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LONG-TERM BEHAVIOUR OF POST-TENSIONED BLOCKWORK AND BRICKWORK MASONRY IN THREE DIFFERENT CLIMATES

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ABSTRACT

The viscoelastic behaviour of masonry has been studied using 18 instrumented short columns with cavity box sections of either concrete blockwork or clay brickwork. Measurements of the axial moisture movement, creep strain and prestress force for two years have provided the basis for a method of calculation of long-term strains in the masonry and change of post-tensioning force in the tendons. Comparisons of the experimental results with theoretical predictions such as those given by the Ross model have been made. A semi-empirical time-dependent relationship is proposed, which gives a suitable fit to measured prestress change and a good prediction for three environmental conditions.

INTRODUCTION

Prestressed masonry is a well established form of construction but there are sometimes doubts about its long term viability because of a lack of information on the way in which the prestress force changes with time. The most widespread use of prestressing in masonry is for the post-tensioning of vertically spanning walls and columns, British Masonry Society (1997).

This paper is concerned with the long term behaviour of such masonry and addresses the problems of measuring and predicting the axial moisture movement and the creep strain of masonry and the change of prestress force over time. The paper describes experimental and theoretical work, which is part of a larger programme of work aimed, in due course, at producing a method of predicting the magnitude of prestress change from a knowledge of the properties of the materials used in the construction and the climate conditions in which the prestressed masonry is working. To get full value from the work the terms used need to be clearly defined and this is done below.

Moisture strain

Moisture strain is defined as the time-dependent strain due to moisture loss at constant temperature and humidity in the absence of an external load and takes place after the mortar in the masonry member has hardened.

Creep

Creep strain is the gradual increase of strain with time under constant load (or constant stress) and is conveniently seen as part of the viscoelastic behaviour of masonry shown in Fig. 1. In that figure the *strain on loading* is the *elastic (instantaneous) strain* produced by applying the load. When the load is removed the masonry recovers some, but not all, of the applied strain: there is an *instantaneous recovery strain* which is analogous to strain on loading and a *creep recovery strain*. The remaining *residual strain* is usually regarded as permanent. If the values of these strains are divided by the applied stress they are called specific values e.g. *specific creep strain*. Thus the modulus of elasticity on initial application of load is the reciprocal of the specific strain on loading *(specific instantaneous strain)*.

When the creep strain is divided by the strain on loading this is defined as the *creep strain ratio* and the maximum value of the creep strain ratio (at infinite time) is the *creep coefficient*.

Change of prestress

The level of prestress in masonry changes with time due to relaxation of the tendons, elastic deformation of the masonry, moisture movement of the masonry, creep of the masonry, tendon losses during anchoring, friction effects and thermal effects. As far as these experiments on post-tensioned masonry are concerned measured change will only stem from tendon relaxation, masonry moisture movement, masonry creep and thermal effects. The cumulative effect of these changes usually results in an overall, or total, *loss of prestress* but brickwork made with fired clay units can undergo moisture expansion and this source of change alone would result in a *gain of prestress*. For masonry therefore a more suitable general term to use is *change of prestress* rather than loss or gain of prestress.

Comparative change of prestress

The change of prestress is related to the level of prestress initially applied. To compare the experimental output therefore the change of prestress is presented as the *comparative change of prestress* x 10^2 per kN which is the percentage change of prestress divided by the applied initial level of prestress and multiplied by 100.

EXPERIMENTS

For the experiments 18 short hollow rectangular columns were built in the laboratory. 9 of the columns were built of brickwork and 9 of blockwork. As far as possible all the brickwork columns were identical and all the blockwork columns were identical. Of the 9 specimens of each masonry type, 3 were prestressed and the prestress force was allowed to degrade so that the change in prestress force with time could be measured, 3 were prestressed and the prestress force was kept constant so that masonry creep measurements could be taken and 3 were unloaded so that masonry movement due to change in moisture content could be monitored. The columns are shown in Fig. 2.

For the blockwork 440 x 215 x 100 mm dense aggregate solid blocks with a compressive strength of 6.3 N/mm^2 (average of 10 unit tests) and nominal density of 2000 kg/m^3 from Boral Edenhall Concrete were used. The bricks for the brickwork were Ibstock Roughdale Deva Red. These bricks were 215 x 102.5 x 65 mm three hole perforated and wire cut with a smooth texture. They had a crushing strength of 63.2 N/mm^2 (average of 10 unit tests) and a nominal density of 1070 kg/m^3. The mortar was a 1:1:6 cement:lime:sand mix made by mixing 1 volume of ordinary Portland cement with 6 volumes of Tilcon ready mixed lime:sand and sufficient water to make a workable mix. The average compressive strength of the mortar was 6.4 N/mm^2 from 51 samples. The characteristic compressive strength of the two masonry types found from crushing tests on a minimum of 3 three unit high prisms was 6.3 N/mm^2 for the blockwork and 28.0 N/mm^2 for the brickwork.

Prestressing was carried out when the columns had reached a minimum age of 28 days. 25 mm high tensile steel Macalloy prestressing bars with a characteristic tensile strength of 1030 N/mm^2 were used for the blockwork columns and similar bars of 40 mm were used for the brickwork columns. For the creep test specimens CB-Disc springs from Bauer Springs were used in the top anchorages to maintain a constant prestress level. The initial applied prestress force on the prestressed columns and the constant level of compression stress on the masonry for the creep columns is given in Table 1.

Once prestress had been applied the specimens were put in one of the three controlled environment rooms. One of each type of specimen, six in all, was put in each of the rooms. One room was a Cold Room kept at 5 ± 1°C and 70 ± 5% RH, one was an Ambient Room at 20 ± 1°C and 60 ± 5% RH and one was a Hot Room at 35 ± 1°C and 50 ± 5% RH. Each room therefore contained a brickwork column and a blockwork column under prestress, a brickwork and a blockwork column under creep load and an unloaded brickwork and blockwork column.

Vertical masonry strain was taken as an average value of measurements at three points on two adjacent faces of each column with a 200 mm Demec mechanical gauge. Prior to installation the Macalloy bars were calibrated in a testing machine so that bar load could be measured with Electrical wire strain gauges.

THEORY

Theoretical models are required to predict masonry moisture strain, masonry creep strain and change of prestress. Moisture strain and creep strain are material properties of masonry which can be represented by a hyperbolic equation of the type put forward by Ross (1937):

$$\varepsilon = \frac{t}{a + b.t} \qquad (1)$$

where, ε = moisture strain or creep strain,
t = time in days,
a, b = constants.

For a given climate, change of prestress is a combined function of tendon relaxation, masonry moisture strain and masonry creep strain and is not so readily represented by the Ross equation. Change of prestress can, however be represented by an equation which recognises three phases of behaviour; an initial, rapid, logarithmic phase; a final, slow, hyperbolic phase and an intermediate combined phase:

$$P_c = a.\ln\left(\frac{b + t}{c + t}\right) + \frac{d + e.t}{F + t} \qquad (2)$$

where, P_c = change of prestress,
t = time in days,
a, b, c, d = constants.

$$F = -\frac{d}{a.\ln\left(\frac{b}{c}\right)} \quad \text{and} \quad e = P_c(t \rightarrow \infty).$$

EXPERIMENTAL RESULTS AND COMPARISON WITH THEORY

Test results are presented for the moisture strain, creep and prestress loss experiments separately. It should be noted that the specimens were built and prestressed in the uncontrolled ambient conditions of the masonry laboratory before being transferred to one of the controlled environment rooms. The test results in the early days therefore represent transitional behaviour from one environment to another.

Moisture strain test results

The measured strains on the unloaded columns are plotted in Figs. 3 and 4 as microstrain x 10^6, shrinkage or expansion, plotted against time, in days. Changes in strain due to temperature alone, based on the coefficient of thermal expansion of the masonry, are not time dependent except over a short period at the beginning of the tests when the specimens are reaching the steady state temperature of the controlled environment room. No attempt has been made to deduct these initial temperature strains from the strains in Figs. 3 and 4.

The Figures show that the changes of moisture strain with time are governed by the temperature and relative humidity of the environment in which the specimens stand. Since an increase in relative humidity is known to reduce moisture strain it is clear that, bearing in mind the three environments used, an increase in temperature significantly reduces moisture shrinkage or increases moisture expansion with time.

The curves shown in Figs. 3 and 4 were fitted to the experimental points by linear regression of Eq. (1), the Ross equation, the value of the constants a and b obtained from the curve fitting being given in Table 2. Table 2 also gives predictions for the moisture strain after 2 years, for the maximum moisture strain and for 95% of the maximum together with a time required to reach the 95% steady state value. The predictions come directly from the Ross equation with the values of a and b given. The predicted steady state times range from 65 years for the brickwork in ambient conditions to 20 days for the brickwork in the cold climate.

Creep test results

The creep test results are presented in Figs. 5 and 6 as specific microstrain values per N/mm^2 plotted against time in days. The experimental specific strain values plotted have been calculated by subtracting the strains measured on the unloaded moisture movement specimens from those measured on the creep specimens and dividing by the imposed stress level.

The curves shown for the specific creep strain and the specific creep recovery strain were fitted to the results by linear regression of Eq. (1). Table 3 gives particular values for salient points on the curves. The constants a and b for the specific creep strain curve are given in Table 4. Table 4 also gives predictions for the maximum specific creep strains and the creep coefficients. The creep coefficients show the highest values under ambient climate conditions.

The predicted creep coefficients of 0.95 to 2.12 for concrete blockwork and 0.65 to 1.01 for brickwork are smaller than those recommended by British Code BS 5628: Part 2 (1995) which gives values of 3 and 1.5 for concrete blockwork and brickwork respectively. Eurocode 6 (1995) gives a range from 1.5 to 2.5 for concrete blockwork and 0.7 for fired clay masonry.

Figs. 5 and 6 show that it took some time for the creep movements to respond fully to the new climate conditions once the specimens were placed in the controlled environment rooms from the masonry laboratory. This transitional period is least marked in the hot climate and most marked in the cold climate where it took about 80 days for the experimental results to follow the predictions of the Ross curve.

Prestress test results

In general the behaviour of the masonry in the prestress tests was similar to the behaviour of the masonry in the creep tests. Figs. 7 and 8 show the comparative change of prestress plotted against time, in days. The points in the figures are the experimental values of the change. The curves are plots of Eq. (2) in comparative change of prestress form. The Eq. (2) curves can be used to predict change of prestress over any period of time and such predictions are presented in Table 5 for 2, 30, 60, 90 and 120 years.

CONCLUSIONS

Measurement of moisture strain, creep strain and change in prestress force have been made over two years in concrete blockwork and clay brickwork in three different climates, cold, ambient and hot. When suitable constants are chosen the Ross equation predicts very well the experimental values of both moisture strain and creep strain. The Ross equation, with the chosen constants, can be used to predict moisture and creep strain and any period of time. For example, the maximum moisture strain for the clay brickwork used, in ambient condition, is predicted to be an expansion of 830 μstrain. Predicted creep coefficients range from 0.95 to 2.12 for concrete blockwork and 0.65 to 1.01 for brickwork.

A proposed new five parameters equation also predicts very well the changes of prestress in the experimental specimens. The equation can be used to predict prestress change over any period of time and values are given for 2, 30, 60, 90 and 120 years for the concrete blockwork and clay brickwork used.

ACKNOWLEDGEMENTS

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Table-1: The initial prestress force on prestressed columns and the constant stress level on creep columns

	Blockwork			**Brickwork**		
Description	**Cold**	**Ambient**	**Hot**	**Cold**	**Ambient**	**Hot**
Prestress force kN, on prestress columns	318	335	355	706	725	735
Creep stress N/mm^2, on creep columns	2.7	2.7	2.7	5.3	4.7	5.1

Table-2: The Ross equation constants and prediction for moisture strain

	Blockwork			**Brickwork**		
Description	**Cold**	**Ambient**	**Hot**	**Cold**	**Ambient**	**Hot**
a, constant, from best fitted, Ross Eq.	1.0472	0.4573	1.2094	0.0483	-2.6887	-0.9351
b, constant, from best fitted, Ross Eq.	0.0047	0.0083	0.0546	0.0465	-0.0012	-0.0009
Value of " a/b " ratio	222.81	55.1	22.15	1.039	2240.6	1039
Prediction of 2 years moisture strain $\times 10^6$, Ross Eq.	163	112	18	21	-205	-430
Max. moisture strain $\times 10^6$ when t →∞, $\varepsilon_{mm}^{max.} = 1/b$	213	120	18	21	-830	-1110
95% × 1/b	202	114	17	20	-792	-1055
Time required for 0.95/b, $t = 19a/(365b)$, year	11.6	2.9	1.1	20 days	65	54

Table-3: Experimental results obtained at loading and unloading times for creep tests in different climates

Description	Blockwork			Brickwork		
	Cold	Ambient	Hot	Cold	Ambient	Hot
Specific instantaneous strain × 10^6	87.5	77.2	110.1	68.5	87.8	76.6
Time under load- days	660	677	663	690	707	694
Specific creep strain, on removal of load × 10^6	69.6	145.9	164	40.2	79.6	56.9
Specific elastic plus creep strain, on removal of load × 10^6	157.0	223.1	274.1	108.6	167.3	133.5
Specific instantaneous recovery strain × 10^6	75.2	78.5	97.7	67.6	88.1	84.5
Specific creep recovery strain × 10^6	9.0	13.7	11.1	10.7	11.9	15
Residual strain × 10^6	72.8	131	165.2	30.4	66.3	34.1

A_{block}=136000 mm^2, A_{25}=491 mm^2, A_{brick}=138375 mm^2, A_{40}=1256 mm^2

Table-4: The Ross equation constants and prediction of maximum specific creep and creep coefficient in different climates

Description	Blockwork			Brickwork		
	Cold	Ambient	Hot	Cold	Ambient	Hot
a, constant, Ross Eq.	1.5687	0.5117	0.2643	1.3833	0.6835	1.2298
b, constant, Ross Eq.	0.012	0.0061	0.0057	0.0229	0.0116	0.0158
Value of "a/b"	130.7	83.9	46.4	60.4	58.9	77.8
Max. specific creep, 1/b × 10^6	83.3	164.9	175.4	43.7	86.2	63.3
Creep coefficient, $\varepsilon_{cr}^{max}/\varepsilon_i$, or $(b.\varepsilon_i)^{-1}$	0.95	2.12	1.60	0.65	1.01	0.83

Table-5: Prediction of prestress changes for block and brick columns in three climates

Age years	Blockwork			Brickwork		
	Cold	Ambient	Hot	Cold	Ambient	Hot
2, experimental data	7.9	13.7	18.2	11.3	13.1	18.1
30	11.6	18.9	23.6	12.9	17.4	23.1
60	11.7	19.8	24.4	13.0	18.1	23.3
90	11.8	20.1	24.8	13.0	18.4	23.4
120	11.9	20.3	25.0	13.0	18.5	23.5

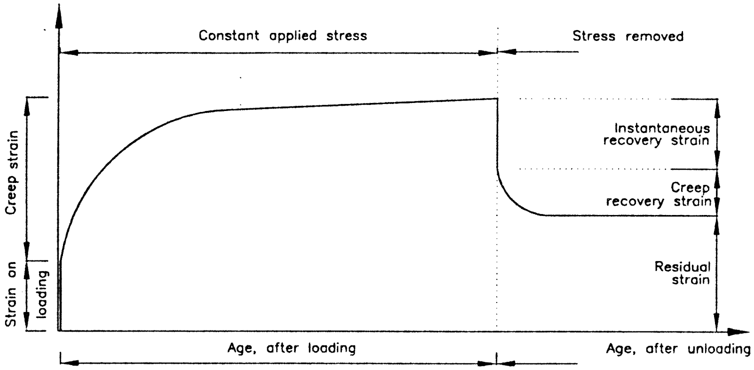

Figure 1: Viscoelastic strain behaviour of masonry.

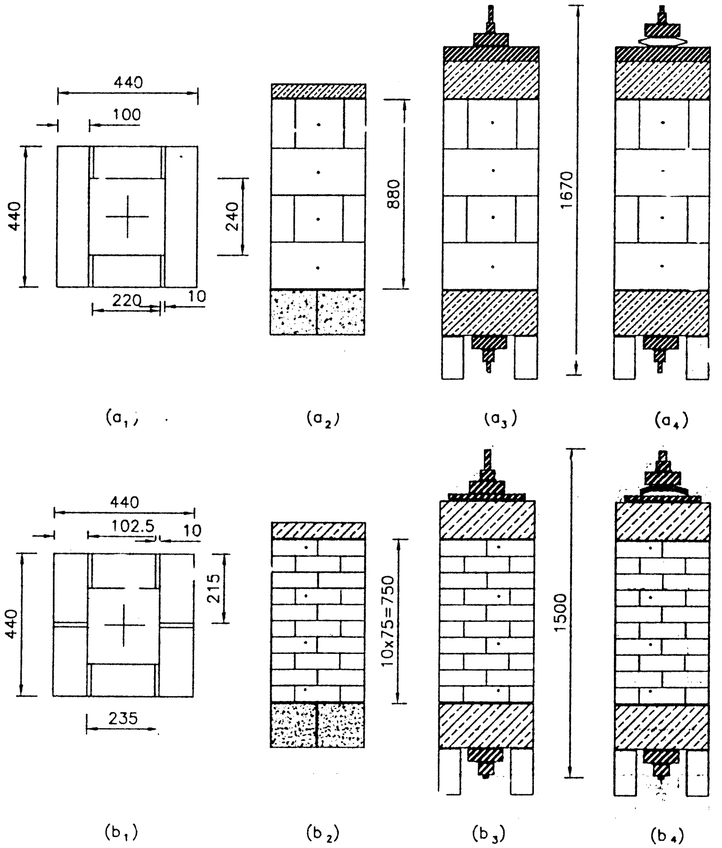

Figure 2: Experimental specimens.

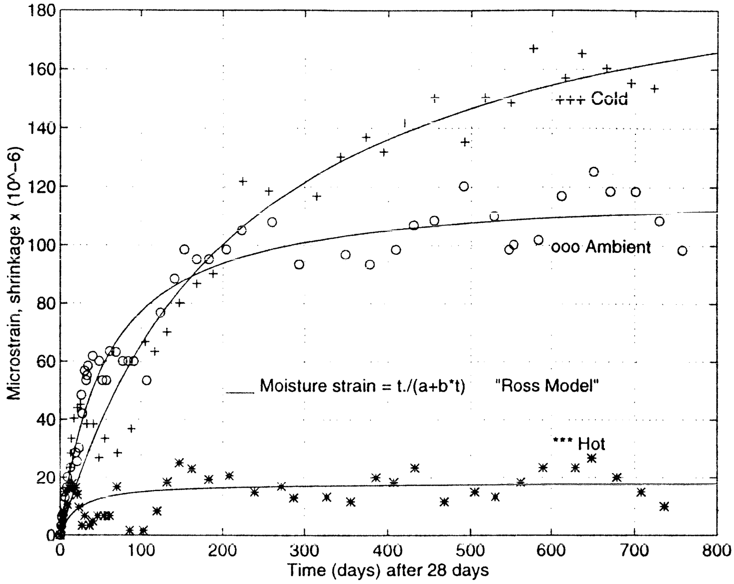

Figure 3: Comparison between blockwork moisture strain (shrinkage) tests in three climates.

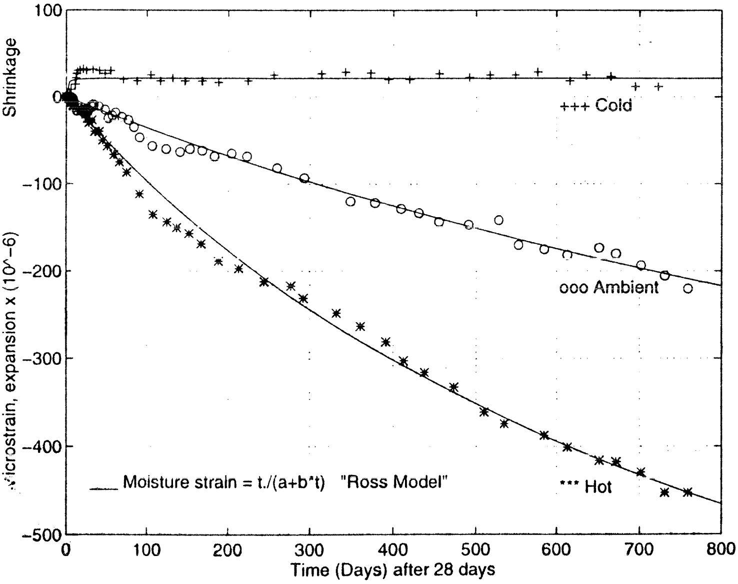

Figure 4: Comparison between brickwork moisture strain (shrinkage and expansion) tests in three climates.

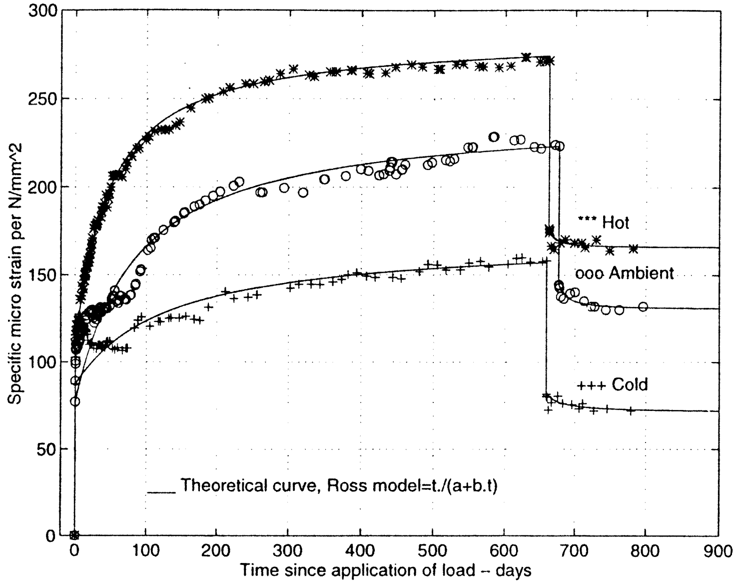

Figure 5: Comparison of specific strains for blockwork in three climates.

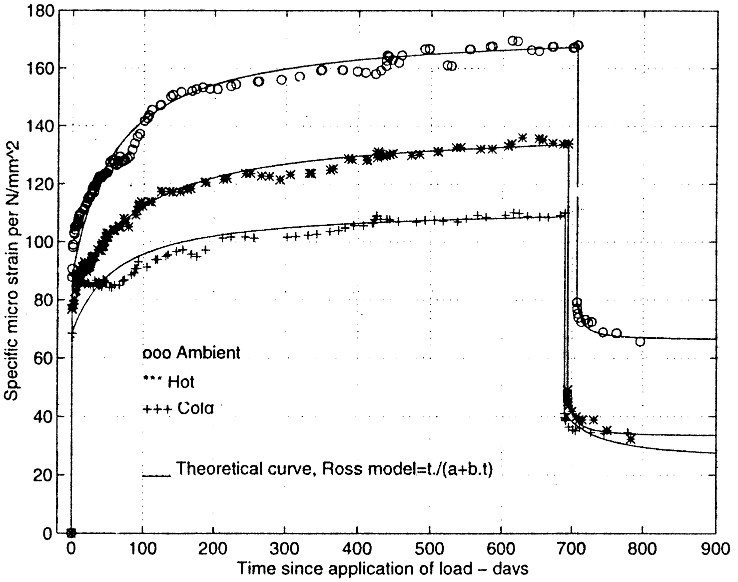

Figure 6· Comparison of specific strains for brickwork in three climates.

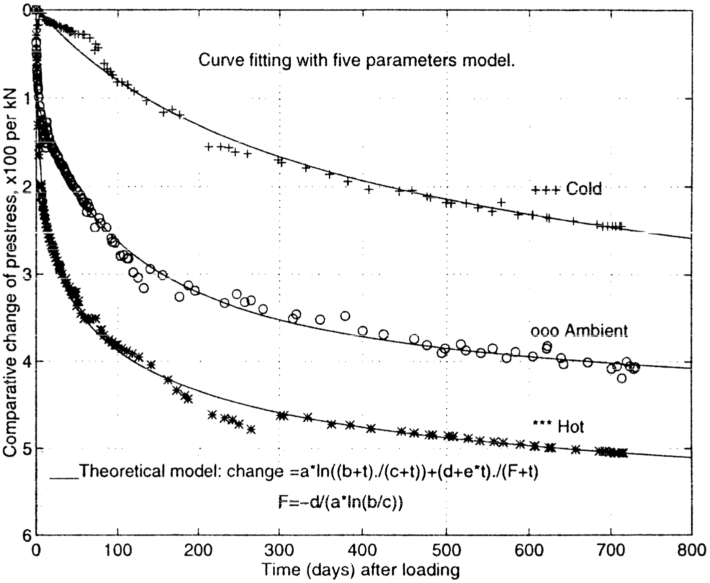

Figure 7: Comparison of prestress changes in blockwork in three climates.

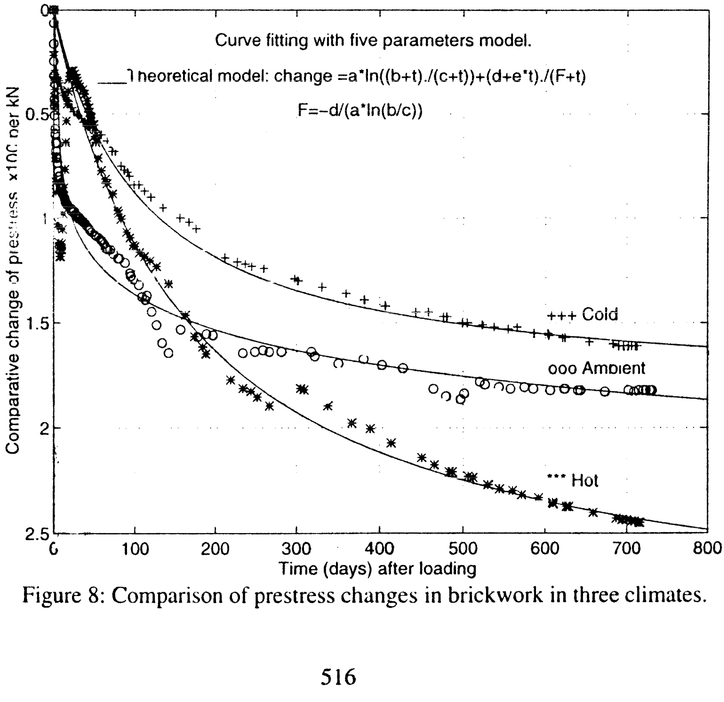

Figure 8: Comparison of prestress changes in brickwork in three climates.