# IV-16. Predicting the Compressive Strength of Brickwork

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## ABSTRACT

*The paper reports the results obtained from the use of a computer package to statistically compare brick wall compressive strength with those of the brick and brickwork prism specimens that are commonly used as predictors of this strength.*

*The data obtained from the testing of 58 full-size walls and their companion brick and small brickwork specimens are given and analysed.*

*It is concluded that, because of its ability to take account of otherwise unknown brick, mortar and workmanship effects, the four-high brick prism is a much better predictor of wall strength than is the brick and that little if any benefit is obtained by factoring brick or prism mean strengths to obtain characteristic values.*

## INTRODUCTION

Among others, British[1] North American[2] and Australian[3] codes of practice used for the design of brickwork to carry compressive loads establish either a permissible stress in or an "ultimate" strength of brickwork from a combination of the compressive strength of the bricks to be used and of the mortar type in which they are to be laid.

In North American and Australia methods are referred to or employed for the determination of wall strength by the measurement of the compressive strength of four-high stack-bonded prisms of brickwork. In Britain the corresponding small specimen was the six-brick cube, but its use is not mentioned in the latest revision of BS 5628.

The Australian code standardises the use of prisms as one method for the determination of the minimum ultimate compressive strength of brickwork[4] and several of those who were involved in the development of this technique have written advocating its widespread adoption[5,6,7].

The aim of this paper is to statistically examine Australian data in an attempt to demonstrate the superiority of the prism over other specimens or methods as a predictor of brickwork strength. A secondary aim is to check the worth of the Australian practice of factoring the means of brick and prism test results to obtain characteristic strengths.

## BRICKS

All bricks were made by the extrusion process, were of manufacturing size 230 x 110 x 76 mm (length, width, height) or 290 x 90 x 90 mm and average brick compressive strengths varied between 13.7 and 123.4 MPa. Perforations varied between zero and a maximum of 38.6 percent, but the majority had less than 25 percent perforation; which is to say, they were "solid" bricks in terms of the widely accepted definition of this title.

## WALLS

Data were collected from the testing of 52 experimental walls carried out at the Building Development Laboratories Pty. Ltd. in Perth and six at the School of Engineering, University of Melbourne. Perth walls and companion prisms were constructed and tested in the manner described by James[7]. Where, in Perth more than one wall was built from the same brick type, the listed brick compression values are from the testing of a single representative sample of bricks and prisms results are averages from sets of six built at the rate of two sets per wall. The Melbourne experiments were detailed by Base[8]. All walls were axially loaded in the flat ended condition and were 2.4m in height. A single experienced bricklayer built the Perth walls and the Melbourne walls were similarly constructed by another operator. All mortars were of the type 1:1:6 (cement : lime : sand) by volume, but were weight-batched by the conversion of volume to masses.

## VARIANTS AND SYMBOLS

Standard statistical methods were employed using a package of computer programs[9] and the following compressive strength variants were examined:

$\bar{F}_b$ —the mean strength of a random sample of 12 bricks determined in accordance with the method given in Australian Standard Methods of Test for Burned Clay and Shale Building Bricks, AS A140-1964

$F'_b$ —the minimum strength of bricks: $F'_b = \bar{F}_b - 0.38$ (Range); where the range is the average of the two strongest bricks in the sample of 12 minus the average of the two weakest. The method is taken from Australian Standard Specification for Burned Clay and Shale Building Bricks, AS A21-1964.

$\bar{F}_p$ —the mean strength of six four-high stack-bonded prisms constructed and tested in accordance with Standards Association of Australia (SAA) Brickwork Code AS 1640-1974. (Rule 6.7).

$F'_p$ —the minimum strength of prisms: $F'_p = \bar{F}_p - 0.38$ (Range); where the range is the difference between the strongest and weakest prism in the group of six. (AS 1640-1974, Rule 6.7).

$F'_m$ —the minimum ultimate strength of brickwork determined from prisms by the method given in AS 1640-1974: $F'_m = 0.75\ F'_p$ (AS 1640-1974, Rule 6.7).

$F_w$ —the strength of a wall.

## DATA, METHODS AND RESULTS

The data for the variants described in VARIANTS AND SYMBOLS are listed in Table 1.

Linear regression methods were used to find models for approximating wall strength from each of the variants in turn. The correlation coefficients between walls and the variants were also calculated as were the percentages of variance accounted for.

The results are listed in Tables 2 and 3 and are shown graphically in Figures 1 to 5 (drawn from computer plots).

## CONCLUSIONS AND DISCUSSIONS

The first conclusion was that the compressive strength of the brick was a better indicator of wall strength than was expected (correlation coefficients: 0.75 or 0.77). The correlation coefficients of prisms to walls were, however, very much higher (0.90, 0.88 and 0.98); so much so that their adoption as the standard method of predicting wall strength appears to be positively indicated.

The results also show that the correlations between bricks and walls and prisms and walls are not significantly improved when the Australian practice is employed of subtracting factored ranges from means to obtain approximate characteristic strengths. One result of this investigation therefore must tend to be to advocate the abandonment of their use. Such a change would have the added advantage of bringing Australian practice more closely into line with that of other countries, but it must be recognised that these particular results reflect the workmanship effects of only two bricklayers, both of whom were very experienced in the making of test specimens of brickwork. The real variability introduced by a full range of practical bricklayers is not measured by the work reported here and further studies of this effect may justify the retention of the concept. The workmanship argument does not, however, apply to characteristic brick strength.

There is a strong indication from this work and from that of others that brick perforation percentages and patterns have a marked effect on the compressive strength of brickwork made from such bricks. It can be expected that more work of the sort carried out by the British Ceramic Research Association[10] will eventually provide a detailed basis for the design of perforation configuration in bricks that will reliably produce high compressive strength brickwork. However, most bricks are produced for uses where few demands are made on their strength properties and high recovery rates of a product with saleable appearance properties are, and are likely to remain the major influences on the manufacturer in this selection of a hole configuration for extruded bricks.

In these circumstances there is a most useful demonstration from this investigation that prism testing has the ability to quantify the effect of perforation patterns and other brick properties on the compressive strength of brickwork and to produce measures of wall strengths on which much more reliance can be placed than is possible when they have been estimated from brick compressive strength and mortar type. The method has the further advantage of measuring the variable effects of mortars made from different sands and cementitious materials, even if they are made to the one formula. The influence of different grades of workmanship is also taken into account when prisms are used.

## SUMMARY OF CONCLUSIONS

The data presented in this paper show:

- Prism compressive strength is a good predictor of wall compressive strength, taking into account the effects of otherwise unknown brick, mortar and workmanship properties.
- Although not inadequate, brick compressive strength is not, by a substantial margin, as good a predictor of wall strength as is the compressive strength of prisms.
- No significant improvement in the prediction of wall strength is obtained when either brick or prism mean strength are factored to obtain their characteristic strengths and, except to the extent that its continued use with prisms may provide some compensation for the effect on brickwork strength introduced by variable workmanship, there is good evidence to favour the abandonment of this concept in standard Australian brick and brickwork specifications and codes.

## REFERENCES

1. British Standards Institute, British Standard Code of Practice for Structural Use of Masonry: Part 1, Unreinforced Masonry, BS 5628, Part 1-1978.
2. Brick Institute of America, Building Code Requirements for Engineered Brick Masonry, August 1969.
3. Standards Association of Australia, SAA Brickwork Code (Metric Units), AS 1640-1974.
4. *Ibid.*, Rule 6.7, pp 60–64.
5. Anderson, G. W., Site Control of Structural Brickwork in Australia, Documentation 3.1 MC, Bundesverband de Deutschen Ziegelindustrie, Bonn, 1975, pp 187–191.
6. Johnston, V. R. and McNeilly, T. H., Specification, Testing and Site Control for Structural Brickwork, *ibid*, pp 202–207.
7. James, J. A., Investigation of the Effect of Workmanship and Curing Conditions on the Strength of Brickwork. *Ibid*, pp192–201.
8. Base, G. D., Compression Tests on Six Single-leaf Brick Walls. University of Melbourne, Department of Civil Engineering, Report on Investigation No. ST78/66, April 1968.
9. Waite Institute GENSTAT package (Version 4.01) as installed at the University of Melbourne Computer Centre.
10. West, H. W. H. *et al*, The Performance of Walls Built with Wirecut Bricks with and without Perforations. B Ceram RA Special Publication No. 60, 1968.

**TABLE 1—Experimental Compressive Strength Data**

| Average Brick ($\bar{F}_b$) | Minimum Brick ($F'_b$) | Mean Prism ($\bar{F}_p$) | Minimum Prism ($F'_p$) | Min.Ult.Prism ($F'_m$) | Wall ($F_w$) |
|---|---|---|---|---|---|
| 82.0 | 71.6 | 27.3 | 24.6 | 18.5 | 21.2 |
| 82.0 | 71.6 | 27.3 | 24.6 | 18.5 | 21.5 |
| 71.8 | 66.5 | 25.0 | 23.2 | 17.4 | 19.7 |
| 71.8 | 66.5 | 25.0 | 23.2 | 17.4 | 20.5 |
| 71.8 | 66.5 | 25.0 | 23.2 | 17.4 | 20.1 |
| 71.4 | 65.5 | 32.0 | 29.9 | 22.4 | 22.0 |
| 71.4 | 65.5 | 32.0 | 29.9 | 22.4 | 23.2 |
| 68.6 | 62.1 | 23.9 | 22.3 | 16.7 | 15.2 |
| 68.6 | 62.1 | 23.9 | 22.3 | 16.7 | 15.9 |
| 68.6 | 62.1 | 23.9 | 22.3 | 16.7 | 18.5 |
| 68.6 | 62.1 | 23.9 | 22.3 | 16.7 | 18.1 |
| 66.1 | 61.3 | 27.2 | 25.4 | 19.1 | 22.5 |
| 66.1 | 61.3 | 27.2 | 25.4 | 19.1 | 20.8 |
| 66.1 | 61.3 | 27.2 | 25.4 | 19.1 | 22.8 |
| 64.8 | 57.8 | 27.2 | 25.1 | 18.8 | 15.1 |
| 64.8 | 57.8 | 27.2 | 25.1 | 18.8 | 17.9 |
| 64.8 | 57.8 | 27.2 | 25.1 | 18.8 | 18.1 |
| 64.8 | 57.8 | 27.2 | 25.1 | 18.8 | 18.5 |
| 58.4 | 54.1 | 22.5 | 20.5 | 16.2 | 20.0 |
| 58.4 | 54.1 | 22.5 | 20.5 | 16.2 | 18.7 |
| 52.8 | 49.4 | 22.1 | 17.3 | 13.0 | 18.7 |
| 47.2 | 40.3 | 20.5 | 15.1 | 11.3 | 15.4 |
| 47.2 | 40.3 | 20.5 | 15.1 | 11.3 | 15.0 |
| 47.2 | 40.3 | 20.5 | 15.1 | 11.3 | 17.3 |
| 46.1 | 43.4 | 23.9 | 21.2 | 17.2 | 16.7 |
| 46.1 | 43.4 | 23.9 | 21.2 | 17.2 | 19.4 |
| 38.8 | 33.8 | 18.7 | 16.9 | 14.4 | 14.5 |
| 38.8 | 33.8 | 18.7 | 16.9 | 14.4 | 15.2 |
| 38.8 | 33.8 | 18.7 | 16.9 | 14.4 | 14.6 |
| 35.0 | 32.8 | 19.2 | 18.3 | 15.7 | 15.4 |
| 35.0 | 32.8 | 19.2 | 18.3 | 15.7 | 17.7 |
| 33.5 | 31.3 | 17.2 | 15.8 | 11.9 | 12.9 |
| 26.7 | 24.0 | 15.9 | 14.1 | 12.0 | 13.0 |
| 26.7 | 24.0 | 15.9 | 14.1 | 12.0 | 13.7 |
| 26.7 | 24.0 | 15.9 | 14.1 | 12.0 | 13.4 |
| 25.6 | 23.5 | 11.8 | 11.1 | 8.3 | 9.5 |
| 25.6 | 23.5 | 11.8 | 11.1 | 8.3 | 10.5 |
| 25.6 | 23.5 | 11.8 | 11.1 | 8.3 | 9.0 |
| 13.7 | 11.7 | 4.8 | 4.0 | 3.0 | 7.0 |
| 28.9 | 25.0 | 15.1 | 14.5 | 10.6 | 11.7 |
| 30.8 | 28.7 | 16.3 | 13.8 | 10.3 | 11.5 |
| 67.4 | 62.4 | 23.0 | 21.9 | 16.4 | 21.9 |
| 30.1 | 27.3 | 13.7 | 11.5 | 8.6 | 7.7 |
| 30.1 | 27.3 | 15.8 | 14.1 | 10.6 | 8.3 |
| 30.1 | 27.3 | 14.5 | 12.9 | 9.7 | 9.9 |
| 13.7 | 11.7 | 4.8 | 4.0 | 3.0 | 7.8 |
| 30.8 | 28.7 | 17.4 | 15.7 | 11.8 | 13.0 |
| 30.8 | 28.7 | 15.4 | 12.8 | 9.5 | 8.5 |
| 67.4 | 62.4 | 23.6 | 21.6 | 16.2 | 16.1 |
| 67.4 | 62.4 | 23.9 | 22.6 | 17.0 | 15.7 |
| 28.9 | 25.0 | 14.3 | 12.7 | 9.5 | 10.8 |
| 49.1 | 46.5 | 19.8 | 17.0 | 12.7 | 12.5 |
| 91.7 | 84.8 | 25.2 | 22.1 | 16.5 | 18.5 |
| 88.3 | 73.1 | 22.8 | 20.3 | 15.3 | 17.8 |
| 68.3 | 55.4 | 15.6 | 13.2 | 9.9 | 13.7 |
| 57.9 | 51.0 | 17.9 | 15.5 | 11.6 | 14.8 |
| 108.9 | 97.2 | 22.7 | 19.1 | 14.3 | 18.3 |
| 132.4 | 111.7 | 27.4 | 26.0 | 19.5 | 19.3 |

NOTE: All units are MPa ($MN/m^2$)

The last six sets of data are for the Melbourne Walls. All others are Perth Walls

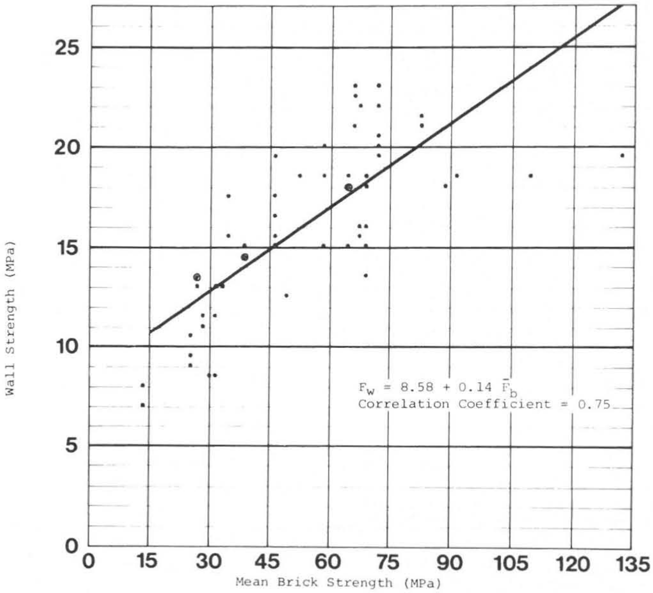


*Figure 1.* Wall Strength ($F_w$) V. Mean Brick Strength ($\bar{F}_b$)

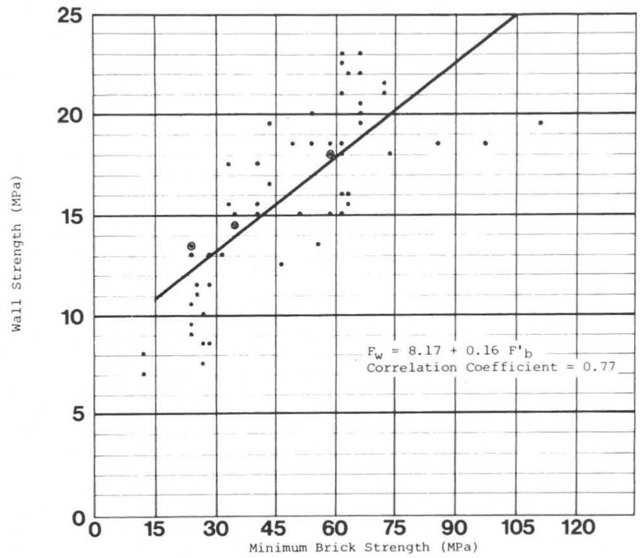


*Figure 2.* Wall strength ($F_w$) V. Minimum Brick Strength ($F'_b$)

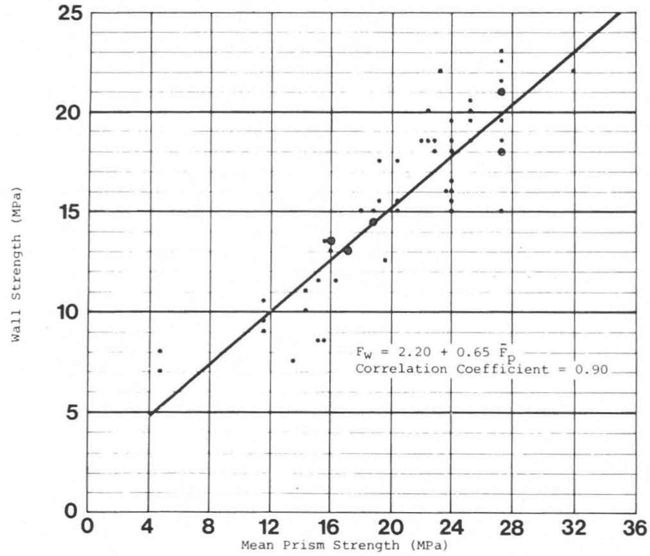


*Figure 3.* Wall Strength ($F_w$) V. Mean Prism Strength ($\bar{F}_p$)

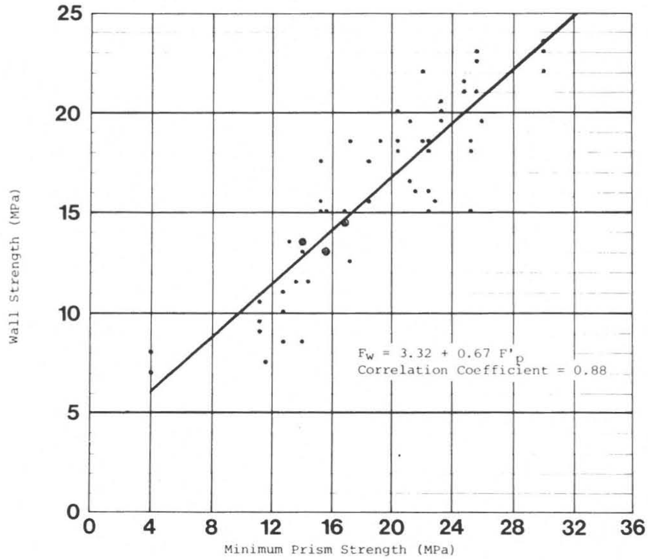


*Figure 4.* Wall Strength ($F_w$ V. Minimum Prism Strength ($F'_p$)

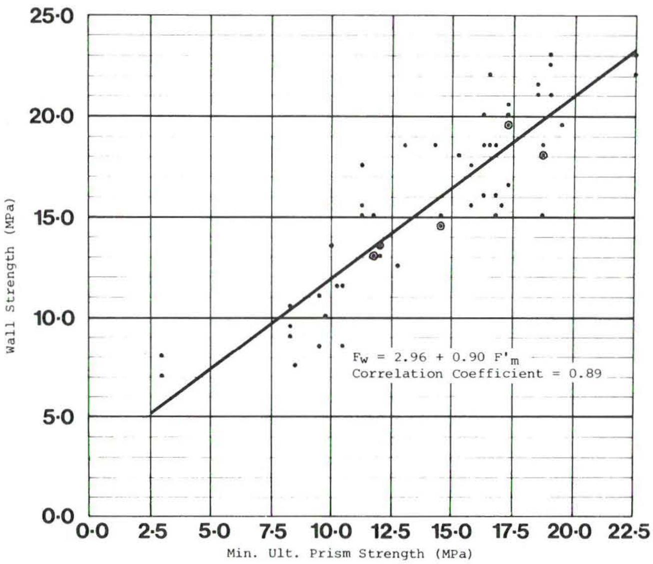


*Figure 5.* Wall Strength ($F_w$) V. Min. Ult. Prism Strength ($F'_m$)

**TABLE 2—Regression: Wall Strength ($F_W$) V. Independent Variant**

| Independent Variant | | Model | Correlation Coefficient |
|---|---|---|---|
| Mean brick strength | ($\bar{F}_b$) | $F_w = 8.58 + 0.14\,\bar{F}_b$ | 0.75 |
| Minimum brick strength | ($F'_b$) | $F_w = 8.17 + 0.16\,F'_b$ | 0.77 |
| Mean prism strength | ($\bar{F}_p$) | $F_w = 2.20 + 0.65\,\bar{F}_p$ | 0.90 |
| Minimum prism strength | ($F'_p$) | $F_w = 3.32 + 0.67\,F'_p$ | 0.88 |
| Min. ult. prism strength | ($F'_m$) | $F_w = 2.96 + 0.90\,F'_m$ | 0.89 |

**TABLE 3—Analysis of Variance**

a) Wall compressive strength ($F_w$) V. Mean Brick Strength ($\bar{F}_b$)

| | Degrees of Freedom | Sum of Squares | Mean Squares | F |
|---|---|---|---|---|
| Regression | 1 | 585.2 | 585.245 | 69.2*** |
| Residual | 56 | 473.8 | 8.460 | |
| Total | 57 | 1059.0 | 18.579 | $C_{0.999}(F1,56) \simeq 12.1$ |

$$\% \text{ variance accounted for} = \frac{\text{Total MS} - \text{Residual MS}}{\text{Total MS}} = 54.5$$

b) Wall strength ($F_w$) V. Minimum brick strength ($F'_b$)

| | DF | SS | MS | F |
|---|---|---|---|---|
| Regression | 1 | 626.0 | 626.968 | 80.9*** |
| Residual | 56 | 433.0 | 7.733 | |
| Total | 57 | 1059.0 | 18.579 | $C_{0.999}(F1,56) \simeq 12.1$ |

% variance accounted for = 58.4

c) Wall strength ($F_w$) V. Mean prism strength ($\bar{F}_p$)

| | DF | SS | MS | F |
|---|---|---|---|---|
| Regression | 1 | 850.8 | 850.821 | 228.9*** |
| Residual | 56 | 208.2 | 3.715 | |
| Total | 57 | 1059.0 | 18.579 | $C_{0.999}(F1,56) \simeq 12.1$ |

% variance accounted for = 80.0

d) Wall strength ($F_w$) V. Minimum prism strength ($F'_p$)

| | DF | SS | MS | F |
|---|---|---|---|---|
| Regression | 1 | 825.0 | 825.021 | 197.5*** |
| Residual | 56 | 234.0 | 4.178 | |
| Total | 57 | 1059.0 | 18.574 | $C_{0.999}(F1,56) \simeq 12.1$ |

% variance accounted for = 77.5

e) Wall strength ($F_w$) V. Min. ult. prism strength ($F'_m$)

| | DF | SS | MS | F |
|---|---|---|---|---|
| Regression | 1 | 829.4 | 829.399 | 202.3*** |
| Residual | 56 | 229.6 | 4.100 | |
| Total | 57 | 1059.0 | 18.579 | $C_{0.999}(F1.56) \simeq 12.1$ |

% variance accounted for = 77.9

NOTES: The notation (F value)*** indicates significance at the 0.1% level.
The notation $C_{0.999}(F_{m,n})$ represents the 0.999 quantile of the $F_{m,n}$ distribution.