

# Discussion on papers published in

*Magazine of Concrete Research*

Volume 21, Number 69 : December 1969

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## The significance of concrete cube tests\*

P. E. Halstead

Contribution by A. P. Mears

*Sir Robert McAlpine & Sons Ltd*

Dr Halstead's very illuminating paper prompted me to look up some analysis of routine tests we made some years ago. In 1951, faced with the problem of interpreting the current B.S.12 tensile and compressive mortar tests into values readily understandable by engineers and management on our contracts, we decided to make our own tests using a 'standard' concrete mix of the then popular 1:2:4 volumetric proportions, made with London area aggregates and having a slump of 50 to 75 mm. The volumetric proportions were converted to 1:2.42:4.04 by weight, appropriate to the aggregates used. These consisted of gravel from Thorpe, which was sieved into clean 19 mm and 9.5 mm single sizes before use, and sand from Hounslow, which was used without sieving into separate sizes. The water/cement ratio was 0.60 net (Abrams's definition).

From previous tests, we had recognized the existence of three sources of variation: between cubes within the same batch, between batches made on the same day, and between batches made on different days. It was therefore decided to make five replicate tests on different days and take the average, so that the effect of these variations would be reduced. The concrete was machine-mixed in batches of three 100 mm cubes which were allocated for test at 3, 7 and 28 days.

Between April 1951 and November 1954, 900 samples of cement (i.e. 4500 cubes at each age) had been tested in this way and the average coefficients of

variation at each age were:

3 days	4.67%
7 days	3.85%
28 days	3.77%

During this period one sample of cement was repeatedly tested between June 1952 and June 1954, a total of 186 tests being made. The over-all coefficients of variation for the 186 cubes at each age were:

3 days	4.93%
7 days	3.15%
28 days	3.95%

All these values are lower than the average values given by Dr Halstead in his Table 2 for total coefficient of variation. This, at first sight, is surprising, particularly because a study of technique given in Dr Halstead's original report shows that, in many respects, our methods appear to fall short of his standards.

There is, however, one aspect which I think might account for our lower values. Our aggregates were, of course, dried before use, but no attempt was made to achieve a constant state and each day, before the tests were started, the sand was made saturated and surface-dry by the gradual addition of water until the desired state was reached. The gravel was tested for absorption after immersion in water for 30 min, this value then being used to adjust the weights of gravel and water, so that the correct proportions by S.S.D. weight were achieved. Values for absorption ranged from 0.1 to 2.7% on the 9.5 mm fraction and from 0.3 to 1.7% on the 19 mm fraction. A potential source of large variations in water/cement ratio was therefore minimized by this procedure.

B.S.12, upon which it appears Dr Halstead's

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\*Pages 187-194 of *Magazine* No. 69.

methods were based, specifies a procedure for drying and storing the aggregates, the object presumably being to achieve a repeatable and stable state of dryness. It may be questionable whether these desirable conditions are always achieved and it seems to me that here may be an unsuspected source of variation affecting tests made over a period of time. Perhaps Dr

Halstead could comment on this.

It is interesting to note in Table 2 that there is a tendency for the total coefficient of variation to increase as the degrees of freedom increase. If the greater degrees of freedom involve a greater number of days' casting, this would be consistent with the foregoing suggestion.

## Contribution by P. A. Warren, BSc

*RMC Technical & Training Services Ltd*

Many of the conclusions Dr Halstead reaches in his paper regarding the significance of the cube test are a statistical development of his finding that 'between-batch variability' is high. This finding rests heavily for its importance upon the statement that "... the cement of any given delivery was material of constant properties throughout the tests".

The tests reported were made on sequences of samples of cement taken from five separate 8 ton lots and, in spite of the importance of knowing or removing the effect of variation between samples (which would have been easy if the experimentation had been so planned), Dr Halstead rejects this possibility of 'within consignment variability' on grounds which I regard as highly questionable. I find his remark "To state the variability of the cements used is to beg the whole question of the work" unforgivable. After all, he does go on to give reasons for believing that 8 ton lots of cement are absolutely uniform.

The truth, I suspect, is that the results analysed in this report were not obtained as part of an investigation into "The significance of concrete cube tests", but were, in fact, control tests made in conjunction with other projects. Thus, work which would have been done in a project designed for the purpose of this paper is understandably lacking.

To give substance to my doubt that 'within consignment of variability' of the cement was zero, I offer two points for consideration.

(1) The 'within consignment variability' of cement is reported to be insignificant because there were no differences in chemical composition and fineness "which could not be accounted for as being within the limits of experimental error of analysis".

This sounds like the statistician's null hypothesis, which says that the assumption that there are no real differences in composition is not disproved because of the smallness of the measured differences in relation to experimental error.

This is a very different thing from saying that there were no differences in cement strength, when one considers that use has been made of experimental techniques (chemical analysis, fineness measurement)

which are themselves of limited accuracy (and since when has it been a fact that a limited knowledge of these characteristics will uniquely define strength?).

(2) The values of 'between batch variability' given in Table 2 are, in every case, lowest for cement B and, in all but one case, highest for cement E.

Assuming that the 'between batch variations' due to aggregates, water, batching and testing were the same for cements A to E (and if not, how not?), the difference of 'between batch variation' for cement B (1.31 N/mm<sup>2</sup> average for all the test ages) from the average value for all five cements (1.98 N/mm<sup>2</sup> average for all the test ages) appears highly significant. Hence it seems clear that there were differences in the 'between batch variation' for the five cements and that 'within consignment variations' did, indeed, exist.

If we take cement B as having had zero 'within consignment variability', it can be argued that the measured 'between batch variability' for cement B (1.32 N/mm<sup>2</sup> at 28 days) was also the actual 'between batch variability' for the other four cements. Hence the 'within consignment variabilities' for the five cements can be calculated (28 day values) as:

Cement A	2.33 N/mm <sup>2</sup>
Cement B	0 N/mm <sup>2</sup>
Cement C	1.15 N/mm <sup>2</sup>
Cement D	1.80 N/mm <sup>2</sup>
Cement E	2.42 N/mm <sup>2</sup>
Mean	1.54 N/mm <sup>2</sup>

Alternatively, we may assume that all the measured 'between batch variabilities' were due to 'within consignment variations' and were equal, on average, to 2.15 N/mm<sup>2</sup> (at 28 days). Thus, 'within consignment variability' can be put at between 1.54 and 2.15 N/mm<sup>2</sup>.

One source of 'between batch variability' that undoubtedly did exist through the tests was variation in aggregate absorption.

Since dry aggregates are used in the B.S.12 test for cement strength, variations in absorption will cause variations in the free water/cement ratio (since tests are carried out at constant total water/cement ratio),

with attendant variations in strength. If Dr Halstead's purpose in this paper is to discourage the testing of cement, he should first have shown that the source of his 'between batch variability' was not absorption variability, since the latter could be avoided (or allowed

for) if desired.

To conclude, I feel that the humble cube is once again under fire and that the significance of cube test results is being understated because of scrappy research.

### Contribution by A. B. Lingam, BSc, BE

*Engineering Materials Laboratory, Himayatsagar, Hyderabad-30 AP, India*

The subject of testing Portland cement for compressive strength by a standard procedure at ages of 3 and 7 days and the method of using these results for the design of a concrete mix of a specified strength has been very thoroughly dealt with by Dr Halstead. He has kept in mind the numerous factors that affect these results, and this paper will give confidence to other laboratory workers tackling similar work, and make them aware of problems they should look out for.

While conducting detailed investigations on Nellore fly ash<sup>(1)</sup>, I have studied the development of strength in cement and fly-ash mortars at the ages of 7, 28, 60, 90 and 180 days. In these studies, mortar with basic cement contents of 260, 340 and 475 kg/m<sup>3</sup> was taken and to it cement and fly ash were added separately in increasing percentages, the sand content being adjusted to maintain the same workability in the resulting mortar. The compressive strength of the mortars was determined by the standard procedure. From the statistical analysis of strength data of the cement mortars, it has been observed that standard deviation is related to the mean strength of the batch and the ratio, i.e. the coefficient of variation decreases with age (Table I). This is what would be expected, when it is considered that variance occurring due to batching and mixing of materials in the same mixer, casting and curing under the same laboratory conditions and testing the specimens on the same machine with the same group of workers on the site, is of an incremental nature and that scatter in the mean strength is related to the ultimate stress level of the test specimen.

From further analysis of the data, I fully support Dr Halstead's assumptions and would say that the coefficient of variation is a function not only of age and strength of concrete, but also of the cement content of the mix. It is observed that, for the same age and at approximately the same strength level, variability decreases for mixes with higher cement content. For the same mix, there is a decreasing trend for later ages. For strength levels below 10 to 15 N/mm<sup>2</sup>, an

TABLE I: Coefficient of variation versus age.

Number of mixes	Number of batches	Age (days)	Regression line
3	24	28	$\sigma = 0.065x + 1.07$
3	22	60	$\sigma = 0.057x - 0.28$
3	20	90	$\sigma = 0.044x + 0.63$
3	21	180	$\sigma = 0.034x + 2.83$

NOTE: In each batch, six test cylinders were taken.

increase in the coefficient of variation is more than likely and this may be because other factors of batching have a stronger influence.

For given quality control measures, whether the standard deviation or the coefficient of variation should be kept constant is still controversial. From analysis of laboratory test data, as well as results from some actual site tests, Neville<sup>(2)</sup> has suggested that a constant coefficient of variation should be adopted for well compacted concrete of different mix proportions with a strength higher than 10 N/mm<sup>2</sup>. How far is this simplification correct, when these factors are considered individually?

For us to arrive at some definite conclusions regarding the effect of ultimate strength level, cement content of the mix and age upon the strength of concrete and its variability, a clearer picture of the whole subject is required. For this, a thorough study of these factors by three or four concrete laboratories with a common programme and materials is strongly urged.

### REFERENCES

1. LINGAM, A. B., RAMAKRISHNA, G. and SANJEEVA RAO, R. *Effect of cement content on cementing efficiency of fly ash*. Paper for discussion at 40th Annual Research Session of the Central Board of Irrigation and Power, Shillong, India, June 1970.
2. NEVILLE, A. M. *Properties of concrete*. First edition. London, Sir Isaac Pitman and Sons Ltd, 1963 (reprinted 1965). p. 471.

### Reply by the author

It is interesting to have from Mr Mears figures for over-all coefficient of variation at different ages when tests were made repeatedly on one cement. The values quoted for coefficient of variation at each age are cer-

tainly lower than those given in my paper, but the significance of this comparison is not clear because we are not comparing like with like. The 'over-all coefficients of variation' which the two sets of figures esti-

mate depend to some extent upon the number of cubes per batch and the number of batches in the particular experiment.

It is surprising that the coefficient of variation of the strengths of the 186 cubes was lower at 7 days than at 28 days and perhaps, if a larger number of cubes had been tested, the over-all coefficients of variation would have decreased progressively with age.

The aggregates in all our tests were dried to a very low residual water content but nevertheless I accept that differing degrees of absorption of water may be responsible for some of the variability of the cube strengths. I cannot, however, agree with the suggestion in Mr Mears's last paragraph, that there is any substantial correlation between total coefficient of variation and degrees of freedom, in the results in Table 2.

Mr Lingam's results are interesting since they give support to the notion that the within-batch variability of strength decreases with increase in specimen age. It is tempting to conclude also that variability of strength of concrete of a given strength decreases as the cement content is raised but I have no evidence for or against this supposition. In Mr Lingam's Table I, the constants quoted for the regression lines are consistent in the case of the concrete of 30, 90 and 180 days age but those for the 28 days old concrete seem anomalous. If the quoted  $+1.07$  were really  $-1.07$ , all the values would be more harmoniously related.

Mr Warren takes me to task for appearing to neglect the possibility that between-batch variations in strength might be due in part to non-uniformity of the cement in each delivery. One of the objects of these tests was to try to assess the variability in properties of samples of cement taken successively from our storage silo, but exhaustive statistical analysis of the cube strengths has not enabled us to quote with a reasonable degree of confidence what fraction of the over-all variability of our results is attributable to non-uniformity of the cement.

The statement which Mr Warren quotes out of context, if taken in its entirety, remains correct, namely that "as far as can be determined, the cement of any given delivery was material of constant properties throughout the tests". I did not state as Mr Warren

suggests, that "within-consignment variability is insignificant because there were no differences in chemical composition and fineness which could not be accounted for as being within the limits of experimental error of analysis".

Since the variability of strength of the cement can only be measured by strength tests, the purpose of the fineness tests and chemical analysis was to discover whether the cement showed significant variability in terms of any other measurable parameter. Had it done so, it would have been rejected as unlikely to be of insignificant variability in terms of strength.

Mr Warren courageously attempts to calculate the intrinsic variability of cements A to E, but his initial assumption that 'between-batch variations' were the same for each cement is unfortunately unjustified: (a) because of variation in quality of workmanship etc; (b) because 'between-batch variability' depends upon the number of cubes per batch which was not the same for all cements; and his calculations are therefore meaningless.

As I remarked earlier, differing absorption of aggregate samples will make its contribution to over-all variability of results but this is inherent in testing according to B.S. 12 and it is not permissible to eliminate it if one is attempting to measure the reliability of the B.S. 12 cube test.

The causes of variability of cube strength results can all be assigned to three categories:

- (1) inherent variability of the cement;
- (2) inherent differences in individual cubes;
- (3) errors which arise during the compressive strength testing (cube-crushing).

These causes are, and will remain, strictly inseparable but their combined effect is to give an over-all variability which nevertheless can be surprisingly low, considering the complexity of the processing between sampling the cement and crushing the cube.

I am sorry that Mr Warren considers that I was attacking the cube test. The aim of the paper was not to attack or defend the cube test, although I consider it to be a good control test, but to arrive at an estimate of its quality, when carried out according to B.S. 12 in our laboratories.