2
7	18.4 19.8 18.6	12.4 11.2 11.2	15.0 13.3 12.2
Average	18.9	11.6	13.5
28	11.9 17.0	10.6 12.7	10.7 11.8
Average	14.5	11.7	11.2

Table A14(b): 28-day water sorptivity (mm/hr$^{1/2}$) of the F2 (OPC/FA) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	25.6 26.1	19.7 17.3	18.7 15.9
Average	25.9	18.5	17.3
3	18.7 16.3	10.4 10.9	10.9 9.2
Average	17.5	10.6	10.0
7	11.8 13.6	8.8 8.7	7.9 7.8
Average	12.7	8.8	7.9
28	8.8 7.5	7.4 8.3	8.8 8.1
Average	8.2	7.9	8.5

Table A14(c): 28-day water sorptivity (mm/hr^{½}) of the F3 (OPC/FA) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	21.1 20.0	15.9 13.5	14.3 12.9
Average	20.6	14.7	13.6
3	14.3 14.3	10.8 10.6	8.3 9.2
Average	14.3	10.7	8.8
7	13.6 12.0	9.7 9.0	9.9 8.0
Average	12.8	9.4	8.9
28	9.6 9.3	7.7 7.0	8.7 7.6
Average	9.5	7.4	8.1

Table A15(a): 28-day water sorptivity (mm/hr$^{1/2}$) of the S1 (OPC/GGBS) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	43.9 43.4	29.8 38.6	* 31.5
Average	43.6	34.2	31.5
3	22.9 22.0	18.7 14.4	18.5 13.6
Average	22.4	16.7	16.0
7	19.6 16.5	12.7 10.5	13.1 10.4
Average	18.1	11.6	11.7
28	14.8 14.6	8.4 7.0	9.5 7.0
Average	14.7	7.7	8.2

Table A15(b): 28-day water sorptivity (mm/hr^{½}) of the S2 (OPC/GGBS) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	29.8 26.8	19.7 16.6	21.4 16.9
Average	28.3	18.2	19.1
3	18.2 20.5	9.2 10.3	10.1 8.7
Average	19.3	9.8	9.4
7	12.9 15.0	9.4 10.4	9.3 11.4
Average	14.0	9.9	10.4
28	15.2 9.9	5.9 5.1	6.5 5.8
Average	12.6	5.5	6.1

Table A15(c): 28-day water sorptivity ($mm/hr^{½}$) of the S3 (OPC/GGBS) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	26.3 24.5	16.4 18.2	14.9 16.7
Average	25.4	17.3	15.8
3	12.3 13.5	8.3 9.0	6.8 7.6
Average	12.9	8.7	7.2
7	12.2 12.0	6.5 8.1	6.3 6.5
Average	12.1	7.3	6.4
28	14.5 13.8	6.7 6.8	7.1 5.4
Average	14.2	6.7	6.3

Table A16(a): 10-month water sorptivity (mm/hr$^{1/4}$) of the P1 (OPC) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	31.0 27.2 23.9	28.1 24.5 25.0	27.8 25.8 19.9
Average	27.4	25.9	24.5
3	19.3 23.1 19.7	18.2 17.2 17.7	17.1 19.8 17.2
Average	20.7	17.7	18.0
7	16.4 18.6 14.1	14.4 17.1 15.3	12.9 14.2 14.2
Average	16.4	15.6	13.8
28	14.6 13.4 11.3	13.6 12.3 10.2	10.7 12.5 10.7
Average	13.1	12.0	11.3

Table A16(b): 10-month water sorptivity (mm/hr$^{1/2}$) of the P2 (OPC) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	26.8 27.6 18.5	24.5 21.6 18.0	19.2 19.9 18.0
Average	24.3	21.3	19.1
3	16.1 20.1 14.7	15.8 13.[illegible] 1[illegible]	15.5 13.2 14.5
Average	17.0	14.[illegible]	14.4
7	12.2 11.5 12.6	12.3 13.[illegible] 13.0	14.8 12.6 14.5
Average	12.1	12.8	13.3
28	9.5 10.5 12.0	11.3 11.9 10.8	9.5 10.7 10.5
Average	10.7	11.3	10.3

Table A16(c): 10-month water sorptivity (mm/hr^{½}) of the P3 (OPC) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	21.1 20.9 22.7	19.2 20.6 16.4	17.9 17.3 17.1
Average	21.6	18.7	17.4
3	15.5 13.8 15.0	15.0 13.8 12.1	13.7 13.3 12.4
Average	14.8	13.6	13.1
7	14.0 9.9 12.1	12.8 11.2 12.8	11.5 11.4 12.6
Average	12.0	12.3	11.8
28	9.0 10.2 11.7	10.2 8.7 9.1	9.5 9.8 10.3
Average	10.3	9.3	9.9

Table A17(a): 10-month water sorptivity (mm/hr^{½}) of the F1 (OPC/FA) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	* * 29.7	25.9 24.8 25.0	24.6 24.3 24.8
Average	29.7	25.2	24.6
3	27.0 26.0 29.8	22.5 23.0 24.9	20.5 16.2 26.9
Average	27.6	23.5	21.2
7	20.0 18.9 24.0	16.7 15.1 *	16.0 15.5 16.8
Average	20.9	15.9	16.1
28	16.2 20.3 20.7	15.9 16.9 15.5	14.8 14.6 15.7
Average	19.1	16.1	15.0

Table A17(b): 10-month water sorptivity (mm/hr^{½}) of the F2 (OPC/FA) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	25.3 25.7 26.7	26.3 26.2 24.4	23.8 25.1 22.9
Average	25.9	25.6	23.9
3	16.6 13.4 16.4	23.4 14.8 16.1	13.7 * 14.6
Average	15.4	14.7	14.2
7	13.8 13.5 12.9	12.6 13.1 11.3	9.6 12.0 11.6
Average	13.4	12.3	11.1
28	8.9 11.0 10.7	7.7 9.1 7.3	6.7 7.6 6.4
Average	10.2	8.1	6.9

Table A17(c): 10-month water sorptivity ($mm/hr^{½}$) of the F3 (OPC/FA) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	19.6 20.7 21.3	16.3 18.2 15.3	15.6 17.6 14.4
Average	20.5	16.6	15.9
3	11.5 10.0 11.5	11.7 10.4 10.8	10.1 9.7 9.8
Average	11.0	11.0	9.9
7	10.4 10.3 8.3	9.3 9.4 9.9	8.9 7.4 8.8
Average	9.7	9.5	8.4
28	8.2 8.9 7.1	7.0 6.3 7.5	5.6 6.4 5.8
Average	8.1	6.9	5.9

Table A18(a): 10-month water sorptivity (mm/hr^{½}) of the S1 (OPC/GGBS) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	32.9 31.9 30.9	25.6 26.2 27.1	30.8 26.7 26.2
Average	31.9	26.3	27.9
3	24.4 28.5 16.2	16.2 16.9 10.8	14.1 18.5 13.8
Average	19.7	14.6	15.5
7	16.8 13.6 14.8	8.9 7.3 11.2	7.5 8.5 9.0
Average	15.0	9.1	8.3
28	15.0 14.7 11.0	8.2 7.1 6.8	7.9 7.0 8.4
Average	13.6	7.4	7.8

Table A18(b): 10-month water sorptivity (mm/hr^{½}) of the S2 (OPC/GGBS) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	26.8 24.5 24.5	15.4 18.5 14.5	13.9 16.2 14.2
Average	25.3	16.1	14.8
3	18.1 13.8 15.0	8.8 7.8 8.9	10.0 9.2 10.2
Average	15.7	8.5	9.8
7	11.7 11.0 13.7	9.1 8.3 8.1	9.7 8.1 8.5
Average	12.2	8.5	8.8
28	14.4 11.6 13.8	7.9 7.2 5.9	7.4 6.7 6.6
Average	13.3	7.0	6.9

Table A18(c): 10-month water sorptivity (mm/hr$^{1/4}$) of the S3 (OPC/GGBS) concrete

Duration of moist curing (days)	Depth from Surface (mm)		
	0 to 15	15 to 30	30 to 45
1	19.7 23.3 22.3	15.7 16.4 17.8	15.6 14.0 15.1
Average	21.7	16.6	14.9
3	12.5 13.3 11.4	7.7 8.9 8.1	7.7 8.0 7.0
Average	12.4	8.2	7.6
7	9.9 8.9 9.2	6.3 5.7 6.7	6.6 6.4 5.9
Average	9.3	6.3	6.3
28	9.5 10.3 10.8	5.4 6.1 5.9	6.1 4.6 5.9
Average	10.2	5.8	5.5