II–20. Influence of Mortar Cube Strength Variability on the Measured Compressive and Flexural Strengths of Clay Masonry Prisms

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ABSTRACT

The results obtained from a job-sites research program in Western Canada, during which mortar was randomly sampled and subsequently tested in accordance with the quality control test methods recommended in CSA Standard A179, Mortar and Grout for Unit Masonry, show that the properties of mortar in use on the job are highly variable.

This paper deals (a) with the causes of such variability, and (b) with the contribution made by variability in mortar cube compressive strength to variability in masonry strength as determined from tests on prisms incorporating such mortar.

It is clearly demonstrated that mortar manufactured on the job site needs to be batch-controlled, with respect to the solid ingredients, if masonry is to be seriously considered by designers as a viable construction material for thin-wall high-rise load-bearing applications.

Les resultats obtenus d'un programme de recherche sur un chantier dans l'ouest du Canada sur lequel le mortier était échantillonné au hasard et testé subséquemment en accord avec les méthodes de contrôle de qualité recommandées par CSA Standard A179 mortier et mortier liquide pour unité de maçonnerie montrent que les propriétés du mortier employé dans les travaux ont très variables.

Cette communications traite (a) des causes d'une telle variabilité (b) de la contribution de la variabilité de résistance des cubes de mortier dans la variabilité de la résistance des maçonneries, déterminee à partir de test effectués sur des prismes incorporant un tel mortier.

Il est clairement demontré que le mortier fabriqué sur les chantiers a besoin d'un contrôle des ingrédients solides si la maconnerie doit être considerer par les concepteurs comme une matériel de construction viable pour des murs hauts et minces et murs supportant des charges.

Die Ersebnisse eines Forschunssvorhabens, bei dem auf Baustellen im Westen Kanadas wahllos Mörtelproben entnmmen wurden, weiche anschliessend semäss den in "CSA Standard A 179, Mortar and Grout for Unit Masonry" empfohlenen Qualitätskontrollversuchen seprüft wurden zeisten, dass die Mörteleisenschaften in situ stark variieren.

Der vorliesende Bericht behandelt a.) die Ursachen für diese Steuuns und b.) den Einfluss den eine streuende Mörtelwürfeldruckfestisunter Verwenduns desselben Mörtels ermittelt wurde, hat.

Es stellt sich eindeutis heraus, dass eine Mischunsskontrolle der Festbestandteile für baustellenhersestellten Mörtel nötis ist, falls Mauerewerk von Insenieuren als ein zuverlässises Konstruktionselement für hohe, dünnwandise lastabtrasende Bauteile ernsthaft in Betracht sezosen werden soll.

I risultati ottenuti in un progetto di ricerche in cantieri nel Canadà dell'Ovest dimostrano che le caratteristiche della malta usata sono estremamente variabili. Durante il progetto la malta fu saggiata a caso e poi esaminata secondo i metodi per il controllo di qualitá raccommandati in CSA Standard A179, Malta e Stucco per costruzione in muratura.

Questa relazione tratta: a) le cause di tale variabilitá, e b) il contributo apportato dalla variabilitá della forza compressiva in un cubo di malta alla variabilitá della forza della costruzione in muratura, determinata da esami su prismi incorporanti tale malta.

E chiaramente dimostrato che la malta preparata in cantiere deve essere controllata volta per volta, per quanto riguarda gli elementi solidi, per venir presa in seria considerazione da architetti come un materiale da costruzione funzionale per edifici a grande elevazione, a muri sottili e portanti.

INTRODUCTION

On the average masonry job-site, no consideration other than "shovel-counting" is given to batch controlling the quantities of the solid ingredients that make up mortar, i.e. sand and cementitious materials. As a result it is not uncommon to obtain a between-batch coefficient of variation of mortar cube compressive strength in excess of 0.40.

The strength of masonry is influenced by the strength of mortar, to some extent, and hence it is to be expected that such high variability in mortar strength will cause variability in masonry strength.

According to CSA Standard S304, Masonry Design and Construction for Buildings, the design value of f'm (compressive strength of masonry) may be obtained by first testing at least 5 prisms which "are built of the same type of materials under the same conditions ... as for the

structure" and then reducing the mean value calculated by a factor 1-1.5 cv, cv = coefficient of variation of the prism strengths.

Such prisms, however, are built from the same batch of mortar, the cube compressive strength of which typically has a within-batch coefficient of variation of only 0.05.

Based on the results obtained in this research program, the difference in f'm obtained from testing masonry prisms incorporating mortars of such different cv's can be as high as 20 percent.

SCOPE

CSA Standard A179, Mortar and Grout for Unit Masonry, will accept alternate methods of batch controlling the preparation of mortar on the job-site, i.e. volume measurement, by use of a suitably gauged hopper or by the use of gauge boxes, and weight measurement. In apparent deference to job-site practice the standard also allows the use of shovel-batching, providing that "where shovel-batching is employed, the shovel count shall be carefully checked periodically against a gauge box".

In this program, three forms of batch control were considered, (i) none at all (equivalent to current job-site practice), (ii) careful shovel-batching with frequent (periodic?) checks against a gauge-box, and (iii) weigh batching.

The nature of the research activity, the results obtained and some discussion is presented in this paper under separate headings identifying the batch control method being considered. Some concluding statements summarize the findings of this program.

TEST SPECIMENS

Throughout the paper, when reference is made to cubes, prisms for compression tests and prisms for flexural tests, the sizes and shapes of these are as shown in Figure D-1. For compression prisms full mortar bedding was used, but the strength values reported are based on net bedded area (face shells only). For flexural prisms, face shell bedding only was used. Values for flexural strength reported were calculated according to the method outlined in Appendix A.

JOB-SITES PROGRAM

General: Over a period of three years, during the summer months, mortar samples were taken at job-sites in Western Canada and tested in accordance with recommended standard procedures. Always with the prior approval of the masonry contractors samples of mortar from mortar boards in use were obtained. Frequently two samples per day were taken, one in the morning and one in the afternoon, but the samplers were careful not to be systematic as to the time of day the sample was obtained. Some days, no samples at all were taken. The samplers carried out their work with minimum disturbance of the on-going construction activity, basically trying to maintain a low profile. This was felt to be important so as not to cause the contractor to exercise extra-ordinary quality control on account of the fact that his work was being monitored.

Data obtained: From each sample of mortar taken six cubes were made for testing in compression at the age of 7-days, a flow test was conducted, and three a/c ratio tests were made. To represent a particular sample, the strength and a/c values were averaged. A minimum of 10 days and a maximum of 30 days on any one job site constituted the time period of sampling and testing. The total number of cubes tested was 4,500, the number of flow tests 750, and the number of a/c tests 2,250. Table S-1 contains information on the site location and the nature of the constructon activity, while Table S-2 summarizes the analyzed data.

Discussion: Variability in job-site sampled mortar cube compressive strength is high. Figure S-1 illustrates the batch to batch mean strengths and variabilities over the sampling period. For "N" mortars the mean values of compressive strength were always higher than the minimum value required by the property specification. The mean values of compressive strength for both "S" mortars, however, did not meet the minimum required by the property specification. Fortunately, for the contractor, no inspector ever came on to the job sites.

Regrettably, we were unable to use the actual mortar sampled on the job-sites to build prisms. Consequently, the following laboratory programs were conducted.

Laboratory Program—1: Weigh Batch Control of Aggregate Content

General: On three separate occasions a mason mixed batches of both Type N and Type S masonry cement mortar, in each case varying the a/c ratio between batches. The volumetric proportions adopted were converted into weight proportions and so batched, with sufficient water added to produce a mix workable enough to be acceptable on the average job site.

Data obtained: From each of these batches six cubes were made from the freshly prepared mortar, for testing in compression at the age of 7-days. Prior to the building of five masonry prisms from each batch, the batch was partitioned into five equal portions. One portion was allowed to stay on the mortar board for two hours and one for three hours, before being used to build a single prism from each. To the remaining three portions was added different amounts of extra water, and one prism from each portion was then built. This procedure was adopted to recognize the job-site situation where, even for accurate weigh batching of the solid ingredients, the workability and use of the mix remains the responsibility of the mason, and hence variability on account of these factors can be expected. Table L-1 contains the data.

Discussion: The variability in prism compressive strength is low. Hence, it is concluded that variation in workability and use of the mortar, within the bounds dictated by job-site acceptability, plays only a minor role in contribution to prism compressive strength variability.

From the data it seems reasonable to suggest that a coefficient of variation for compressive strength of masonry prisms of 0.08 is appropriate for this case of weigh batch control.

Laboratory Program—2: Volumetric Batch Control of Aggregate Content

General: On twelve different days over a period of two months, mortars were batched by our mason to the nominal mix proportions 1:1:4½, 1:1:5½ and 1:1:6¼. A gauge box was used periodically in an attempt to control the volumetric proportion of sand being added to the cementitious material. The relative proportions of lime and portland cement were more carefully controlled: Gauge boxes of appropriate batch size in each case were used for every mix.

Mortars were mixed to two consistencies, to represent the extremes of stiffness and sloppiness likely to be tolerated on the job site.

Data obtained: From each mortar one cube for testing in compression at 7-days, one prism for testing in compression at 7-days and one prism for testing in flexure at 7-days were manufactured.

In this manner, over the 12-days, the values of mean strength obtained, and their associated variabilities, are considered indicative of the job-site values that could reasonably be expected when only *periodic* use of gauge-box batch control is made. Table L-2 contains the data.

Discussion: Some interesting results were obtained. First, by only periodically using a gauge-box to control the aggregate content the variability in mortar cube strength is not reduced as much as might be expected; although it is approximately one-half that of shovel-batched job-site mortar, it is nevertheless still four times that of weigh-batched mortar. Second, but perhaps more important, the variability in masonry prism compressive strength for the case where periodic use of the gauge box is made is still approximately twice that characteristic of prisms incorporating weigh-batched mortar. Third, the highest prism strengths correspond with use of the more workable mortar at a fixed a/c ratio.

From the data it seems reasonable to suggest that a coefficient of variation for compressive strength of masonry prisms of 0.16 is appropriate for this case of batch control.

COMMENTARY

Figure D-2 is a plot of the average cv of mortar cube compressive strength against the average cv of masonry prism compressive strength for the two cases investigated in the laboratory. A curve has been drawn and projected in order to postulate the value of cv of masonry prism compressive strength that could be expected of prisms built using the job-site sampled mortar when tested on a between-batch basis.

Consider the influence of cv on the reduction factor applied to f′m.

For a cv of 0.08, reduction factor $(1\text{-}1.5 \times 0.08) = 0.88$
For a cv of 0.20, reduction factor $(1\text{-}1.5 \times 0.20) = 0.70$

$$\text{Resulting difference in f'm} = \frac{0.88 - 0.70}{0.88} \times 100 = 20\%$$

While it is recognized that Figure D-2 has only two actual data points on it, the third one being a projected point, the authors feel that the curve drawn represents the trend to be expected and, in any case, yields a value for cv of masonry prism compressive strength that would be conservative.

CONCLUDING STATEMENTS

The following statements seem justified by the data:

If it is desired to minimize the variability of masonry prism strength, and hence wall strength, then strict batch control over the aggregate content of mortar prepared on the job-site is essential; this means the use of weigh batch equipment.

Note: Appendix B contains a brief description of an apparatus which would, with modifications, be suitable for use on the job-site for this purpose.

Provided that the aggregate content is so controlled, designers of loadbearing and load resisting masonry structures should specify maximum possible workability for the mortar being used.

If weigh batch control is not adopted, designers must be cognizant of the high variability which characterizes the compressive strength of masonry.

ACKNOWLEDGEMENTS

The work herein reported was funded by the Alberta Masonry Institute, utilizing a grant from the National Research Council of Canada (IRAP). The prism testing program was carried out in the University of Calgary's Masonry Research Laboratory. The authors gratefully acknowledge the cooperation of these two organizations, and the work of the mason, Mr. Reg Rodney. The Clay units used in this research were kindly donated by I.XL Industries Ltd., of Medicine Hat, Alberta.

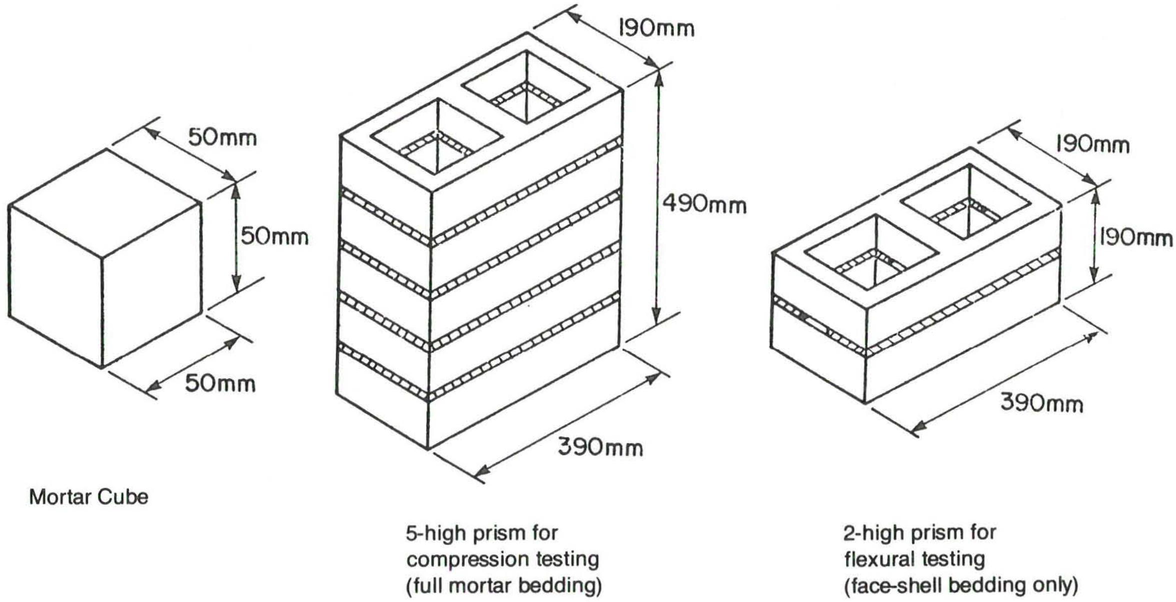


Figure D-1. Sizes and Shapes of Cubes and Prisms

TABLE S-1—Details of Job-Sites Visited

Job Site Designation	Geographic Location	Nature of Construction
A	Calgary, Alberta	Apartment building, Single-storey school, and Condominium housing
B	Vancouver, B.C.	Shopping Plaza/Commercial high rise
C	Calgary, Alberta	Warehouses
D	Winnipeg, Manitoba	Three storey and four-plex apartment buildings

TABLE S-2—Properties, and their Variability, of Job-Site Mortars: Shovel-Batch Control of Aggregate Content

		Statistical Data								
		Cube Strength (Compression-MPa)			Flow (%)			a/c (by weight)		
Job Site Designation	Type of Mortar	$\bar{x}$	sd	cv	$\bar{x}$	sd	cv	$\bar{x}$	sd	cv
A	N(MC)	6.24	1.36	0.22	117	19.7	0.17	3.08	0.52	0.17
B	S(MC)	7.21	3.10	0.43	98	9.0	0.09	3.80	0.87	0.23
C	S(MC)	8.86	3.55	0.40	120	11.6	0.10	3.00	0.81	0.27
D	N(L)	6.48	2.44	0.38	123	9.6	0.08	3.40	0.39	0.11

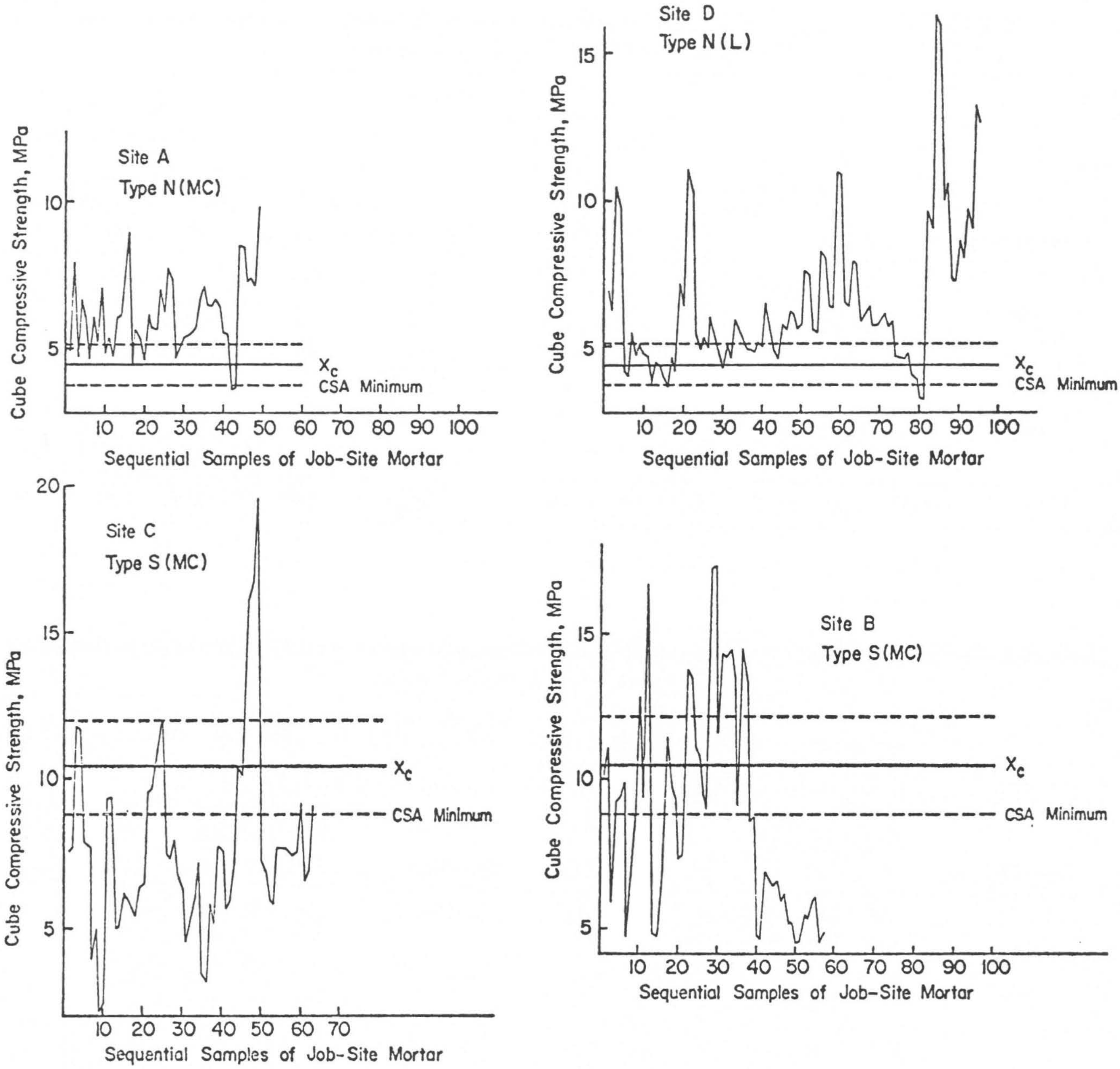


Figure S-1. Batch to Batch Mean Strengths and Variabilities

TABLE L–1—Properties, and Their Variability, of Laboratory Prepared Mortars and Prisms: Weigh-Batch Control of Aggregate Content

Type of Mortar	Statistical Data: Mortar Properties: Cube Strength (Compression-MPa) $\bar{x}$	sd	cv	Initial Flow (%)	a/c equivalent, (by weight)	by volume	Masonry Properties: Prism Strength (Net Area, Compression-MPa) $\bar{x}$	sd	cv
N(MC)	8.34	0.28	0.03	98	1:2	2.09	10.14	1.00	0.10
	6.41	0.33	0.05	116	1:3	3.26	7.55	0.50	0.07
	2.59	0.21	0.08	104	1:3½	3.82	8.14	0.62	0.08
	1.93	0.06	0.03	94	1:4	4.39	7.41	0.56	0.08
S(MC)	20.06	0.94	0.05	126	½:1:3	2.07	19.69	1.27	0.07
	12.96	0.50	0.04	121	½:1:4½	3.14	18.24	1.24	0.07
	4.10	0.14	0.04	123	½:1:6¼	4.35	11.38	0.59	0.05
	1.72	0.08	0.05	114	½:1:7½	5.50	8.76	0.76	0.09
N(L)	4.52	0.14	0.03	109	1:1:5½	3.38	10.83	0.97	0.09

TABLE L–2—Properties, and their Variability, of Laboratory Mortars: Periodic Use of Gauge Boxes for Batch Control of Aggregate Content

Type of Mortar	Statistical Data: Mortar Properties: Cube Strength (Compressive-MPa) $\bar{x}$	sd	cv	Flow (%) $\bar{x}$	sd	cv	Nominal a/c (by volume)	Masonry Properties: Prism Strength (Compression-MPa) $\bar{x}$	sd	cv	Prism Strength (Flexure-MPa) $\bar{x}$	sd	cv
	7.00	1.51	0.22	113	6.8	0.06	1:1:4½	10.72	1.97	0.18	0.25	0.11	0.44
	5.58	1.11	0.20	135	6.6	0.05		11.10	2.54	0.23	0.31	0.07	0.22
N(L)	3.90	0.78	0.20	118	8.7	0.07	1:1:5½	10.58	1.75	0.17	0.25	0.08	0.33
	3.14	0.61	0.19	139	5.7	0.04		11.14	1.25	0.11	0.31	0.08	0.24
	2.38	0.59	0.25	123	8.2	0.07	1:1:6¼	9.27	1.46	0.16	0.21	0.08	0.38
	2.00	0.40	0.20	143	4.8	0.03		10.89	1.41	0.13	0.24	0.06	0.27

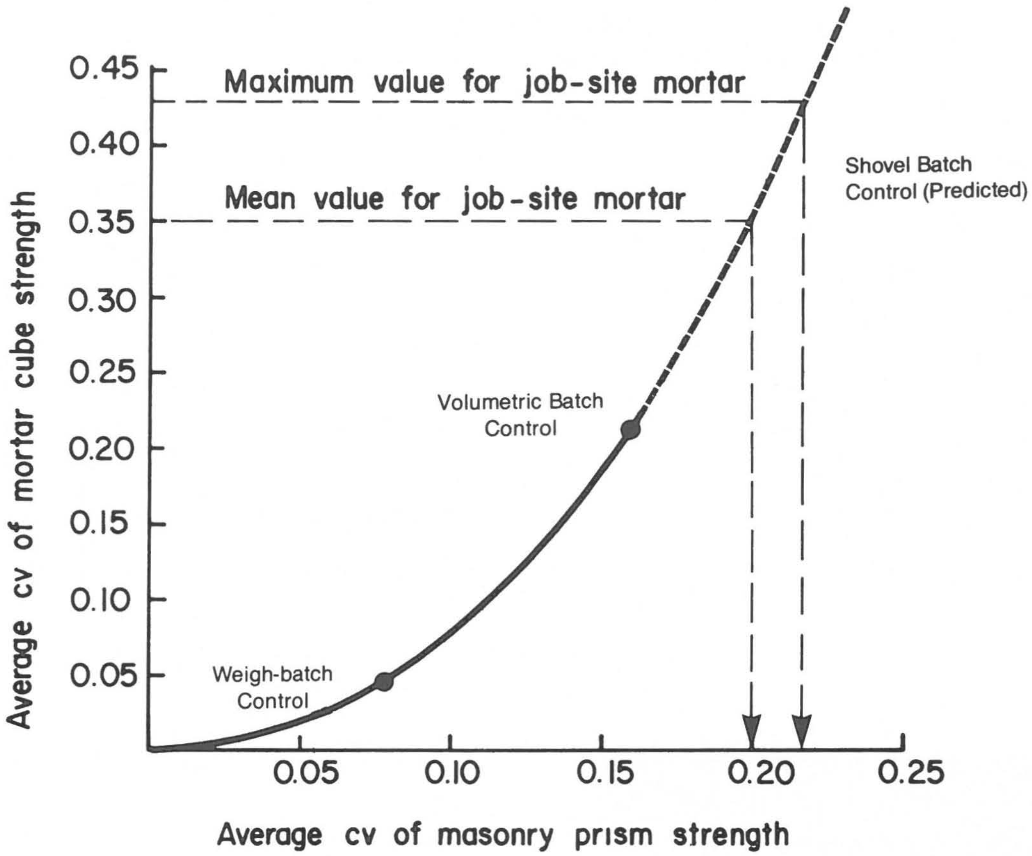


Figure D–2. Relationship Between cv's of Mortar Cube Strength and Masonry Prism Strength in Compression

APPENDIX B
Apparatus for Job-Site Weigh Batch Control

During the course of this research a simple portable weigh batch apparatus was constructed and used for demonstration purposes on job-sites. It is shown below in Figure D-3, next to a 4 cubic foot mixer.

The sand is shovelled into the weigh container and then added into the cementitious slurry in the mixer via a conveyor belt, to avoid double shovelling. The weighing mechanism is very simple. With more careful design, the apparatus could provide a relatively inexpensive means of batch controlling mortar on the job-site.

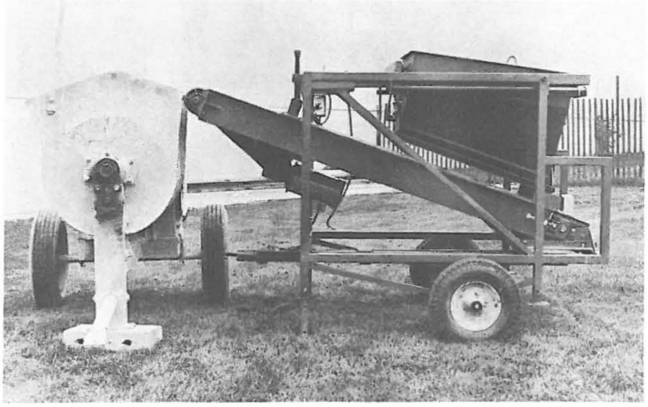
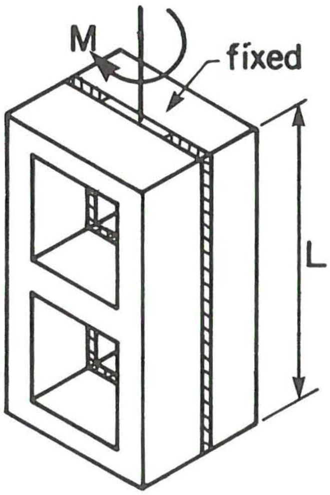


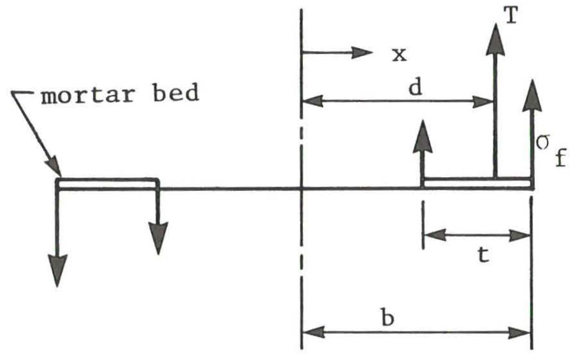
Figure D–3. Weigh Batch Control Apparatus for Aggregate

APPENDIX A
Calculation of Bond Failure Stress (Flexural Strength)



Assumptions:

(i) failure will occur when outside stress reaches the bond strength.
(ii) the stress-strain relationship is linear until bond failure.



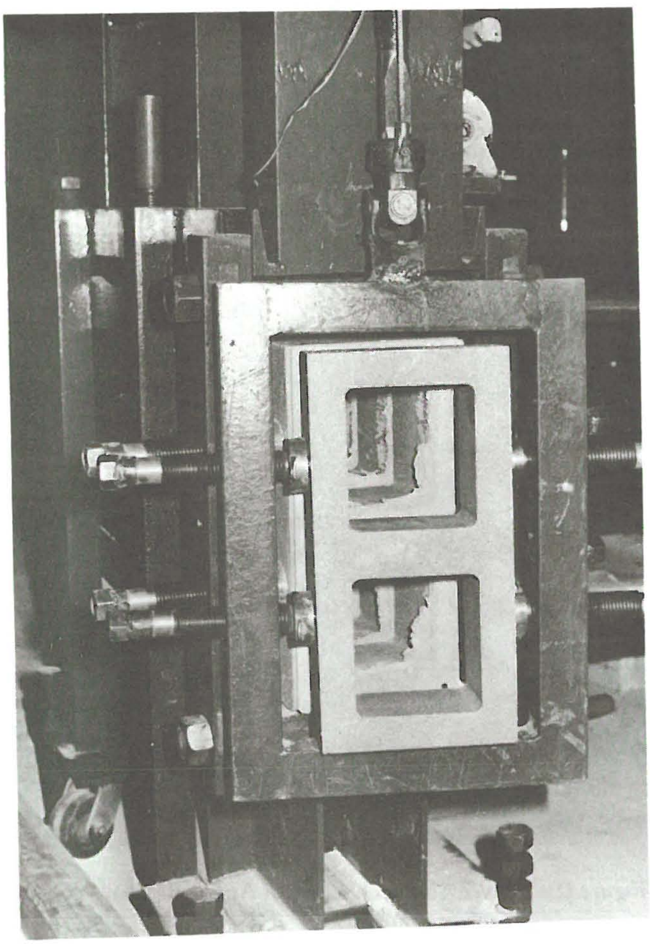


Figure D–5. Apparatus for Determining the Flexural Strength of Masonry

$$M = \int \sigma \times dA$$

$$= 2\int_{b-t}^{b} \sigma_f \frac{x^2}{b} \cdot L\, dx$$

and $M = 2Td$

from this, $T = tL\, \sigma_f \left(\frac{2b-t}{2b}\right)$

from geometry, $d = 2/3 \left(\frac{3b^2-3bt+t^2}{2b-t}\right)$

and, knowing M, σ_f may be calculated.

T – resultant force

σ_f – tensile failure stress