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A STATISTICAL ANALYSIS OF MASONRY COMPRESSION TEST DATA

R.C.de Vekey

ABSTRACT

In order to comment intelligently on the methods of test to be adopted as the reference methods for the CEN (European) standard on compression strength measurement for masonry, some data has been analysed. Three main questions are addressed - (1) whether 3 or 5 replicates should be tested (2) What are the implications of using different statistical indicators as the characteristic strength and (3) whether full sized (storey-height) walls or small walls (wallettes) should be tested .

It is concluded that three replicates would generally give a satisfactory result but a reduction to two in cases where damage occurs before test would be unacceptable and would necessitate a retest. Of the four methods of calculating the characteristic strength, the characteristic mean (char. mean) gives a 15% reduction from the mean (50 percentile) and the EC default method gives a 17% reduction, (equivalent to the char. mean at a CV of 10%). If a normal distribution based 5% fractile method (@ P=95%) is used there is 30% average reduction while the same assuming a Log-normal distribution averages 25% reduction. If wallettes are used a correction factor may need to be applied to maintain the safety of brick walls to the existing UK practice but block walls would not require a factor. The data for block walls is very limited, however. The database needs to be widened to improve the reliability of the analysis.

INTRODUCTION

As part of the DOE / BRE sponsored programme of work at BCRL on compression test methods as background for the CEN standard method of test for masonry assemblages (EN1052-1) a large number of related tests were carried out on units, mortars, wallettes, stack-bonded prisms, half-storey height walls and full storey height walls using common material batches, preparation methods and conditioning. Some of this work was reported in the proceedings of the British Masonry Society, BMS (Edgell et al 1990). Additionally a substantial database of compression wallettes and associated unit and

Head of Masonry Structures Section, Building Research Establishment, Watford, UK, WD2 7JR.

mortar tests were generated in some work on mortar sands and reported in the same proceedings (de Vekey et al 1990). In both of these programmes of work five replicates were generally used for wallettes and three to four replicates for storey height walls. This short paper exploits this database in order to examine three points in relation to the possible form of the test standard: (1) the implications, in respect of the indicated value of the mean or the characteristic strength, of using either 3 or 5 replicates in the wallette test and (2) the relationship between the strength of storey height walls and wallettes (small walls) as measured using the draft CEN method, as a background to the choice of size of the reference specimen, and (3) the effect of four possible statistically-based indicators of characteristic strength.

DATABASE

The data from the compression test work is given in Table 1. It consists of seven sets of five wallette tests using designation (i) mortar, fourteen sets using designation (iii) mortar and fourteen matching sets of storey-height wall tests using (iii) mortar. More detailed data on the units and mortars is given in the original paper. The data in the tables uses the decimal point and each value is separated by a comma.

Table 1: ISO Compression work (ultimate strength N/mm²)

UNIT TYPE	Wallette - (i) Mortar.	Wallette - (iii) Mortar.	WALL - (iii) M.
Class A clay eng.	29.9,50.9,44.6,39,33.2,	39.0,40.7,41.1,35.2,39.5,	21.5,22.9,19.8,
Class B clay eng.	41.4,41.7,38.4,41.2,39.9,	24.1,23.3,25.3,27.7,26.5,	25.4,25.3,25.1,
MWA. W/C clay	15.2,16.7,16.4,17,15.6,	8.6,10.4,10,8.7,9.3,	7.2,5.5,6.3,6.6,
Semi-dry pres. clay	11.3,12.0,9.6,11.2,11.3,	6.9,6.6,7.2,6.4,6.9,	7.5,6.4,6.2,
London stock	-	8.7,8,7.5,5.8,6.6,	4.3,4.8,5.3,5.7,
Class A clay eng.	-	26.2,41.1,39.4,42.4,25.5,	21.5,22.9,19.8,
23 hole perf. clay	-	13.5,17.1,17.2,16.0,17.1,	9.7,11.8,12.8,
Calsil brick	16.4,17.3,15.8,14.4,14.3,	12,12.8,10.9,13.8,12.9,	10.2,9,10.4,10.3,
Calsil brick		14.2,14.9,14.8,13.7,14.8,	7.8,8.9,7.4,
Concrete brick	18.8,17.9,18.3,20.5,19.9,	19.5,15.9,16.6,18.2,16.6,	17,14.4,14,0.
DAC block	13.4,13.2,13.7,15.4,15.3,	12.1,12.9,12.5,9.7,10.8,	13.7,12.4,13.2,
LWAC block	-	4,4.9,3.6,3.9,3.9,	4.5,3.9,4.6,4.3,
LWAC block	-	2.3,2.7,2.5,2.9,3,	3.4,4.1,3.8,
AAC block	-	4.5,4.9,3.2,4,3	3.8,3.2,3.3,3.5,
Abreviations in tables 1&2 are: eng. = engineering; MWA= Medium water absorption; W/C = Wire-Cut; perf = perforated; Calsil = Calcium silicate; DAC = Dense Aggregate Concrete; LWAC = LightWeight Aggregate Concrete; AAC = Autoclave Aerated Concrete; LWA = low water absorption; MWA = medium water absorption; HWA = high water absorption;			

The data from the work on sands is given in Table 2. It consists of eight sets of five wallette tests using designation (i) mortar, eight sets using designation (ii) mortar and 64 sets of five wallette tests using designation (iii) mortar. Half of the sets were made using a structural grade (S) sand and half with a general purpose grade (G) sand. More detailed data on the sands, units and mortars is given in the original paper.

Table 2: Sand work (N/mm²)

UNIT TYPE	WALLETTE STRENGTH
	Designation (i) Mortar.
LWA clay	27.9,32.1,39.9,36.4,51.9,
MWA clay	30.3,30.2,31.4,21.0,21.6,
HWA clay	6.1,6.5,6.8,6.7,6.4,
DAC block	13.8,14.4,11.9,13.3,16.6,
LWA clay	43.6,43.1,41.4,39.5,41.9,
MWA clay	23.5,18.1,19.6,21.4,20.1,
HWA clay	5.9,5.8,6.3,6.0,6.0,
DAC block	11.7, 9.4,11.9,13.2,14.4,
	Designation (ii) Mortar.
LWA clay	36.1,36.1,33.9,35.7,35.3,
MWA clay	24.2,12.0,21.9,24.0,28.5,
HWA clay	5.8,6.1,5.8,5.7,6.0,
DAC block	9.3,13.7,14.0,11.4,10.9,
LWA clay	43.1,49.9,45.6,57.6,47.7,
MWA clay	33.5,30.0,27.3,30.9,29.5,
HWA clay	6.1,6.1,5.8,6.6,6.4,
DAC block	10.7,12.4,11.9,13.3,13.6,
	Designation (iii) Mortar.
LWA clay	33.2,39.3,39.2,37.2,29.2,
	41.1,44.0,31.3,35.0,31.1,
	33.5,32.5,27.8,35.5,37.1,
	39.8,39.9,38.7,32.5,35.8,
MWA clay	29.5,24.7,23.2,22.6,23.5,
	24.2,23.7,23.3,24.6,18.1,
	16.9,24.1,24.7,23.0,25.3,
	19.4,15.6,15.8,18.5,15.8,
HWA clay	6.1,6.5,5.8,6.0,6.0,
	5.9,6.0,5.7,5.9,5.8,
	7.2,6.6,6.5,6.4,6.4,
	4.6,5.2,4.9,4.9,5.1,
Concrete brk.	15.7,14.4,16.1,16.6,17.0,
	15.9,17.4,13.5,20.2,18.6,
	21.0,23.4,22.0,22.1,24.2,
	13.8,16.8,15.5,17.0,17.9,
Calsil brick	11.6,10.7,10.4,10.5,12.2,
	13.8,14.8,11.4,10.2, 9.9,
	13.0,12.3,11.5,12.2,12.7,
	11.0,13.0,13.5,12.4,13.7,

UNIT TYPE	WALLETTE STRENGTH
DAC block	13.3, 8.2,14.4,15.3,10.2,
	12.8,13.1,14.0,11.3,12.6,
	12.3,11.7,12.9,12.7,MV,
	11.2,12.7,11.2,11.3,12.8,
LWAC block	3.7,5.0,3.1,5.9,4.0,
	4.3,4.0,4.9,4.4,4.2,
	3.9,4.0,4.2,4.9,3.5,
	3.7,3.7,3.9,3.6,3.9,
AAC block	5.0,4.9,4.6,5.5,5.7,
	4.9,5.2,5.2,5.1,5.5,
	5.2,4.9,4.1,3.8,5.9,
	5.4,4.4,5.3,4.4,4.4,
LWA clay	32.6,29.4,32.4,28.3,32.7,
	51.3,46.1,51.4,51.7,44.1,
	43.7,40.0,34.4,39.7,38.7,
	38.5,41.9,39.6,36.9,39.8,
MWA clay	21.3,19.9,22.5,19.8,23.3,
	18.7,16.5,19.2,19.7,24.9,
	20.9,20.2,16.6,21.0,17.7,
	16.0,14.1,17.0,16.8,15.6,
HWA clay	5.1,5.6,5.4,5.5,5.7,
	6.0,6.3,6.0,5.9,5.4,
	5.8,5.6,6.0,6.3,6.1,
	4.9,4.8,5.0,4.6,4.9,
Concrete brk.	16.3,13.8,14.7,14.9,15.9,
	18.4,17.6,18.2,16.4,18.5,
	17.3,18.0,16.2,17.6,19.0,
	15.5,15.8,14.9,15.3,16.8,
Calsil	8.1, 8.1, 8.0, 8.0, 9.1,
	8.1, 7.9, 7.7, 6.7,11.0,
	10.0, 9.9, 9.7,10.7, 9.3,
	13.2,12.6,12.8,11.9,13.4,
DAC block	13.0,10.1,13.5,11.4,13.3,
	12.4,13.3,13.1,12.2,13.6,
	7.6,13.5,12.4,12.2,10.8,
	12.1,13.1,12.1,13.2,12.8,
LWAC block	5.5,5.5,4.7,4.3,4.8,
	3.7,3.8,3.4,3.5,4.6,
	4.5,4.9,5.4,5.0,MV,
	4.0,3.9,3.9,4.0,4.3,
AAC block	4.4,5.8,4.5,6.0,5.4,
	5.3,5.3,5.3,4.2,4.1,
	5.6,5.5,4.1,5.1,4.2,
	4.8,5.1,4.6,4.3,4.8,

BASIS OF CALCULATIONS & RESULTS

Figure 1 is a histogram of the two groups of data together with the data pooled which illustrates that while there are at least two or more populations; a weaker and a stronger range, there is no reason to suppose that the data from the two sources are distinctively different in character. Thus to simplify the analysis the data has been pooled.

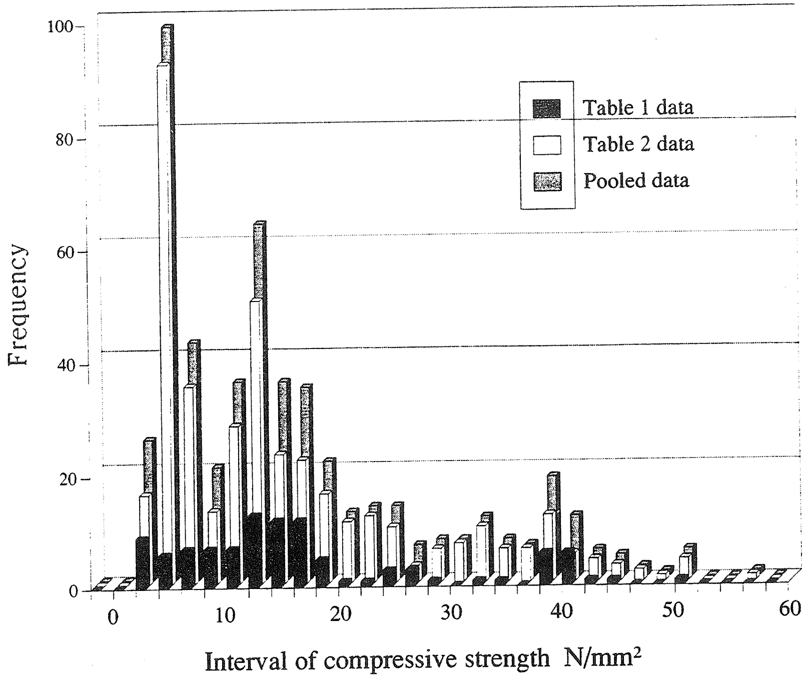

Fig.1 The Distribution of the Pooled Wallette Strengths

From this data four files were generated (1) the original data for sets of fives, (2) Sets of the first three results, (3) Sets of the middle three results, (4) Sets of the last three results. Other permutations are possible but were felt to be unnecessary. Since the order of test is random, the selection of any particular group of three should be equally random. The standard statistics were then generated for each group including (i) the best estimate of population mean characteristic at 95% probability (Moroney 1951), (ii) the EC default characteristic, (iii) the 5% fractile based on the normal distribution and the Fisher fiducial limit method (Beach 1977) and (iv) the 5% fractile based on an assumed log-normal distribution (Beach 1977). In the Swedish comments on CEN prEN 845-1 (CEN 1994) an alternative set of values for K are given for use with the third method but they differ only marginally from those suggested by Beach and thus are not used.

The formulæ used are as follows:

(i) Best estimate of population mean $f_k = \overline{X} - k\sigma/N^{1/2}$

(ii) EC characteristic: $f_k = \overline{X} / 1.2$

(iii) 5% fractile based on a normal distrib. $f_k = \overline{X} - k\sigma$

(iv) 5% fractile based on a log/normal distrib.

$y_k = \overline{Y} - k\sigma_{log.}$ $f_k = \text{antilog}\ (y_k)$

Where:

f_k is the characteristic value and y_k is the logarithmic equivalent

k Where k for method (i) is derived from tables of the single-tailed student's t distribution for 95% probability and k for methods (iii) and (iv) is based on the same value of t multiplied by $((N+1)/N)^{1/2}$- see Table 3.

$\overline{X}$ is the mean of the sample and $\overline{Y}$ is the mean of the logs of the sample

σ is the standard deviation of the sample and σ_{log} of the logs of the sample

N is the number of replicates in the sample

Table 3. Values of the statistical constant k for varying specimen numbers.

No. in sample	2	3	4	5	6	7	8	9	10	15	20	40	100
k for method (i)	6.31	2.92	2.35	2.13	2.02	1.94	1.90	1.86	1.83	1.75	1.72	1.68	1.66
k for (iii) & (iv)	7.73	3.37	2.63	2.24	2.18	2.08	2.01	1.96	1.92	1.80	1.76	1.70	1.67
k as per ref. 4 ‡	-	-	2.68	2.46	2.33	-	2.18	-	2.10	1.99	1.93	1.83	1.75

Table 4a gives the mean values etc. for the full five and the three reduced sets of 3 based on all the data and Figure 2 illustrates these results. Table 4b gives the ratio of the characteristic values based on the four formulae and the mean (50 percentile).

Table 4a. Average of all 101 of the calculated statistical results

STATISTIC	MEAN	Char. mean	Mean/1.2	5% fractile (LD)	5% fractile (ND)
All five	15.93	14.4	13.27	12.6	12.18
1st three	15.9	13.51	13.25	11.96	11.12
2nd three	15.97	13.69	13.31	12.12	11.4
3rd three	15.92	13.46	13.27	11.85	11.01

Table 4b. CV% and Ratios of characteristic/mean for the data in table 5a

STATISTIC	CV%	Char. mean	Mean/1.2	5% fractile (LD)	5% fractile (ND)
All five	8.50	0.91	0.83	0.8	0.77
1st three	8.56	0.86	0.83	0.76	0.71
2nd three	8.83	0.86	0.83	0.76	0.71
3rd three	9.62	0.85	0.83	0.75	0.7

Table 5 gives example sets of the mean and the 4 suggested statistical indicators of characteristic strength for the first five data sets in Table 1 for the four data sets.

Table 5: Example sets of mean, CV% and characteristic values for the first five sets of data in Table 1 for groups of 5, 3, 3, and 3. (N/mm² except CV%)

Mean	CV%	Char.Mean (i)	Char. EC6 (ii)	Normal Char.(iii)	Log Char. (iv)
		Set	**of five results**		
39.52	21.47	31.43	29.90	19.70	23.47
40.52	3.38	39.21	33.77	37.32	37.39
16.18	4.67	15.46	13.48	14.41	14.48
11.08	8.01	10.23	9.23	9.01	9.10
15.64	8.27	14.41	13.03	12.62	12.86
		1st set	**of three results**		
41.80	25.78	23.63	29.90	5.48	16.04
40.50	4.51	37.42	33.75	34.35	34.70
16.10	4.93	14.76	13.42	13.43	13.60
10.97	11.25	8.89	9.14	6.81	7.40
16.50	4.58	15.23	13.75	13.96	14.14
		2nd set	**of three results**		
44.833	13.28	34.80	37.36	24.77	28.46
40.433	4.40	37.43	33.69	34.44	34.78
16.70	1.80	16.19	13.92	15.69	15.72
10.933	11.18	8.87	9.11	6.82	7.41
15.833	9.16	13.39	13.19	10.95	11.59
		3rd set	**of three results**		
38.933	14.64	29.32	32.44	19.72	23.49
39.833	3.52	37.47	33.19	35.11	35.36
16.333	4.30	15.15	13.61	13.97	14.11
10.70	8.92	9.09	8.92	7.49	7.83
14.833	5.65	13.42	12.36	12.01	12.28

A one way analysis of variance was carried out for each parameter comparing the values derived using either 5 values or the three alternative sets of 3. All the analyses gave fractional values for the variance ratio which indicates that there is no significant difference between them. This is not surprising since the original data sets were not all drawn from the same parent population.

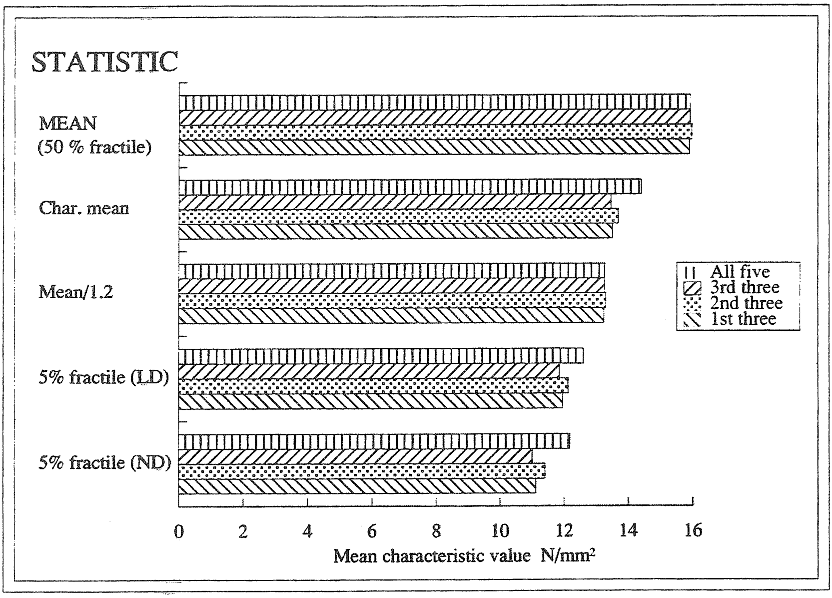

Fig.2 The Means of the Calculated Characteristic Strengths

THREE VERSUS FIVE SPECIMENS

As would be expected, on such a large body of data, there is no effect on the mean value or the mean/1.2 between using 5 and 3 replicates. There would occasionally be fortuitous differences on smaller bodies of data which tend to balance out in a long run of data such as this. Clearly there is a reduction between characteristics (i),(iii) and (iv) based on 5 and those based on 3 replicates.

The differences would be expected because (1) the Bessell correction (N/N-1) has been used to estimate the population variance from the sample variance. (2) the value of k will be larger for 3 samples than for 5 samples and the value of $N^{1/2}$ will reduce. Table 6 gives the factors for the characteristic mean value.

The values in Table 6 suggest that the penalty for using 3 versus 5 values should be around 17% and a similar single value is in near agreement at 15% but the observed average penalty was only 6%. This is presumably due to non-linear behaviour which biases the result towards the less variable data.

Table 6. Penalties for use of 3 versus 5 specimens for Char. Mean

Parameter	σ	$N^{½}$	k	$kσ/N^{½}$	Ave CV	$X - kσ/N^{½}$
Calc. ratio 3/5 repl.	$(3:2/5:4)^{½}$	$3^{½} / 5^{½}$	2.92/2.13	-	-	-
Calc. ratio 3/5 repl.	1.095	0.775	1.37	1.935	8.88%	0.83 X
Obs.Single example ‡	-	-	-	-	8.92%	0.849 X
Obs.Ave. from table 5	-	-	-	-	8.88%	0.94 X
Calc. ratio 2/5 repl.	$(2/1:5/4)^{½}$	$2^{½} / 5^{½}$	6.31/2.13	-	-	-
Calc. ratio 2/5 repl.	1.26	0.632	2.96	5.91	8.88%	0.48 X

‡ The example taken is the penultimate single example from table 4 which has the nearest CV% to the mean value.

If the use of 3 specimens is adopted the loss of one result due to breakage or other reasons could have a disproportionate effect on the characteristic based on methods (i), (iii) and (iv) since the value of $kσ/N^{½}$ based on the Student's t for two specimens (degrees of freedom = 1) is about three times that for 5 specimens. A test on the compression data indicated an almost 50% overall reduction in characteristic for one group where only two specimens survived. Thus it would be important to ensure that a retest is a requirement in such circumstances to be fair to the product.

CHOICE OF CHARACTERISTIC VALUE

There are several views:

(1) that the mean (together with appropriate factors of safety) is an adequate characteristic for all purposes.

(2) that the mean (together with appropriate factors of safety) is an adequate characteristic for situations where the failure (or poor performance) of one item or small area of material would not cause failure of the whole assemblage. (eg. a brick in a wall).

(3) that the best estimate of the mean of the population (=batch = consignment) (together with appropriate factors of safety) is a better characteristic for either all situations or where the failure (or poor performance) of one item or small area of material would not cause failure of the whole assemblage. (eg. a brick in a wall). Because it gives a small penalty for variability and thus an advantage to a producer with better quality control.

(4) that a 5% fractile method (together with appropriate factors of safety) is the only acceptable statistic for situations where the failure (or poor performance) of one item or small area of material could cause failure of the whole assemblage. (eg. a single lintel). Because it gives a large penalty for variability and thus a substantial advantage to a producer with better quality control.

(5) that a 5% fractile method (together with appropriate factors of safety) is the only acceptable statistic for all situations. Because it gives a large penalty for

variability and thus an advantage to a producer with better quality control.

For this data, with an average coefficient of variation of 10%, the best estimate characteristic is generally greater than that derived from the EC method while the fractile methods are significantly lower. This would not be the case for CV%s of 15% or more where the EC characteristic would be expected to be the higher value. For CVs above 15% the 5% fractile methods give very pessimistic values often below 50% of the mean and negative in some cases. For example the first item of data in table 5 has a coefficient of variation of just below 15% for the 3rd choice of 3 and has a mean of 39, char. mean of 29.3 and a 5% fractile value of only 19.7 while the EC value is 32.4. For the 1st set of 3, where the CV% shoots up to 26%, the corresponding values are 41.8, 23.6, 5.5 and 29.9. Thus for the occasional batch with a high variability the 5% fractile gives very pessimistic and unrepresentative results. In the 101 sets of 5 values there are 9 with coefficients of variation above 20% thus a significant proportion of data will give low 5% fractile values.

Taking all the data the average characteristic values (for an average CV% of 9%) are given in Table 4a. This indicates that the EC value (mean/1.2) is equivalent to the best estimate of the mean @ a probability level of 0.95 assuming a population coefficient of variation of about 10% which seems a reasonable reflection of the data. All the full statistical calculations will tend to reduce the value below this for the more variable samples. The current proposal in the draft standard is a compromise where the Mean/1.2 value is used for small samples of 5 or less but where the 5% fractile based on an assumed lognormal distribution is taken for larger samples. These two approaches give equivalent results for a coefficient of variation of about 6%, ie. slightly below the observed average.

ANALYSIS and DISCUSSION OF THE WALLETTE VERSUS WALL EFFECT

The data is given in Table 1 in the second and third columns. The means have been plotted against each other in Figures 3 and 4. The results of simple linear regression analysis are also shown on Figures 3 and 4.

The data are plotted such that the regression of Y on X statistic is obtained with either the wall or the wallette data as the X parameter. The block data is insufficiently varied to give a conclusive result but suggests that it would not cause any problem to consider the wall and wallette to be equivalent especially if the wallette is chosen as the reference test method.

The brick data covers a better range and indicates that the wallette will be stronger on average and the average wallette could be predicted from the average wall by multiplying by 1.4. In this case if the wallette is chosen as the reference method a correction factor would have to be introduced based on data of this type to maintain the safety level of the Code.

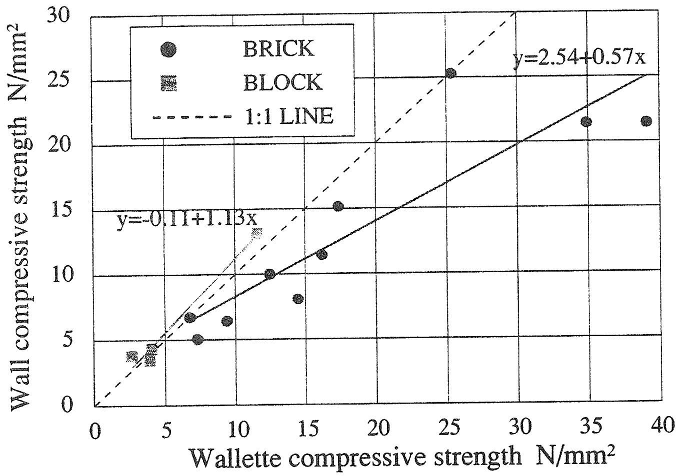

Fig. 3 Wallette versus wall data

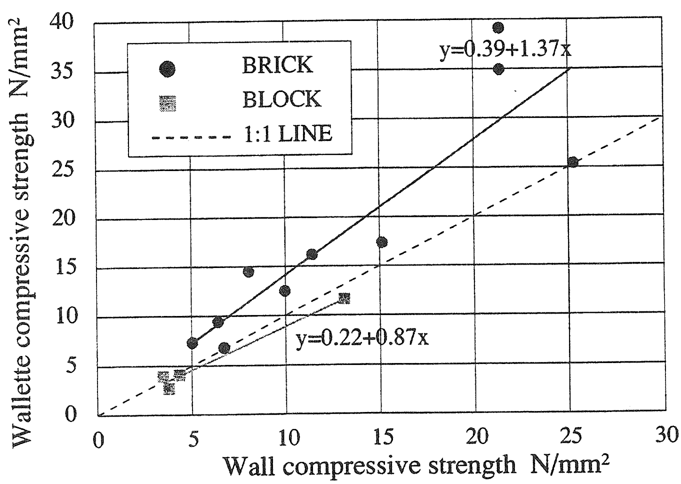

Fig. 3 Wall versus wallette data

BROAD CONCLUSIONS

1) The use of three as opposed to five replicates for compression testing would give only a modest average reduction of the characteristic depending on which statistic is used. These are not statistically significant different results for this range of data.
2) The use of three as opposed to five replicates for compression testing would not be expected to affect the mean significantly.
3) The use of three as opposed to five replicates for compression testing would not be expected to affect the characteristic result as calculated in accordance with prEN 1052-1:Clause 10.3 significantly.
4) The use of three as opposed to five replicates for compression testing would cause a 5.5% reduction of the best estimate of population mean result calculated in accordance with prEN 845/1:Clause 3.2.
5) The use of three as opposed to five replicates for compression testing would cause a 7.8% reduction if 5% fractile statistics based on the normal distribution are adopted.
6) The use of three as opposed to five replicates for compression testing would cause a 4.5% reduction if 5% fractile statistics based on the lognormal distribution are adopted.
7) The reductions are not statistically significant for this database but would be for homogeneous data - ie. where many repeat measurements were made on the same unit /mortar combination. They would also be significant and extremely pessimistic for data with a higher average variability. For example data with a 20% CV gives a lognormal 5% fractile value about 50% of the mean while data with a 30% CV gives a lognormal 5% fractile value about 30% of the mean. The normal 5% fractile value is even worse and will be negative in some cases.
8) If three replicates are used the method would be too sensitive to tolerate missing values if the characteristic mean is adopted so in such cases it should be a requirement that the whole test be repeated. Alternatively spare specimens could be made but only tested if required.
9) It is likely that walls and wallettes of blockwork can be considered equivalent and thus it should not matter which is used as the reference method.
10) If wallettes are chosen for the reference method for brick masonry then a correction factor may be necessary in order to safely predict the strength of storey height walls. On the basis of this database it is approximately division by 1.4.
11) If the wallette test is chosen as the reference method the database of linked wall and wallette tests should be widened to include more block strengths and some very low strength and medium strength bricks and more mortar strengths.

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FLEXURAL RIGIDITY OF CONCRETE MASONRY WALLS

G.G.Aridru[1] and J.L Dawe[2]

ABSTRACT

An evaluation of axial and flexural rigidities of concrete masonry walls is very important for calculations involving axial and ultimate moment capacities as well as lateral deflections. Currently approximate and empirical methods are used to evaluate these parameters and to date there is no good agreement between theoretical and experimental results. Preliminary results of effective flexural rigidities of short concrete masonry walls based on strain measurements on the surface of these walls are presented and discussed. Results indicate an exponential nature of the relationship between total applied moment and effective flexural rigidity for the heights of walls tested. Complete results of the experimental study will be published in future papers.

PREVIOUS RESEARCH

A reliable prediction of the modulus of elasticity of masonry is essential in calculations involving the axial rigidity or flexural rigidity of a section. Axial rigidity, AE, is a function of net cross-section area, A, and modulus of elasticity, E, which decreases with increasing stress. The magnitude of flexural rigidity depends on intensity and distribution of stresses on a cross-section as well as the modulus of elasticity, E, which decreases with increasing stress and the moment of inertia, I, which decreases with flexural cracking.

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1 PhD. Graduate Student.
2 Professor, Department of Civil Engineering, University of New Brunswick. P.O.Box 4400, Fredericton, N.B. E3B 5A3. Canada