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SOUTH AFRICAN ROADS BOARD

The linear shrinkage test: justification for its reintroduction as a standard South African test method

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SINOPSIS:

Verskeie probleme met die liniêre krimpingstoets soos gespesifiseer in Metode A4 van die Tegniese Metodes vir Hoofweë nommer 1 (TMH 1, 1979) word behandel. Hierdie ondersoek is uitgevoer in 'n poging om die swak herhaalbaarheid van die toets te verbeter en die heropname daarvan in TMH 1 te regverdig. 'n Nuwe oop-kant trog is aanbeveel vir die toets wat, indien geïmplementeer, die probleem van boogvorming by hoë plastisiteit aansienlik sal verminder en die akkuraatheid van die werklike krimpingsmeting sal verbeter. Aanbevelings word ook gegee met betrekking tot die toepaslikheid van die korreksiefaktor vir materiale met toenemende plastisiteit. Die verslag beklemtoon ook die belangrikheid daarvan om die toetsmetode streng te volg, veral gedurende die droging van die monsters. Alternatiewe drogingsmetodes mag lei tot 'n beduidende variasie in liniêre krimpings resultate.

SYNOPSIS:

Several problems with the linear shrinkage test specified in Method A4 of the Technical Methods for Highways number 1 (TMH 1, 1979) were addressed as part of this investigation in an effort to improve the alleged poor reproducibility of the test and justify its reintroduction into TMH 1. A open-sided trough is recommended for the test which, if implemented will reduce the problem of bowing at high plasticity significantly and improve the accuracy of the actual shrinkage measurement. Recommendations are also given regarding the appropriateness of the correction factor for soils of increasing plasticity. The report also highlights the need to adhere rigidly to the test method, especially during the process of drying of the samples. Alternative drying methods may lead to a significant variation in linear shrinkage results.

TREFWOORDE:
KEYWORDS: Linear shrinkage, soils testing.

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This report was reviewed by:

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1 INTRODUCTION

The bar linear shrinkage (LS) test was specified in the South African Technical Methods for Highways (TMH 1) until 1986. However, in 1986 the Materials Testing Sub-Committee of the Highway Materials Committee (HMC) decided to exclude the method from the revised version of TMH 1. The reason for the exclusion was cited as the poor reproducibility of the test method based on investigations carried out by the Department of Transport in the 1970's and an investigation on reproducibility limits produced by Sampson (1985).

However, research on calcretes (Netterberg 1971) and subsequent research on materials for unpaved roads (Paige-Green, 1989) and compactibility of untreated road building material (Semmelink, 1990) and a number of other studies showed that the bar linear shrinkage was one of the best indicators of performance. In the case of materials for unpaved roads, Paige-Green (1989) showed that their performance can be accurately predicted by the shrinkage test, whereas the Atterberg limits have an almost random chance of separating good from bad gravels. The test was also identified as being ideally suited for field laboratories and laboratories in developing areas as minimal equipment and testing skills are necessary to quantify the suitability of materials.

Subsequent to the investigation of Paige-Green, the results from the reproducibility study carried out by Sampson (1985) were re-examined to identify reasons for the poor reproducibility of the test. Further discussions with the participating laboratories revealed that in at least one case, the laboratory did not adhere to the method specified in TMH 1. In this instance, the laboratory decided to modify the drying procedure in an attempt to prevent bowing of the soil sample out of the trough at high plasticities. All the results in this laboratory differed significantly from the mean result of the participating laboratories. It also became evident through discussions that operators tended to reject results or modify them if the linear shrinkage was not half of the plasticity index.

In the light of new findings becoming available, the Materials Testing Sub-Committee recommended to the HMC that the linear shrinkage should be re-evaluated and modified to take into account the problems identified with the test method and also to highlight the variations in results likely to be expected if the test procedure is not followed accurately. The objective of this project is to provide results which will justify the reintroduction of the bar linear shrinkage test and give recommendations on modifications to the test method to reduce operator-susceptibility and improve reproducibility.

2 SOUTH AFRICAN BAR LINEAR SHRINKAGE

The last recorded method used for the bar linear shrinkage in South Africa was specified as method A4 of TMH 1 (1979). The method defined linear shrinkage as follows:

The linear shrinkage of the soil for the moisture content equivalent to the liquid limit, is the decrease in one dimension, expressed as a percentage of the original dimension of the soil mass when the moisture content is reduced from the liquid limit to an oven dry state.

The method requires a shrinkage trough with internal dimensions of 150 ± 0,25 mm long x 10 ± 0,25 x 10 ± 0,25 mm and made of 1,16 mm thick tinned copper or stainless steel and that once the trough has been filled, the soil should be placed in an oven immediately and dried at 105 - 110°C.

After drying, if the soil bar is curved, it should be pressed back into the trough so that the top surface of the soil bar is parallel with the top of the trough. The method also requires that loose dust and sand should be removed from the ends of the soil bar as well as from between cracks in the soil bar. The soil bar is then pressed tightly against one end of the trough and the distance between the other end of the soil bar and the respective end of the trough is measured to the nearest 0,5 mm.

The linear shrinkage is calculated from the following formula:

$$LS = LS_N \, x \, \frac{0{,}8}{1 - 0{,}008N}$$

where

LS = linear shrinkage, expressed as a percentage of the original wet length of 150 mm, when the moisture content is reduced from the liquid limit to an oven-dry state.

LS_N = linear shrinkage, expressed as a percentage of the original wet length of 150 mm, when the moisture content corresponding to N taps in the liquid limit test is reduced to an oven-dry state.

The linear shrinkage is reported to the nearest 0,5 %.

The formula may also be written as follows:

LS = shrinkage in mm as measured x f

where

$$f = \frac{100}{150} x \frac{0,8}{1 - 0,008N}$$

The values for the correction factor f are tabulated in method A4 for the respective number of blows taken to determine the liquid limit.

2.1 PROBLEMS IDENTIFIED WITH THE TEST METHOD

The main problem with the test method was that of its poor reproducibility, in that the mean inter-laboratory precision was shown by Sampson (1985) to be 34,1 % when expressed in terms of D2S %. The Difference Two-Sigma limit (D2S) is defined as follows (ASTM E177):

In most cases, less than 5 % of all random pairs of measurements from a statistical universe can be expected to differ from each other by more than $2.\sqrt{2}.s$ (where s is the standard deviation of the measurement process at level n-1). D2S % is the D2S value expressed as a percentage of the mean ($\bar{x}$).

However, the reproducibility of the linear shrinkage at 34,1 % is nevertheless much better than that of the PI at 46,8 % (Sampson, 1985)

Following discussions with participating laboratories and observations of testing procedure, the following problems with the method were identified that could lead to poor reproducibility:

- **cracking and bowing of the soil sample out of the trough, especially with soils of high plasticity.** This led to inconsistencies in determining the actual shrinkage length. Some laboratories pressed the curved sample back into the trough and measured the shrinkage, some laboratories measured the inner curved length and the outer curved length of the sample and subtracted the average length from 150 mm and some laboratories just took the difference between the end of the curved sample and the edge of the trough. Variations in actual shrinkage measurements with some soils was significant when the different methods of measurements were compared.

- **variations in drying techniques.** Some laboratories have modified their drying techniques in an effort to minimise effects of bowing and cracking at high plasticities. At least one laboratory used the technique of air drying the samples overnight before oven drying at 105 - 110°C. The implications of not following the specified drying procedure will be investigated here.

- **variations in the results obtained using the correction formula.** Reservations were expressed as to the accuracy of results obtained when the correction formula was applied to some soils. The variations likely to be expected and the material-dependence of the formula will be covered as part of this investigation.

- **lubrication of the troughs.** TMH 1 specifies the use of paraffin wax to lubricate the troughs to assist shrinkage. However, other forms of lubrication such as silicone grease are known to be used in certain laboratories.

- **filling of linear shrinkage troughs.** It appears that different masses of material could be placed in the shrinkage troughs by different technicians for the same sample and thus affect the degree of shrinkage. A small experiment was devised to assess the variations.

The experimentation was designed to investigate the implications that the changes to the test method and apparatus would have when compared with the present TMH 1 method on which most of the present specification limits have been based. Each problem area will be dealt with separately.

2.2 OPINIONS OF THE LINEAR SHRINKAGE TEST IN SOUTH AFRICA

To determine the present usage of the LS test in South Africa, people from various institutions involved in the testing and evaluation of road building materials were interviewed. Senior staff of all the laboratories of the Roads Authorities were questioned on their usage and opinion of the LS test along with staff of major consulting firms (namely Bruinette Kruger and Stoffberg (BKS), Van Niekerk Kleyn and Edwards (VKE) and Ninham Shand) and researchers at the Division of Roads and Transport Technology.

It was determined that despite the test being omitted from TMH 1, all Roads Authorities still carry out the test. This is also the case with the major Consulting firms. In the case of researchers, the test is included in most investigations where materials characteristics are compared with performance.

Two of those interviewed were not in favour of the test. The reasons given were that the test was not unduly reproducible (even though studies have shown it to be at least as reproducible as the PI test, of which they were in favour) and also that operators often changed PI results to fit the theory that PI is equal to twice the linear shrinkage. In some cases the test was merely used as a check on the PI. In most cases, however, the LS was used to assess the suitability of materials for road construction purposes.

2.3 Current important uses for the linear shrinkage test

The test is presently used by all the Roads Authorities, major consulting firms, research institutions etc., mainly for the for the classification of materials and also to assess the suitability of materials for road construction purposes.

Other important uses for the test are given below in sections 2.3.1 to 2.3.3.

2.3.1 An index for describing the compactibility of untreated roadbuilding materials

Semmelink (1990) investigated the compactibility of 21 different materials in an extensive laboratory study. These materials ranged from high quality, class A-1 materials to poor quality, class A-7-6 materials. Samples were compacted at different moisture contents to different density levels and the unsoaked CBR was determined for each sample immediately after vibratory compaction.

It was found that the properties of the materials that have the greatest influence on the compactibility, moisture regime, and bearing capacity of the materials were; the total grading, the liquid limit (LL), the **linear shrinkage** (LS), the loose bulk density (LBD) and the physical shape of the individual particles (as expressed by the shape factor (SF)).

From this study he developed several models to determine the Maximum Dry Density (MDD), Optimum Moisture Content (OMC), Zero Air Voids Moisture Content (ZAVMC) and Critical Moisture Content (CMC) which is the moisture content at which the highest California Bearing Ratio (CBR) is obtained. The models are as follows:

$$MDD = k_1.GF^{0,85} + k_2.C + k_3.Q + k_4.C^3 + k_5$$
$$OMC = k_6.GF^{0,85} + k_7.C + k_8.Q + k_9.C^3 + k_{10}$$
$$ZAVMC = k_{11}.GF^{0,85} + k_{12}.C + k_{13}.Q + k_{14}.C^3 + k_{15}$$
$$CMC = k_{16}.GF^{0,85} + k_{17}.C + k_{18}.Q + k_{19}.C^3 + k_{20}$$

where:

$$GF = [\, \sum \text{(\%passing sieve / sieve size)} \,] / 100$$

for sieves (mm) 75; 63; 53; 37,5; 26,5; 19; 13,2; 4,75; 2,0

and:

k_n = regression analysis constants (Table 1)
$C = (\% < 0{,}425\ mm/100)(LL/100)^{0,1}$
$Q = (\% < 0{,}425\ mm/100)(\mathbf{LS})$

The results of the regression analysis are listed in Table 1, with and without the inclusion of the Linear shrinkage values. It is evident that the linear shrinkage value plays an important role in the compactibility of the materials. It can be seen from the table that when this parameter is omitted from the regression equation both the R squared and the standard error of estimate are significantly affected. In the OMC prediction model for example, when the linear shrinkage is excluded from the prediction model only 68,8 % of the variance within the model is accounted for. By including the linear shrinkage (in the form of the shrinkage product), the total variance accounted for increases to 97 %. The predicted value in the former model is thus equal to the actual value ± 6,0 units, with 95 % confidence whereas when the linear shrinkage is used in the prediction model the standard error becomes ± 1,98, with 95 % confidence.

TABLE 1: Regression constants with and without the inclusion of the LS test

Regression Constants	MDD		OMC		ZAVMC		CMC	
	LS in	LS out	LS in	LS out	LS in	LS out	LS in	LS out
Std Err of Y est	2,0303	4,3209	0,9923	2,9960	1,1147	2,6392	0,6920	1,4204
R squared	0,9442	0,7314	0,9668	0,6781	0,9607	0,7657	0,9407	0,7346
X coefficient	k_1=-35,79 k_2=9,71 k_3=-2,85 k_4=21,81 k_5=104,64	k_1=-25,72 k_2=2,81 k_3=-16,78 k_4 --- k_5=98,11	k_6=21,02 k_7=-9,01 k_8=2,11 k_9=-13,13 k^{10}=-5,60	k_6= 13,59 k_7= -3,92 k_8= 15,34 k_9 --- k_{10}= -0,79	k_{11}=21,90 k_{12}=-9,22 k_{13}=1,79 k_{14}=-7,22 k_{15}=-5,28	k_{11}=15,60 k_{12}=-4,90 k_{13}=16,94 k_{14} --- k_{15}=-1,19	k_{16}=11,13 k_{17}=0,96 k_{18}=0,93 k_{19}=-12,41 k_{20}=-2,14	k_{16}=7,85 k17=3,20 k_{18}=0,15 k_{19} --- k_{20}=-0,02

2.3.2 Specifications for wearing course materials for unpaved roads

Paige-Green (1989) developed performance related specifications for unpaved roads based on the testing and monitoring of 91 unpaved sections of road in the Transvaal Province of South Africa and 19 sections in Namibia. These specifications are based on a simple grading analysis, the bar linear shrinkage and the California Bearing Ratio determination. Figure 1 (taken from Paige-Green, 1989) shows the relationship between shrinkage product, grading coefficient and performance of unpaved wearing course gravels. The specifications derived from this figure have been included in the draft Technical Recommendations For Highways (TRH 20).

Figure 1 indicates that materials having shrinkage products (LS x % passing 0,425 mm sieve) less than 100 are unacceptable as the road surfacings constructed with these materials tend to ravel and corrugate (zone B Figure 1). Materials with shrinkage product values of over 360 tend to be slippery when wet (zone D, Figure 1). Materials in zone E perform well (shrinkage product between 100 and 360; grading coefficient between 16 and 34). Those with shrinkage products between 240 and 360 are relatively more dusty than those with values less than 240.

The importance of the linear shrinkage test method for the evaluation of road building materials is once again emphasized. Figure 1 suggests that an important property of road building materials which is measured by linear shrinkage is not identified by other test methods. It is thus important that the linear shrinkage test method be retained as its value for the testing of road building materials is clearly evident.

2.3.3 Calcretes in road construction

Netterberg (1971) reviews the composition, distribution, origin and age of South African calcretes. In this publication the engineering properties of calcretes and specifications for calcrete roads are also dealt with in some detail. He states that calcretes differ from most roadbuilding materials in that they have an unusual composition and may exhibit unusual properties and for this reason certain precautions are necessary when carrying out the usual standard tests. He adds that non-standard tests are necessary to measure some of the unusual properties of calcretes. Various methods for testing calcretes are discussed.

The Bar Linear Shrinkage test is discussed at some length and it is suggested that because of the difficulties encountered in determining the Liquid Limit and PI on calcretes, more weight should be attached to the Linear Shrinkage than to the PI and Liquid Limit. The reasons given by Netterberg for this suggestion are the following:

- the bar linear shrinkage test is actually more accurate (± 2 % of the value obtained) than the PI, for calcretes
- the test is quick and the calcrete need only be dried to a little below the shrinkage limit
- it does not depend on the result of two other tests (as is the case with the PI)
- no moisture content determination is required
- its cost is less than 20 per cent of the PI
- hardly any apparatus is required
- the personal factor plays a very small role, and if a specially calibrated rule is used, all calculations can be eliminated.

Although Netterberg (1971) did not show the LS to correlate better with the performance of calcrete roads than the PI both the LS and the Linear Shrinkage Product (LSP) were used in his specifications for calcrete pavements and wearing courses. The test is therefore necessary in order to be able to utilise these specifications.

Also, the linear shrinkage of calcretes is less often affected by predrying than is the PI or LL (Netterberg, 1978; TRB Record 675).

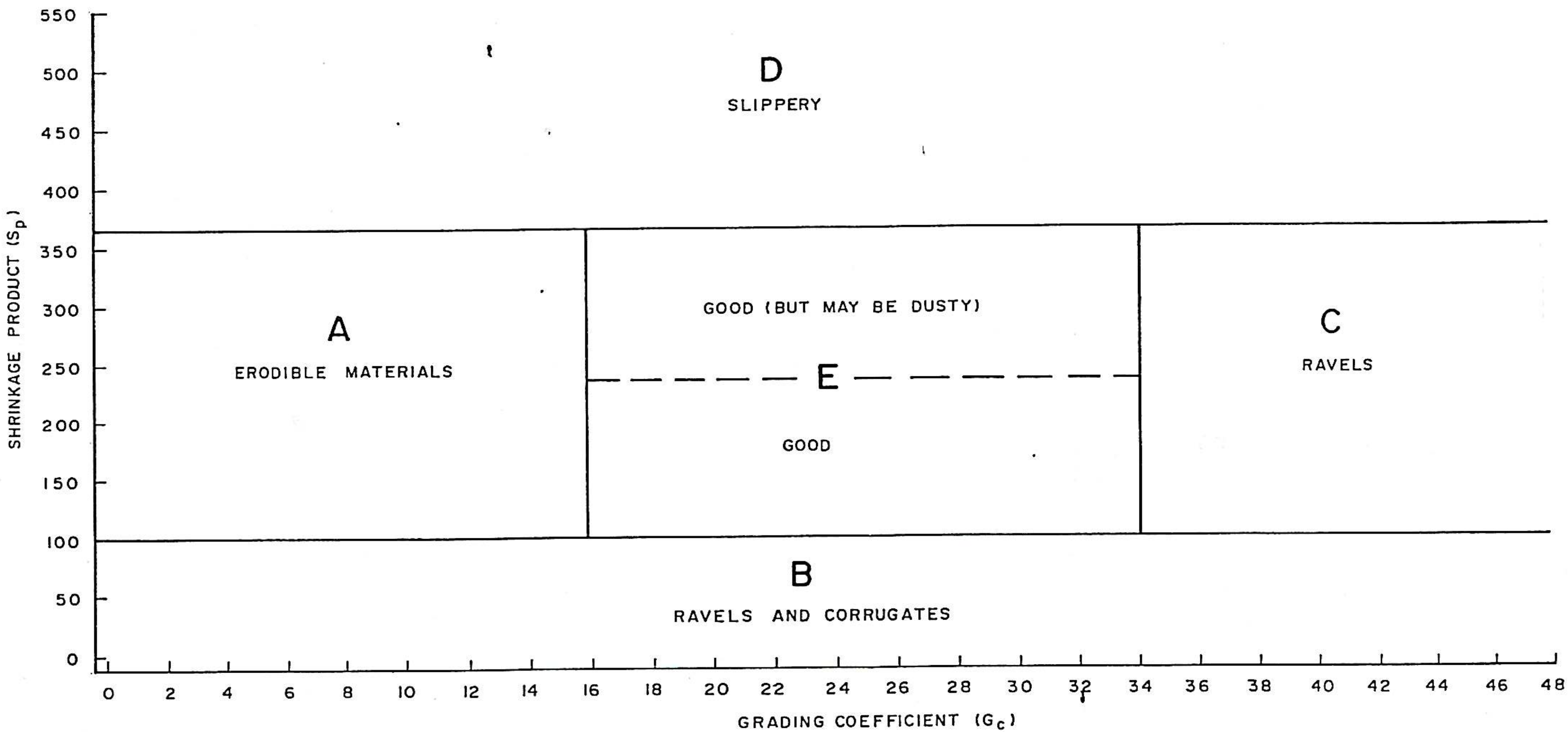


FIGURE 1 *RELATIONSHIP BETWEEN SHRINKAGE PRODUCT, GRADING COEFFICIENT AND PERFORMANCE OF UNPAVED WEARING COURSE GRAVELS*

3 INVESTIGATION OF ALTERNATIVE TROUGHS TO PREVENT BOWING AND CRACKING

The bowing and cracking experienced at high plasticity with the present trough appears to be a function of the trough configuration. The present trough with three closed sides dictates that differential drying occurs through the depth of the sample in that the exposed upper surface will dry and shrink quicker than the closed-in, lower surface of the sample. In an effort to reduce the bowing and cracking and subsequently reduce the measurement error, several troughs were investigated as follows:

- the standard trough used in TMH 1. This is also specified by the American Association of State Highway and Transportation Officials (AASHTO) and the American Society for Testing Materials (ASTM) in their standard methods of testing materials for road construction.

- the British Standard trough as specified in BS 1377 : 1975 test 5. This trough differs from the TMH 1 trough in that it is semi-circular in cross-section and has an internal length of 140 mm. The internal radius of the semi-circular cross-section is 12,5 mm.

- the ASTM trough recommended for the determination of volumetric shrinkage. This is a circular trough of 45 mm diameter and is 12,7 mm deep.

- a trough similar to the one specified in TMH 1 except that it was 15 mm deep compared with the 10 mm of the specified trough.

- a trough with the same internal dimensions as the TMH 1 trough except that the two sides are open to allow drying to take place evenly along both faces of the soil bar. The trough is filled by placing it on a glass plate with one open side facing upwards. It is then placed in an oven on its side to allow the exposed surfaces to dry evenly. This is similar to the trough described in Central African Standards CAS No. A43 Part 1 as used in Zimbabwe.

- a standard TMH 1 trough with a metal plate placed on the top surface of the soil bar and loaded with a 1 kg weight. The intention was to restrict the bowing and cracking of the soil by confining the upper, exposed surface.

- a cylindrical, perspex trough of 20 mm internal diameter and 150 mm in length.

3.1 TESTING PROCEDURE

Apart from the different trough configurations, the testing procedure was that of TMH 1 with the exception that silicone grease was used to lubricate the troughs (The reason for using silicone grease is given in section 6). Duplicates of each trough type were all filled with soil at the moisture content representing 25 blows with the TMH 1 Casagrande liquid limit apparatus (ie at liquid limit). The troughs were then dried overnight in an oven at 105°C. The shrinkage was measured for each trough and the mean of the replicates was recorded for each trough type. The testing was carried out on 8 soil types in the linear shrinkage (LS) range 2 to 23 and the results are shown in Table 2.

In addition to the shrinkage measurements, an assessment was made of the degree of bowing and cracking experienced by each trough type. The symbols used are explained in Table 2.

As the testing proceeded, it became evident that the trough used to measure volumetric shrinkage and the perspex cylindrical trough were unsuitable. In the first instance, the testing procedure was difficult and hazardous in that the test method requires the soil pat to be immersed in mercury to measure the volumetric shrinkage and in every case, the specimen broke up during drying.

The perspex tube was also found to be unsuitable as, in nearly every case, excessive cracking completely distorted the specimen. In addition, the ends of the specimen were pushed out of the end of the trough on drying by an expansion of air and water vapour.

3.2 DISCUSSION OF RESULTS

3.2.1 Prevention of bowing

Table 2 shows that the TMH 1 trough experienced bowing of the soil sample in every case with excessive bowing experienced with the soils of high plasticity (ie PI > 30). In these cases, the measurement of the shrinkage proved to be very difficult and confirmed the problems identified in Section 2.1.

The 15 mm deep trough exhibited almost identical bowing characteristics to the 10 mm deep trough and is not recommended as a substitute for the TMH 1 trough.

In the case of the BS trough, in most cases the bowing effect was reduced but the cracking in some instances was more pronounced. The advantage of this trough is that it is easier to fill, but in seven of the eight samples tested, the linear shrinkage from the BS trough was higher than that of TMH 1. Whilst there was a slight improvement in the bowing characteristics, the increase in cracking and apparent lack of direct correlation with the TMH 1 method will dictate that this trough is not recommended as a substitute for the TMH 1 trough.

Table 2 : Results from different troughs related to LS, bowing and cracking

Sample No	Material Type	Trough Type														
		TMH1			TMH1 (loaded)			TMH1 (open faced)			TMH1 (15 mm)			British Standard		
		LS	Bowing	Cracks	LS	Bowing	Cracks	LS	Bowing	Cracks	LS	Bowing	Cracks	LS	Bowing	Cracks
D1201	Black clay PI=31 LL=57	18,7	Be	Cs/t	20,7	Bs	Cs/t	18,7	Bn	Cs/t	18,7	Be	Cn	22,0	Be	Cs/t
10509	Calcrete PI=49 LL=118	15,7	Bs	Cs/t	15,8	Bn	Cs/t	15,7	Bn	Cn	15,8	Bs	Cn	16,1	Bs	Cs/t
10499	Weathered Granite PI=13 LL=36	6,3	Bs	Cs/t	6,7	Bn	Cn	6,0	Bn	Cn	5,5	Bs	Cs/t	6,6	Bn	Cs/t
10639	Clay PI=24 LL=51	9,7	Bs	Cn	9,3	Bn	Cs/t	8,7	Bs	Cn	10,0	Bs	Cn	11,7	Bs	Cn
10501	Calcrete PI=10 LL=25	3,8	Bs	Cs/t	3,3	Bn	Cs/t	3,3	Bn	Cs/t	4,0	Bs	Cs/t	5,2	Bs	Cs/t
11390	Black soil PI=5 LL=19	2,3	Bs	Cm/t,l	2,5	Bn	Cs/t,l	3,0	Bs	Cs/t	2,3	Bn	Cm/t,l	2,5	Bs	Cm/t,l
1207B	Black clay PI=60 LL=94	22,7	Be	Cm/o	24,0	Bn	Cs/t	22,0	Bn	Cm/t	22,7	Be	Cs/t	21,4	Bs	Ce/t
1207A	Black clay PI=49 LL=90	20,0	Be	Cm/l,o	23,3	Bn	Cs/t	23,3	Bn	Cm/t	20,7	Be	Cm/t,o	21,9	Bs	Ce/t,l

Legend:

LS = % linear shrinkage

Degree of bowing:

Bn = no bowing
Bs = slight bowing
Be = excessive bowing

Degree of cracking:

Cn = no cracking
Cs = slight cracking
Cm = moderate cracking
Ce = excessive cracking

Crack type:

t = transverse
l = longitudinal
o = oblique

The two troughs which showed a significant reduction in bowing, were the TMH 1 loaded trough and the open-sided trough. Whilst cracking still occurred in both troughs, the measurement of the linear shrinkage was much easier as bowing did not occur. It is only when cracking and bowing occur simultaneously that measurement becomes difficult.

While both troughs appeared to have overcome the problem of bowing, observations during testing showed that the loaded troughs had two distinct disadvantages:

- the apparatus was awkward to handle and place in the oven with the weight on top
- the apparatus was relatively expensive to make (each mould would have to have a weight).

Based on the observations during this part of the investigation, it is recommended that the open-sided trough be considered as a replacement of the present TMH 1 trough as it prevents the problem of bowing and reduces the problem of cracking and hence should improve the consistency of measurement of the linear shrinkage of the soil, especially at high plasticity.

3.2.2 Linear Regressions

Having selected a trough to prevent bowing, it is important to understand the correlation of results obtained on this trough, compared to the TMH 1 trough on which present linear shrinkage specifications are based. Table 3 shows the correlation models for the linear shrinkage results shown in Table 1 with the results from each different trough type are compared with the TMH 1 results.

In every case, the correlation coefficient (r) and the r^2 values suggest excellent correlations. Figure 2 shows the regression line for the recommended open-sided trough compared with the results from the TMH 1 trough. The results suggest that for all practical purposes, the LS obtained from this trough can be considered to be equal to the LS obtained from the TMH 1 trough.

Fig 2: Linear shrinkage determinations
TMH 1 trough v open-sided trough

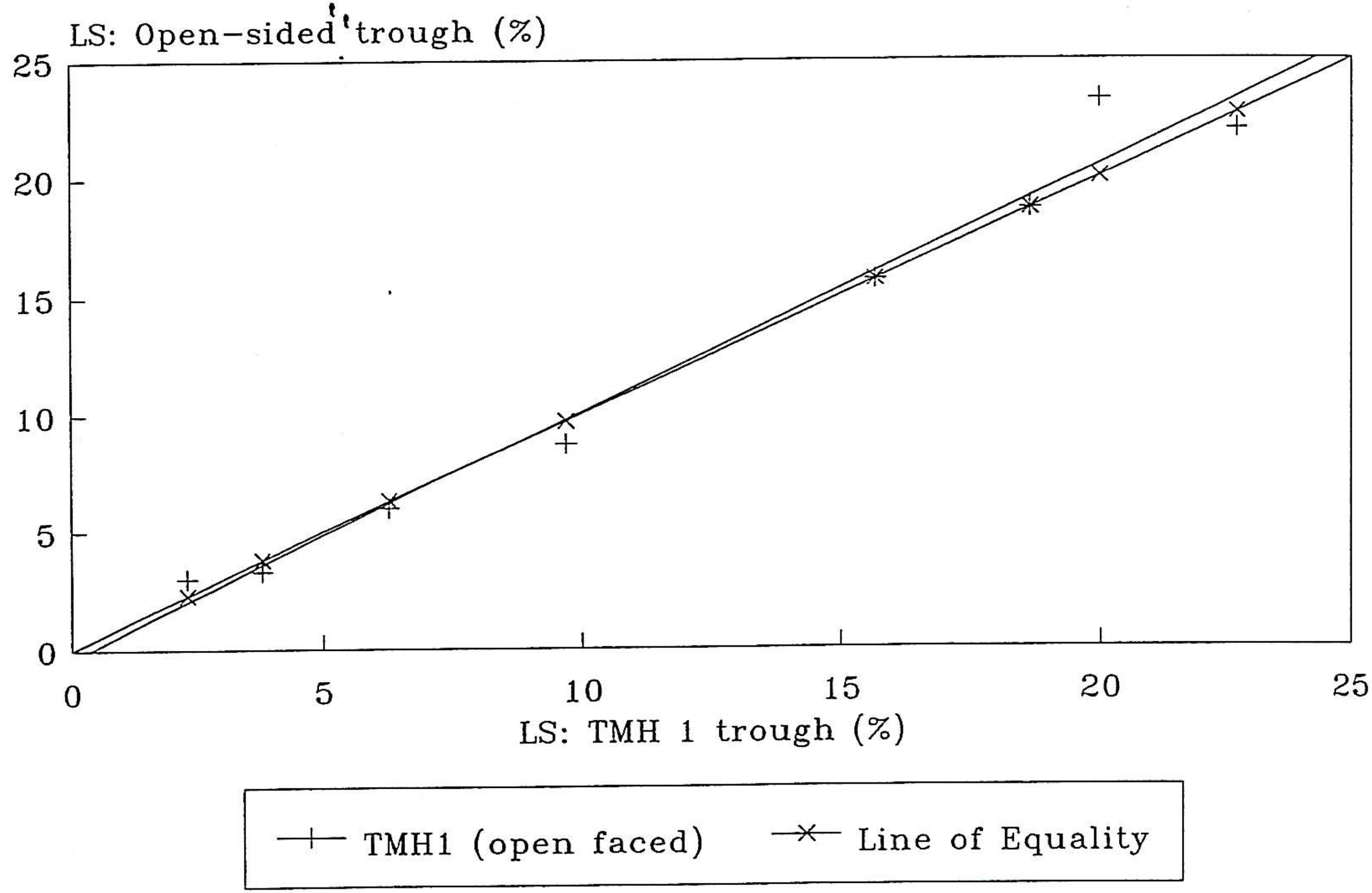


Table 3 : LS correlation models for the various troughs used compared with the TMH1 trough					
Dependent Variable	**MODEL**	**r**	**R^2**	**F**	**SE**
TMH1	0,74 + 0,88 TMH1LOADED	0,995	98,95	566	0,87
TMH1	0,65 + 0,93 TMH1OPEN	0,988	97,53	236	1,34
TMH1	0,19 + 0,98 TMH115	0,999	99,76	248	0,42
TMH1	-0,55 + 0,96 BS	0,984	96,90	187	1,50

TMH1 = Linear shrinkage using TMH 1 trough
TMH1LOADED = Linear shrinkage using TMH 1 trough with 1 kg loaded plate on exposed surface
TMH1OPEN = Linear shrinkage using a trough of TMH 1 dimensions with two open sides
TMH115 = Linear shrinkage using a TMH 1 trough, but 15 mm deep
BS = Linear shrinkage using a BS trough

4 INVESTIGATION OF DIFFERENT DRYING PROCESSES

As outlined in Section 2.1, a possible contributing factor to the poor reproducibility was identified as the drying process used by any particular laboratory. Therefore, it was decided to investigate four different drying techniques to assess the variation in results that could be expected.

All samples were tested according to the specified TMH 1 method at the liquid limit. The troughs specified in TMH 1 were used. The lubricant used in the troughs was silicone grease and the four drying processes were as follows:

- overnight air-drying
- overnight oven-drying at 50°C
- overnight oven-drying at 105°C (TMH 1 method)
- overnight air-drying followed by oven-drying at 105°C

Eight soils were tested with PIs ranging from 6 to 49 and the linear shrinkage results along with material behaviour in terms of cracking and bowing are shown in Table 4.

Table 4 : LS results obtained from different drying methods

Sample No	Material Type	Drying Process											
		Oven dried 105°C (TMH1)			Oven dried 50°C			Air dried			Air dried and oven dried 105°C		
		LS	Bowing	Cracks	LS	Bowing	Cracks	LS	Bowing	Cracks	LS	Bowing	Cracks
D1208	Brown sandy soil PI=6 LL=18	1,3	Bs	Cs/t	1,3	Bs	Cm/t	0,7	Bn	Cs/t	1,7	Bn	Cm/t
11390	Brown soil PI=7 LL=23	2,4	Bs	Cm	2,0	Bn	Cs/l	2,2	Bn	Cm/t	3,1	Bn	Cm/t
D1209	Weathered Granite PI=16 LL=32	5,4	Bn	Cs/t,l	4,4	Bn	Cm/l,t	5,4	Bn	Cm/t	5,3	Bn	Cm/t
D1206	Clay PI=21 LL=38	9,4	Be	Cn	6,7	Be	Cn	6,7	Bn	Ce/t	7,1	Bs	Cm/t
10639	Clay PI=24 LL=51	9,3	Bs	Cn	6,7	Bn	Ce/l,t	9,9	Bn	Cm/t	7,7	Bn	Cs/t
D1205	Black clay PI=33 LL=59	13,1	Be	Cm/l	10,6	Be	Ce/t,l	5,3	Bn	Ce/t,l	11,7	Bs	Cm/t
D1201	Black clay PI=39 LL=56	13,8	Bs	Cs/t,l	no result	Bn	Ce/l,o	12,7	Bs	Cs/o	12,4	Bn	Cm/t,l
D1207A	Black clay PI=49 LL=90	20,0	Bs	Cs/t	19,5	Bs	Cm	9,0	Bn	Cs/t	20,0	Bs	Cm/t

Legend:

LS = % linear shrinkage

Degree of bowing:

Bn = no bowing
Bs = slight bowing
Be = excessive bowing

Degree of cracking:

Cn = no cracking
Cs = slight cracking
Cm = moderate cracking
Ce = excessive cracking

Crack type:

t = transverse
l = longitudinal
o = oblique

4.1 DISCUSSION OF RESULTS

The results in Table 4 show that air-drying overnight eliminated the problem of bowing out of the trough, but had no effect on the degree of cracking it even increased it in some cases. It is also shown that air-drying overnight followed by oven-drying at 105°C significantly reduces the bowing effect but also increases the cracking in some cases. However, oven-drying at 50°C has no significant effect on the degree of bowing and cracking.

Based on the results shown in Table 4, it is not recommended that the drying temperature be reduced to say 50°C as samples of high plasticity can still be expected to bow out of the trough. However, further investigation of the correlation between air-drying and a combination of air-drying and oven-drying is required.

Table 5 shows the correlation models obtained for the three methods compared with the standard TMH 1 drying method. The lines-of-best-fit for the models are shown in Figure 3.

It is shown that the correlation between air-drying and oven-drying at 105°C (TMH 1 method) is poor and does not give a direct correlation. The likely reason for this is that some of the soils were not completely dry when the shrinkage was measured. It is in any event not recommended that air-drying should replace the standard oven-drying at 105°C because it tended to increase the cracking.

Whilst the correlation between the standard method and a combination of air and oven-drying is very good, the air and oven-drying tend to under-predict the TMH 1 linear shrinkage. The under-prediction increases with increased plasticity. For example, a TMH 1 linear shrinkage of 10 would on average be reported 1,5 units lower (8,5) using the combination of air and oven-drying. Similarly, a TMH 1 linear shrinkage of 20, would on average, be 3 units lower.

Although, air-drying followed by oven-drying significantly reduces the bowing effect and improves the accuracy of shrinkage measurement, this advantage is counter-balanced by the variation in results. The results highlight the importance of following the specified test method rigidly, unless the implications of changing any of the procedures within the test methods are fully understood.

From the results of this investigation, it is shown that the method of drying the linear shrinkage trough may significantly affect the result recorded. Under no circumstances, should the standard method of drying immediately in an oven at 105°C be deviated from. Air drying or a combination of air and oven dryingat 105 °C tends to increase the degree of cracking.

Fig 3: Comparison of drying techniques

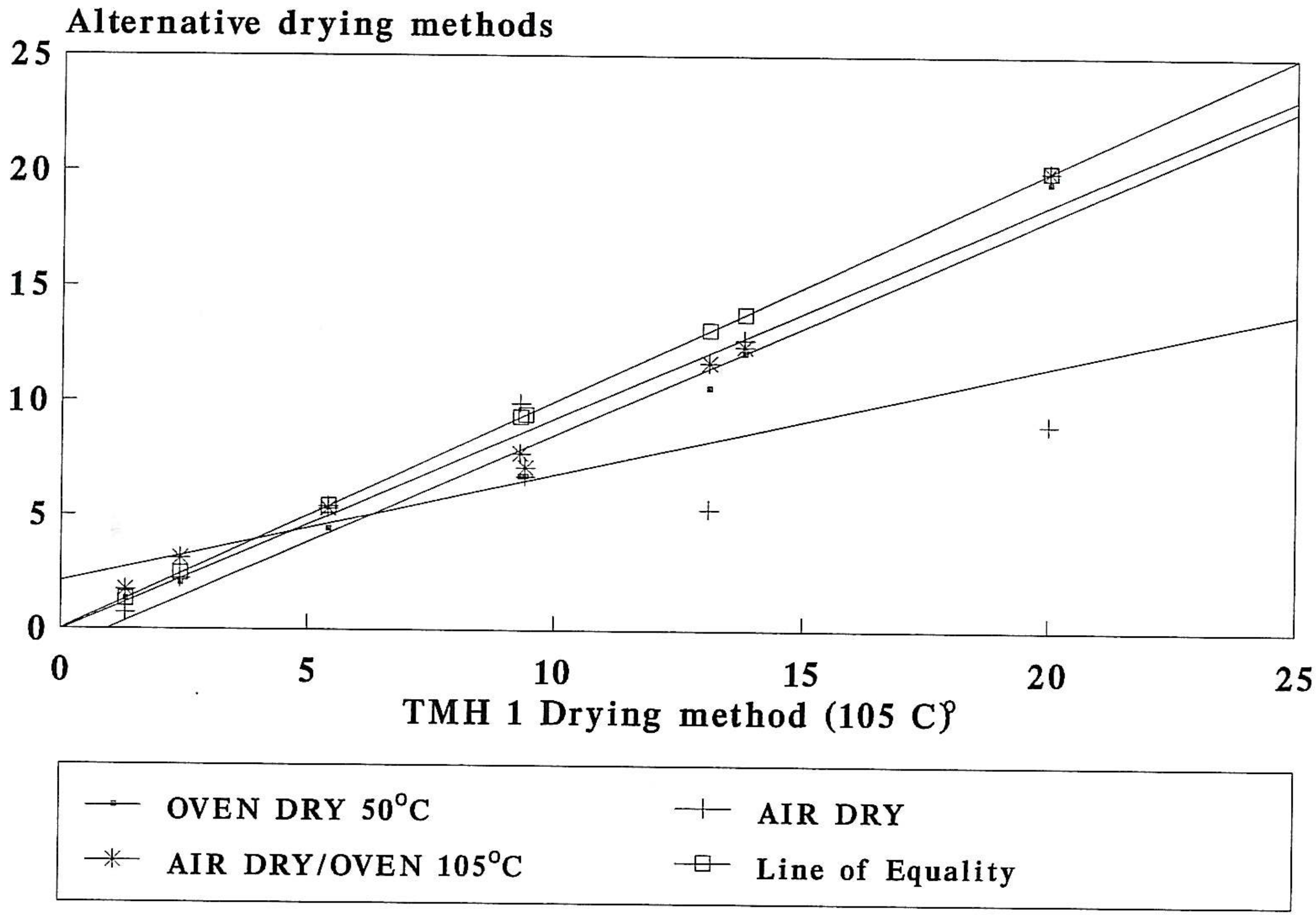


Table 5 : LS correlation models for different drying methods					
Dependent Variable	**MODEL**	**r**	**R_2**	**F**	**SE**
TMH 1 OVEN DRY	1,2 + 1,03 DRY 50	0,985	97,05	197	1,16
TMH 1 OVEN DRY	1,7 + 1,17 AIR DRY	0,745	55,53	7	4,52
TMH 1 OVEN DRY	0,3 + 1,04 AIR/OVEN 105	0,986	97,14	204	1,15

TMH 1 OVEN DRY = Linear shrinkage using TMH 1 method of oven drying at 105°C
OVEN 50 = Linear shrinkage using oven drying at 50°C
AIR DRY = Linear shrinkage using air drying overnight
AIR DRY/OVEN 105 = Linear shrinkage using air drying overnight and drying at 105°C

5 INVESTIGATION OF CORRECTION FACTOR (f)

Note 5.1 of TMH 1 method A4 states that for a soil paste with a moisture content requiring between 15 and 35 taps for groove closure in the liquid limit test, a linear relationship exists between the number of taps N and the shrinkage of the soil paste when dry. Different soil types give different straight line curves and there is a tendency for these lines to converge at about N = 125 when the shrinkage = 0. For this family of straight lines, the relationship between the linear shrinkage from a moisture content equivalent to a liquid limit and the linear shrinkage from the moisture content corresponding to N taps in the liquid limit test is as given in the formula in Section 2 where:

LS = shrinkage in mm as measured x f

The investigation was carried out to evaluate whether or not the values for f given in method A4 are valid for different soil types with different Plasticity Indices and thus, determine the impact of the correction factor (f) on the accuracy of the test results. Twenty different soils with PIs ranging from 3 to 60 were used for the investigation. The shrinkage troughs used were those specified in TMH 1 with silicone grease lubrication instead of the recommended paraffin wax. The full troughs were dried overnight at 105°C. The number of blows shown in Table 6 were achieved by adding water to the dry soil ie the test was carried out from the dry to the wet state.
The linear shrinkage of each soil was determined at five different moisture contents (represented by the number of blows of the Casagrande cup), both by direct measurement (no correction) and by

using the correction formula according to test method A4 of TMH 1 (1979). The uncorrected results were calculated as a percentage of the original length of the soil bar, using the formula:

LS = shrinkage in mm as measured x 100/150

The results are shown in Table 6.

The results from the two linear shrinkage measurements were plotted on the same axis against number of taps for comparative purposes. Examples of the graphs obtained are shown in Figures 4 to 6. The true linear shrinkage value is by definition the value obtained at 25 blows and as can be seen in Figure 4, the results of both methods are the same at this point. The reason for this, is that the correction formula would be 1 at this point, ie:

$$\frac{0{,}8}{1 - 0{,}008 \times 25} = 1$$

As would be expected, the maximum divergence of the curves for the two methods occurs furthest from 25 blows due to the nature of the correction factor. Due to the graphical determination of the LS the two methods do not always coincide at exactly 25 blows

However, observations of the curves obtained with the twenty soils investigated, showed three distinct relationships:

1 The linear shrinkage value of the corrected curve at 15 or 35 blows is further from the true value obtained at 25 blows, than is the case with the measured value (Figure 4). In these cases, the measured value between 15 and 35 blows (at varying moisture content) practically remains the same.

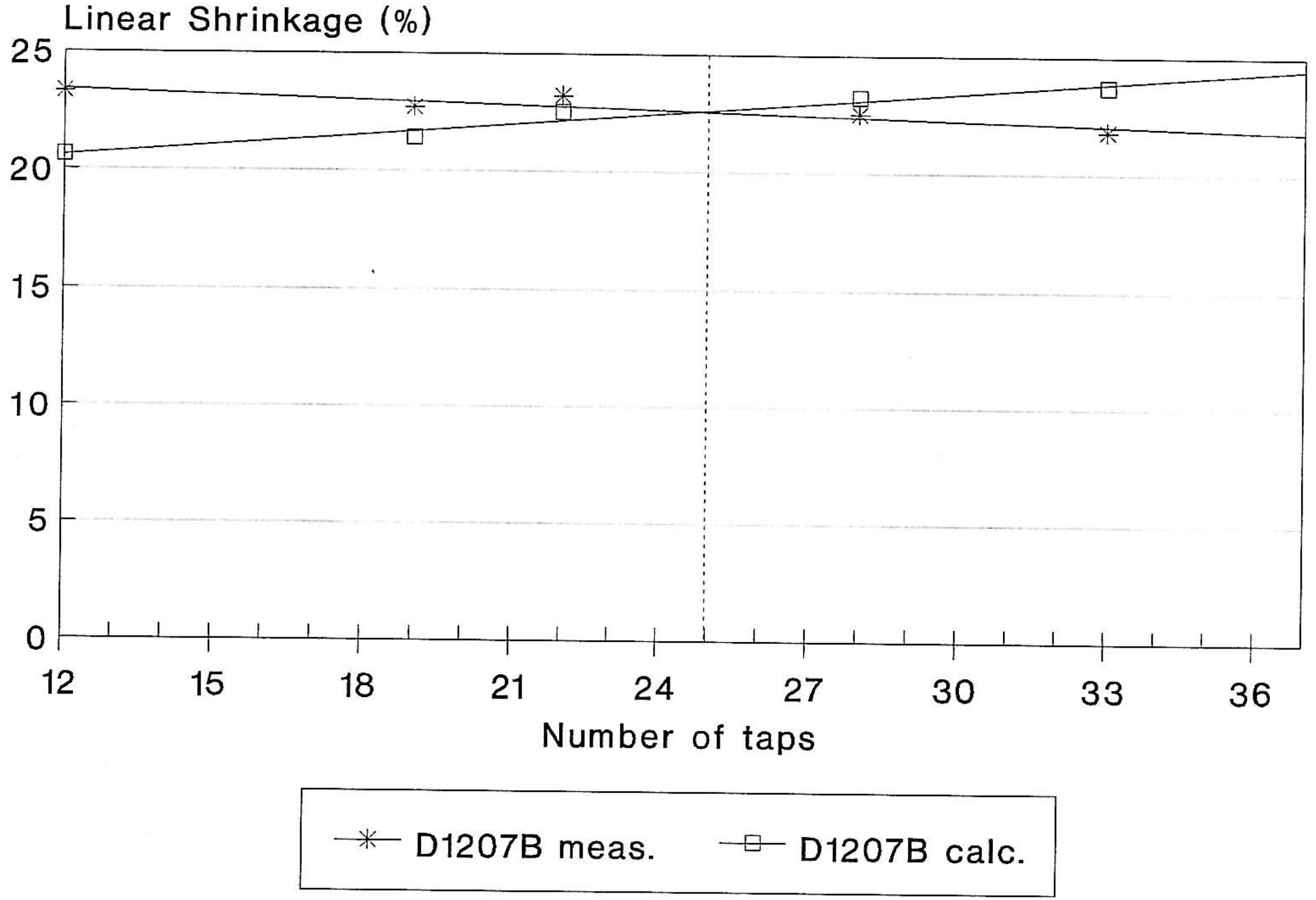
2 The results obtained using the correction factor were all close to the desired value obtained at 25 blows (Figure 5). In these cases the correction factor actually corrected the measured LS to give the true LS at 25 blows.

3 The situation also occurred when neither the correction factor, nor the direct measurement method gave satisfactory results (Figure 6).

TABLE 6 : LINEAR SHRINKAGE - CORRECTION FACTOR

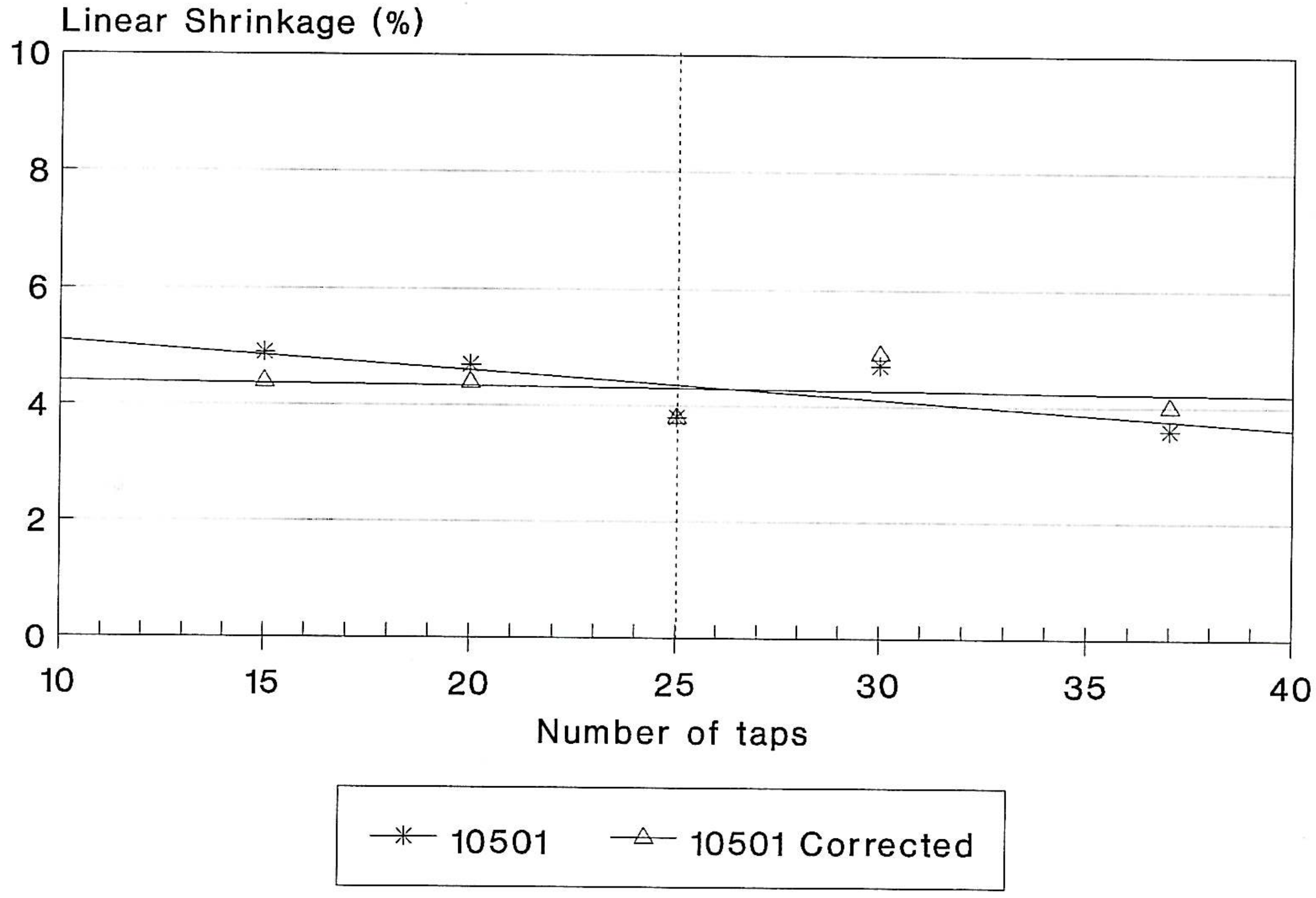
SAMPLE NO	No OF BLOWS	MEASURED SHRINK (mm)	% SHRINK	PRED LS (%)	ACTUAL LS (%) 25 BLOWS	DIFF	MEAN DIFFERENCE	PI
12699	12 18 28 35	5,6 4,8 5,0 4,1	3,7 3,2 3,3 2,7	3,2 3,0 3,4 3,0	3,4	0,2 0,4 0 0,4	0,25	5,8
12739C	15 19 23 30 36	5,6 5,0 6,0 5,0 4,5	3,7 3,3 4 3,3 3	3,4 3,1 4,0 3,5 3,4	3,5	0,1 0,4 0,5 0 0,1	0,22	7
12739A	15 21 26 30 37	5,0 6,0 6,0 5,6 5,6	3,3 4 4 3,7 3,7	3,0 3,8 4,0 3,9 4,2	3,8	0,8 0 0,2 0,1 0,4	0,30	9
12714	15 21 25 29 35	4,5 3,0 4,1 3,5 3,0	3 2 2,7 2,3 2	2,7 1,9 2,7 2,4 2,2	2,4	0,3 0,5 0,3 0 0,2	0,26	4
D1206	16 22 26 31 37	15,5 15,5 14,0 13,1 12,0	10,3 10,3 9,3 8,7 8	9,5 10,0 9,4 9,2 9,1	9,5	0 0,5 0,1 0,3 0,4	0,26	22
D1207	12 19 22 28 33	35,0 34,1 34,8 33,8 32,7	23,3 22,7 23,2 22,5 21,8	20,6 21,4 22,5 23,2 23,7	22,5	1,9 1,1 0 0,7 1,2	0,98	60
D1209	18 21 26 31 36	11,0 10,5 8,0 9,0 9,0	7,3 7 5,3 6 6	6,8 6,7 5,4 6,4 6,7	6,5	0,3 0,2 1,1 0,1 0,2	0,38	15
D1210	17 26 35	22,1 22,1 22,1	14,7 14,7 14,7	13,6 14,8 16,3	14,7	1,1 0,1 1,6	0,93	38
D1211	15 20 27 36	20,0 21,0 20,3 17,6	13,3 14 13,5 11,7	12,1 13,3 13,8 13,1	13,1	1 0,2 0,7 0	0,48	29
10499	11 12 14 17 24 30 35	12,6 12,0 11,0 11,0 9,5 9,8 9,0	8,4 8 7,3 7,3 6,3 6,5 6	7,4 7,1 6,6 6,8 6,3 6,8 6,7	6,7	0,7 0,4 0,1 0,1 0,4 0,1 0	0,26	13
D1202	17 20 26 32 37	30,0 30,5 30,0 30,0 29,4	20 20,3 20 20 19,6	18,5 19,5 20,1 21,4 22,2	20,1	1,6 0,6 0 1,3 2,1	1,12	49
10639	14 19 21 25 31 34	16,7 16,7 14,6 15,2 14,9 15,3	11,1 11,1 9,7 10,1 9,9 10,2	10 10,5 9,3 10,1 10,5 11,3	10,5	0,5 0 1,2 0,4 0 0,8	0,48	24
D1201	16 22 27 31 37	28,1 26,3 28,1 28,1 26,1	18,7 17,5 18,7 18,7 17,4	17,1 17 19 19,9 19,8	18,3	1,2 1,3 0,7 1,6 1,5	1,26	31
11616	16 21 26 31 37	2,9 2,6 2,0 3,3 3,2	1,9 1,7 1,3 2,2 2,1	1,7 1,6 1,3 2,3 2,4	1,8	0,1 0,2 0,5 0,5 0,6	0,38	4
11390	15 21 26 31 35	4,7 3,6 3,5 3,9 3,9	3,1 2,4 2,3 2,6 2,6	2,8 2,4 2,4 2,7 2,8	2,6	0,2 0,2 0,2 0,1 0,2	0,18	5
10501	15 20 25 30 37	7,4 7,1 5,7 7,1 5,4	4,9 4,7 3,8 4,7 3,6	4,4 4,4 3,8 4,9 4	4,4	0 0 0,6 0,5 0,4	0,30	10
10500	11 17 24 27 35	9,2 9,0 8,3 7,8 6,8	6,1 6 5,5 5,2 4,5	5,4 5,5 5,4 5,3 5	5,3	0,1 0,2 0,1 0 0,3	0,14	14

Fig. 4: Example where corrected LS is further from true LS



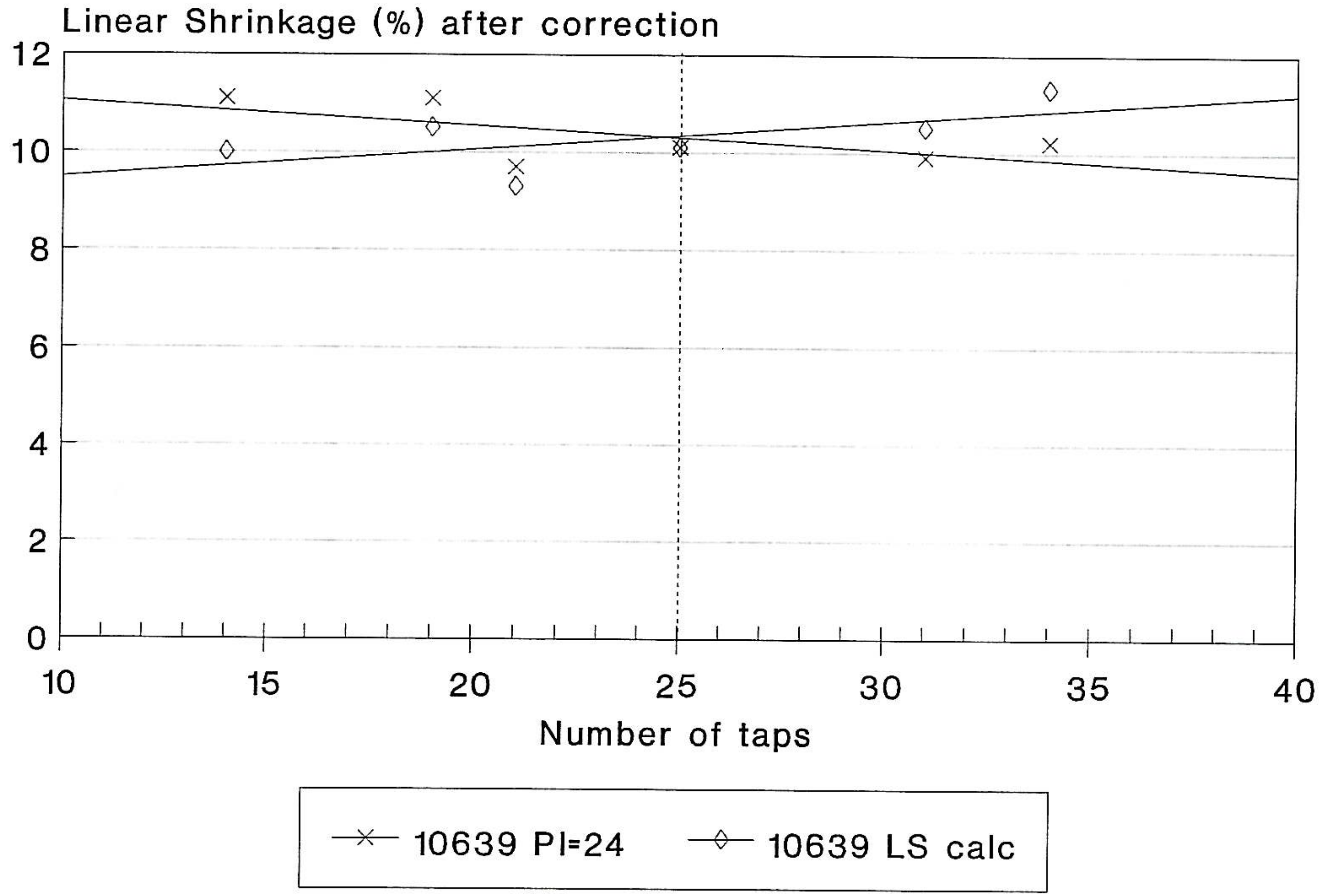
(Drying at 105°C)

Fig. 5: Example where corrected LS is close to true LS



(Drying temp. 105 ℃)

Fig. 6: Example where LS from both methods diverge from true LS



(Oven drying at 105°C)

The results suggest that the present correction factor should not be used indiscriminately to obtain the true linear shrinkage value at 25 blows for all soil types. There appears to be three different situations; one where the correction formula should be applied to obtain the correct shrinkage value; another where no correction is necessary and a third, where a different correction formula should be devised to obtain an accurate linear shrinkage result.

To further investigate the problem, the maximum error possible (at 15 and 35 blows) was calculated for both the corrected and measured linear shrinkage. An example of this is shown in Figure 7 where the actual linear shrinkage value at 25 blows is 13,1 %. The measured and corrected shrinkage values at 15 blows are 13,9 and 12,7 respectively. This represent an error of 6,1 % for the measured linear shrinkage value and an error of 3,1 % for the corrected linear shrinkage value.

The maximum error for both the measured linear shrinkage and the linear shrinkage after correction were plotted against plasticity index (Figure 8). The results show the following three distinct areas:

- Sector F1 for soils with PIs between 0 and 24 where the linear shrinkage obtained by using the correction factor, shows little variation from the true linear shrinkage
- Sector F2 for soils with PIs from 24 to 30 require a different correction formula to be applied.
- Sector F3 for soils with PIs equal to or greater than 30 where no correction factor is required.

For soils falling in sector F2 (ie soils with PIs from 24 to 30), both the measured and the corrected values would apparently give maximum errors of approximately 8 % when compared to the true linear shrinkage at 25 blows. An alternative correction formula was therefore devised which reduced the maximum error to 2,5 %. The recommended correction formula for these soils is as follows:

LS = shrinkage in mm as measured x f1

where

$$f1 = \frac{100}{150} \times \frac{0,9}{1 - 0,004N}$$

Fig. 7: Example of maximum error at 15 taps

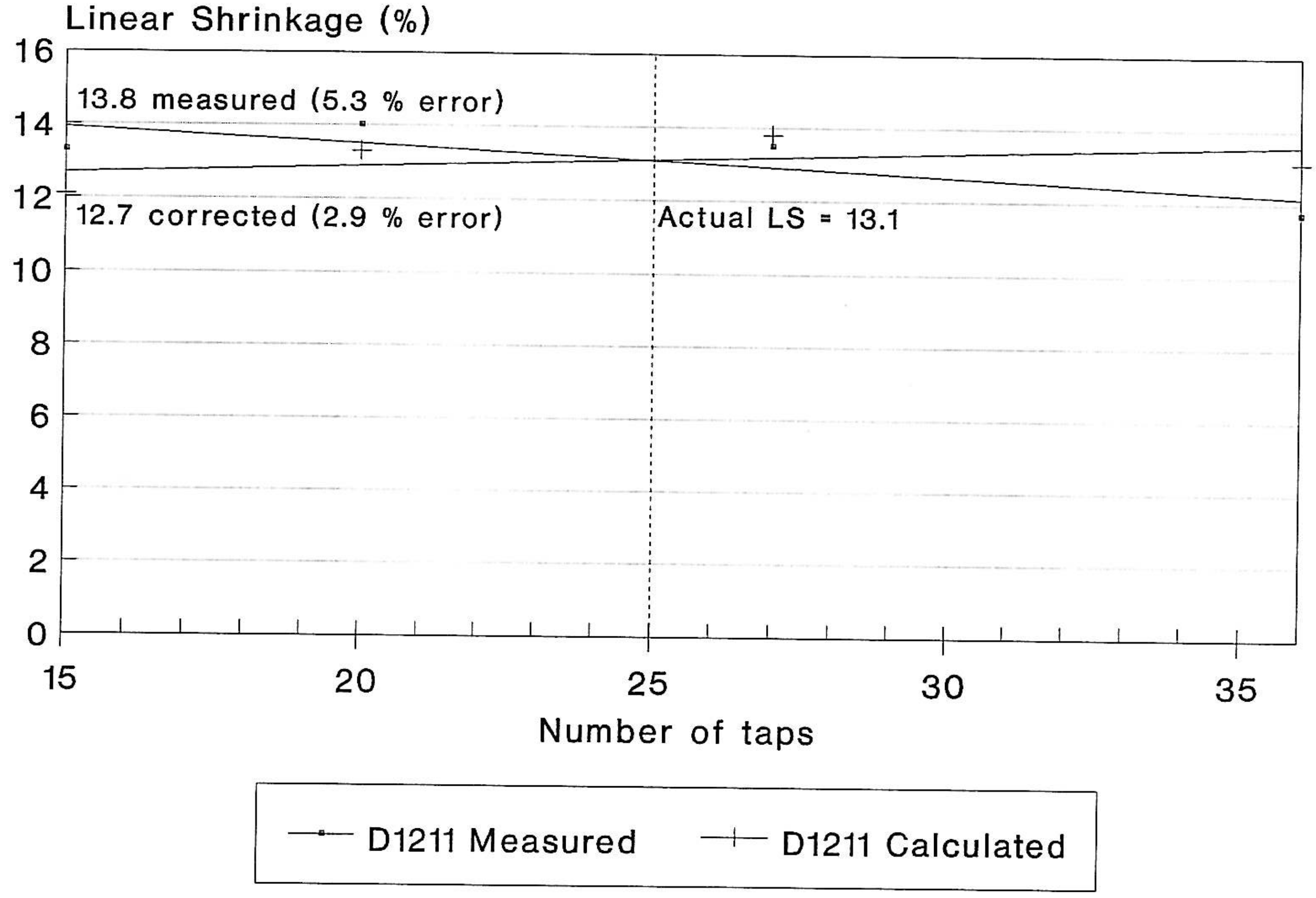
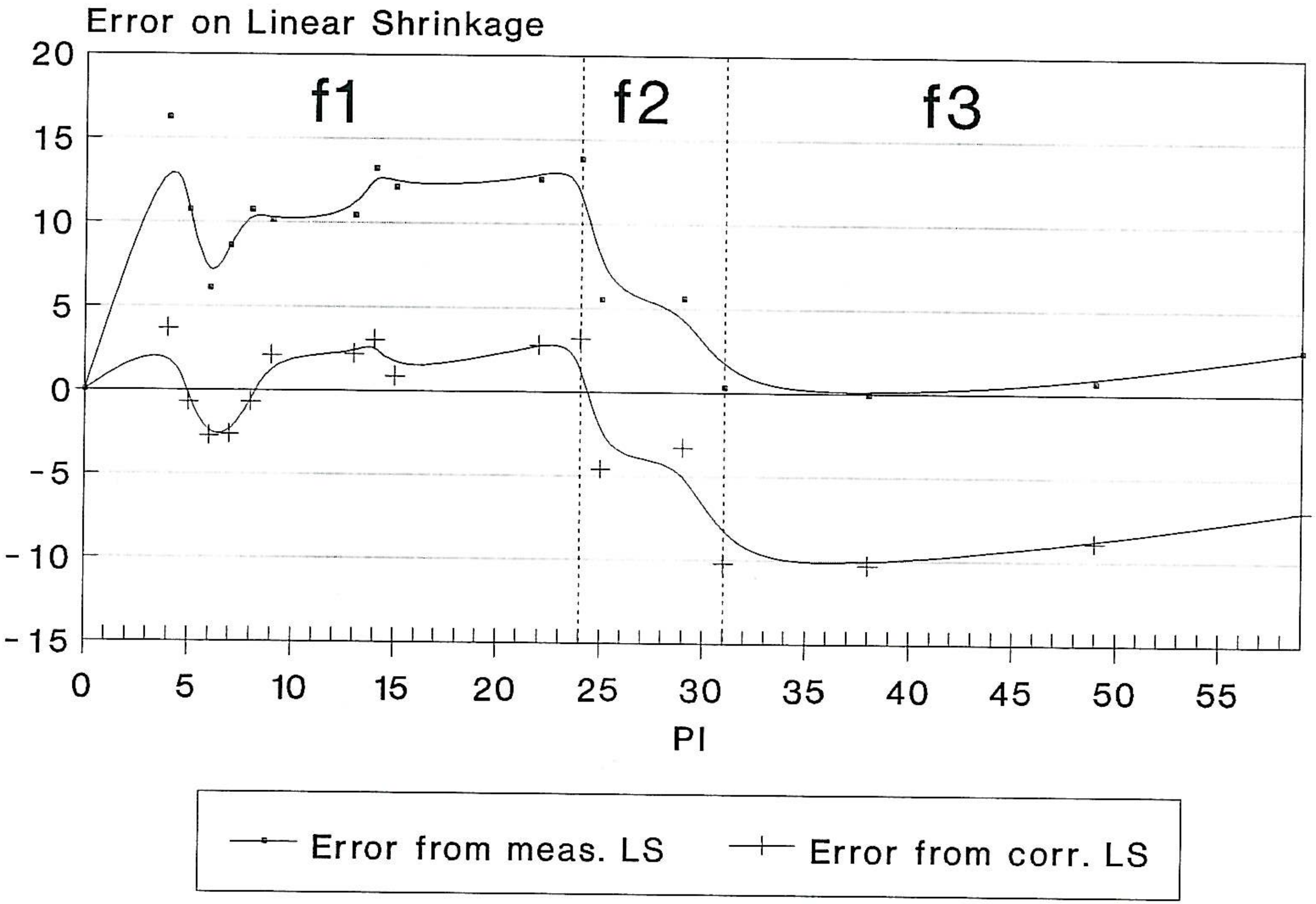


Fig. 8: Maximum error of L.S before and after correction.



6 LUBRICATION OF TROUGHS

It was postulated that the type of lubricating agent used in the troughs would have an effect on the amount of shrinkage and the degree of cracking and bowing. To verify this, four different kinds of lubricating agent were used in the standard trough:

silicone grease
lithium-based grease
vaseline
paraffin wax (specified in TMH 1)

The troughs with the different lubricating agents were all filled with soil and dried overnight in an oven at 105°C. The linear shrinkage measured were all of the same order and the degree of bowing and cracking was similar. Therefore, in terms of the results reported, the type of lubrication is unlikely to have a significant effect on the reported linear shrinkage results.

However, the silicon grease was found to be more suitable from a practical point of view in that it was easy to apply and retained its effectiveness over the temperature range used in the test. Vaseline and paraffin wax penetrated the specimen during drying and was less satisfactory. A study by Newill (1961), also showed that silicone grease was the most suitable lubricating agent. In his investigation, the suitability of paraffin wax, silicone grease, vaseline, oil and graphite was assessed. Newill also found that the paraffin wax, vaseline and oil penetrated the sample during drying and also that the graphite coating did not prevent the soil from sticking to the trough.

7 FILLING OF THE LINEAR SHRINKAGE TROUGH

Another possible reason for the poor reproducibility was identified as the possible variation that could occur in the amount of soil placed in the shrinkage troughs. It is possible that a reduced mass of soil compacted into the same volume could shrink and crack more than a well compacted, homogeneous mass with lower air voids.

In this investigation, three different soils were thoroughly mixed with water to a moisture content equivalent to the liquid limits. Two troughs (TMH 1 type) were filled according to the TMH 1 method by three different operators. The troughs were then weighed and the density of the soil calculated after which the wet mass was corrected for a standard trough volume of 15,2 ml.

From the results in Table 7, it is shown that the mass differences obtained were negligible. The highest average difference for the results of one operator was 0,22 gms or 0,8 %. The highest average difference between operators was 0,33 gms, or 1,2 %. It was therefore concluded that in these cases the mass difference in filling the troughs was not a contributing factor to poor reproducibility and that the method of filling the troughs specified in TMH 1 (1979), is acceptable.

TABLE 7 : SOIL MASS DIFFERENCES OF FILLED TROUGHS

Sample	Corrected mass of soil in troughs (g)					
	Operator A		Operator B		Operator C	
	Trough 47	Trough 50	Trough 52	Trough 53	Trough 56	Trough 57
D1206	27,00	27,68	27,51	27,68	27,31	27,38
D1205	24,85	24,94	24,94	24,79	24,85	24,75
D1208	30,73	30,63	30,29	30,10	31,40	31,13
Mass Average	27,53	27,75	27,58	27,52	27,85	27,75

8 CONCLUSIONS AND RECOMMENDATIONS

From the results and observations of the test method, the following conclusions and recommendations are made:

- the open-sided (two-sided) Central African Standard type shrinkage trough is recommended to replace the present TMH 1 trough. The results show that this trough significantly reduces the bowing effect experienced with the present trough at high plasticities. This should give a significant improvement to the accuracy and consistency of actual shrinkage measurements which will also significantly improve the reproducibility of the method.

- the use of the open-sided trough will not affect the present specification limits related to linear shrinkage. For all practical purposes, the two troughs give identical results within the PI range 0 to 60.

- under no circumstances should drying methods which deviate from that specified in TMH 1 be used. The results show that air-drying during any part of the drying process could have a significant effect on the linear shrinkage recorded. The importance of not deviating from any activity in the specified method cannot be over-emphasised. Whilst it reduces bowing air drying may increase cracking and also gave lower LS results when compared to oven drying.

- the correction formula given in method A4 should only be applied for soils in the PI range 0 to 24. For soils with PIs in the range 24 to 30, the alternative correction factor shown in Section 5 should be used and for soils with PIs greater than 30, no correction factor should be used.

- Ater perusal of the data it is also recommended that the test be carried between 20 and 30 blows of the Cassagrande cup as this also increases the accuracy of the results obtained.

- the type of lubrication appears to have little or no effect on the linear shrinkage results. However, for practical purposes, it is recommended that method A4 is changed to specify silicone grease as opposed to paraffin wax. Observation show that paraffin wax is absorbed into the soil sample on drying and could affect the lubrication of the troughs.

- the mass of soil used for filling the troughs appears to be very consistent and is unlikely to have any significant effect on the reproducibility of the test.

- Operators should be instructed to report the results as obtained and never to adjust them to half the PI, or the PI to twice the LS.

- the above recommendations should be conveyed to the Materials Testing Sub-committee for approval, following which the test method A4 of TMH 1 (1979) should be modified to incorporate the changes. It is recommended that this method is then reinstated as a standard method in TMH 1. With the changes made, it is likely that this test will have precision limits better than those for the plasticity index.

9 ACKNOWLEDGEMENTS

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10 REFERENCES

1 AMERICAN SOCIETY FOR TESTING AND MATERIALS (1990). Use of the terms precision and bias in ASTM test methods. In: 1990 Annual book of ASTM Standards, Part 14: Designation E177 - 90a, pp 501 - 512, ASTM Philadelphia,.

2 British Standards Institution, Methods of test for soils for engineering purposes. BS1377, BSI, London, 1975.

3 Committee of State Road Authorities. The structural design, construction and maintenance of unpaved roads. Technical Recommendation for Highways No 20, Department of Transport, Pretoria, 1990.

4 National Institute for Transport and Road Research, Standard methods of testing road construction materials. Technical Methods for Highways No. 1, CSIR, Pretoria, 1979.

5 Netterberg, F., Calcrete in road construction. Research Report 286, CSIR, Pretoria, 1971.

6 Netterberg, F., Calcrete wearing courses for unpaved roads. Research report 228, CSIR, Pretoria, 1978.

7 Netterberg, F. (1979a), Effect of drying temperature on the index properties of calcretes. Trans. Res. record, (675), pp. 24-32.

8 Newill, D., An investigation of the linear shrinkage test applied to tropical soils and its relation to the Plasticity Index. Research Note No. RN/4106/DN (Unpublished), Department of Scientific and Industrial Research, Road Research Laboratory, 1961.

9 Paige-Green, P., Specifications for wearing-course materials for unpaved roads. NITRR Research Report DPVT 75, CSIR, Pretoria, 1989.

10 Sampson, L. R., A reproducibility study of Atterberg limits determined by the Casagrande methods and by an extended British cone penetrometer method. Division of Road and Transport Technology, Technical Report RP/5, CSIR, Pretoria, 1985.

11 Semmelink, C. J., An index for describing the compactibility of untreated roadbuilding materials. NITRR, Report DPVT-141, CSIR, Pretoria, 1990.

12 STANDARDS ASSOCIATION OF CENTRAL AFRICA. Methods of testing soils for engineering purposes. Central African Standard No. 185: Part 2. SACA, Harare, 1977.