SIMULATION ON THE EFFECT OF WATER ABSORPTION ON THE STRENGTH OF MASONRY WALL

by

CHOW SHIAO TENG

Dissertation submitted as partial fulfillment
of the requirements for the degree of
Master of Science (Structural Engineering)

June 2006

ACKNOWLEDGEMENT

First and foremost, I would like to express my sincere appreciation to my supervisor, Dr. Badorul Hisham bin Abu Bakar for his guidance, encouragement and friendship throughout the period of my research. I am very grateful for the opportunity to work under his supervision.

In addition, I would like to thank PM Ahmad Shukri for his guidance on the application of Statistical software, MINITAB R14. His recommendations on the references books help a lot in giving the knowledge of statistical analysis and regression modelling.

Besides, I would like to express my gratitude to the lab technicians of Structure Laboratory who have provided information and advices on various occasions. Without their co-operation and assistance, the experimental works might not have come to light.

My sincere appreciation is also extended to my senior, Mr. Bashar, for his willingness to give useful helps and tips. He also provided me with some relevant materials, information and journal articles.

Finally, I would like to thank all my family members and friends for their support and encouragement. Acknowledgement also goes to many other people for their helps, though their names are not mentioned here.

ABSTRACT

Unit water absorption is an important characteristic in the construction of masonry structure as it plays a significant role in strength and durability performance. The moisture transfer mechanism between mortar joint and brick unit would lead to a reduction in the water content of fresh mortar, thereby causing shrinkage and moisture expansion in mortar and brick unit, respectively. In addition, poor and porous mortar joint would be produced. This would affect the masonry's strength, durability, serviceability and cause frost damage in seasonal regions. This research was carried out to develop a new model for predicting the compressive strength of masonry wall considering the unit water absorption, unit strength and mortar strength as well as to simulate the effect of water absorption on the strength of masonry wall and to compare the developed model with other established models. Experimental investigation was conducted on 60 specimens (individual bricks and brickwork prisms made up of calcium silicate, clay and cement sand bricks) in obtaining the brick's compressive strength, mortar strength, unit water absorption and initial rate of absorption. Based on the test results, empirical modelling of the masonry wall compressive strength with regression analysis was carried out using statistical software, MINITAB R14. A series of multiple regression analyses revealed that brick's compressive strength and initial rate of absorption were the most significant predictor variables in the research. The results of simulation indicated that unit water absorption contributes to the strength reduction in masonry wall by 0.43 %. Comparison between all models showed that EC 6 and BS 5628 respectively underestimate the wall's compressive strength by 31.69 % and 80.10 %, while Mann's model overestimated the masonry strength by 14.41 % as compared to the developed model.

TABLE OF CONTENTS

CONTENT			PAGE
ACKNOWLEDGEMENT			ii
ABSTRACT			iii
CONTENT			iv
LIST OF TABLES			viii
LIST OF FIGURES			x
LIST OF PLATES			xi
NOTATIONS			xii
CHAPTER 1 INTRODUCTION			
	1.1	Introduction	1
	1.2	Problem statement	2
	1.3	Objectives of research	4
	1.4	Scope of work	4
CHAPTER 2 LITERATURE REVIEW			
	2.1	Introduction	5
	2.2	Factors affecting compressive strength of masonry wall	5
	2.3	Transition zone in concrete/masonry and the effect of moisture movement	8
	2.4	Influence of unit water absorption	10
	2.5	Current models for the estimation of masonry compressive strength	
		2.5.1 British standards, BS 5628	13
		2.5.2 Eurocode 6	14
		2.5.3 Hendry and Malek's model	15
		2.5.4 Dymiotis and Gutledere's model	16
		2.5.5 Baur, Noland and Chinn's model	17
		2.5.6 Atkinson et al.'s model	18

2.5.7 Pande et al.'s model 18
2.5.8 Francis et al's model 19
2.5.9 Grimm's model 20
2.5.10 Mann's model 21
2.6 Concluding remarks 21

CHAPTER 3 MATERIAL AND DETAILS OF EXPERIMENT
3.1 Introduction 23
3.2 Outline of research work 23
3.3 Materials
3.3.1 Masonry units 24
3.3.2 Sand 25
3.3.3 Cement 26
3.3.4 Lime 26
3.3.5 Water and water/cement ratio 27
3.3.6 Mortar 27
3.4 Determination of material properties
3.4.1 Dimension test 28
3.4.2 Compressive strength
3.4.2.1 Masonry units 29
3.4.2.2 Mortar 31
3.4.2.3 Brickwork prisms 31
3.4.3 Water absorption
3.4.3.1 5-hour boiling test 34
3.4.3.2 Initial rate of absorption (IRA) 35

CHAPTER 4 RESULTS OF MATERIAL PROPERTIES
4.1 Introduction 36
4.2 Dimension test 36
4.3 Compressive strength test
4.3.1 Masonry unit 37
4.3.2 Mortar 39
4.3.3 Brickwork prism 40

4.4 Water absorption test

4.4.1 5-hour boiling test 42

4.4.2 IRA test 43

4.5 Failure mode of brick units, mortar cubes and brickwork prisms 45

4.6 Summary 47

CHAPTER 5 MODELLING OF MASONRY COMPRESSIVE STRENGTH

5.1 Introduction 49

5.2 Statistical software, MINITAB Release 14 49

5.3 Definition of terms used in regression modelling

5.3.1 Regression analysis 51

5.3.2 Analysis of variance 53

5.3.3 Matrix plot 55

5.3.4 Residual plot 55

5.4 Procedures of statistical modelling 57

5.5 Modelling with multiple linear regression (Least square method)

5.5.1 Linear form 62

5.5.2 Exponential form 65

5.6 Evaluation of models

5.6.1 Coefficient of determination, r^2 68

5.6.2 Hypothesis test for the model 68

5.6.3 Hypothesis test for the predictor variables 69

5.6.4 Residual analysis 71

5.7 Selection of final model 72

5.8 Simulation of the masonry strength based on the developed model 73

5.9 Comparison with other established models 76

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1	Introduction	79
6.2	Conclusions	79
6.3	Recommendations for future research	81

REFERENCES 82

APPENDICES A-C 86-128

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Effect of different joint material on the compressive strength of three brick stack-bond prisms	8
2.2	Characteristic compressive strength of masonry, f_k	14
2.3	Models developed by previous researchers	22
3.1	Mortar designation to BS 5628: Part 1: 1992	28
4.1	Dimension of calcium silicate, clay and cement sand bricks	37
4.2	Compressive strength of calcium silicate, clay and cement sand bricks	38
4.3	Result of dropping ball test	39
4.4	Compressive strength of mortar cubes for calcium silicate, clay and cement sand bricks	40
4.5	Compressive strength of calcium silicate, clay and cement sand brickwork prisms	41
4.6	Water absorption of calcium silicate, clay and cement sand bricks	43
4.7	IRA test results for calcium silicate, clay and cement sand brick	44
4.8	Summary of all test results for calcium silicate bricks	48
4.9	Summary of all test results for clay bricks	48
4.10	Summary of all test results for cement sand bricks	48
5.1	Combinations of predictor variables used in all models	61
5.2	Data range of compressive strength, water absorption and IRA test	62
5.3	Correlation between prism, brick, mortar strength, WA and IRA	64

5.4	Summary of regression analysis in linear form	65
5.5	Correlation between log prism, log brick, log mortar strength, log water absorption and log IRA	67
5.6	Summary of regression analysis in exponential form	68
5.7	Summary of test statistics F and p-value for selected exponential models	69
5.8	Summary of test statistics T and p-value for predictors	70
5.9	Masonry strength estimated by the developed model	74

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Stresses in brick-mortar composite	20
3.1	Sieve analysis of sand	26
4.1	Deformation of brick unit subjected to compressive stress	47
5.1	Regression and variance analysis using MINITAB release 14.	51
5.2	Matrix plot for response variable and predictor variables	55
5.3	Residual plot using MINITAB release 14	56
5.4	Flow chart for the procedures of statistical modelling using MINITAB R 14	59
5.5	Matrix plot for prism, brick, mortar strength, water absorption and IRA	63
5.6	Matrix plot for log prism, log brick, log mortar strength, log WA and log IRA	66
5.7	Residual plots for the final model	72
5.8	Histogram of masonry strength	75
5.9	Graph of strength predicted by model vs. measured strength	77
5.10	Histogram of masonry strength for all models	78
A1	The failure mode of masonry in compression	87
A2	Masonry assemblage test prisms	89

LIST OF PLATES

PLATE NO.	TITLE	PAGE
3.1	Masonry unit used in the investigation	25
3.2	Sieve analysis with BS sieve size 5 mm, 2.36 mm, 1.18 mm, 600μm, 300 μm and 150 μm	25
3.3	Dropping ball apparatus	27
3.4	Dimension test to BS 3921:1985	29
3.5	Compression test for clay brick	30
3.6	Compression test for mortar cube	31
3.7	Prism samples with four bricks stack-bonded and 10 mm mortar joint	32
3.8	Compression test for brickwork prisms	33
3.9	5-hour boiling test for calcium silicate, clay and cement sand bricks	34
4.1	Failure mode of brick unit	46
4.2	Failure mode of mortar cube	46
4.3	Failure mode of brickwork prisms	49

NOTATIONS

f_{wc}	Masonry wall compressive strength
f_{bc}	Brick compressive strength
f_{mc}	Mortar compressive strength
f_{pc}	Prism compressive strength
t_m	Joint thickness
t_w	Wall thickness
h_w	Wall height
h_b	Brick dimension
n_c	No. of course
V_h	Volume of perforation/overall brick volume
f'_{mt}	Ultimate prism compressive stress, measured or predicted
S_f	Dimensionless stress factor
E_b	Elastic moduli of the brick
E_m	Elastic moduli of the mortar
ν_b	Poisson's ratio of the brick
ν_m	Poisson's ratio of the mortar
ξ	Brick masonry prism slenderness factor
η	Material size factor
WA	Water absorption
IRA	Initial rate of absorption for brick unit

CHAPTER 1

INTRODUCTION

1.1 Introduction

Masonry is one of man's oldest building materials. It has been widely used in many structures such as buildings, retaining wall, tunnel lining, bridge, etc. The use of masonry for construction during many centuries includes the building of the pyramids at Giza in Egypt, the Great Wall of China, the temples and palaces of the Incas in Peru and numerous baths, amphitheatres and Aqueducts of the Roman Empire.

Masonry is a non-homogeneous and anisotropic composite material, which exists in many forms comprising units of varying shape, size and physical characteristic and mortar joints. Examples of unit used in masonry are such as bricks, blocks, ashlars, adobes, irregular stones and others. Mortar can be clay, bitumen, chalk, lime/cement based mortar, glue or other [Lourenco, 1998]. The properties of masonry are strongly dependant upon the properties of its constituents. Nowadays, masonry composed of masonry units and mortar has been widely used as construction material for both structural and non-structural members.

Masonry wall construction has a number of advantages. It can fulfil several functions including structure, fire protection, thermal and sound insulation, weather protection and sub-division of space. Apart from that, with appropriate selection, masonry may be expected to remain serviceable for many decades, if not centuries, with relatively little maintenance.

1.2 Problem statement

Compressive strength of masonry in the direction normal to bed joints has been traditionally regarded as the sole relevant structural material property. It is the most significant mechanical property that serves as a general index to the characteristics of the masonry structures. Compressive strength of masonry depends on the geometry and type of the units, unit strength, mortar grade, slenderness ratio, workmanship, etc. Apart from that, an interaction between unit and mortar element of masonry due to water absorption behaviour of masonry unit also influence the compressive strength of masonry wall.

Water absorption is an important characteristic in the construction of masonry structures as it plays a significant role in strength and durability performance. In masonry unit, absorption has been discovered to have heavily implicated the development of masonry bond. Masonry bond is developed by mechanical interlocking of cement hydration products growing in the masonry pores on the unit surface and connected to the mortar matrix [Goodwind and West, 1982]. The migration of water from fresh mortar to masonry unit may reduce or even stop the hydration process of mortar, and impair the crystallization of C-S-H, ettringite and calcium hydroxide. As a result, mortar joint contains more unhydrated cement. The loss of moisture in mortar leaves voids in mortar, which is later filled by air, and leads to weak and porous mortar joint, which is often an inherent weakness of masonry structure.

According to Henry [2001], although mortar accounts for as little as 7% of the total volume of masonry, it influences performance far more than this proportion indicates. Mortar requires certain properties prior to setting, particularly workability. Hardened mortar has to be sufficiently strong and to develop adequate adhesion to the units and also to set without excessive shrinkage, which will affects the performance of masonry and cause cracking of the units. Lawrance and Cao [1988] also explained that the high absorption of unit would remove too much water from the mortar and thus reduce the degree of hydration of mortar and the amount of hydration products deposited in the pores of the unit. As a result, shrinkage cracks may be induced in the mortar weakening the masonry/mortar interface. The moisture transfer mechanism between masonry unit and mortar lead to reduction in the water content of the bonded mortar, thereby causing shrinkage and moisture expansion in mortar and masonry unit respectively. This leads to strength reduction and affect the durability, performance and serviceability of masonry structures.

Numerous models, without considering the effect of unit water absorption have been developed and successfully validated on a number of occasions over the years for the prediction of masonry wall strength. However, for masonry built from units with high water absorption, the accuracy of the established models was considerably reduced. Therefore, it is desirable to investigate all aspects in detail and a new model including the effect of unit water absorption with higher accuracy should be developed for estimating the masonry wall compressive strength.

1.3 Objectives of the research

The objectives of this research are:

i. To develop a new model for predicting the compressive strength of masonry wall with reference to unit water absorption, brick strength and mortar strength.
ii. To simulate the effect of water absorption on the strength of masonry wall based on the developed model.
iii. To compare and verify the developed model with other established models.

1.4 Scope of work

The materials used in this research are calcium silicate bricks, clay bricks and cement sand bricks. Prism consists of four bricks and 10 mm mortar joint was chosen as the geometry. The research involved experimental works and statistical modeling and it was conducted in two stages. In the first stage, experimental testes were conducted to determine the properties of materials. Meanwhile, in the second stage, empirical modelling using MINITAB R14 based on the obtained experimental results was carried out. The experimental testes conducted were as follows:

i. Dimension test.
ii. Compression test for individual bricks, mortar and brickwork prisms.
iii. Water absorption test (5-hour boiling test and Initial Rate of Absorption test).

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a literature review of work published by previous researchers on the compressive strength of masonry wall, influence of unit water absorption and the current models used for the estimation of masonry compressive strength. Apart from that, the failure mechanism of masonry in compression and the determination of masonry strength were detailed in Appendix A.

2.2 Factors affecting compressive strength of masonry wall

Compressive strength of masonry wall depends on a number of factors. Research work by Sinha [1990] showed that the uni-axial compressive strength of brickwork in any direction depends on the brick strength, mortar grade, slenderness ratio and workmanship. The compressive strength of brickwork decreases with the decrease in mortar strength and it was observed that brickwork with lower slenderness ratio produced higher compressive strength. The stress-strain relationship of brickwork is non-linear where the deformation of resulting compressive strain depends on the type of test prisms and is significantly affected by the grade of mortar. The deformation increases with decreasing mortar strength or grade.

Hendry [1983] stated that strength of unit, geometry of unit, strength of mortar, deformation characteristics of unit and mortar, joint thickness, suction of units, water retentivity or mortar and brickwork bonding are of importance in determining the compressive strength of brick masonry. Some of the factors, such as the unit characteristics, are determined in the manufacturing process, while others such as mortar properties, are susceptible to variations in constituents materials, proportioning, mixing and accuracy of construction. In addition, site workmanship affects the strength of brickwork. Amongst the most obvious workmanship factors are incorrect proportioning and mixing of mortar, incorrect adjustment of suction rate of bricks, incorrect joining procedures, disturbance of units after laying, failure to build walls ‘plumb and true to line and level and unfavorable curing conditions.

Mckenzie [2001] reviewed that the compressive strength of masonry is dependent on numerous factors such as the mortar strength, unit strength, relative values of unit and mortar strength, aspect ratio of the units (ratio of height to least horizontal dimension), orientation of the units in relation to the direction of the applied load and the bed-joint thickness. The listed factors give an indication of the complexity of making an accurate assessment of the masonry strength.

Shrive [1991] stated that mortar type, unit type, workmanship, variation in joint thickness and eccentricity of loading also contribute to the factors affecting the compressive strength of masonry. The compressive strength of masonry was found dependent on both the mortar and unit type, but not on a 1:1 ratio with the strength of either component. Workmanship also affects the strength of masonry. Poor workmanship contributes to the reduction of compressive strength, e.g. not laying the units plumb and square can reduce strength by 15 percent; overzealous furrowing of bed joints will also reduce strength because supposedly fully bedded solid units end up being essentially face-shell bedded. Besides, variations in joint thickness cause variation in strength, where thinner joints produce stronger masonry. In addition to that, Houston and Grimm [1972] showed that for a brick of given height, brick strength is reduced as the joint thickness is increased. Eccentricity of loading also influences the masonry strength. When load is applied away from the center of a uniformly loaded wall or prism, there is often an apparent increase in compressive strength.

Maisarah [2004] found that variation in mortar designations would also influence the compressive strength of brickwork. High strength mortar was discovered to be insignificant in improving brickwork prisms strength if low strength masonry units were used during the construction of brickwork and vice versa. Masonry unit with lower strength will fail before the mortar. Other than that, it is also found that there is a direct relationship between the construction materials and the modulus of elasticity. The usage of high strength masonry unit and mortar designation will contribute to high modulus of elasticity. As the deformation rate is slow, higher failure load was obtained. Tan [1999] discovered that the loading position, header face or bed face also contribute to the factors influencing the brickwork strength. Higher strength was observed in brickwork prisms loaded in bed face.

Apart form that, the properties of the bed material were found to be exerting a controlling influence on the brickwork strength from a number of investigations. Research by Francis et. al [1971] showed that brickwork prisms consisting of loose bricks and ground flat bedding planes achieved compressive strengths approximately twice as high as those obtained from prisms with normal mortar joints.

Morsy [1968] also investigated the effect of bed material on brick prism strength. A series of brick prisms with different bed material was tested. The test result as summarized in Table 2.1 shows that there is an eight-fold change in the prism strength with the substitution of steel to mortar in the bed joints. Rubber jointing material was found to suffer from failure in tension as a result of tensile stresses induced by the deformation of the rubber, whereas the steel as bed joint material was observed to restrained the lateral deformation of the brick, and this induced a state of triaxial compressive stress in bed joint, which leads to failure in crushing.

Table 2.1: Effect of different joint material on the compressive strength of three brick stack-bond prisms

Effect of different joint materials on the compressive strength of three brick stack prisms; one-sixth scale model bricks, faces ground flat; six specimens of each type tested (Morsy[4])

Joint material	Compressive strength (N/mm^2)	Ratio to brick strength
Steel	56.48	1.4
Plywood	46.39	1.15
Hardboard	43.89	1.09
Polythene	16.99	0.42
Rubber with fibres	11.71	0.29
Soft rubber	6.99	0.17
No joint material	37.20	0.93
Mortar ($1:\frac{1}{4}:3$)	14.0	0.35

2.3 Transition zone in concrete/masonry and the effect of moisture movement

The transition zone in masonry structures consists of the interfacial region between masonry units and mortar joint and the analogy for the existence of transition zone in masonry can be explained and illustrated by the phase of transition zone in the concrete.

Mehta and Monteiro [1993] defined the transition zone as the interfacial region between the particles of coarse aggregate and the cement paste, which is in the form of thin shell and typically with the thickness of 10 to 50μm around the aggregate. The transition zone appears to be the weakest phase between cement paste and aggregate. The influence of transition zone is dependant on the mechanical behaviour of the concrete and is time dependant. According to Maso [1980], water films form around the larger aggregate particles in fresh concrete. As the hydration process takes place, a transition zone created by the formation of large ettringite and calcium hydroxide occurred. However, with time the transition zone will be filled up by products of crystallization of C-S-H and a second generation of smaller crystals of ettringite and calcium hydroxide and eventually improve the density and strength of the transition zone.

Abu Bakar [1998] reviewed that the adhesion between the aggregate and the cement paste is caused by the van der Waals forces of attraction. Thus, strength in the transition zone depends on the volume and size of voids present. At early stages, even for a low water/cement ratio, the volume and size of voids (capillary pores) in the transition zone will be larger than in cement paste, consequently decreasing in strength. However, as the age increase the strength of transition zone improves as a result of crystallization of new products in the voids.

Other than the existence of voids in the transition zone, Mehta and Monteiro [1993] also discovered that the presence of microcracks contributes to the poor early strength. Neville [2002] explained that the occurrence of fine cracks at the interface between aggregate and cement paste are probably due to the inevitable differences in mechanical properties between the aggregate and the hydrated cement paste, coupled with shrinkage or thermal movement. Apart from that, there are several factors that aggravate microcracks in transition zone, e.g. aggregate size and grading, relative humidity and curing conditions. Concrete mixture with poorly graded aggregate is prone to segregation during the compaction stage, thus thick water films can be formed around the aggregate. The larger the aggregate size, the thicker the water films will be. The formation of transition zone under these conditions will be susceptible to cracking when subjected to the influence of tensile stress induced by differential movement occur in the transition zone of concrete prior to loading.

2.4 Influence of unit water absorption

Water absorption behaviour of masonry unit is an important factor affecting the fresh mortar, and consequently the properties of mortar joint and masonry strength. Water suction in masonry units represents a restrained water movement affected by capillary forces, chemical binding forces and physical absorption force [Taha, El-Dieb and Shrive, 2001]. The suction exerted by the units is dependant upon the unit water absorption and the initial rate of absorption. Unit water absorption is explained by the amount of water required to saturate the unit and to fill the pores and voids while IRA is the indication of the ability of unit to remove water from mortar in certain period. IRA measures how quickly a unit could suck water out of a mortar as the unit is laid.

Water absorption characteristic plays an important role in the strength and durability performance of masonry structures. Masonry unit tends to absorb water from the fresh mortar when they are laid dry. If the rate of water absorption is high, the migration of water from fresh mortar to masonry unit will impair the hydration process and subsequently result in poor bonding between unit and mortar interface. Apart from affecting the hydration of mortar due to capillary action of the units, the possibility of reduction in strength increases. As a result, the mortar joint contains more unhydrated cement. The loss of moisture in mortar leaves cavities in mortar, which are later filled by air and result in a weakened material on setting. This produces poor and porous joint in the composite interface. Moreover, brickwork built with saturated bricks develops poor adhesion between bricks and mortar interface. These increase the possibility of strength reduction, frost damage in seasonal regions, etc.

Anderegg [1942] found that the compressive strength of the mortar bed-joint would increase with an increase in the initial rate of suction, although for mortars with a high OPC content, the compressive strength would be expected to decrease when the 'product combination' involved high absorption bricks. The condition of the brick (dry or undocked) prior to laying, the type of mortar and its water/ cement ratio also influence the quantity of water absorbed. The variation in pore structure throughout the body of the brick and the interrelationship that exists between the pore properties of the bonded brick and mortar also complicate the relationship.

Haller [1969] found that in certain circumstances, suction rate has a considerable effect on brickwork strength. The de-watered mortar tends to form a rounded joint during building owing to a loss of 'elasticity'. He observed that with eccentric loading, an increase in the suction rate from 2 kg/m^2/min to 4 kg/m^2/min could halve the compressive strength of the brickwork.

Forth [1995] investigated the influence of unit water absorption on the deformation of masonry wall constructed with Armitage class 'B' brick units. He compared the movement of mortar joint in the masonry with the unbonded mortar prisms and found that shrinkage of mortar was 25% less than the shrinkage exhibited by an unbounded prism at 160 days. This happened, as there is a reduction in water content of mortar joint due to the unit water absorption. The loss of moisture in mortar joint might induce shrinkage cracks in the mortar, which would weaken the joint surface and subsequently the masonry strength. Other than that, the effect of the unit absorption was found to reduce creep of the mortar joint by 5%.

Abu Bakar [1998] investigated the effect of anisotropy, unit water absorption and length of curing on elasticity, creep and shrinkage of masonry. His research involved the measurement of movement of single leaf walls and 5-stack high masonry built with a Class ‘B’ clay brick, a calcium silicate brick and a concrete block and a grade (ii) mortar with cement: lime: sand in the proportion of 1: ½ : 4 ½. The results revealed that the clay walls loaded in both directions exhibited anisotropy while the calcium silicate and concrete wall exhibited isotropy. The composite model underestimated creep of the clay wall in bed direction. Apart from that, the model gave good prediction for shrinkage in bed and header direction for calcium silicate and concrete walls. Also, the elastic moduli of masonry was found to be lower for a shorter period of curing, subsequently shrinkage and creep were also reduced.

Apart from that, Lawrence and Cao [1988] explained the existence of an optimum range of water absorption by the fact that low absorption will not allow enough hydration products to migrate towards the unit surface to create bond. In contrary, high absorption will remove too much water from the mortar and thus reduce the degree of hydration of the mortar and the amount of hydration products deposited in the pores of the unit. Shrinkage cracks may also be induced in the mortar weakening the masonry /mortar interface.