Thomas[13] reports that the higher the temperature the higher the rate of expansion.

Autoclaving has been found not to correlate well with actual expansions, whereas steaming has been found to have close correlation with natural expansion[8, 10].

Many authors have derived formulae to predict both short-term and long-term expansions from information on loss on ignition, from chemical analyses and from short-term expansion readings, but the evidence in support of these is inadequate and some of the authors have differed from and criticized others. Cole[14] proposed a regression line of the form $q = n \log (t + t_o)$ to fit a plot of expansion against log time, but, although this regression line fits the known expansions, it will not necessarily reliably predict future expansions if materials suddenly change their rate of expansion on the log-time axis as has been found in the case of the clays investigated in this thesis. The regression equations are not likely to be independent of clay type or firing temperatures as is claimed to be the case. Cole[15, 16] proposed a method of predicting moisture expansion on the basis of the $(CaO + MgO)/(K_2O + Na_2O)$ molecular ratio, but his method was found not to apply to work done by Lehmann and Nicoletti[17] and quite an argument has developed.

In an investigation on 22 South African clays, it was found[4] that the sericite clays had the highest moisture expansion, followed by the illitic and kaolinitic clays, respectively. A clay which contained vermiculite, montmorillonite and kaolinite had virtually no moisture expansion.

There are a few references on precautions to be taken when building with bricks liable to moisture expansion, such as careful selection of firing temperatures to avoid peak expansions, by storing of bricks before use and by the planned

use / .....

use of expansion joints.[1, 7, 15, 18]

No reference to any investigation on the effect of restraint on moisture expansion of bricks has been found in the literature.

CHAPTER 4

MOISTURE EXPANSION OF TWO FIRED CLAYS

4.1 Clay Properties and Composition

The material on which this investigation was done came from the South Western area of the Cape Province. Clay and extruded raw bricks were obtained both from Bellville and Georgedale.

The details of the determinations of the clay properties and compositions are given in Appendix A.

4.1.1 Relative density

The relative density of the clay fractions -1200 µm +600 µm, -600 µm +200 µm and -200 µm were determined for the two clays and are given on Table 1.

TABLE 1 Relative densities of clay fractions

Particle size (µm)	Average relative densities	
	Georgedale clay	Bellville clay
-1200 +600	2,773	2,783
-600 +200	2,753	2,757
-200	2,746	2,738

The coaser / ....

The coaser material had higher relative densities than the finer material. Later X-ray diffraction analyses showed mainly quartz in the coaser fractions. Quartz has a relative density of about 2,62 so that there must be other heavier amorphous material also present in these fractions.

4.1.2 Particle size distribution

The +1200 µm, +600 µm and +200 µm fractions were sieved out of large samples of the Georgedale and Bellville clays. Fractions greater than 1200 µm are often ignored when reporting on particle size distribution but as these samples were taken from actual raw bricks, this fraction is included in the results.

Because of the large variations found in the 100 µm, 60 µm and 37 µm fractions obtained when sieving the residue in the Andreassen vessels, fairly large samples of the -200 µm material from each clay were sieved to determine these fractions and the results so obtained used in Table 2.

For the clay fractions smaller than -37 µm a sedimentation technique was used to determine the particle size distribution. Such a determination is dependent on sedimentation principles as expressed by Stoke's law which deals with the settling rate of small spherical bodies suspended in a fluid medium. Brick clays generally occur as minute plates or other irregularly shaped particles, so that the concept of 'equivalent spherical diameter' is introduced. Therefore the percentages given on Table 2 are those for particles with equivalent spherical diameters.

TABLE 2 / ....

TABLE 2 Particle size distribution

Particle diameter (µm)	Percentage finer than diameter given	
	Georgedale clay (per cent)	Bellville clay (per cent)
1200	93,1	97,8
600	90,6	97,0
200	86,1	87,2
100	83,1	80,6
60	77,8	75,0
37	71,6	72,1
20	66,8	67,1
10	56,8	54,5
6,3	47,7	44,7
2	27,4	31,9
0,63	13,2	22,8

The particle size distribution of the clays is also shown graphically in Figures 10 and 11. Both clays had similar weights of particles from 100 µm to 6,3 µm but the Bellville clay had fewer particles in the 2 µm to 0,63 µm range and far more material finer than 0,63 µm.

4.1.3 Mineralogical composition

4.1.3.1 Unfired clay

X-ray diffraction analyses were done on samples of the two clays taken directly from broken bricks, as well as on the different fractions smaller than 200 µm.

The Georgedale clay was yellowish in colour and contained approximately 35 per cent quartz and the minerals forming the major clay constituents were kaolinite about 35 per cent and hydro-muscovite about 20 per cent. The percentage

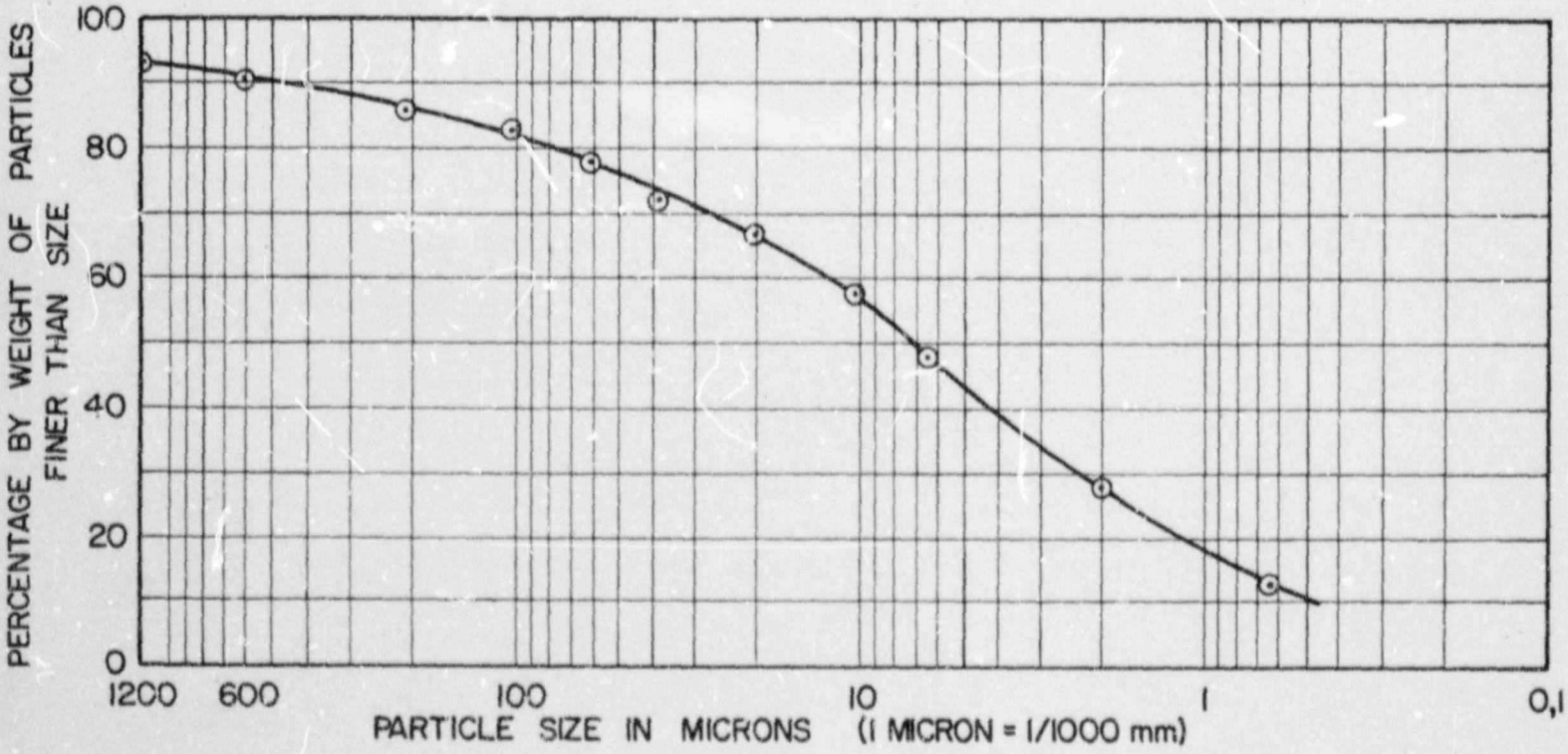

FIGURE 10

Particle size analysis - Georgedale clay

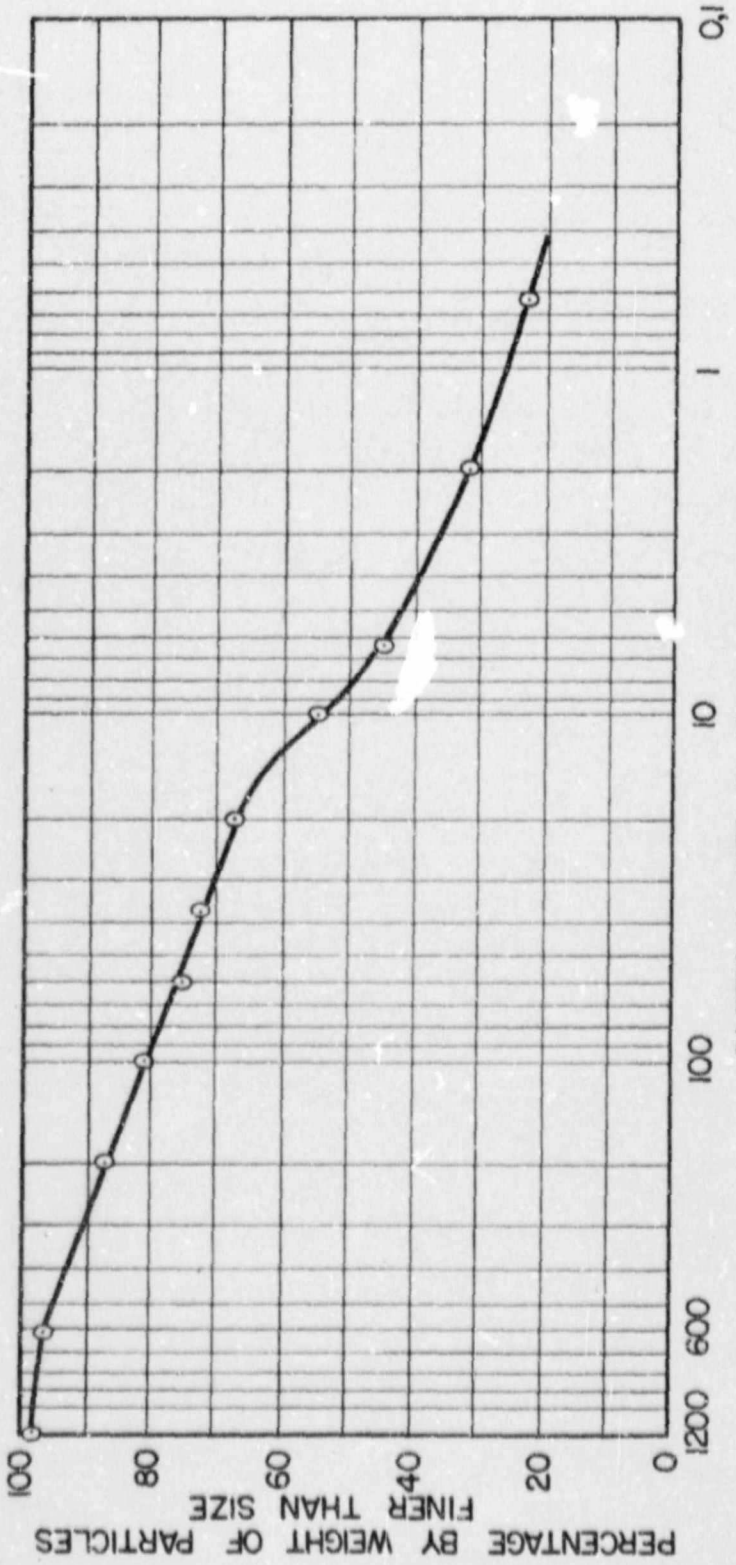

FIGURE 11

Particle size analysis - Bellville clay.

kaolinite and hydro-muscovite were based on the rational analysis given later. It was not possible on the X-ray diffraction chart to identify whether the hydro-muscovite was sericite or illite as the peaks which might have indicated which it was could not be found, i.e. for sericite 2,77 dÅ and 2,34 dÅ and for illite 3,65 dÅ and 3,09 dÅ. It was thought to be probably sericite as the vitrifying temperatures of the major portions of the clays appeared to be over 1 000 °C. There were traces of montmorillonite and feldspar. The mineralogical composition of the fractions is given on Table 3.

TABLE 3 Mineralogical composition of Georgedale clay fractions

Fraction (µm)	Quartz (per cent)	Kaolinite	Hydro-muscovite	Montmor-illonite	Feldspar
-200+100	95	very little	very little	-	-
-100+60	95	very little	very little	-	very little
-60+37	95	very little	very little	-	trace
-37+20	83	little	little	-	
-20+10		medium	medium	trace	
-10+6,3		medium	medium	trace	
-6,3+2		high	high	-	
-2+0,63		high	high	trace	
-0,63		high	high	trace	

The X-ray diffractions only covered a small portion of the spectrum in the case of the last five fractions in an effort to see whether montmorillonite was present. Both ordinary X-ray diffractions and diffractions when the sample was mixed with glycol were done between 40Å and 5,52Å on these. Therefore the percentage quartz could not be estimated nor

could / ....

could the feldspar peaks be seen in the vicinity of 3,23Å and 3,17Å.

The Bellville clay was reddish in colour and a full sample contained about 30 per cent quartz with the minerals forming the major clay constituents being kaolinite and hydro-muscovite in about equal proportions. The same remarks apply as with the Georgedale clay as to whether the hydro-muscovite was sericite or illite. There were small amounts of feldspar and traces of heamatite. The mineralogical composition of the fractions from -200 µm +100 µm to -0,63 µm are given on Table 4. The material between +37 µm and -200 µm had more hydro-muscovite than kaolinite whereas the -2 µm material had slightly more kaolinite than hydro-muscovite. The diffraction pattern for the -0,63 um clay was slightly disordered.

TABLE 4 Mineralogical composition of Bellville clay fractions

Fraction (µm)	Quartz (per cent)	Kaolinite	Hydro-muscovite	Montmor-illonite	Feldspar
-200+100	90	very little	little	trace	very little
-100+60	90	very little	little	-	very little
-60+37	80	very little	medium	-	very little
-37+20	10	high	high	-	trace
-20+10	20	medium	high	-	-
-10+6,3	15	high	high	-	-
-6,3+2	3	high	high	-	-
-2+0,63	-	high	medium	-	-
-0,63	-	high	medium	-	-

4.1.3.2 Fired clay

When the work on the expansion of the briquettes had been completed, X-ray diffraction analyses were done on material taken from the middle of six briquettes. The briquettes used were those fired at 1035 °C, 1085 °C and 1135 °C.

The diffraction plots for both clays were very similar except for the quartz contents which were respectively:

Georgedale clay	:	1035 °C	: 22%
		1085 °C	: 22%
		1135 °C	: 14%
Bellville clay	:	1035 °C	: 27%
		1085 °C	: 22%
		1135 °C	: 17%

The sericite and kaolinite peaks had disappeared entirely. There was now mullite and cristobalite present besides traces of haematite and feldspar. Although the quartz content had reduced on firing there was still a comparatively large percentage of crystalline quartz present, as well as the high temperature form, cristobalite.

4.1.4 Chemical analysis

Chemical analyses were done on the clays and the results are given in Table 5. The clay does not occur naturally in the form of oxides. It is important to know its mineralogical composition and this can be calculated from such chemical analyses. The main mineral constituents from the X-ray diffraction were quartz, kalonite and hydro-muscovite i.e.

quartz	:	SiO_2
kaolinite	:	$Al_2O_3.2SiO_2.2H_2O$
potash mica	:	$K_2O.3Al_2O_3.6SiO_2.2H_2O$
soda mica	:	$Na_2O.3Al_2O_3.6SiO_2.2H_2O$

A rational / ....

TABLE 5 Chemical analyses of the clays

	Georgedale clay (per cent)	Bellville clay (per cent)
Fe_2O_3	5,46	8,41
MgO	1,94	2,07
CaO	0,41	0,18
Na_2O	0,o8	0,24
K_2O	1,98	2,64
SiO_2	62,86	58,60
TiO_2	1,02	0,92
Al_2O_3	20,33	21,13
L.O.I.	5,46	6,13

A rational (proximate) analysis was carried out on both clays and is given in Appendix A. The mica convention[19] was used because the X-ray diffraction patterns showed hydro-muscovite minerals present in the clay. The rational analyses were:

Georgedale clay		Bellville clay	
Sericite	17,8	Sericite	25,3
Kaolinite	34,1	Kaolinite	28,8
Quartz	38,9	Quartz	33,7
Fe_2O_3	5,5	F_2O_3	8,4
MgO	1,9	MgO	2,1
CaO	0,4	CaO	0,2
TiO_2	1,1	TiO_2	0,9
Organic matter, CO_2, etc, 0,3 (by difference)		Organic matter, CO_2, etc, 0,6 (ty difference)	

4.1.5 Suitability of the textures of these clays for brickmaking

Using the soil texture triangle[20], agriculturists determine the class name of a soil by means of its particle size distribution. Figure 12 shows a clay texture triangle as used by Winkler[21] to

determine / ....

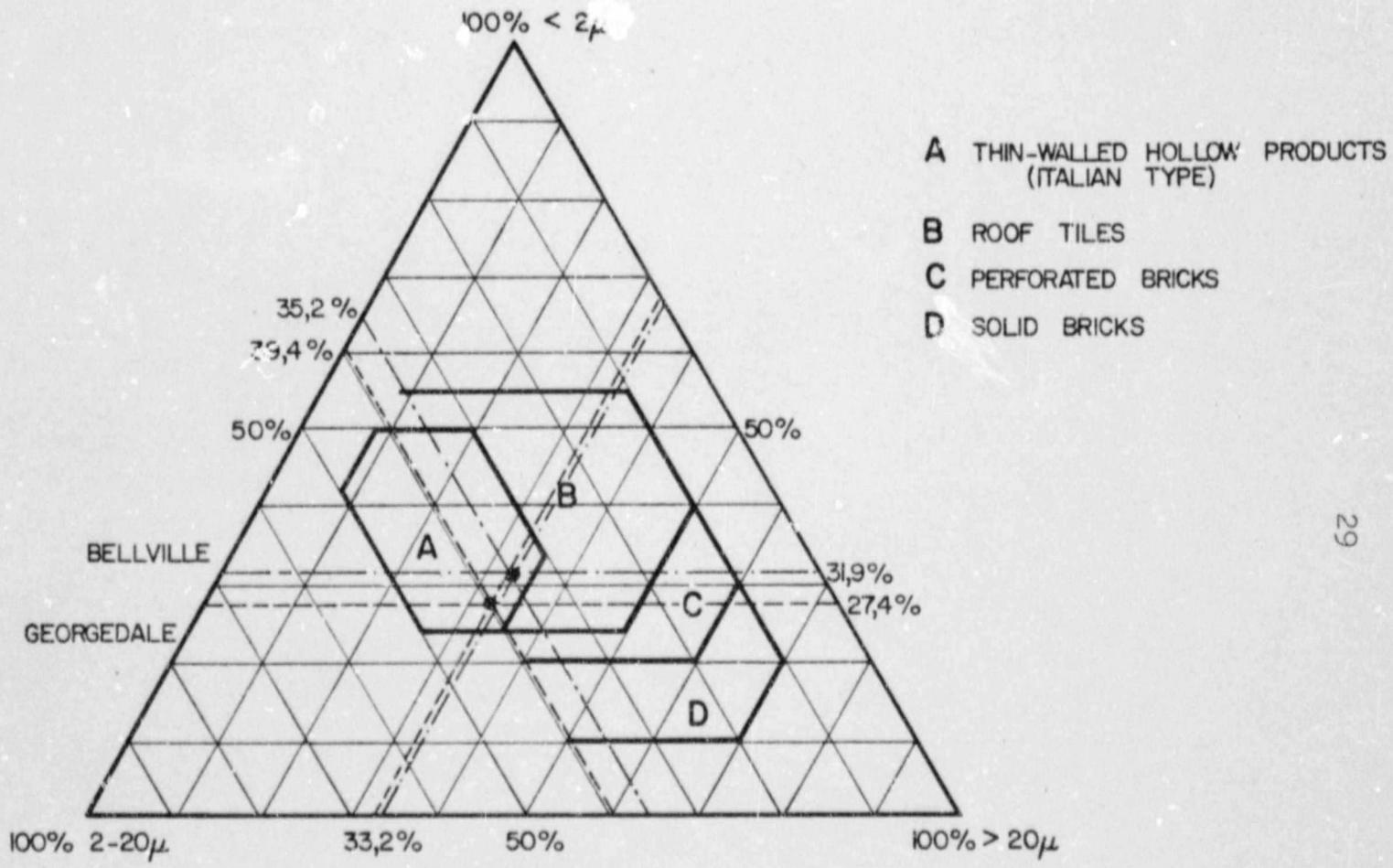

FIGURE 12

Suitability of sample for industrial uses.

determine the suitability of ceramic types of clays for the manufacture of different fired clay articles. As can be seen in Figure 12 both clays fall in the A zone but close to the B and C zones so that they could be suitable for all these uses. They tend to be too fine for solid bricks according to this diagram as they will take too long to dry after extruding. Nevertheless bricks fired both in the laboratory and at brickworks appear satisfactory for building purposes - except that they have excessive moisture expansion.

4.2 Moisture Expansion after Different Firing Temperatures

4.2.1 Extruding specimens

The samples of loose clay obtained from both Georgedale and Bellville were used separately to make briquettes to be fired at different temperatures, as well as specimens to determine absorption, porosity and bulk density.

Each clay was broken up in a small hammermill until all material passed through a 1 200 µm sieve. It was reduced to this size because of the small size of the specimens to be extruded. The clay had the minimum quantity of water added to give it a satisfactory extruding consistency, and was thoroughly mixed by passing it through the de-airing extruder (vacuum 74,6 kPa) a number of times, before extruding a column of clay of cross-section 38,1 mm by 25,4 mm. The column of clay was cut into 30 briquettes 304 mm long. The die was changed and a column of clay of 25,4 mm by 25,4 mm was extruded. This column was cut into specimens 300 mm long from which 30 specimens 50,8 mm long were cut for the water absorption, porosity and bulk density determinations. All specimens had code numbers and the temperatures at which they were to be fired impressed into two opposite surfaces. The moisture contents of the clay when extruded were 27,5% for the Georgedale clay and 28,7% for the Bellville clay.

After / .....

After cutting on the extruder belt, the briquettes were trimmed on a table to a length of 280 mm, marked on both sides with fine sharp scratches about 100 mm apart, allowed to dry in the air on racks in the laboratory for at least 7 days and then they were placed in an oven at 110 °C to complete the drying. They were placed in a desiccator to cool, before cutting to lengths of 235 mm and measuring the distances between the marks. The linear drying shrinkage of the Georgedale briquettes was 2,6 per cent and that of the Bellville briquettes was 5,5 per cent.

4.2.2 Firing of specimens

The furnaces in which the specimens were fired were electrically heated and their temperatures were automatically controlled. A different cam was fitted to the control mechanism for each firing temperature. The cams were designed so that the furnace temperature increased at a rate of 80 °C per hour until the firing temperature was reached. The furnace was maintained at the firing temperature for 5 hours before the furnace was switched off to cool. The furnaces cooled very slowly taking more than 24 hours to cool from the higher temperatures. At 300 °C the door was opened about 5 mm and at about 150 °C the specimens were removed to cool in a desiccator. After cooling and until required they were quickly transferred for storage to bins with air-tight lids and containing trays of calcium chloride.

Three raw briquettes of each clay as well as three absorption specimens from each clay were stacked in the kiln and fired together. The specimens were stacked near each other and well away from the electric elements. The briquettes were fired at temperatures differing by 50 °C between 835 °C and 1135 °C. The intention was to fire the specimens at 50 °C intervals from 850 °C to 1150 °C, but, on checking the calibration of the temperature controls, they were found to be controlling the temperatures at 15 °C below the settings. After firing and cooling, the distance between the marks was

measured / .....

measured and the firing shrinkage calculated. The percentage firing shrinkage is given in Table 6.

The percentage drying shrinkage and percentage firing shrinkage are used by manufacturers to determine what the extruded size of an article must be if, after firing, a particular size is wanted. In this work these shrinkages were determined so that, with future work on expanding bricks it will be seen whether they have any particular significance with regard to moisture expansion.

TABLE 6 Percentage linear firing shrinkage of briquettes

Firing temperature °C	Georgedale clay	Bellville clay
835	-0,6*	0,3
885	0	0,3
935	0	0,3
985	1,9	2,7
1035	4,9	4,0
1085	9,0	5,6
1135	10,8	7,1

* the minus sign indicates expansion

4.2.3 Water absorption, porosity and bulk density of fired clays

The 25 mm x 25 mm x 50 mm fired specimens were used to determine the above properties.

Before the fired specimens were tested, they were first placed in a drying oven at 110 °C for 24 hours and then allowed to cool in a desiccator. The dry specimens were weighed. After submerging them in a bath of water at room temperature for 24 hours, they were weighed while saturated but with the surfaces dried off with a cloth. They were then replaced

in the / .....

in the bath of water, boiled for 5 hours and allowed to cool under water. They were weighed while suspended in water and then removed from the water. Their surfaces were dried with a cloth and they were weighed in air.

From these tests the following were obtained:

(i) dry mass (W_1),

(ii) saturated mass after 24 hours soaking (W_2),

(iii) suspended in water, mass after 5 hours boiling (W_3),

(iv) impregnated mass (W_4)

The following calculations were carried out:

$$\text{Percentage absorption (soaked 24 hours)} = \frac{W_2 - W_1}{W_1} \times 100$$

$$\text{Percentage absorption (after 5 hours boiling)} = \frac{W_4 - W_1}{W_1} \times 100$$

$$\text{Percentage apparent porosity} = \frac{W_4 - W_1}{W_4 - W_3} \times 100$$

$$\text{Bulk density} = \frac{W_1}{W_4 - W_3}$$

The average calculated values of each group of three specimens fired at the same temperature are given in Table 7. The sharp change in values of the Georgedale clay specimens when fired at 1035 °C was accompanied by a sharp change in colour of the specimens from light pink when fired at 1035 °C to a dark red at 1085 °C and a very dark purplish red at 1135 °C. There was not a sudden colour change in the case of the Bellville clay; it became darker with each firing above 1035 °C.

From the mineralogical composition of the clays, it is surprising that the two clays behaved so differently when fired at 1085 °C.

The importance / ....

TABLE 7 PROPERTIES OF FIRED CLAYS

Firing Temperature °C	Georgedale Clay				Bellville Clay			
	% Absorption (24 hours in water)	% Absorption (after boiling 5 hours)	% Apparent porosity	Bulk density	% Absorption (24 hours in water	% Absorption (after boiling 5 hours)	% Apparent porosity	Bulk density
835	24,7	25,6	40,2	1,56	21,6	22,7	37,9	1,67
885	24,0	25,3	40,0	1,58	21,5	22,6	38,3	1,69
935	23,6	25,1	40,1	1,59	20,6	21,9	37,4	1,70
985	20,1	21,9	37,1	1,68	17,3	19,0	34,3	1,79
1035	17,2	18,3	33,0	1,84	14,8	16,6	31,6	1,87
1085	4,6	4,8	10,9	2,25	9,7	11,8	24,3	2,06
1135	0,2	0,2	0,4	2,46	7,3	9,4	20,1	2,13

The importance of absorption and porosity on moisture expansion is not known, but these properties have been determined so that if a relationship is established, it can be tested against these values. Porosity is important to manufacturers of glazed ware as it affects drying rates, in general terms is related to mechanical strength, affects 'pick up' of glaze, and can give them guidance on a number of other matters.

4.2.4 Moisture expansion of briquettes at different firing temperatures

The moisture expansion was measured by means of Demec gauges. Measuring targets were fixed to the two opposite 38 mm wide faces of the briquettes 203,2 mm apart and measurements were taken as described in Appendix B.

The fired briquettes were subjected to 24 hour steaming cycles to cause accelerated expansions, so that an indication could be obtained of the temperatures causing maximum expansion. Raw bricks would then be fired at those temperatures and close to them. The briquettes were placed on racks in a steam cabinet in which the steam around the bricks would be about 96 °C and at atmospheric pressure. Each steaming cycle consisted of placing the briquettes in steam for 7 hours and then storing them in a constant temperature laboratory at 21 °C for 16 hours before measuring their expansion. The lengths of the briquettes fired at 835 °C were sensitive to moisture content at the time of measuring, whereas those fired from 985 °C to 1135 °C were not. The briquettes fired at 885 °C and 935 °C were only slightly sensitive to moisture content when measuring. The percentage moisture in the briquettes was checked later and found to be close to the percentage absorptions in columns 3 and 7 of Table 7. After cycles (119 hours) of steaming, the expansion per steaming cycle had become very low and the steaming was stopped.

When / .....

When these results were plotted on Figures 14 and 17, it was seen that the Georgedale briquettes fired at 1085 °C and the Bellville briquettes fired at 1035 °C and 1085 °C were expanding at faster rates than the rest of the briquettes, so it was decided to steam the briquettes for a longer period. The steaming cycles were changed and the briquettes were steamed continuously from each Monday to Friday. They were removed from the steam cabinet on Friday afternoons and placed in a constant temperetaure (22 °C) and humidity (50 per cent relative humidity) room during the weekends before being measured on the Monday morning and replaced in the steam cabinet.

Graphs were drawn of the moisture expansion of the briquettes. Figures 13, 14 and 15 show the expansions of the Georgedale briquettes and Figures 16, 17 and 18 those of the Bellville briquettes.

Figures 13 and 16 show how with increased hours of steaming the maximum expansion moves towards briquettes fired at higher temperatures with a double peak in the case of the Georgedale bricks. It is also seen that Georgedale bricks fired at 1135 °C or higher will not cause moisture expansion problems. The Bellville clay when fired at 1135 °C will take a time to start expanding rapidly but will then expand at a fast rate.

As shown on Figures 14 and 15 the Georgedale briquettes fired at 1085 °C started expanding at a much increased rate after 119 hours and the expansion with log time maintained an increased rate up to 2000 hours of steaming, and then the rate appeared to slow down slightly between 2000 to 3400 hours. The Georgedale briquettes fired at 1135 °C, which expanded very little during the first 500 hours of steaming, started expanding at a slightly faster rate with log time between 500 to 3400 hours. From Figure 15 it can be seen that the major difference in the expansion of the briquettes

fired / .....

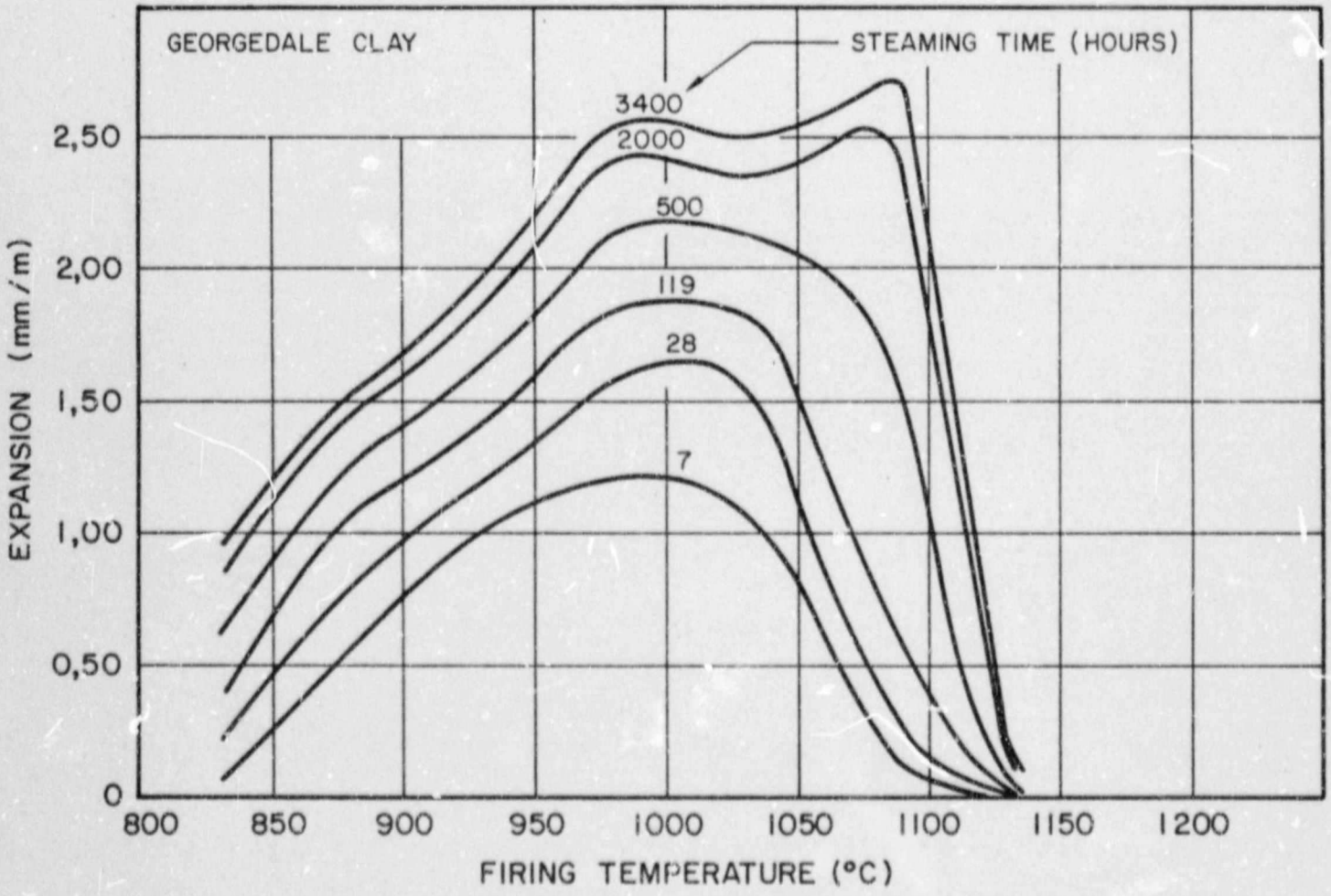

FIGURE 13

Accelerated expansion of briquettes

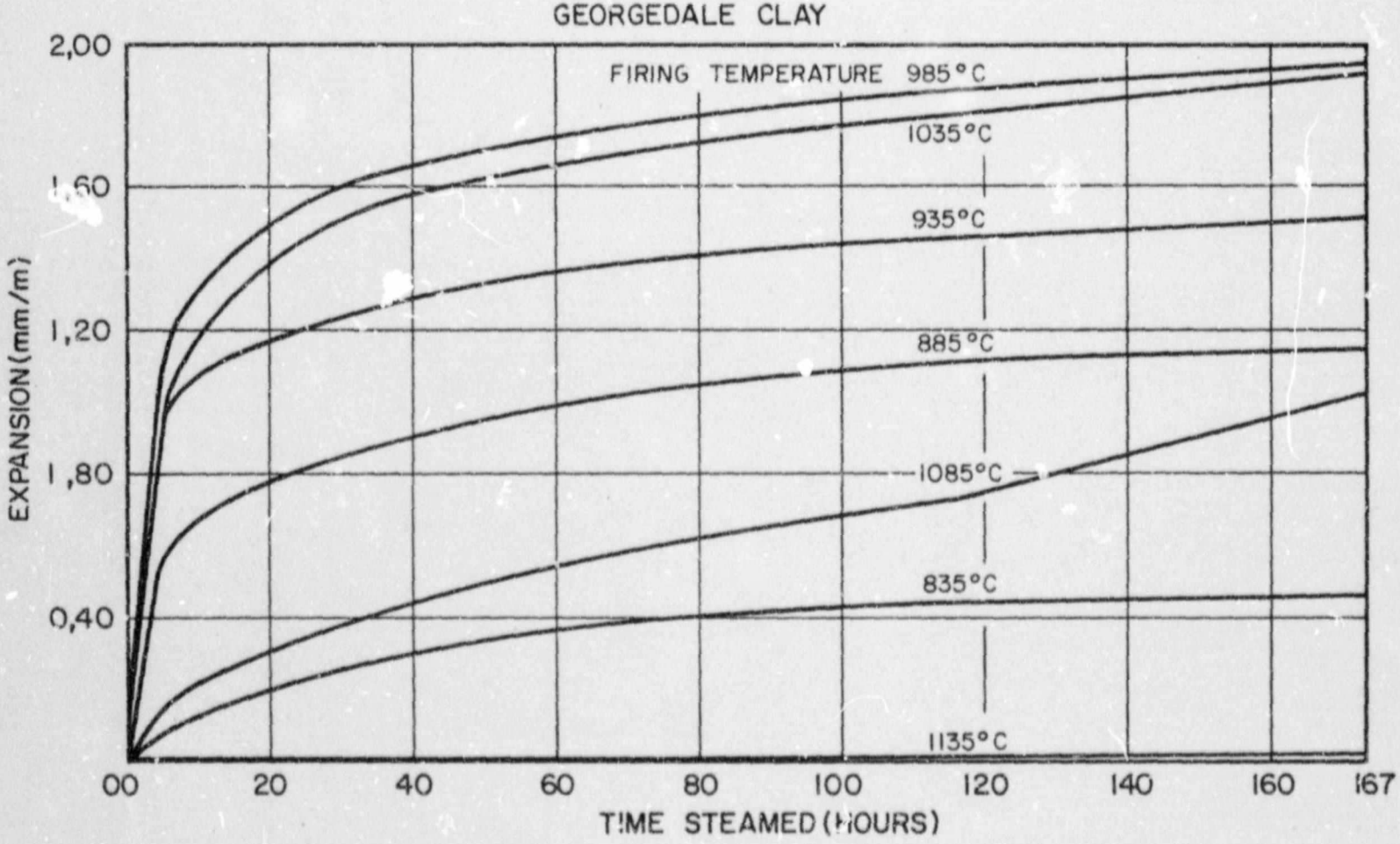

FIGURE 14

Accelerated expansion of briquettes

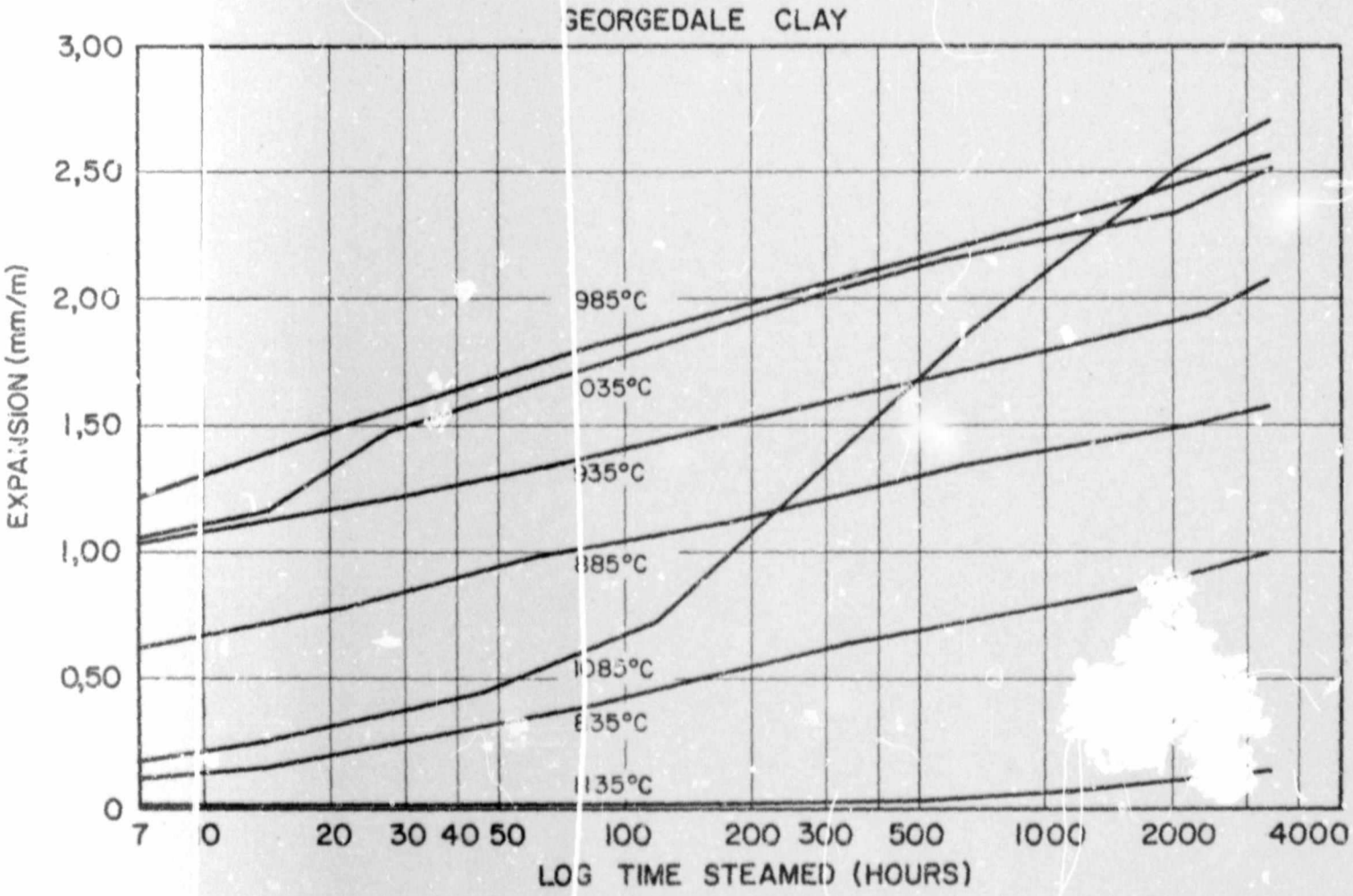

FIGURE 15

Accelerated expansion of briquettes

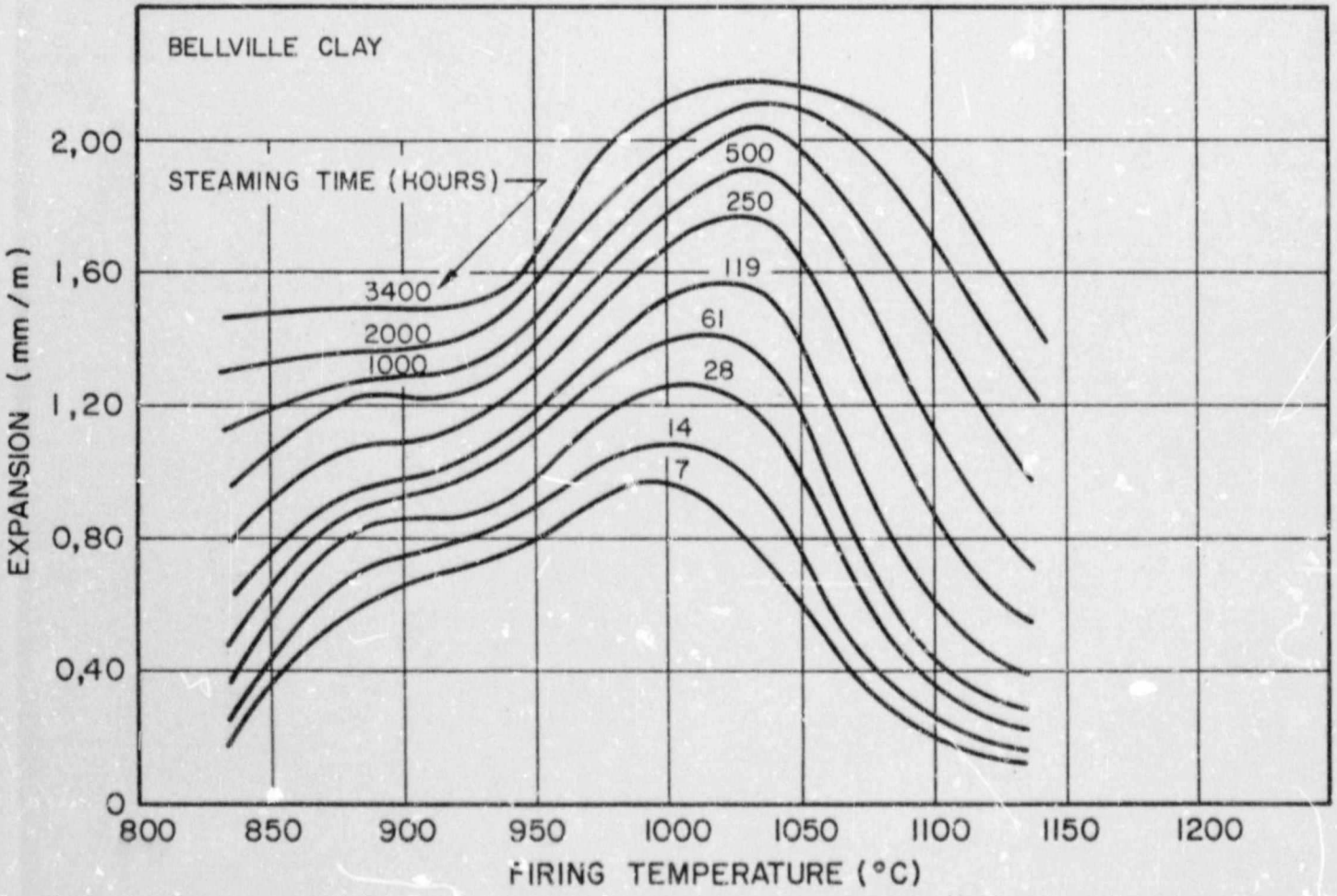

FIGURE 16

Accelerated expansion of briquettes

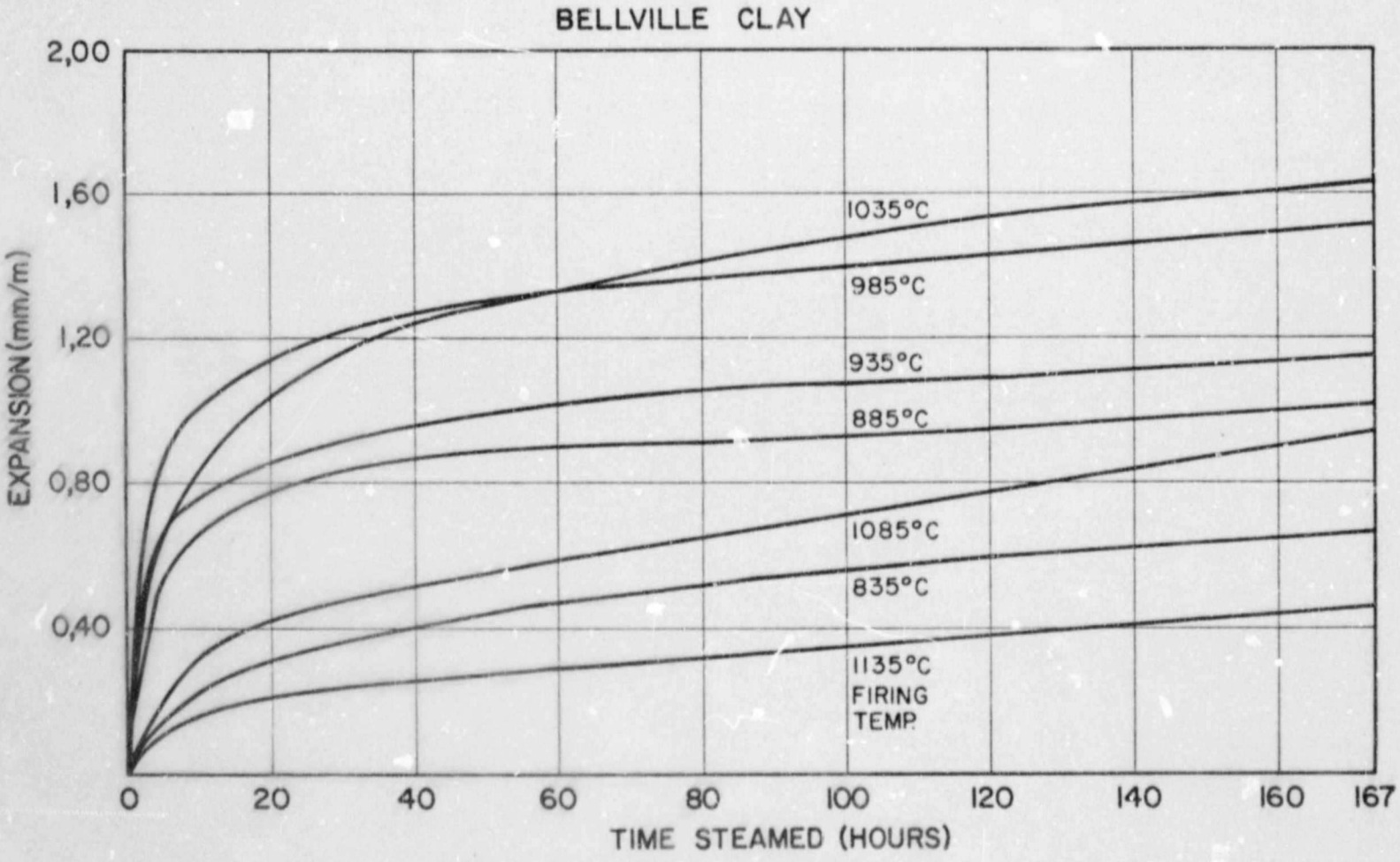

FIGURE 17

Accelerated expansion of briquettes

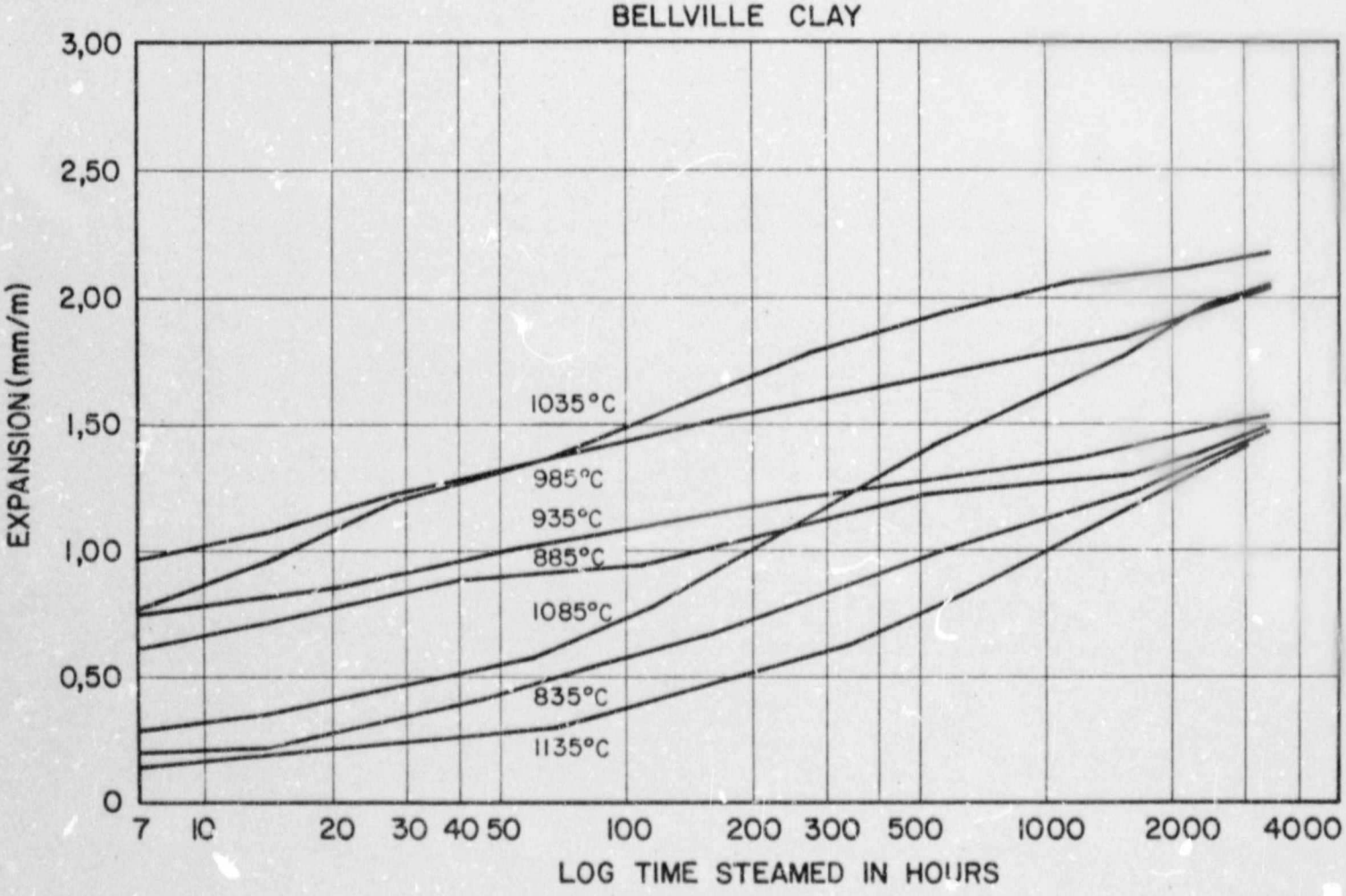

FIGURE 18

Accelerated expansion of briquettes

fired at 835 ℃, 885 ℃ and 935 ℃ was the expansion that took place during the first 7 hours because, after this time, the rates of the expansion were almost identical.

The Bellville briquettes, fired at different temperatures, did not have similar rates of expansion except for those fired at 885 ℃ and 935 ℃ which were approximately the same. Figure 18 shows that the briquettes fired at 1085 ℃ and 1135 ℃ have an increased and similar rate of expansion with log time as the total number of hours steamed increases above 700 hours. These briquettes had the most rapid expansion after 3400 hours of steaming.

From Figures 15 and 18 it can be seen that the maximum total expansion of the briquettes cannot be predicted. Bricks are likely to continue expanding indefinitely but at very much reduced rates. The expansion of the briquettes after any specific long period of steaming can be predicted from Figures 15 and 18, but this has no practical significance at present. However research workers are investigating the relationship between hours steamed and actual expansions when exposed to the weather.

The reason why briquettes fired in the region of 1085 ℃ increased their rates of expansion on a log time scale after many hours of steaming is not known. The reason for the Bellville briquettes which were fired at 1135 ℃ only starting to expand after a long period could have been because of the following:

(i) much of the material was vitrified at this temperature and the internal surface area would be very much reduced,

(ii) the more vitrified material has a higher tensile strength and elastic modulus than material which is less vitrified,

(iii) / .....

(iii) moisture will penetrate the pores and start reacting with some of the material making up the surface of the pores, but because of the high-tensile strength and elastic modulus negligible dimensional change will occur,

(iv) as the internal pressures build up, they start causing internal micro-cracks and therefore a larger internal surface area which in turn reacts with moisture causing the weakend body to expand,

(v) as an increasing number of micro-cracks are formed the briquette continues expanding.

CHAPTER 5

EXPANSION OF BRICKS WHILE SUBJECTED TO COMPRESSION

5.1 Brick Samples

5.1.1 Fired bricks

When this work started, damage to many buildings was occurring in Cape Town and the surrounding areas because of the moisture expansion of brickwork, so it was decided to obtain bricks for the investigation from this area.

The first samples taken were stock bricks that had just been fired and were still hot as they were removed from a Hoffman kiln. The kiln was oil fired and the oil burners were moved to new firing positions as the firing of each batch was completed. When the temperature had cooled to about 60 °C, the bricks were removed from the kiln. Sample of bricks that were well-fired, medium-fired and just less than medium-fired (called light-fired, or light-burnt in this thesis) were collected as they were removed from the kiln. The majority of the bricks taken were well-fired. Each brick was wrapped in brown paper, taped and placed in a double polythene bag which was sealed by melting the edges of the openings together after pressing as much air as possible out of the bag. The paper wrapping was to protect the polythene from sharp edges and projections on the bricks. Effective sealing of the polythene bags was insured by earlier practice on bags containing water. The brick in the polythene bags was finally wrapped in another sheet of brown paper. These wrapped and sealed bricks were placed in straw in strong wooden boxes for transporting to Pretoria.

The sealed bricks were placed in a large galvanized steel tank containing trays of fresh calcium chloride and having

a limited / .....