INFLUENCE OF MIX CONSTITUENTS AND WORKMANSHIP FACTORS ON CONCRETE STRENGTH AND DURABILITY

by
Dr. W.P.S. Dias

Abstract

The relative effects of mix, slump, compaction and curing on concrete compressive strength and durability (characterised by sorptivity) were assessed by means of factorial experimentation and analyses of variance. This approach was expected to identify the sensitivity of a given property to changes in the above four factors, and thus to assist practitioners in focusing attention appropriately, especially during in-situ concreting. The mix and slump, which together can be represented by the water/cement ratio, had a very significant influence on both strength and sorptivity. Of the workmanship factors, compaction was a very significant factor for concrete strength and curing for sorptivity. The importance of supervision for site curing is highlighted, since it is the factor most likely to be neglected.

Keywords: - in-situ concrete, strength, durability, sorptivity, workmanship factors, mix constituents, slump, compaction, curing, water/cement ratio, pulse velocity, density, factorial experiment.

1.0 Introduction

The properties of in-situ concrete are subject to considerable variability, because it is not a factory produced construction material such as steel, for example. The principal factors that affect the properties of concrete are mix proportions (especially the cement content), slump achieved (primarily dependent on the water content), compaction during placing and curing after casting. The first two factors represent concrete mix constituents, and taken together will be characterised by the water/cement. ratio, which is by far the greatest single influence on concrete properties. However, this composite index is here separated into mix and slump because the latter have more practical significance for concrete production and placing. Compaction and curing can be considered as workmanship factors.

Although the advent of ready mixed concrete has in fact shifted the production of some concrete to factory conditions, those conditions still do not match the ones under which steel is produced. This is because there is greater raw material variability in the concrete production process and also because different batches will be produced to different client requirements. In any case, a considerable amount of concrete around the world is still produced on site, often by volume batching, resulting in relatively poor control of mix and slump. Furthermore, whether produced in a factory or on site, all in-situ concrete has to be compacted and cured under site conditions. This can often involve adverse weather conditions and error or negligence by human operatives. Hence, it is very important to ascertain the effects of these workmanship factors on concrete properties.

Although the initial concern about concrete properties was regarding strength, there is now much greater concern about concrete durability. Here too, the principal worldwide focus regarding concrete durability is on the protection of embedded steel (which is present in most concrete) from corrosion, although there is also some attention given to the protection of the concrete itself (from phenomena such as sulphate attack and alkali aggregate reaction). Durability however is a long term property. Hence, appropriate indices have to be chosen for characterising it. One such index that is gaining increasing acceptability is sorptivity[1], especially since it is concerned with the surface areas of concrete which protect the steel reinforcement, and also because sorptivity testing reflects to a reasonable extent some of the processes by which actual deterioration of concrete will take place on site.

Dr. W.P.S. Dias, *BSc(Eng)Hons, PhD(Lond), DIC, CEng, MIE(SL) is a Senior Lecturer in the Department of Civil Engineering at the University of Moratuwa. His current research interests are in the area of Concrete Structures and Materials.*

2.0 Research Significance

The particular significance of this research lies in the fact that the relative effects of mix, slump, compaction and curing on concrete properties are assessed through full factorial experimentation and analyses of variance. This will make it possible to identify the sensitivity of a given property to changes in the above four factors. The results will guide supervisors and operatives to focus attention appropriately in concreting practice.

3.0 Approach to the Problem

Two independent test programmes were employed to study the relative effects of (i) mix, (ii) slump, (iii) compaction and (iv) curing on concrete properties. The first programme concentrated on strength and related properties and the second on sorptivity. Each of the four factors above were held at two levels and complete factorial experimentation carried out. The concrete mixes were made with Ordinary Portland Cement, river sand fine aggregate and crushed gneissic coarse aggregate of 20 mm maximum size.

Analyses of variance were carried out on the results to find out the relative significance of each of the factors and two factor interactions. After carrying out analyses of variance, the following definitions were used to classify the influence of the various factors and two factor interactions, depending on the levels of significance (l.o.s.) they were placed at.

"Very significant" - < 1 % l.o.s.
"Significant" - 1 % to 5 % l.o.s.
"Not significant" - 5 % to 10 % l.o.s.
"Insignificant" - > 10 % l.o.s.

4.0 Strength, Pulse Velocity and Density

4.1 Experimental Programme

Two volume batched mixes were used for this programme (Series 1) and are shown in Table 1. Mix B was chosen because of the widespread use of 1:2:4 concrete, while Mix A (i.e. 1:3:6 concrete) was used to represent a concrete which had been made leaner due, for example, to site malpractice. The table also indicates the water/cement ratios employed and the consequent slumps. The slump variation in this test programme was fairly small, one level of slump being zero (i.e. a very stiff mix) and the other level being 5-10 mm. In fact, the water/cement ratio was used as a guide for increasing the slump from zero, the ratio being increased by 0.1 for each mix.

Compaction was carried out at two levels, half of the specimens being compacted on a vibrating table in three layers (until air bubbles ceased to appear at each layer) into six inch (152.4 mm) cube moulds, and the other half being merely trowelled into these moulds with the minimum of energy used to place the concrete and level the surfaces. Demoulding was done on the day after casting. Curing was also carried out at two levels, half of the cubes being covered with wet hessian until demoulding and cured in a water bath until an age of 28 days, the other half being uncovered until demoulding and stored in air until an age of 28 days. Laboratory air conditions averaged around 30 deg. C and 85 % R.H.

All testing was performed at an age of 28 days. The cubes were first weighed and a rough estimate of density made on the basis of the approximate volumes of the cubes, obtained by linear measurements. After this, ultrasonic pulse velocity measurements were taken on the cubes. Finally, the cubes were crushed in a compression testing machine to determine their compressive strengths.

4.2 Results and Analysis

The results of the tests are shown in Table 2. Only one cube per condition was used, since the entire factorial experiment was expected to yield the significant trends. Each specimen is characterised by a four field code. The first field indicates the mix, i.e. either A (leaner) or B (richer) - see Table 1. The second field stands for slump, whether low (X) or high (Y). The third field corresponds to the degree of compaction, whether high (1) or zero (0), and the last field to the curing method, i.e. whether wet (W) or dry (D). The outcomes of the analyses of variance are shown in Table 3 for the properties strength, pulse velocity and density.

Let us first consider strength. Mix, slump and compaction are very significant influences on strength. As stated before, the combination of mix and slump will be a measure of the water/cement ratio, which has long been recognised as the dominant influence on concrete strength[2]. However, of the workmanship factors, compaction is very significant, while curing is insignificant.

Curing therefore does not seem to affect concrete strength, when compared to the effects of the other factors. This is because the interior of the concrete will be self cured due to internal moisture, even if the cube as a whole is not water cured. It is only the areas close to the surfaces of the cubes that will dry out and be affected by non curing. If such areas are small in relation to the volume of the cube - as is probably the case in a six inch (152.4 mm) cube - the net effect on the strength of the cube will be small. The fact that curing affects the quality mainly of the surface concrete[3] and that the effect of curing on strength is a function of specimen size[4] have been clearly established. In fact, researchers wishing to use strength as an index of the effect of various curing regimes on concrete quality have deliberately chosen small specimens - e.g. 50 mm cubes[5,6]. It must be appreciated that the results of the air stored cubes would have incorporated an increase in strength over the wet cured ones, because of the differences in moisture conditions at testing[4,5]. This effect was not isolated in the present test programme; its contribution however, is not likely to be very great in the fairly large 152.4 mm cube specimens.

The slump-compaction interaction is also a very significant influence on strength. This could also be expected, since a high slump concrete would be self compacting to an extent. It also means that compaction becomes especially important for low slump concretes.

Where pulse velocity is concerned (Table.3), all four of the main factors are very significant influences. One would in fact expect factors influencing strength to influence pulse velocity as well, as the latter is sometimes used as an index of the former in non-destructive testing[7]. The reason that curing has become a very significant factor for pulse velocity (unlike for strength) is probably because the wet cured cubes were wet and the air stored cubes dry when tested for pulse velocity; the wet cubes would yield a higher pulse velocity than the dry cubes even if their cement microstructures were similar, because the ultrasonic pulse travels faster in a wet medium[8]. The slump-compaction interaction is a significant influence on pulse velocity, and this can be explained as above for strength. In addition, the mix-compaction interaction is also significant, a leaner mix responding more to compaction than a richer one.

The analysis of variance for density (Table 3) indicates that compaction is the dominant very significant factor influencing it. The factors influencing density bear no relation to those influencing strength and pulse velocity. This is probably why density has never been considered as an index of concrete strength, whereas pulse velocity has.

5.0 Sorptivity

5.1 Experimental Programme

Two volume batched mixes were used for this programme (Series 2), as shown in Table 4. Although the 1:2:4 mix was used in Series 1 as well, the other mix in this series was richer, rather than being leaner as in Series 1. The range of mixes in this series therefore was not chosen to reflect site malpractice (as in Series 1), but rather to reflect the range of concretes in normal concreting practice. The variation in slump was also made greater in this programme, low slump being 0-10 mm and high slump 100 mm. This variation was also considered to be more representative of site conditions.

The moulds used for this programme were specially fabricated for casting concrete cylinders of 100 mm dia. x 100 mm length. Half of the specimens for each mix prepared were compacted into the moulds in two layers, until air bubbles ceased to appear at each layer, on a vibrating table. The times required for such "high" compaction to occur were recorded on a stopwatch for each mix prepared. The other half of the specimens were also compacted in two layers on a vibrating table, but only for a quarter of the duration employed for "high" compaction. Thus the difference between the levels of compaction was lower in this series than in Series 1, where "low" compaction meant "zero" compaction. There were two reasons for using a "medium" level of compaction in this series. The first was that it was a more realistic representation of site (mal)practice, where at least some compaction would probably be carried out. The second was that it would be difficult to carry out sorptivity testing on specimens if they were very badly honeycombed as a result of zero compaction.

The demoulding and curing procedures employed were identical to those in Series 1. Half the specimens were wet cured until an age of 28 days, while the other half were stored in air for that duration. After 28 days, the wet cured specimens were also stored in air. Sorptivity testing was carried out on both wet cured and air cured specimens only after they had achieved weight stability with the surrounding air. After such stability was achieved, the curved surfaces of the cylinders were coated with an epoxy resin to ensure that moisture movement during subsequent water sorption would be uniaxial.

The cast surfaces of the specimens were placed on sponges that were in turn placed in a shallow tray of water. Cast surfaces of specimens were used for sorptivity testing because most surfaces of site cast concrete would be cast as opposed to free. It should be noted that the sorptivity of cast and free surfaces varies considerably[9].

The weights of specimens were taken after 1, 4, 9, 25 and 49 hours of absorption. This enabled the weights, and hence volumes of water absorbed per unit surface area at each time step to be calculated. These volumes were plotted against the square root of time. The coefficients of linear correlation were 0.99 and above for all cases, except for the air cured specimens of mix B, where the coefficients ranged from 0.67 to 0.79. In these latter cases, only the data upto 9 hours were used for the linear regression analysis; this resulted in an improvement in the coefficients of correlation, the range becoming 0.88 to 0.99. Two typical sorptivity plots are shown in Figure 1; one of these corresponds to an air cured specimen of mix B. Sorptivity is defined as the slope of the above plots and has units of mm/hr$^{0.5}$.

5.2 Results and Analysis

The values of sorptivity obtained for the various specimens are presented in Table 5. It must be appreciated that a lower sorptivity will indicate better durability. Two specimens per condition were tested, to get an indication of the replicability of the results. As seen from Table 5, such replicability is very good. Each specimen is characterised by a five field code. The first field indicates the mix, whether B (leaner) or C (richer) - see Table 4. The second field stands for slump, whether low (X) or high (Y). The third field corresponds to the degree of compaction, whether high (H) or medium (M), and the fourth field to the method of curing, whether wet (W) or dry (D). The final field is a serial number and is either 1 or 2, since two specimens per condition were tested.

The sorptivity values in Table 5 are lower than those obtained by Ho and Lewis[10], probably because their specimens were continually sprayed on all faces at an air pressure of 0.5 kPa, as opposed to absorbing water passively from a single face. Kelham[11] also obtained sorptivity values that are an order of magnitude greater than those in Table 5, because his specimens were dried at 105 deg. C, rather than being dried in air.

However, the values of 1.350 and 1.481 mm/hr$^{0.5}$ for specimens BYHW1 and BYHW2 respectively (w/c = 0.75) compare well with the values of 1.213 mm/hr$^{0.5}$ obtained by the present author[12] and 1.39 mm/hr$^{0.5}$ obtained by Hall[1], both the latter values being for concretes having water/cement ratios of 0.8. Furthermore, the values of 0.373 and 0.472 mm/hr$^{0.5}$ for specimens CYHW1 and CYHW2 respectively (w/c = 0.6) compare reasonaby well with that of 0.515 mm/hr$^{0.5}$ obtained previously by the present author[12] for a concrete having a water/cement ratio of 0.6.

The results of the analysis of variance are shown in Table 6. Of the main factors, mix, slump and curing influence sorptivity very significantly. Once again, we see the key influence of the combination of mix and slump (which can be characterised by the water/cement ratio) on concrete properties, in this case sorptivity, which is related to durability.

However, curing is now a very significant main factor, whereas compaction is an insignificant one. This is the reverse of the situation for strength, where these two workmanship factors are concerned. In fact, the highly significant influence of curing (or the lack thereof) can be seen in Table 5 itself, without even performing an analysis of variance. This result is consistent with the fact that curing primarily affects areas close to the concrete surface[3,4]. Sorptivity is in fact a measure of the cover zone concrete quality, and it is this area that would be influenced by curing.

One reason for the influence of compaction being small may be the fact that the cast bottom faces would have been reasonably well compacted even under the "medium" level of compaction described beforehand; the curved faces of the cylindrical specimens showed significant honeycombing, whereas the cast bottom faces displayed only isolated air voids. Another reason is that compaction serves to eliminate only the air voids in concrete. These relatively large voids would not contribute towards absorption through capillary suction as much as the smaller capillary pores would.

Where the two factor interactions are concerned, the mix-curing interaction is very significant - i.e. leaner mixes will benefit more by curing. The mix-compaction and slump-curing interactions are significant. Higher slump concretes will benefit more by curing and richer mixes will benefit more by compaction. The phenomenon of concretes with higher water/cement ratios benefitting more by curing has been reported before[13]. It should be noted that the leaner 1:2:4 mix actually increased in sorptivity with increased compaction. This anomaly may be due to excess slurry being forced out of the mix by inadvertant over-compaction. Over-compaction has been found to reduce strength despite increasing density, probably as a result of such segregation[14].

6.0 Discussion

The dominant effect of mix and slump on both strength and sorptivity has been clearly established. As stated before, the combination of mix (reflecting cement content) and slump (reflecting water content) can be aliased by the water/cement ratio, which is universally accepted as the key factor affecting the properties of concrete[2,12,15]. When the analyses of variance were carried out replacing mix and slump by a single water/cement ratio factor, it was found to be very significant for strength, pulse velocity and sorptivity, as expected; the rest of the variance tables were also similar to the variance tables when both mix and slump were used as independent factors. The dominant influence of the water/cement ratio on concrete properties can also be seen when strength and sorptivity are plotted against it as in Figures 2 and 3 respectively. These figures show the variations of (i) the mean values over the different slump, compaction and curing combinations employed and (ii) the best values resulting from the above combinations. Hence, the results in this paper confirm the importance of the proper batching of concrete mix constituents, as they affect strength and sorptivity (an index of durability) very significantly.

Where the workmanship factors are concerned, it must be appreciated that the degree of compaction corresponding to the lower level of compaction was different in the two test series. In Series 1, this lower level corresponded to virtually zero compaction, whereas in Series 2 it corresponded to a quarter of the time taken for "high" compaction on a vibrating table. As such, a direct comparison of the effects of compaction on strength and sorptivity cannot strictly be made. The levels of curing used in Series 1 and 2 however, were identical.

Nevertheless, comparisons between the overall effects of compaction and curing for strength and sorptivity are made in Figures 4 and 5 respectively. The values in the figures are the overall means for a particular level of compaction or curing.

Figure 4 indicates that there is a very significant influence of compaction on strength, when the degree of compaction is varied between "high" and "zero". On the other hand, the effect of curing is negligible. The difference in strength between specimens subjected to "high" and "incomplete" compaction has also been found by Chandrakeerthy et al.[14] to be significant for 1:2:4 concrete, where properly vibrated concrete yielded a mean equivalent cube strength of 21.6 N/mm^2 and incompletely vibrated concrete one of 13.9 N/mm^2. The above "incomplete" level of compaction would be similar to the "medium" level of compaction used in Series 2. Hence, it could be posited that changes in the levels of compaction influence concrete strength significantly, whether those level changes are between "high" and "zero" or "high" and "medium".

Figure 5 indicates that there is a very significant influence of curing on sorptivity. The change between the levels of curing is identical to the change corresponding to Figure 4 for strength. On the other hand, the effect of compaction on sorptivity is negligible, and anomalous in the sense that the higher level of compaction actually increases the sorptivity, whereas it would be expected to decrease it. This anomaly can be explained by the fact that the means for compaction are influenced by those for the leaner mixes in this series, where inadvertant over-compaction may have caused slurry loss and deterioration in concrete quality[14]. It must also be appreciated that the difference between the levels of compaction is less than that corresponding to Figure 4 for strength.

Despite the above drawbacks in the lack of uniformity between compaction levels in Series 1 and 2, if we draw on the findings of Chandrakeerthy et al.[14] reported earlier as well, it appears that compaction is more important for strength than it is for sorptivity. It can also be categorically stated that curing is very important for sorptivity, but that its effect on strength is minimal especially if the sizes of concrete elements are around 150 mm or greater. At a slight risk of over-simplification we can therefore conclude that where the workmanship factors for most practical concrete elements are concerned, compaction is more important for strength and curing for sorptivity. Given that sorptivity is a measure of the quality of cover zone concrete and the fact that this zone plays a crucial barrier function in concrete durability - i.e in the protection of concrete (especially reinforced concrete) over time - we can say that curing is very important for durability.

The significant influences of water/cement ratio and curing for concrete durability have been demonstrated by other researchers as well. Ho and Lewis[10] and Parrott[16] have shown that water absorption is influenced by these two factors, as this present study has, while Dhir et al.[15] have demonstrated the effect of these same factors on a range of permeation properties using the initial surface absorption test, the Figg air permeability method and the covercrete absorption test. Ben-Bassat et al.[13] have shown that water/cement ratio and curing significantly affect depth of carbonation, drying shrinkage, initial surface absorption, total absorption and oxygen permeability; however, the importance of curing was reduced as the water/cement ratio decreased. This latter interaction was detected in the present study as well.

Results obtained by Rasheeduzzafar et al.[17] indicate that inadequate curing has a more dramatic effect than inadequate compaction on the time required to initiate corrosion and on the severity of sulphate attack. Hall and Yau[18] however did find that variations in compaction had a greater influence on sorptivity than did variations in water/cement ratio; this however has to be considered as a result that is contrary to the majority of research findings. Furthermore, they did not study the influence of curing. Fattuhi[6] has shown that the rate of carbonation decreased with an increase in water curing period. Senbetta and Scholer[19] showed that curing had the effect of reducing the differences between concrete quality at different depths in their specimens, using absorptivity as an index.

Although the present study has used only the index of sorptivity to establish the very significant influence of water/cement ratio and curing for concrete durability, this same significance has also been demonstrated by other researchers using a variety of other indicators[13,15,17,19,20], as mentioned above. This is important because durability is very difficult to test directly, being a long term property, and hence has to be characterised by appropriate indices. The use of a range of indices, covering various processes of concrete deterioration, will give greater confidence for predicting the influence of various factors on the actual durability of concrete.

The importance of good compaction and curing on site for achieving good strength and durability properties respectively has therefore been clearly established. There are however some inbuilt aspects of site practice that help to ensure good compaction. For one thing, compaction is performed during the concreting process itself, when there is likely to be reasonably good supervision of operatives. For another, poor compaction can be found out by the resultant honeycombing that will become visible on the removal of formwork. On the other hand, curing has to be carried out after the concrete has been placed, when the level of supervision may drop. Furthermore, there is no visible sign such as honeycombing to indicate the lack or inadequacy of curing. For these reasons, even greater emphasis should be placed on ensuring good curing of in-situ concrete.

The period of wet curing employed in Series 2 was 28 days. This is of course too long for everyday site practice. Therefore, the period of wet curing after which the reduction in sorptivity or improvement in durability becomes small is also an important factor for guiding site curing. Further research into this aspect is currently under way, although there is already some data concerning it[6,10,16,17,19]. In general, most durability indicators tend to improve significantly with wet curing upto around 3-7 days, but the rate of improvement drops with curing durations beyond that.

In concluding this discussion, it must be pointed out that there are emerging technologies that could reduce or even eliminate the need for supervising workmanship factors, just as ready mixed concrete has improved the control of concrete mix constituents. These technologies are (i) flowing or self compacting concrete[21] and (ii) controlled permeability formwork, which improves the properties of the concrete cover zone by reducing the effective water/cement ratio in that zone[22]. However, in many parts of the world, the batching of mix constituents and the workmanship involved in compaction and curing have to be very carefully supervised on site, if concrete of the required strength and durability is to be produced.

7.0 Conclusions

The first two of these conclusions are based on the the results of the two series of experiments described herein, while the third is based on the implications of those results for in-situ concreting practice.

1.The 'mix (reflecting cement content) and slump (reflecting water content) are very significant factors for both strength and sorptivity. This confirms that the water/cement ratio is the single most important index of concrete properties, because this index can be used to alias the combined effects of mix and slump.

2.Of the workmanship factors, it can be said that curing is more important for sorptivity, influencing it very significantly, whereas compaction is more important for strength, also influencing it very significantly. It should be appreciated that sorptivity is a good index of durability.

3.Given that concrete mix constituents can be reasonably well controlled if batching is done in concrete plants and that concreting practice has some inbuilt safeguards to ensure good compaction, the aspect of in-situ concreting presently requiring the greatest attention of practitioners is good curing.

8.0 Acknowledgements

This research was carried out on a grant from the University of Moratuwa. The author would also like to acknowledge the contributions of Technical Assistant A.D.R. Sasanka and students B. Wickramaarachchi and M.M. Marasingha in some of the casting and testing described in this paper. The continuing assistance of the technical staff in the Structures and Building Materials laboratories at the University of Moratuwa is also appreciated.

9.0 References

1. Hall, C. "Water sorptivity of mortars and concretes: a review." *Magazine of Concrete Research*, Vol. 41, No. 147, June 1989, pp. 51-61.

2. Popovics, S. "Analysis of the concrete strength versus water/cement ratio relationship." *ACI Materials Journal*, Vol. 87, No. 6, September-October 1990, pp. 517-529.

3. Carrier, R.E. "Concrete curing tests." *Concrete International*, Vol. 5, No. 4. April 1983, pp. 23-26.

4. Meyer, A. "The importance of the surface layer for the durability of concrete structures." *SP 100 - Concrete Durability: Katherine and Bryant Mather International Conference*, American Concrete Institute, Detroit, 1987, pp. 49-61.

5. Popovics, S. "Effect of curing method and final moisture condition on compressive strength of concrete." *ACI Journal*, Vol. 83, No. 4, July-August 1986, pp. 650-657.

6. Fattuhi, N.I. "Concrete carbonation as influenced by curing regime." *Cement and Concrete Research*, Vol. 18, No. 3, pp. 426-430.

7. Bungey, J.H. *Testing of concrete in structures, 2nd ed.*, Blackie and Son Ltd., Glasgow, 1989, 228 pp.

8. Tomsett, H.N. "Ultrasonic pulse velocity measurements in the assessment of concrete quality." *Magazine of Concrete Research*, Vol. 32, No. 110, March 1980, pp. 7-16.

9. McCarter, W.J. "Influence of surface finish on sorptivity of concrete." *ASCE Journal of Materials in Civil Engineering*, Vol. 5, No. 1, February 1993, pp. 130-136.

10. Ho, D.W.S. and Lewis, R.K. "The water sorptivity of concretes: The influence of constituents under continuous curing." *Durability of Building Materials*, Vol. 4, 1987, pp. 241-252.

11. Kelham, S. "A water absorption test for concrete." *Magazine of Concrete Research*, Vol. 40, No. 143, 1988, pp. 106-110.

12. Dias, W.P.S. "Durability indicators of OPC concretes subject to wick action." *Magazine of Concrete Research*, December 1993, scheduled for publication.

13. Ben-Bassat, M., Nixon, P.J. and Hardcastle, J. "The effect of differences in the composition of Portland cement on the properties of hardened concrete." *Magazine of Concrete Research*, Vol. 42, No. 151, June 1990, pp. 59-66.

14. Chandrakeerthy, S.R. de S., Wanigadeva, G.H.U.A., Tissera, P.K.D. and Wijeratne, A.S. "Influence of compaction on 1:2:4 volume batched concrete." *Proceedings, Institution of Engineers, Sri Lanka*, Vol. 1, 1986, pp. 87-99.

15. Dhir, R.K., Hewlett, P.C. and Chan, Y.N. "Near surface characteristics of concrete: Assessment and development of in situ test methods." *Magazine of Concrete Research*, Vol. 39, No. 141, December 1987, pp. 183-195.

16. Parrott, L.J. "Water absorption in cover concrete." *Materials and Structures: Research and Testing*, Vol. 25, 1992, pp. 284-292.

17. Rasheeduzzafar, Al-Gahtani, A.S. and Al-Saadoun, S.S. "Influence of construction practice on concrete durability." *ACI Materials Journal*, Vol. 86, No. 6, November-December 1989, pp. 566-575.

18. Hall, C. and Yau, M.H.R. "Water movement in porous building materials - IX. The water absorption and sorptivity of concretes." *Building and Environment*, Vol. 22, No. 1, 1987, pp. 77-82.

19. Senbetta, E. and Scholer, C.F. "A new approach for testing concrete curing efficiency." *ACI Journal*, Vol. 81, No. 1, January-February 1984, pp. 82-86.

20. Gowripalan, N., Cabrera, J.G., Cusens, A.R. and Wainwright, P.J. "Effect of curing on durability." *Concrete International*, Vol. 12, No. 2, February 1990, pp. 47-54.

21. Ozawa, K., Maekawa, K. and Okamura, H. "New concrete with high filling capacity - Development of high performance concrete." *3rd East Asia-Pacific Conference on Structural Engineering and Construction*, April 1991.

22. Barfoot, J. "Controlled permeability formwork." *Concrete*, Vol. 25, No. 3, March/April 1991, pp. 12-13.

TABLE 1 - MIX AND SLUMP DETAILS FOR SERIES 1

Mix Code	Mix proportions Ct:Sand:Coarse Agg.	Low slump		High slump	
		W/C	Slump (mm)	W/C	Slump (mm)
A	1:3:6	0.75	0	0.85	5
B	1:2:4	0.55	0	0.65	10

Note : Max. size of coarse aggregate is 20 mm.

TABLE 2 - TEST RESULTS FOR SERIES 1

Specimen Code	Density (kN/m³)	USPV (km/s)	Strength(N/mm²)
AX0W	19.25	3.50	5.83
AX1W	23.34	4.35	15.80
AX0D	18.47	3.46	6.50
AX1D	22.47	4.07	16.13
AY0W	17.84	3.49	4.31
AY1W	23.26	3.98	11.57
AY0D	18.31	3.28	5.41
AY1D	22.16	3.59	11.28
BX0W	20.12	4.34	13.43
BX1W	23.73	4.70	28.13
BX0D	18.70	3.89	12.84
BX1D	22.87	4.44	24.41
BY0W	20.43	4.09	11.24
BY1W	23.02	4.14	17.91
BY0D	20.27	3.94	11.49
BY1D	22.08	3.96	15.50

TABLE 3 - FACTORS INFLUENCING STRENGTH, PULSE VELOCITY AND DENSITY (SERIES 1)

FACTORS	STRENGTH	PULSE VELOCITY	DENSITY
Main Factors			
Mix	Very Significant	Very Significant	Not Significant
Slump	Very Significant	Very Significant	Insignificant
Compaction	Very Significant	Very Significant	Very Significant
Curing	Insignificant	Very Significant	Not Significant
Two Factor Interactions			
Mix-Slump	Not Significant	Insignificant	Insignificant
Mix-Compaction	Insignificant	Significant	Not Significant
Mix-Curing	Insignificant	Insignificant	Insignificant
Slump-Compaction	Very Significant	Significant	Insignificant
Slump-Curing	Insignificant	Insignificant	Insignificant
Compaction-Curing	Insignificant	Insignificant	Insignificant

TABLE 4 - MIX AND SLUMP DETAILS FOR SERIES 2

Mix Code	Mix Proportions Ct:Sand:Coarse Agg.	Low slump		High Slump	
		W/C	Slump(mm)	W/C	Slump(mm)
B	1:2:4	0.65	0	0.75	100
C	1:1.5:3	0.50	10	0.60	100

Note : Max. size of coarse aggregate is 20 mm

TABLE 5 - TEST RESULTS FOR SERIES 2

Specimen Code	Sorptivity ($mm/hr^{0.5}$)
BXHW1	0.533
BXHW2	0.491
BXHD1	3.228
BXHD2	2.967
BXMW1	0.715
BXMW2	0.690
BXMD1	2.228
BXMD2	2.228
BYHW1	1.350
BYHW2	1.481
BYHD1	3.680
BYHD2	3.559
BYMW1	0.838
BYMW2	0.933
BYMD1	3.692
BYMD2	2.400

Specimen Code	Sorptivity ($mm/hr^{0.5}$)
CXHW1	0.131
CXHW2	0.203
CXHD1	0.529
CXHD2	0.260
CXMW1	0.215
CXMW2	0.134
CXMD1	1.248
CXMD2	0.890
CYHW1	0.373
CYHW2	0.472
CYHD1	2.428
CYHD2	2.096
CYMW1	0.473
CYMW2	0.624
CYMD1	1.877
CYMD2	1.988

TABLE 6 - FACTORS INFLUENCING SORPTIVITY (SERIES 2)

Main Factors	
Mix	Very Significant
Slump	Very Significant
Compaction	Insignificant
Curing	Very Significant
Two Factor Interactions	
Mix-Slump	Insignificant
Mix-Compaction	Significant
Mix-Curing	Very Significant
Slump-Compaction	Insignificant
Slump-Curing	Significant
Compaction-Curing	Insignificant

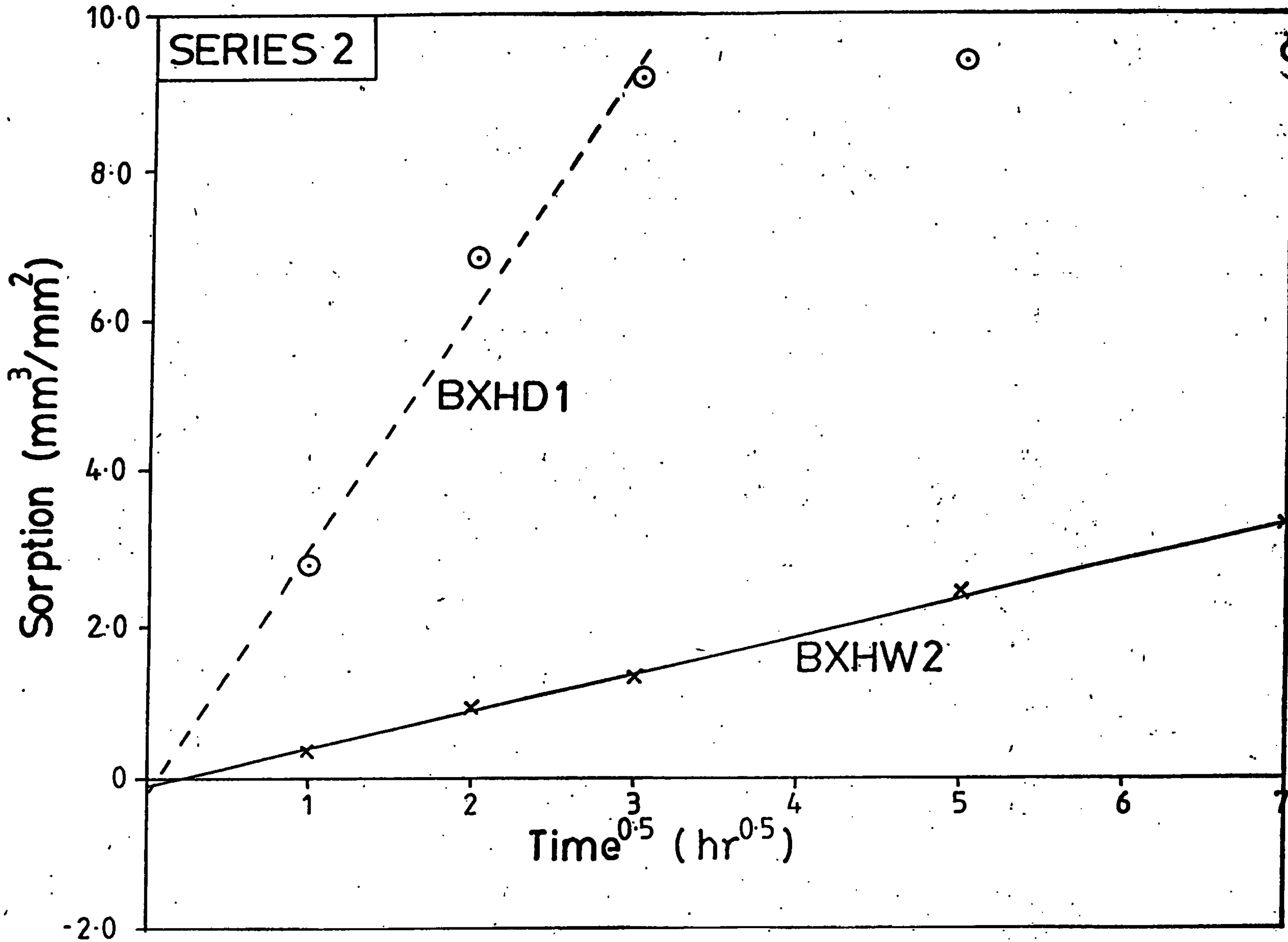

FIGURE 1 - TYPICAL SORPTIVITY PLOTS

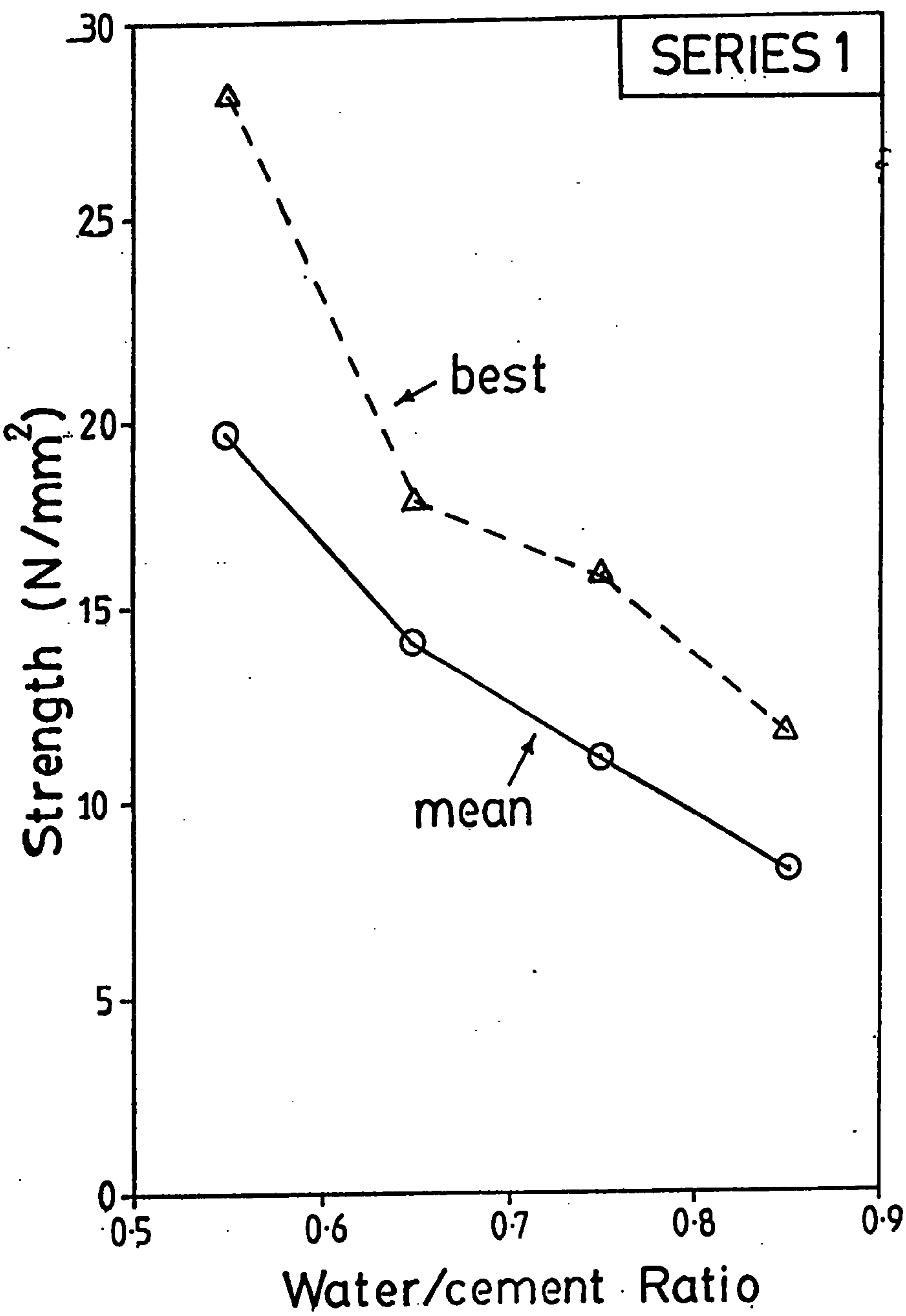

FIGURE 2 - INFLUENCE OF WATER/CEMENT RATIO ON STRENGTH

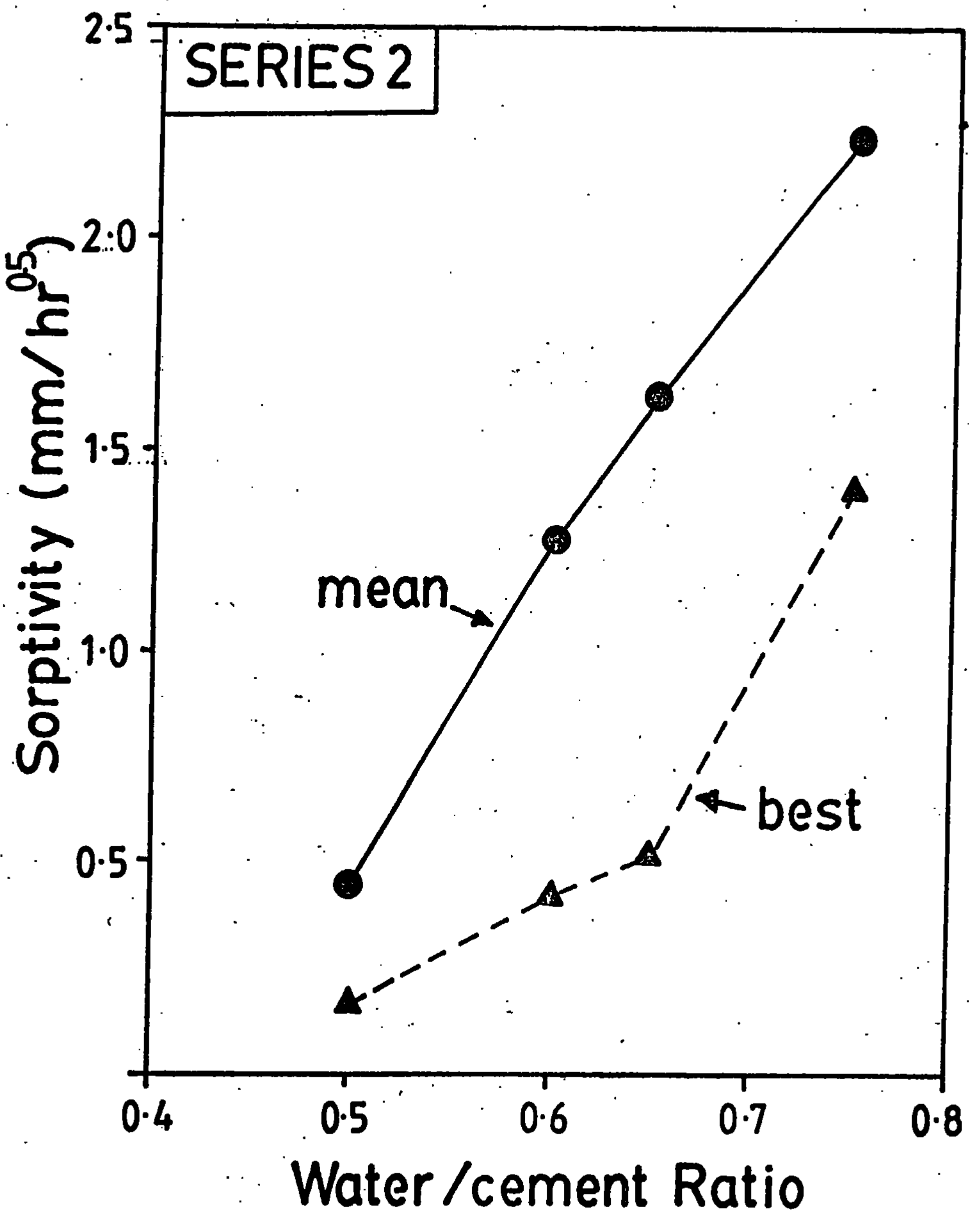

FIGURE 3 - INFLUENCE OF WATER/CEMENT RATIO ON SORPTIVITY

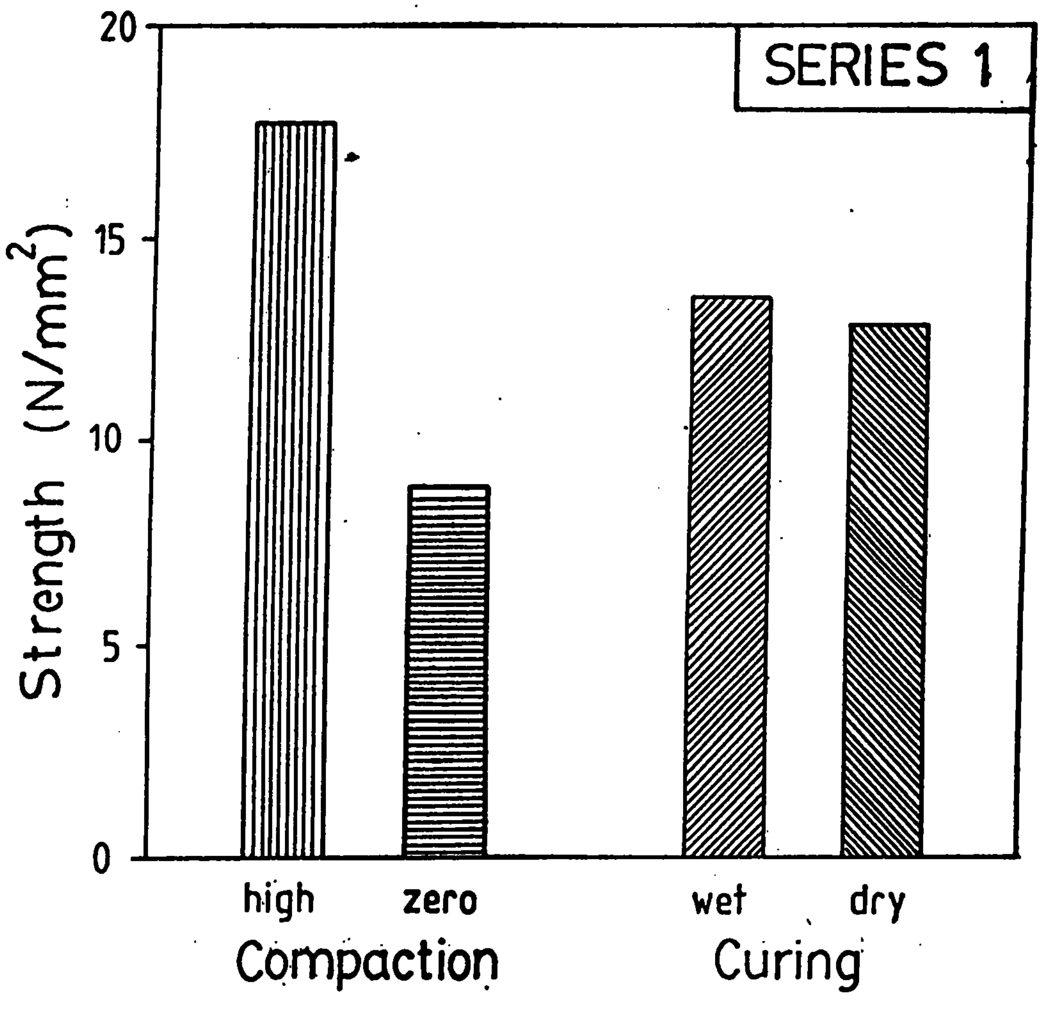

FIGURE 4 - INFLUENCE OF COMPACTION AND CURING ON STRENGTH

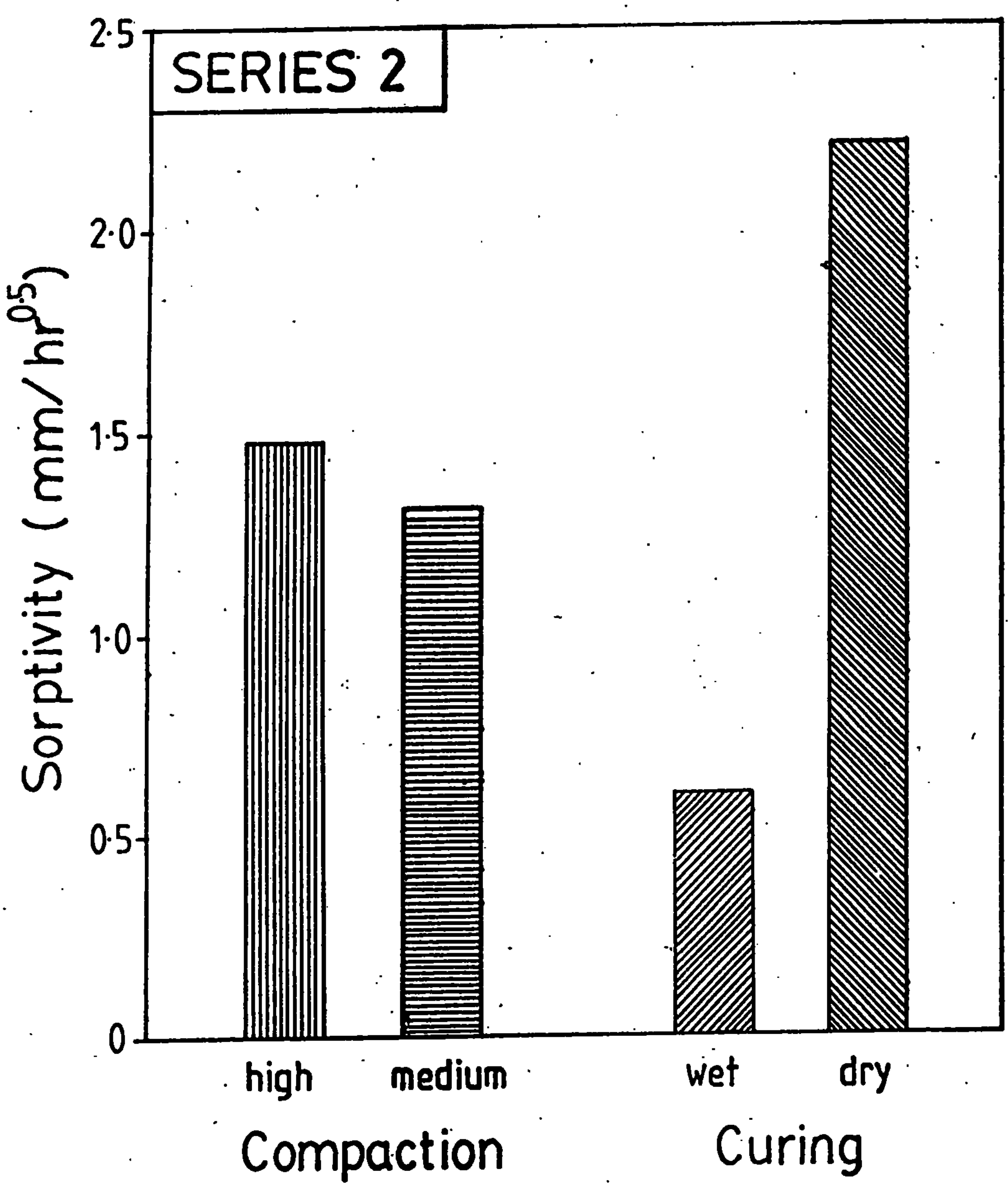

FIGURE 5 - INFLUENCE OF COMPACTION AND CURING ON SORPTIVITY