Pergamon

Cement and Concrete Research, Vol. 25, No. 5, pp. 999-1010, 1995

0008-8846/95 $9.50+.00

0008-8846(95)00095-X

ABSORPTION CHARACTERISTICS OF CONCRETE AS A FUNCTION OF LOCATION RELATIVE TO CASTING POSITION

J M KHATIB* and P S MANGAT**
* Centre for Research in the Built Environment,
University of Glamorgan, Pontypridd CF37 1DL, UK
** School of Construction, Sheffield Hallam University, Sheffield S1 1WB, UK

(Refereed)
(Received August 22, 1994; in final form March 21, 1995)

ABSTRACT

Three different concrete mixes were prepared, the control mix in which no cement replacement material was added, and mixes where 22% and 9% by weight of cement was replaced with fly ash and silica fume respectively. Mixes were cast in 100mm cube moulds and cured at 20°C and 45°C using a variety of different curing regimes with respect to relative humidity and curing time to simulate concretes in hot and temperate climates. After curing, sliced samples were taken from various locations (faces) of the cube to determine their absorption. Two methods were used to study the absorption characteristics, the shallow immersion and the capillary rise. A large variation in absorption values existed between the upper surface during casting of the concrete cubes, the base and the sides. The absorption value of the complete unsectioned cube (100 mm) is similar to that of sectioned side face. A near-linear relationship exists between the two absorption methods.

Introduction

There is world-wide concern about the lack of durability of reinforced concrete structures resulting from corrosion of the reinforcement. It is well established that the quality and the thickness of the concrete cover from the exposed surface to the reinforcing bar is of paramount importance(1). The concrete cover is more susceptible to drying and will have a different quality from that obtained within the bulk of the unit (2-8). In addition to the existing differences in concrete properties as a function of the distance from the exposed surface, concrete can differ in quality horizontally compared with vertically(6), e.g. a concrete sample located at a distance of 30mm from the upper exposed trowelled face will have different characteristics that differ from those at the same distance from the side face.

The porosity and pore size distribution are indicative of concrete quality as they determine the ease with which fluid can penetrate into concrete (6). Permeability of concrete is that property which permits the flow of fluid that occurs under an applied pressure differential, but the term is also used to describe other transport mechanisms such as absorption and diffusion. However, permeability is more appropriate in relation to water-retaining structures while in above-ground structures, tests on water penetration may be more realistic (6,9).

In absorption tests the volume of voids in the concrete that have been filled or partially filled with water is measured for specific conditions of immersion and time intervals. The water absorption obtained by total immersion of specimens in water gives an indication of the open pore volume. However, if water is absorbed into concrete by capillary action, a measure of the rate of absorption provides a useful indication of the pore structure of concrete(10). For example a high rate of water absorbtion is indicative of a relatively open pore structure(3); the higher the rate of water absorbed, the poorer the quality of concrete. The tests do not measure true permeability, but they are simple and quick, and can provide a convenient means of obtaining a permeability index and are relevant to the durability of concrete (6,11-15).

Large variations in water absorption with depth from the exposed surface have been reported by some researchers (3,8,16). It was found that for concrete specimens cured at 72%RH and 27°C, that the absorption values obtained by capillary rise at a depth of 20mm from the top exposed surface were four times higher than those at 30mm depth. However at a depth of 70mm the absorption value was only 1.2 times less than the value at a depth of 30mm (3). The differences between the values at 20 and 30mm depth were reduced for specimens cured under wet burlap for 3 days at 22% RH (3).

In design of reinforced concrete structures, engineers tend to treat concrete as a material which has uniform properties. This study reports the variation in absorption values of the concrete taken from different distances from exposed surfaces of cube test specimens. Curing regimes were chosen to simulate concrete curing in hot climates and temperate climates; so that comparison can be made between various curing methods.

Experimental

Mix Proportions and Materials

Three different mixes were employed to examine the water absorption of the concrete matrix in relation to the position of concrete samples within a cube specimen. Details of the mixes are given in Table 1. The cementitious materials (binder) used were ordinary Portland cement, fly ash and condensed silica fume which was supplied in the form of slurry of equal proportions of solid to water. The control mix (M1) contained only ordinary Portland cement (OPC) as binder. In mixes M2 and M3 the OPC was partially replaced by respectively 22% fly ash, and 9% condensed silica fume (by weight). The water/cementitious materials ratio and the cementitious materials content were kept constant at respectively 0.45 and 350 kg/m^3 Superplasticizer which was added to the mixes conformed to type F and G materials of ASTM-C494. 1.2% of superplistisizer by weight of cement was added to mix M1 and M2 whereas 1.5% was added to mix M3.

TABLE 1

Table 1 - Details of Concrete Mixes

	Mix Proportions (Kg/m^3)							
Mix	OPC	Fly Ash	Silica Fume	Water	FA[1]	CA[2]	Slump (mm)	Strength[3] MPa
M1	350	0.0	0.0	157.7	708.6	1201.4	95	47.8
M2	273	77	0.0	157.7	687.1	1201.4	105	36.0
M3	318.5	0.0	31.5	157.5	698.6	1201.4	80	48.5

1- Fine aggregate, 2- Coarse aggregate, 3- 28 compressive strength(water cured at 20°C)

Composition of the cement and pozzolanic materials is given elsewhere (17,18). The fine aggregate used complied with categories C&M of BS882, 1983, and the coarse aggregate used was 20mm nominal size crushed and washed gravel.

Mixing and Casting

For mix M2 the cement was first blended with the fly ash prior to adding to the mix. In mixes M1 and M2, coarse aggregate was first added, followed by fine aggregate, then cement or cement blend material on top. Superplasticiser was mixed with the water which was added slowly to the uniformly mixed materials. Mixing was proceeded for about 2.5 minutes.

For mix M3, the silica fume slurry was poured over the coarse aggregate in the mixing pan to disperse the silica fume particles. Water which contained the superplasticizer was then added to the mix followed by cement and fine aggregate. Mixing was continued for 4 minutes.

Specimen preparation and Curing

100mm cube specimens were cast in steel moulds. Three different curing methods were employed are listed in Table 2 and are described below:-

(a) After casting and demoulding, specimens were subjected to air curing at 45°C, 25% RH for a period of 90 days. Specimens were designated as C1 and are called air cured at 45°C, 25% RH.

(b) After casting, the specimens were covered with plastic sheeting and wet burlap in an environmental chamber set at 45°C and 25% relative humidity (RH). After 24 hours from casting, the specimens were demoulded and immediately re-covered with wet burlap, which was kept moist and further covered with plastic sheeting. Curing was continued in the same environment for further 13 days. After this period the covers were removed and specimens were left exposed to air in the curing chamber at 45°C and 25% RH for a further 76 days. The specimens were designated as C2 and they are called wet/air cured at 45°C, 25% RH.

(c) Specimens were cast and cured in the same way as in (b) but the temperature and relative humidity of the controlled room were 20°C and 55% RH. Specimens were designated as C3 and they are called wet/air cured at 20°C, 55% RH.

TABLE 2
Details of Curing Methods

Curing	Up to 24 Hours	After 24 Hours and up to 14 days	After 14 days and up to 90 days
C1	Exposed to air at 45°C & 25%RH	Exposed to air at 45°C & 25%RH	Exposed to air at 45°C & 25%RH
C2	Covered with plastic sheeting and wet burlap at 45°C & 25%RH	Covered with wet burlap and plastic sheeting at 45°C & 25%RH	Exposed to air at 45°C & 25%RH
C3	Covered with plastic sheeting and wet burlap at 20°C & 55%RH	Covered with wet burlap and plastic sheeting at 20°C & 55%RH	Exposed to air at 20°C & 25%RH

Curing methods C1 and C2 were chosen to simulate curing in hot climates.

Sampling

In most cases, each cube was sectioned into slices, using a masonry saw. A few millimetres were lost between two consecutive slices due to the thickness of the blade, hence the thickness of each slice was about 22.75 ± 1.5mm.

Studies to determine variations in water absorption (shallow immersion) and water absorption coefficient (capillary rise), between the top surface (trowelled) during casting and bottom surface were carried out on slices cut from the cube, in a plane parallel to the trowelled face, as shown in Fig. 1. The top slice (slice 1) was designated as S_t and was considered to represent the material at the centre of the slice at a depth of 11.4mm from the top surface. The bottom slice (slice 4) was designated as S_b and was considered to represent the material at a depth of 88.6mm from the top surface. Slices 2 and 3 were considered to represent the material at depths of 37 and 63mm respectively from the top surface.

Investigations of the side faces during casting were carried out on slices cut perpendicular to the trowelled face as shown in Fig. 2, and the slice (slice 5) was designated as S_s.

In some cases the whole cube was tested for water absorption and these specimens were designated as S_c.

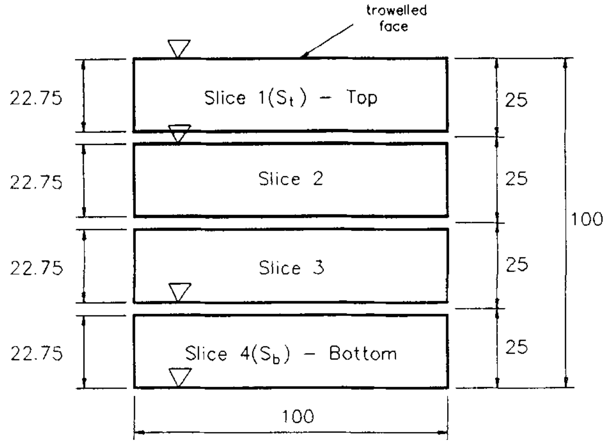

FIG. 1
Sliced Sample Parallel to the Top Cast Face (Dimensions in mm)

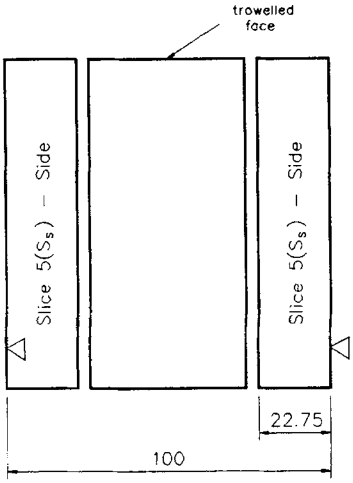

FIG. 2
Sliced Sample Perpendicular to the Top Cast Face (Dimensions in mm)

Drying of Specimens

After slicing, samples were dried by first holding them in the environmental chamber at 45°C and 25% RH for 4 hours, followed by oven drying to constant weight at 100 ± 5°C. The total period of drying was about 48 hours for slices and 96 hours for the cubes. The specimens were then transfered to an air-tight container at 20 ± 1°C prior to testing. Water absorption tests using shallow immersion were performed on the slices and the cubes and measurments of water absorption coefficient by capillary rise were made on the slices.

Testing

a) Water Absorption (shallow immersion): The dry weight (W_d) for the cubes and slices were recorded and specimens were then immersed in water at 20°C until they achieved a constant weight (W_s). W_s was taken as the saturated weight. This took up to 48 hours for the slices and 72 hours for the cubes. The water absorption (WA) is given by:

$$WA(\%) = 100 \times (W_s - W_d)/W_d$$

b) Water Absorption Coefficient(Capillary Rise): The capillary rise test was conducted at 20 ± 1°C and 60 ± 5% RH. Dried slices were placed on supports in a shallow tray (Fig.3) and water was added until the water level was 1.5mm above the base of the sample in contact with the water. The water level was kept constant throughout the test. The arrows in Figures 1 and 2 indicate the faces of the slice which are in contact with water.

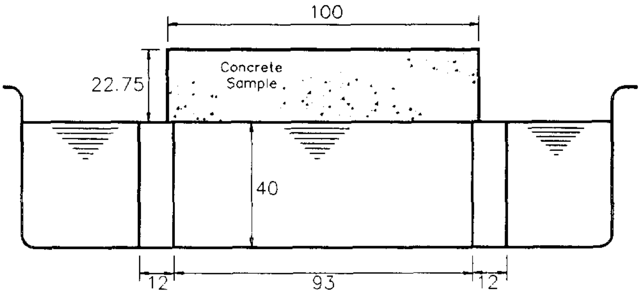

FIG. 3
Capillary Rise Test (Dimensions in mm)

The increase in sample weight was measured at regular intervals,. The weight (g) of water absorbed per unit area (mm^2) was plotted against the square root of time (s). The initial slope of the straight line is taken as the water absorption coefficient (WAC). The units are in $g/mm^2s^{0.5}$. This method is similar to the tentative recommendations made by RILEM(19). Figure 4 shows a typical relationship between the water absorbed per unit area versus the square root of time for mix M2 under C3 curing for the four samples taken from the top to the bottom part of the cube.

Results and Discussion

Absorption (WA and WAC)

The results on water absorption (WA) for the top, side and bottom faces as well as for the whole cube are presented in Figure 5 for mixes M1,M2 and M3 respectively for the

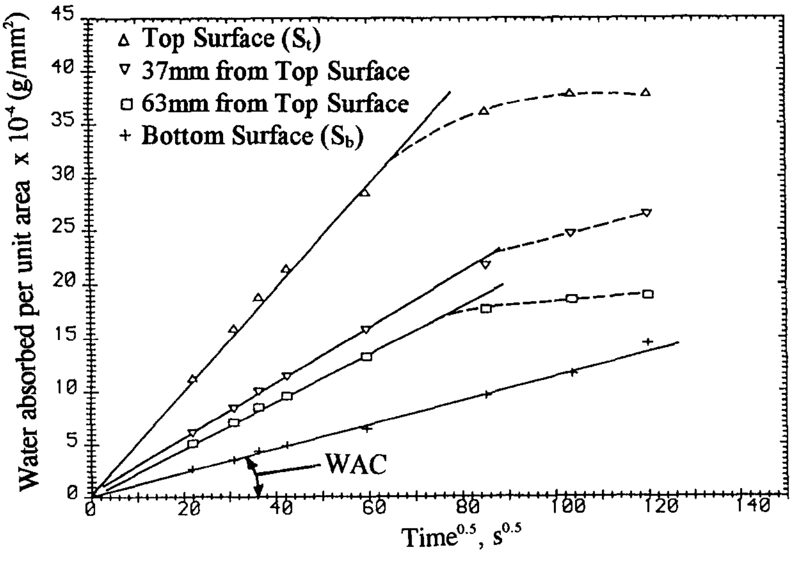

FIG. 4
Determination of Water Absorption Coefficient(Mix M2, Curing C2)

different curing regimes. The results show that a considerable variation exists between the various positions considered in this investigation. In all cases concrete close to the top part (trowelled) of the cube absorbs the largest amount of water compared with the side slice (S_s), which shows intermediate values and the bottom slice (S_b), which shows the least values. Also the whole cube (S_c) consistently has a water absorption value between those for the top and bottom faces and is similar to that of the sides.

For example for the C2 cured specimens of mix M1 (Figure 5-a), the top slice has a water absorption value about 40% higher than that of the bottom slice, whereas this difference is reduced to about 23% between the top face and the side face.

Also large differences in water absorption coefficient (WAC) were found between the top and the bottom parts of the cubes especially when C1 curing (i.e. dry curing) was employed as shown in Figure 6. In Figure 6-a, for example, the C1 cured specimens display WAC values of 38.6×10^{-6}, 31.5×10^{-6} and 11.85×10^{-6} g/mm^{2}s$^{0.5}$ for samples taken from the top, side and bottom parts respectively, which shows that the WAC for the top surface can be over three times that for the bottom surface. The side surface, however, exhibits WAC values intermediate between those obtained for the top surface and those for the bottom surface. Similar results are obtained for the different sections

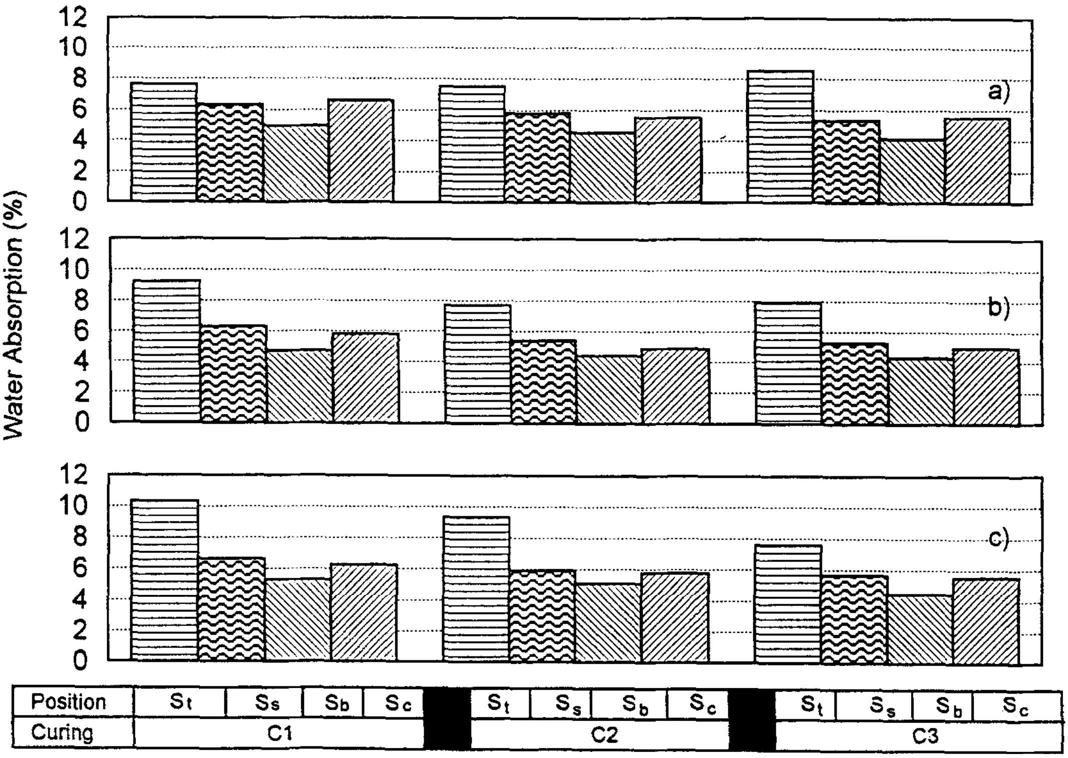

FIG. 5
Influence of Position on Water Absorption (WA) for Different Curing Conditions, a) control mix M1, b) 22% fly ash mix M2, c)9% silica fume mix M3

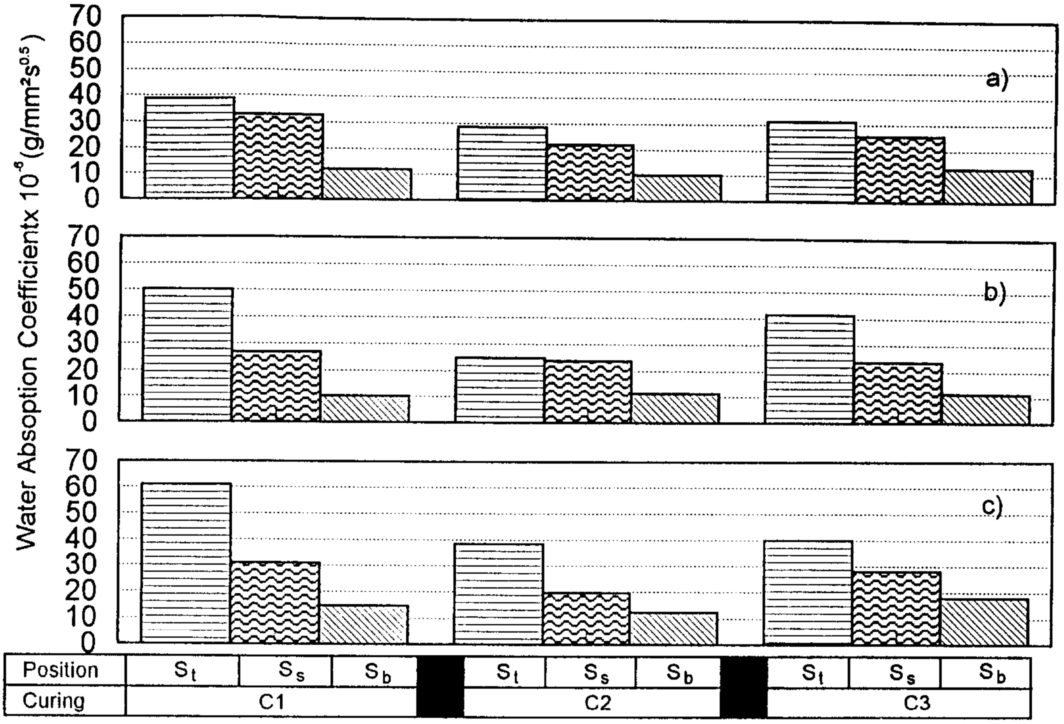

FIG. 6
Influence of Position on Water Absorption Coefficient (WAC) for different Curing Conditions, a) control mix M1, b) 22% fly ash mix M2, c)9% silica fume mix M3.

taken from cubes of mixes M2 (22% fly ash) and M3 (9% silica fume) as shown in Figure 6-b & c respectively.

The WAC test is much more sensitive to changes in porosity and pore structure than in the WA test. This is because the former test measures the rate at which water is drawn into a single face by capillary action whereas the latter measures the total absorption.

Variation of absorption with depth

The variation of water absorption (WA) and water absorption coefficient (WAC) with depth are presented in Figures 7 and 8 (for mixes M1, M2 and M3) respectively, under the various curing regimes used in this work. The results show clearly that, despite some variability, the first 30mm from the top (trowelled) surface, possess the highest values of WA and WAC. These values tend to decrease sharply with depth from the surface zone particularly for the WA values where only small differences exist between 40 to 90mm from the top surface. For example, consider Figure 7-b for mix M2; it can be noticed that the WA values at the concrete top surface (S_t) is 1.6 times higher than that of about 37mm depth (slice 2). The WA value of the bottom slice (S_b), however, is only 20% less than that at a depth of around 37mm. Similar differences are obtained for the other mixes

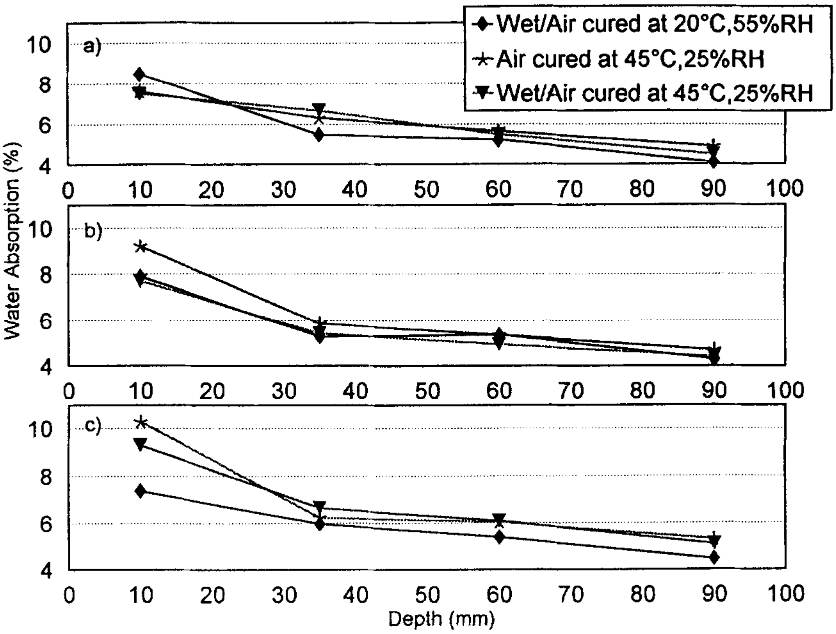

FIG. 7
Variation of Water Absorption (WA) with Depth for Different Curing Conditions, a) control mix M1, b) 22% fly ash mix M2, c)9% silica fume mix M3

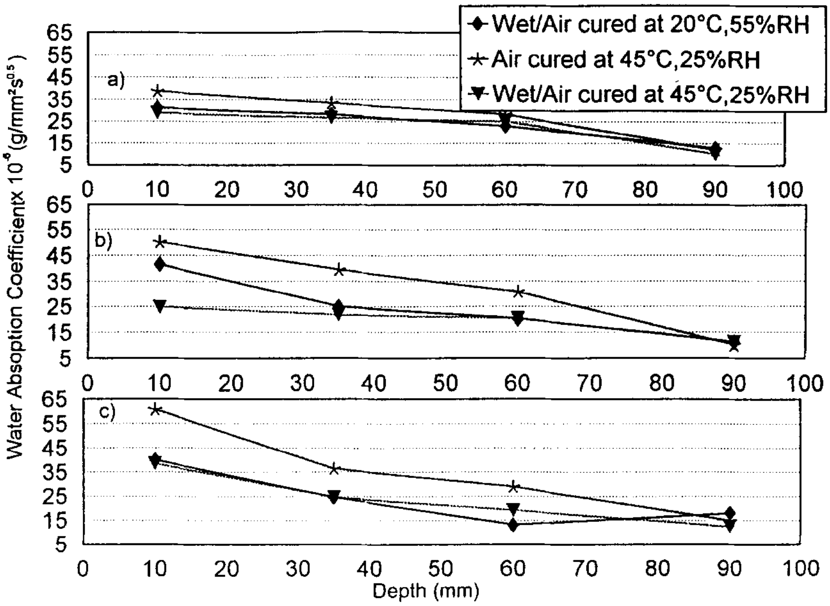

FIG. 8
Variation of Water Absorption Coefficient (WAC) with Depth for Different Curing Conditions, a) control mix M1, b) 22% fly ash mix M2, c)9% silica fume mix M3

and for other curing methods as clearly shown in figures 7 and 8. The variation in the rate of water absorbed with depth is in agreement with results reported elsewhere (3,8,16).

General discussion

When a concrete cube is cast some segregation of the sand and aggregate particles occurs during compaction and the lower density water moves upwards. In consequence there are property gradients in the specimen and the water/cementitious material ratio will be higher close to the trowelled surface. The coarse porosity close to the surface will be greater than that in the more compact lower regions of the cube and hence loss of moisture will also be greater. Hence the variations in the initial distribution of the concrete constituents will affect not only the pore structure but also the subsequent hydration if the concrete dries out. Such effects will have a marked influence on the absorption characteristics of the different concrete layers.

The general of the results obtained suggest that initially air cured specimens at 45 °C, 25%RH (C1) exibit higher values of water absorption and water absorption coefficient in comparison with curing regimes C2 and C3. This is more pronounced when the whole cube is considered. The whole cube has a larger exposed area than that of the slice and therefore it is more vulnerable to dry curing where the loss of moisture is greater. previous work by the authors (17) indicates that dry curing in addition to creating a larger pore volume, also results in larger pore size owing to the cessation of hydration when water is not present. This explains the higher values of absorption in air cured specimens (C1) relative to wet/air cured specimens (C2 and C3).

Influence of cement replacement materials

The results of Figures 5 and 6 suggest that replacing of 22% of cement with fly ash did not significantly influence the absorption values (WA & WAC). Surprisingly, the silica fume mix in most cases yields values higher or similar to those of the control mix and the 22% fly ash mix. The only exception was the water absorption coefficient (WAC) values of samples taken from side faces where the silica fume mix exhibit lower values than the values of the control mix under C1 and C2 curing. Such higher values of absorption in the silica fume mix (M3) is thought to be due to the larger open pores when silica fume is present. It was shown previously that pastes containing 9% silica fume exhibit higher values of pore volume obtained by mercury intrusion porosimetry compared with the control pastes (17).

Relationship between WA and WAC

The values of water absorption (WA) are plotted against the values of water absorption coefficient (WAC) for mixes M1,M2 and M3 in Figure 9. This suggests that a near-linear relationship exists between WA and WAC for the range of data obtained in this study. The relationship does not seem to be affected by the exposure conditions or by the presence of cement replacement materials. WA is a function of the porosity of the concrete, whereas WAC is a function of porosity and pore structure; for example specimens which have similar porosity give the same value of water absorption but may give different values of water absorption coefficient depending upon the size of capillaries; therefore a better relationship may be achieved if these factors are taken into consideration.

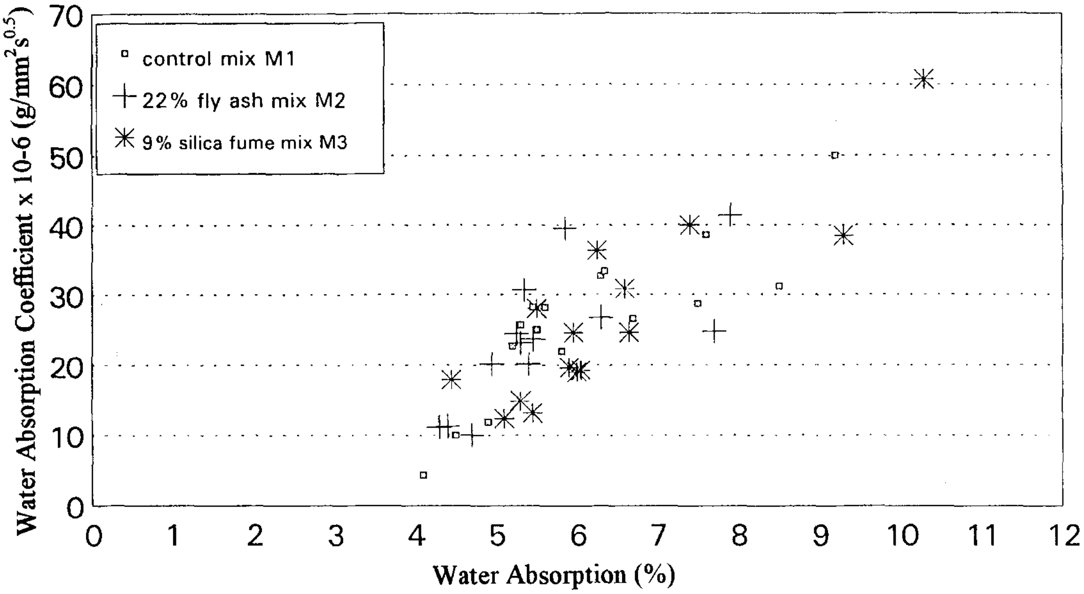

FIG. 9

Relationship between Water Absorption (WA) and Water Absorption Coefficient (WAC)

Conclusions

a) There is a considerable difference in water absorption between the top surface (trowelled) and the bottom surface of cast concrete. The values of WA on the top surface can be 50% greater than those of the bottom surface. This difference is even greater for WAC values where rate of absorption on the top surface can be more than twice that on the bottom surface.

b) The water absorption for the whole 100mm cube is similar to that of the side surface of the sectioned sample. The absorption values of the side surface are intermediate between those obtained for the top and the bottom face.

c) The results suggest that great attention should be paid to the concrete cover to the main reinforcement at the trowelled face; i.e. where there is a hogging bending moment in in situ reinforced concrete. In other words the thickness of the cover at the trowelled (top) face should be increased relative to that of the bottom face.

Acknowledgements

The first author would like to thank Dr S Wild at the University of Glamorgan for useful discussions.

References

1. R.K. Dhir, Y.N. Chan and P.C. Hewlett, Mag. Concr. Res.,38, 54(1986).
2. J.W. Figg, Mag. Concr. Res., 25, 213(1973).
3. E. Senbetta and C.F. Scholer, J. Ame. Concr. Ins., 81, 82(1984).
4. D.W.S. Ho, F.D. Bresford and R.K. Lewis, 3rd Int. Conf. Durability Build. Mater. Components, Finland, 163(1984).
5. P.C. Kreijger, Mater. Strct. Res. Test., 17, 275(1984).
6. J.D. Dewar, Concrete, 19, 40(1985).
7. D.W.S. Ho and R.K. Lewis, Durability of Building Materials, 4,241(1987).
8. L.J. Parrott, Mag. Concr. Res., 22, 1077(1992).
9. W.H. Glanville, Building Res. Tech. paper No. 3, Dept. Scie. Ind. Res., London, 1926.
10. L.J. Parrott, Mater. Struc., 25, 284(1992).
11. C. Hall and T. Kam Min Tse, Build. Envir., 21, 113(1986).
12. C. Hall and M.H.R. Yau, Build. Envir., 22, 77(1987).
13. C. Hall, Mag. Concr. Res., 41, 51(1989).
14. S. Kelham,Mag. Concr. Res., 40, 106(1988).
15. D.S.W. Ho and R.K. Lewis, Symp. Concr., Perth, 37(1990).
16. P.B. Bamforth and Pocock, Corrosion of Reinforcement in Concrete, Editors, C.L. Page, K.V.J. Treadaway and P.B. Bamforth, p.119, SCI, 1990.
17. P.S. Mangat and J.M. El-Khatib, Proc. 4th Int. Conf.,Editor V.M. Malhotra, Amer. Concr. Inst. - SP132, 1, 813(1992).
18. P.S. Mangat and J.M. El-Khatib, Cem. Concr. Res., 22, 1089(1992).
19. RILEM, RILEM Tent. recomm., Test No. 11.6, Mate. Struc., 13, 208(1980).
20. T.C. Powers, Bull. Res. Lab. Port. Cem. Ass., 2, 1939.