The effect of water absorption by aggregates on the water/cement ratio of concrete*

by K. Newman, B.Sc.(Eng.), A.M.I.C.E.

Contribution by E. C. Dillon, M.E., Ph.D., A.M.I.C.E., M.I.C.E.I.

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Some tests on the absorption of Cork aggregates, which I carried out in 1941 under the direction of the late Professor H. N. Walsh[1], are relevant to Mr Newman's paper. Cork gravels and sands of old red sandstone origin are more absorbent and less well shaped than many aggregates from other districts in Ireland. Typical values of absorption in the saturated, surface-dry (S.S.D.) state as determined by the ASTM method (1939) are given in the accompanying Table.

Particle size (in.)	$1\frac{1}{2}$–$\frac{3}{4}$	$\frac{3}{4}$–$\frac{3}{8}$	$\frac{3}{8}$–$\frac{3}{16}$	sand
Absorption (%)	1·16	1·35	1·70	2·00

I agree with Mr Newman's observation that mixes with saturated gravel aggregates can give higher strengths than supposedly similar mixes with dry aggregates, but I consider that incomplete hydration of the boundary layers of cement paste may be the cause of the reduced mobility and strength when dry aggregates are used. Setting of the cement paste, which reduces the free movement of water within the concrete, causes the absorption demand of the aggregate to be satisfied from sources near to it. Layers of dust on the artificially dried aggregates contribute to this reduction in strength.

Contribution by B. W. Shacklock, M.Sc., A.M.I.C.E.

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Mr Newman is to be congratulated on his courage in entering such a complex field of research. His results are very interesting but I feel his conclusions are not altogether satisfactory.

In reference to Figure 2, he concludes that "Any difference between these curves is due to the air-dry aggregates not achieving the same degree of saturation . . ." and goes on to consider this in relation to water/cement ratio alone. I do not doubt that changes in water/cement ratio are an important and perhaps the major factor but there are at least two other feasible theories for explaining a part of the difference noted between the two curves in Figure 2.

Firstly, initially dry coarse aggregates absorb water not only before, but after, the concrete has been compacted into the cube moulds. After compaction mixing water continues to be drawn by capillary attraction into the finer pores and air is forced out through the larger pores, collecting in the form of small bubbles round the outside of the particles of coarse aggregate. These air bubbles can, in fact, often be seen on breaking open cubes after testing. It is this interface of coarse aggregate and paste at which failure of most cubes takes place on testing. Thus, the air displaced from the aggregate, though small in amount, may have a disproportionately large effect on the strength of the concrete.

The second theory concerns the effectiveness of curing. If, after curing in water for, say, 28 days, dense high-strength cubes are broken open, the interior is almost always fairly dry. Now if saturated aggregates are used initially, the curing of the interior of the cubes may well be better and, as the failure of cubes on testing starts in the interior, the strength of the cube may well be higher than if air-dry aggregates are used.

The two possibilities above, both of which would appear to have a greater effect on high-strength mixes, are admittedly only theories but they do cast doubt on Mr Newman's conclusions, including that concerning the relation between absorption and the proportion of coarse to fine aggregate in the mix. Thus Mr Newman's justification for Figure 6 would seem very questionable. Apart from this, it is difficult to imagine that, in a mix with $\frac{3}{4}$ in. aggregate and a water/cement ratio of 0·4, there would be little or no saturation of the coarse aggregate if the aggregate/cement ratio was 2, whereas, in a mix with the same water/cement ratio but an aggregate/cement ratio of 9, there would be nearly 75% saturation: the first mix would obviously be highly workable whereas the second would have a workability so low that compaction under pressure as well as vibration would be necessary.

Figure 4 of Mr Newman's paper leads to the most useful conclusion since it shows either that due allowance should be made during mix design for the use of dry aggregate in trial mixes, or that saturated aggregate should be used in trial mixes. In this conclusion, however, the definition of water/cement ratio is irrelevant, and remains largely a matter of convenience. Thus, Mr Newman's conclusion (page 141) that "Laboratory trials should be based on the effective

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water/cement ratio, if rich uneconomical mixes are to be avoided " seems to miss the point.

Reply by the author

As so few comments have been made on the effect of water absorption by aggregates since the symposium in 1954[2], I much appreciate the contributions of Dr Dillon and Mr Shacklock. The paper did not fully explain the absorption effect but the contributions, together with more recent work carried out at Imperial College, help to give a clearer picture.

Firstly, I cannot agree with Dr Dillon that the reduction in strength is due to the incomplete hydration of the boundary layers of cement paste and to the layers of dust on dry aggregates. In none of the mixes cast was there any drying-out of the paste by the aggregates. The water/cement ratios chosen ensured proper hydration of the cement and there was sufficient paste of the right consistence to lubricate the aggregates and to fill the voids. Dust can be regarded as additional aggregate of fine particle size which merely reduces the workability of the mix. A drying effect might, however, occur in lean mixes having very low water/cement ratios. But I agree that the absorption demand of the aggregate is satisfied from the surrounding paste.

Mr Shacklock's two theories are a valuable contribution. I think the theory on the effectiveness of curing interesting, but not valid. After a crushing test the inside of a cube does appear dry, but I have always attributed this to generation of heat, which quickly evaporates moisture on the cracked surface. Crushed particles of cement also appear dry and are lighter in colour. This was confirmed by comparing three cubes crushed in the normal way with three split open with a sharp chisel. (The concrete had a water/cement ratio of 0·30, and was tested at 28 days.) The crushed cubes appeared dry but the split cubes to be still saturated. Cubes cured in water are unlikely to be affected by the initial condition of the aggregate but, as stated in the paper (p. 138), in concrete that dries out, the absorbed water might well help hydration of the cement to continue.

But Mr Shacklock's other theory is more feasible. In addition to strength and workability, a third property of concrete affected by absorption is its density. More recent work at Imperial College[3] appears to confirm the suggestion that dry coarse aggregates continue to absorb water from cement paste after casting. As absorption proceeds owing to capillary action, dissolved air coalesces in small bubbles at the entrance to the capillaries. This process probably continues until the paste hardens. The amount of air that can be expelled after casting will depend on: the absorption capacity of the aggregate, i.e. its initial condition; the delay between mixing and casting; the consistence of the cement paste.

Tests were carried out on mixes containing only $\frac{3}{4}$–$\frac{3}{8}$ in. Thames Valley river gravel patina material, with an aggregate/cement ratio of 1·5 and a total water/cement ratio of 0·33. Table I shows the effect of the initial condition of the aggregate. The cubes were cast within 15 min of mixing.

TABLE I

Initial condition of aggregate	Saturated, surface-dry aggregates: 24 h saturation	Saturated, surface-dry aggregates: 30 m in saturation	Air-dry aggregates
Crushing strength at 14 days (lb/in^2)	6,370	6,230	5,780
Apparent specific gravity at 14 days	2·337	2·332	2·315

Figure I shows the impressions left by typical particles of coarse aggregate in the cement paste for each of the initial conditions of the aggregate.

Table II shows the effect of delaying the time between mixing and casting on mixes containing air-dry aggregate. For the 60 min delay, the concrete was remixed at intervals before the cubes were cast.

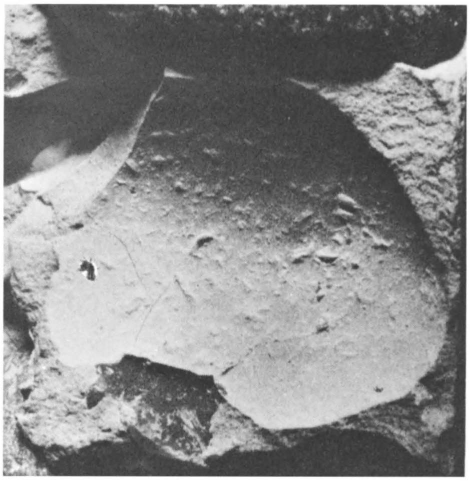
TABLE II

Delay before casting (min)	5	60
Crushing strength at 14 days (lb/in^2)	5,820	6,010
Apparent specific gravity at 14 days	2·311	2·329

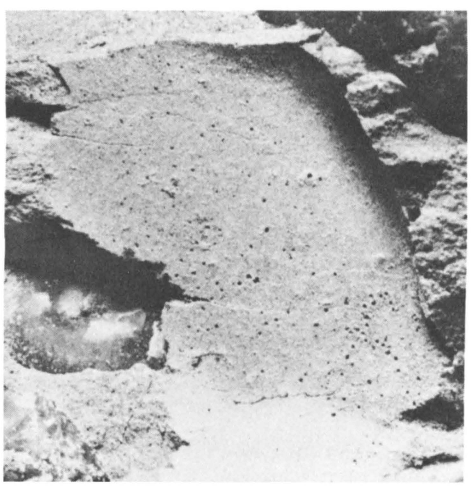
The impression left by a typical particle of coarse aggregate in the paste for the 60 min delay is shown in Figure II, the impression for the 5 min delay being similar to the impression in Figure Ic.

Figure III shows (left) a piece of Thames Valley river gravel aggregate, taken at random, and (right) the impression left by it in the cement paste. The specimen comprises patina material surrounding a dense portion with an unweathered surface.

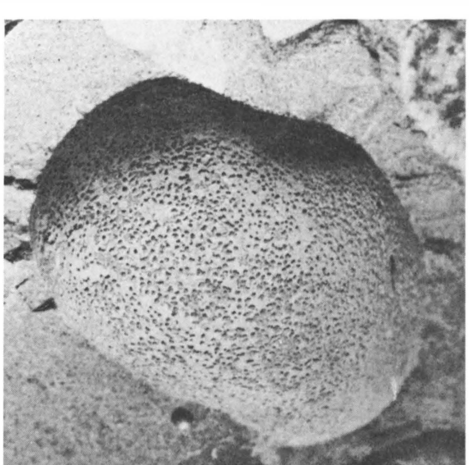
The photographs show clearly that pre-saturated aggregates give a smooth bonding face with cement paste, whereas, owing to the presence of air bubbles expelled after casting, dry aggregates give a honeycombed interface. If mixing is prolonged, absorption continues and less air remains to be expelled after casting. The air bubbles tend to reduce the bonding area of paste to aggregate and so cause a reduction in strength. The rate of absorption after casting will probably depend on the consistence of the cement paste, being greater for pastes with high water/cement ratios. Although more air might be expelled in wetter mixes, the probable cause of failure is the low strength of the paste; the reduced bond between the aggregate and paste is of little importance. But I agree with



(*a*) *S.S.D. aggregate, saturation for 24 h*



(*b*) *S.S.D. aggregate, saturation for 30 min*



(*c*) *Air-dry aggregate*

Figure I: Impressions left by particles of coarse aggregate in the cement paste for each of the initial conditions of the aggregate.

Figure II: Impression left by particle of coarse aggregate after 60 min delay before casting.

Mr Shacklock that in high-strength mixes failure takes place at the interface between paste and aggregate. Therefore the absorption effect becomes more noticeable as the water/cement ratio decreases.

Originally it was inferred from the density results that rich mixes retarded water absorption by dry aggregates. But, as the photographs show, absorption does occur, and it is the expelled air remaining around particles of aggregate that causes the decrease in apparent density.

The effect only occurs with coarse aggregates having an outer porous layer. Dry sands did not affect strength because, having little patina material, they expelled no air bubbles after casting. Crushed rock materials of low absorption capacity adsorb water from the mix quickly without expelling air bubbles.

Therefore, the reason for the difference in strength between mixes made with saturated aggregates and those made with dry aggregates is due not so much to reduced absorption as to the different character of the bond between the aggregate and paste. It is possible that dry aggregates do achieve saturation equivalent to immersion for 30 min, but expelled air causes a reduction in strength. The problem is obviously complex and it is difficult to express the difference in strength simply in terms of water/cement ratio. If the expelled air bubbles were uniformly distributed through the mix they would affect strength in the same way as an equal volume of water; but they are located where they do most harm, round the particles of coarse aggregate. However, if equation (1) (p. 140) is rewritten as

$$\text{effective water/cement ratio for strength} = \text{total water/cement ratio} - (a_s S/C + a_{ca} CA/C) + (1 - w) a_{ca} CA/C \quad \text{(1a)}$$

then $(1 - w)$ is a factor, related to the amount of air expelled after casting, whose importance increases with decreasing water/cement ratio.

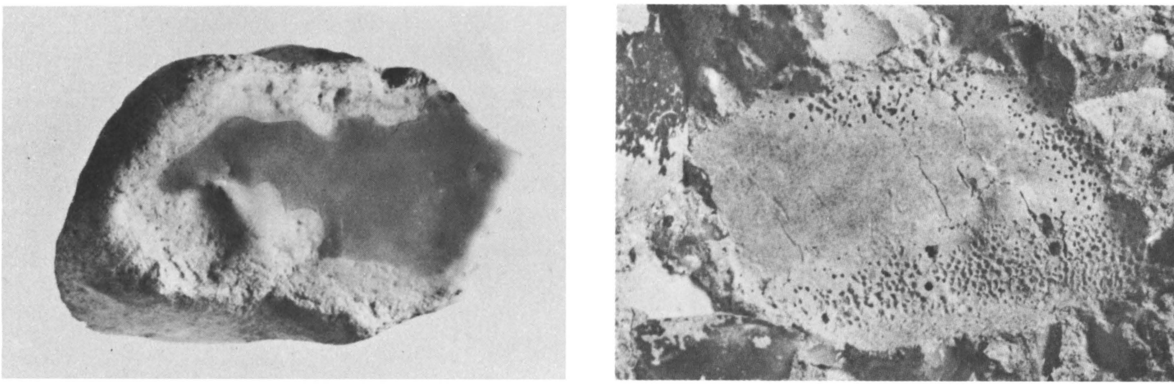


Figure III: Typical piece of Thames Valley river gravel aggregate (taken at random) and impression left by it in cement paste.

These clarifications do not alter the general conclusions of the paper. When patina material is used, mixes with dry aggregates have a different composition from those with saturated aggregates, and it is difficult to express this difference in terms of water/cement ratio. All absorption effects must be eliminated if proper comparisons are to be made between laboratory and site mixes and the true effects of different aggregates on concrete properties found. This can be achieved by using pre-saturated aggregates and basing trial mixes on the effective water/cement ratio as defined. Incidentally, recent work has also shown that for complete saturation to occur aggregates should be immersed for 30 min. This may entail adding extra water to the aggregates, which is drained off before mixing takes place.

REFERENCES

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2. *Proceedings of a symposium on mix design and quality control of concrete, London, May 1954.* London, Cement and Concrete Association, 1955. pp. 548.
3. NEWMAN, K. *The design of concrete mixes for density.* Concrete Structures and Technology Research Report. CSTR 3. Imperial College, London, May 1960. (Not yet published.)