

example, Figure IIb. How is a value for  $r$ , which is not in fact constant, to be obtained when predicting the behaviour of an untested specimen? More progress in this subject is to be made by work directed into improving understanding of the aggregate-interlock and dowel-action mechanisms, than by searches for more sophisticated curve fits to existing test data.

The two-phase model is based upon a combination of crushing and sliding of spherical particles, of a realistic range of sizes, embedded in a softer cement paste. This is an approximation to what we believe to be occurring in aggregate interlock. Furthermore, this model gives a quite close prediction of the shear-slip/crack-width path and hence the shear stiffness, which cannot easily be obtained from the alternative model proposed.

In cracked reinforced concrete, the interaction between aggregate interlock and dowel action is indeed complex. In Figure 11 (MCR 130) the role of the initial crack width is less marked than in Figure 10, partly because the range of initial crack widths is smaller and partly because the breakdown of bond in

test 4 causes a significant reduction in the normal stiffness and hence masks the effect of a smaller initial crack.

It would seem unlikely that the 'softness' of these test results is related to the maximum size of aggregate used. For crack widths of 0.1 to 1 mm a change of the maximum aggregate size from 10 mm to 20 mm is not going to make much difference. Previous tests (MCR 126, reference 16) have shown very little sensitivity to the maximum size of aggregate. Walraven's (MCR 126, reference 9) work has shown that the whole range of fine and coarse aggregates contribute towards aggregate interlock. It is more plausible that any differences may be due to localized damage to the concrete around the reinforcing bars. Walraven has reported that cones of crushed concrete were seen around each bar and that the crack-widening effect in reinforced concrete was greater than that expected from aggregate interlock tests. Neither effects were observed in our tests and this certainly warrants further study.

## Permeability of normal and lightweight mortars\*

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Contribution by Nick Buenfeld

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A mortar made with lightweight aggregate may have a different permeability from that of a sand mortar (made with a similar water/cement ratio and aggregate volume and grading) due to the influence of a number of factors:

- (1) *aggregate permeability*—lightweight aggregates are more porous and hence generally more permeable than normal aggregates;
- (2) *aggregate/cement paste bond*—the porous nature of lightweight aggregate generally enhances aggregate-cement-paste bond, reducing flow paths at the aggregate/cement-paste interface; and
- (3) *the availability of water to allow prolonged hydration*—lightweight-aggregate particles contain a greater volume of absorbed moisture and may act as internal reservoirs allowing prolonged hydration, thereby producing cement paste of reduced permeability.

Unfortunately Dr Nyame has introduced several other variables, owing to the way that he has designed his mixes, which do not relate to current practice and which may have masked the effects of the factors listed above.

In practice, lightweight aggregate is generally pre-soaked so that a sufficiently workable yet cohesive

mix is achieved. Dr Nyame used dry aggregates, "so that absorption effects would be brought into the composite action", and did not even adjust the water content to allow for aggregate absorption. As a result, Dr Nyame's supposedly equivalent normal and lightweight mortars have *different free water/cement ratios*. If Dr Nyame has data relating to the absorption and moisture content of the aggregates, an assessment could be made of the actual free water/cement ratios. For example, if the lightweight aggregate absorbed 5% (by weight) of water during the first 2 or 3 h after mixing, the free water/cement ratio of the 65% aggregate volume concentration mix would be reduced by around 25%, i.e. from 0.47 to 0.35. Such a reduction would be expected to cause a very substantial reduction in permeability. Furthermore, the absorption of mix water reduces the volume of cement paste and hence increases the aggregate volume concentration. In this context, it should be pointed out that equation 1, the expression apparently used by Dr Nyame to calculate the aggregate volume concentration, is incorrect.

Secondly, the use of sand and lightweight aggregate of different gradings has resulted in supposedly equivalent normal and lightweight mortars having *different effective path lengths* and also *different areas of aggregate/cement paste interface*, thereby distorting the effect of aggregate/cement paste bond (factor 2

\*Pages 44–48 of MCR 130.

above). These additional variables have made it very difficult for Dr Nyame to draw sensible conclusions from his results.

Conclusion (2), "The permeability of mortars increases as porosity reduces, contrary to the response of hardened cement pastes", should be qualified. Certainly Dr Nyame observed an increase in mortar permeability and a reduction in porosity as the aggregate volume concentration increased, but clearly a reduction in porosity due to a reduction in free water/cement ratio would be accompanied by a reduction in permeability.

Conclusion (3), "Lightweight mortar is about twice as permeable as, and not of a different order of permeability from sand mortar at a given aggregate volume concentration", should also be qualified, since the lightweight mortars had considerably lower free water/cement ratios than their supposedly equivalent sand mortars. If free water/cement ratio had been

maintained at a constant level, the lightweight mortars with high aggregate volume concentrations could well have permeabilities of an order of magnitude greater than those of the equivalent sand mortars.

Finally, Dr Nyame regards oven-drying (at 105°C) surface-dried samples to be a reliable method of determining porosity. Our experience confirms the widely held view that oven-drying at 105°C does *not* give a particularly accurate measure of porosity because:

- (1) oven-drying at 105°C not only removes the capillary pore water and most of the gel pore water, but also a proportion of the chemically bound water; and
- (2) the gel pore water has a greater specific gravity than free water and hence occupies a smaller volume than its weight suggests.

I suspect that Dr Nyame's technique is more sophisticated than simple oven-drying. If this is the case, perhaps he would elaborate on his method.

### Reply by the author\*

The discussion of the paper by Dr Buenfeld comes at a good time, when 'free water/cement ratios' have been linked with durability control. His interpretation of my paper is mainly based on a quality control parameter—the 'free water/cement ratio' of pastes in concrete and mortars.

Dr Buenfeld makes six points, which are as follows.

- (1) Other complicating variables have been introduced by a mix design which is not based on current practice.
- (2) The 'free water/cement ratio' was not adjusted to constant values in the mixes used.
- (3) The equation for calculating aggregate volume concentration

$$V_c = 100s/Da^2(s + Da/Dp) \dots \dots (1)$$

is incorrect, because of effects of aggregate absorption of mix water.

- (4) Aggregate grading was not controlled.
- (5) Porosity measurements by oven-drying at 105°C is not simple, but more sophisticated.
- (6) The second and third conclusions of the paper may be explained by the possible changes in the 'free water/cement ratios' of pastes.

In reply to the points raised, it must be *stated clearly* that the work described was based on a mix designed with:

- (a) a constant initial water/cement ratio of 0.47;
- (b) a constant aggregate grading (particle size 600–2400 µm);

- (c) aggregate dried at 105°C;
  - (d) different aggregate volume concentrations.
- Points (1) and (4) raised by Dr Buenfeld are therefore not substantiated.

The mix was designed to help obtain experimental evidence on the effects of aggregate volume concentration and absorption upon the composite response to permeability and pore structure. In scientific methods, when a set of parameters combine to produce a particular response, it is useful to study the response by considering the factors, and the interaction of factors. Table I is presented to help visualize the effects of 'free water/cement ratio' on composite behaviour. It is a morphologic chart which establishes the ranges and combinations of the constituents of mortars and concretes, using initial water/cement ratios and aggregate moisture contents. The combinations on the diagonals of Table I help produce the type of speculations on 'free water/cement ratios' suggested by Dr Buenfeld.

TABLE I: Combinations of constituents of mortar.

Cement paste	Condition of aggregate		
	Wet (saturated)	Moist	Dry (oven-dry 105°C)
High w/c > 0.7	Bad practice		Good practice
Normal 0.4 < w/c < 0.7		Normal practice	Reported data
Low w/c < 0.4	Good practice		Special practice

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The 'free water/cement ratio' depends upon the paste-to-aggregate:

- (a) moisture content gradients;
- (b) permeability and diffusion ratios;
- (c) interface areas.

For example, in mortars of *high initial w/c ratio* and *dry aggregate*, aggregate absorbs the paste water so that the 'free water/cement ratio' is less than the initial water/cement ratio. The exact change depends upon the factors (a), (b), (c) listed. Estimates can be made, as suggested by Dr Buenfeld—with reliable data similar computations have been done in the doctorate thesis on permeability.<sup>(3)</sup>

In contrast, for mortars with *low initial water/cement ratio* and *wet aggregates*, the paste absorbs the aggregate water. The 'free water/cement ratio', therefore, increases. In essence, then, 'free water/cement ratio' is a variable, *controllable* with data on the constituents of concrete, and realistic assumptions.

Dr Buenfeld's suggestion that it should be used to *find out* the effects of absorption in composite action is presumptuous. It is less fundamental than the initial water/cement ratio used in the paper.

The initial water/cement ratio allows absorption to occur so that the effects can be seen. Dr Buenfeld's suggestions—point (2)—on adjustments would rather mask the effect of absorption.

The conclusion that, at equal aggregate volume concentrations, the permeability ratio for normal and lightweight mortar prepared with dry aggregates is only about 2, indicates that the inferences drawn by Dr Buenfeld in his points (2), (4) and (6) are not substantiated.

However, the use of high initial water/cement ratios in preparing mortars could have amplified the effects of change in 'free water/cement ratios'. The reason is that the changes in permeability with water/cement ratio up to 0.55 are small (Figure 5 of paper), but increase when water/cement ratio exceeds 0.55.

On point 3, the equation for aggregate volume concentration in mortars is a good first approximation. It is based on the dry densities of pastes and aggregates,

$D_p$ ,  $D_a$ , in Table I of the paper, for a given sand/cement ratio,  $S$  = cement ratio,  $s$ . Any adjustments of the equation for 'free water/cement ratios', shrinkage etc. have to be made with realistic assumptions and data for each combination of constituents of mortar, as in Table I.

Finally, the porosity measurements on oven-drying at 105°C are simple, reliable, and hence sophisticated, as described in the paper. The complications of the method include:

- (a) microstructural collapse;
- (b) imprecise removal of free and combined water.

Such problems are, however, resolved by the DTG techniques of Sabri and Illston<sup>(1)</sup> or with alcohol displacement (Parrott<sup>(2)</sup>). As permeability mainly depends upon the larger macropores, these complications have practically no effect at all upon the trends found.

Oven-drying at 105°C produces porosities for comparative work on permeability.

In conclusion, Dr Buenfeld's explanations, based on 'free water/cement ratio' must recognize that the parameter is less fundamental. It needs reliable data and assumptions for estimation. Additionally, as effects of absorption are shown by changes in the 'free water/cement ratio', there is little basis to adjust it in *experiments designed to find out* the effects of absorption. The presence of aggregate, too, is important. The morphological chart (Table I) indicates the other ways to draw sensible conclusions as produced in the paper.

## REFERENCES

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