

Effect of Drying Temperature on the Index Properties of Calcretes

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Atterberg limits, shrinkage factors, and other properties of calcrete soil fines determined after drying at 105°C were compared with the results of similar tests carried out on air-dried material and showed significant decreases in liquid limits and in plasticity indexes by up to 4 percentage points. The maximum decrease in any particular case is predictable. Bar linear shrinkage was affected relatively little. The effects caused by drying at 50°C were generally more subdued and erratic, but more tests are required to determine whether drying at the lower temperature offers any advantage. These phenomena are chiefly ascribed to the presence of the clay mineral palygorskite, which is common in calcretes and other soils of the arid and semiarid zones. The contribution of wetting and drying cycles to a further decrease in liquid limit, plasticity index, and bar linear shrinkage is ascribed to cementation effects. The effects found provide a partial explanation of the good performance of apparently substandard calcrete roads. The practical significance of such effects can be minimized by standardization of drying procedures, which must be the same both in deriving specifications and in quality control.

Soils are usually air- or oven-dried as part of preparation methods for particle size analysis and testing of Atterberg limits and shrinkage factors. However, it is well known that oven drying and even air drying affect the properties of some soils. Thus, for example, AASHTO T 87-72, AASHTO T 146-49, Tex-101-E of the Texas Highway Department, and FAA P-210-2.2 of the Federal Aviation Agency specify drying at not more than 60°C. BS 1377:1975 of the British Standards Institute specifies a maximum of 50°C, with a note that even air drying may affect organic and tropical soils, whereas in the case of many other soils drying at 105°C to 110°C has little effect. ASTM D 421-58 specifies air drying at room temperature only, whereas ASTM D 2217-66 makes provision for two procedures—one for drying at up to 60°C and one for maintaining a sample at or above its natural moisture content (although removal of excess water added during preparation by boiling or heating to 110°C is permitted). The method most commonly used for highway work in South Africa, Department of Transport DOT A.1 (a)—

1970, permits drying at 105 to 110°C. Soils in arid and semiarid zones are usually assumed to be insensitive to drying although no work appears to have been published on the effect of heat on the properties of calcretes (caliches) and other such soils. Extensive use has been made of caliches in the United States by the Texas Highway Department and the Federal Aviation Agency (FAA), both of whom specify a maximum drying temperature of 60°C (3, 4). It is also probably significant that the soil preparation method of the Texas Highway Department, Tex-101-E, is a wet slaking method, whereas FAA specifically states that their wet slaking modification, item P.210-2.2 of AASHTO T 87, shall be used on caliches. The work of Gillette (1) and McDowell (2) suggests that caliches are among those materials most strongly affected by whether a dry or wet preparation method is used, but no comment was made on the importance of drying temperature. At the time of Gillette's earlier study (3), it would appear that only air drying (4) was in use.

As part of a wider study (5) and in view of the common use in South Africa of a method that permits drying at 105°C to 110°C, a limited investigation was carried out on the effect of drying temperature on South African calcretes, the results of which are reported in this paper.

MATERIALS, METHODS, AND RESULTS

Some relevant properties of the 18 southern Africa calcretes used are given in Tables 1 and 2. Most were unused natural (bank run) soil-aggregate calcretes. A few were taken from bases with more than 20 years' service and included some crushed calcrete as a form of waterbound macadam. All were composed of subrounded to subangular, equant to irregularly shaped coarse aggregate composed of calcite- or dolomite-cemented fines in a matrix of fines composed chiefly of quartz, calcite, dolomite, and clay minerals. The calcretes were chosen to represent materials ranging from subgrade to base course quality and a wide variety of clay minerals. All had been dry or only slightly moist when sampled

Table 1. Classification and gradation data for calcretes studied.

Sample Number	Source	AASHTO Classification	Percentage Passing Sieve						
			38 mm	19 mm	6.4 mm	2.0 mm	0.42 mm	0.074 mm	0.002 mm
2114	Stockpile	A-2-6(0)	100	95	84	65	43	24	8
2116	Stockpile	A-2-6(0)	78	67	52	41	34	23	10
2223	Stockpile	A-4(3)	100	95	90	87	83	73	6
2367	Stockpile	A-1-b(0)	93	89	68	52	46	17	11
2478	Stockpile	A-2-6(0)	87	71	49	41	33	7	7
2479	Stockpile	A-2-7(0)	96	86	58	45	35	10	9
2493	Stockpile	A-2-4(0)	100	80	56	48	39	14	7
6822	Stockpile	A-2-6(0)	100	100	63	44	30	13	9
6839	Stockpile	A-2-4(0)	100	83	62	50	46	21	12
6842	Stockpile	A-1-b(0)	97	76	53	41	37	20	9
6844	Stockpile	A-2-4(0)	96	87	56	45	33	11	9
6846	Stockpile	A-2-7(0)	92	69	49	39	27	14	9
6872	Base	A-2-4(0)	92	86	77	70	58	18	14
6889	Base	A-2-4(0)	100	96	88	77	61	32	19
6897	Base	A-2-6(0)	100	100	92	81	63	34	15
6935A	Pit face	A-2-6(0)	100	100	99	95	74	18	16
7088	Base	A-1-b(0)	91	83	70	61	44	15	11
7089A	Base	A-1-a(0)	78	56	40	32	21	8	6
7089B	Base	A-1-a(0)	85	67	48	38	26	10	7

Table 2. Physical and chemical properties of soil fines of calcretes studied (minus 0.42-mm fraction).

Sample Number	w _L (%)	I _p (%)	L _p (%)	G _s	Mineralogical ^a	CO ₂ (%)	FeO (%)	Organic C (%)	pH	Salts (%)
2114	40	14	8.0	2.680	Q, C, P, M	19.9	0.08	0.42	7.9	0.05
2116	26	11	6.0	2.694	Q, C, P	20.6	0.13	0.39	8.2	0.04
2223	24	7	0.6	2.709	C, Q, M, F, V, P	37.9	0.02	0.38	8.2	0.02
2367	32	SP	6.3	2.689	Q, C, I, D, M, A	39.0	-	0.13	9.0	0.4
2478	33	13	3.2	-	Q, F, C, S, P, I	4.56	0.10	0.24	8.8	0.2
2479	42	21	5.7	-	Q, C, D, F, S, I, P	7.86	0.14	0.31	8.2	0.06
2493	33	9	5.3	2.662	C, Q, D, S, P, A	5.3	-	0.46	8.0	0.05
6822	33	14	6.3	-	Q, C, F, D, S, I, P	12.57	0.37	0.33	8.4	0.09
6839	26	10	3.0	-	Q, F, C, P, D, I	9.49	0.85	0.30	8.3	0.3
6842	20	6	3.3	-	Q, C, F, MU, CH, H	15.71	1.00	0.25	8.2	0.03
6844	33	10	4.7	-	Q, F, C, P	7.05	3.08	0.19	9.6	0.2
6846	50	23	8.0	-	Q, F, D, C, P, I	5.91	0.12	0.16	8.7	0.03
6872	-	NP	0.0	-	Q, C	20.07	0.53	0.34	8.4	0.04
6889	25	9	4.7	-	Q, C, F, I	27.43	1.05	0.59	8.0	1.2
6897	27	11	4.2	-	C, Q, I, F	27.91	0.40	0.30	8.4	0.1
6935A	34	14	4.0	-	Q, S	0.94	0.21	0.06	7.9	0.03
7088	16	2	0.0	-	Q, C	23.76	0.21	0.33	7.8	0.2
7089A	22	4	1.8	-	Q, C	25.96	0.48	0.40	8.1	0.1
7089B	22	6	1.6	-	-	-	-	-	-	-

^aProperties are given in approximate order of abundances by X-ray diffraction. A = amorphous, D = dolomite (ferroan), I = illite, P = palygorskite, S = sepiolite, C = calcite, F = feldspar, M = montmorillonite, Q = quartz, V = vermiculite, MU = muscovite, CH = chlorite, and H = hornblende.

Table 3. Precision of index tests by single operator using single apparatus on one calcrete and four British soils.

Item	w _L (%)	w _p (%)	I _p (%)	I _r (%)	I _r (%)	L _p (%)
Sample 7089B ^a						
	22.1	16.2	5.9	5.8	1.0	2.0
	22.5	17.0	5.5	5.8	1.0	2.0
	22.5	16.7	5.8	6.8	0.9	1.7
	22.7	16.3	6.4	6.8	0.9	1.7
	22.5	17.5	5.0	7.6	0.7	1.3
	22.0	16.2	5.8	5.6	1.0	1.3
	21.9	16.1	5.8	5.6	1.0	1.5
	22.5	17.5	5.0	4.6	1.1	1.5
	22.8	15.9	6.9	6.0	1.2	2.0
	22.4	17.3	5.1	7.0	0.7	1.3
Statistical data						
\bar{X}	22.4	16.7	5.7	6.2	1.0	1.6
s	0.3	0.6	0.6	0.9	0.2	0.3
Range	-0.5 to +0.4	-0.8 to +0.8	-0.7 to +1.2	-1.6 to +1.4	-0.3 to +0.2	-0.3 to +0.4
s, %	1	4	11	15	20	18
D2S	1.0	1.9	1.9	2.9	0.6	1.0
D2S, %	3.2	13	35	48	64	58
n	10	10	10	10	10	10
Four British soils ^b						
s	0.4 to 0.6	0.2 to 0.7	0.4 to 0.9	-	-	-
s, %	0.8 to 1.4	0.9 to 3.7 ^c	0.8 to 4.3	-	-	-
D2S	1.3 to 1.9	0.6 to 2.2	1.3 to 2.8	-	-	-
D2S, %	2.9 to 4.5	2.9 to 11.8 ^d	8.0 to 13.4	-	-	-
Selected D2S	1.5	2.0	2.0	3.0	1.0	1.0

^aTested by operator B by using one ASTM D 423-66 type of liquid limit device and method a.

^bWith w_L = 31 to 66 and n = 6 or 10/soil (9).

^cOnly one above 1.0.

^dOnly one above 3.6.

and had been in storage for some months or years before testing. All came from the semiarid or arid zone, which receives a normal annual rainfall of less than about 550 mm.

Except for the FeO and organic matter determinations on samples 2114 to 2367 and 2493, which were carried out after drying at 105°C to 110°C, all testing was carried out on material air-dried at ambient temperature, and the results were expressed on an oven-dry (105°C to 110°C) basis. The National Institute for Transport and Road Research (NITRR) methods current at the time (6) were used in determining Atterberg limits, bar linear shrinkage from the liquid limit, specific gravity, and particle size. These methods involved a preparation method for dry soil, permitted only air drying, and required a period of overnight presoaking of the soil fines (minus 0.42-mm fraction) before testing by a four-point flow curve method that required using a BS 1377:1961 liquid limit device and an ASTM D 423-66 grooving tool. The maximum error made by operator A in interpreting liquid limit from the flow curve during routine liquid limit

determinations on 60 calcretes by this method was found to be 0.5 percentage points at the 95 percent confidence level (5). Organic matter contents of samples 2114 to 2367 and 2493 were determined by dichromate oxidation with protection against chlorides (7) and of the others by dry combustion after removal of carbonate, pH on the saturated paste (8), and soluble salts by electrical conductivity of the saturated paste (8).

The ability of an operator to repeat results on nominally identical material by using the same apparatus must be known before the results of a comparison of methods can be properly evaluated. Table 3 gives an estimate of this precision of operator and apparatus for some index tests on one calcrete sample in comparison with the precision found for tests by comparable methods on four British soils (9) that covered a roughly similar range of Atterberg limits. The difference two-sigma (D2S) limits were calculated by Netterberg and are corrected for the sample number (n). The D2S limit is the recommended form of precision statement for construction materials and

represents the maximum acceptable difference between two results obtained on test portions of the same material "that would be equalled or exceeded in the long run in only one case in 20..." (10). The flow index (I_f) was calculated from the following formula, modified from Casagrande (11):

$$I_f = 2 (W_{10 \text{ blows}} - W_{32 \text{ blows}}) \quad (1)$$

The toughness index (I_T) was calculated from the following formula (11):

$$I_T = I_p / I_f \quad (2)$$

First, a pilot study was carried out on five calcretes in which the effect of heating both wet and dry material at both 50°C and 105°C to 110°C on a number of index properties was investigated. After each sample was air-dried (most were already air dry) at ambient temperature (about 20°C), the soil fines were separated by dry screening, mixed in a rotary mixer for 10 min, and split into five portions by using a riffler with 6.7-mm slots, each portion just large enough for the particular test planned. Portion a was tested untreated, portion b after heating at 50°C for 36 h, and portion c after heating at 105°C for 24 h. Portions d and e were soaked for 24 h at about 1.5 times the liquid limit and dried at 50°C for 36 h and at 105°C for 24 h respectively. The 36-h drying had to be adopted because 24 h at 50°C was insufficient. The old NITRR method (6) was used for liquid limit (w_L), plastic limit (w_p), and bar linear shrink-

age (L_s) except that all material was presoaked for 24 h at about 1.5 times the liquid limit before testing in place of the usual "overnight" presoaking. Except for the liquid limit method, these methods were similar to methods of the South Africa Department of Transport current at the time (12). The shrinkage factor (V_s , w_s , R) method was that of Lambe (13) (from the liquid limit), and methods for absorption limit (w_a) and petrification degree (PD) were those of Nascimento, de Castro, and Rodrigues (14).

The results of this study are given in Tables 4, 5, 6, 7, and 8.

A further study limited to the effect of air drying (method a) versus drying a wet material at 105°C to 110°C (method e) on the index properties of greatest interest, i.e., liquid and plastic limits and bar linear shrinkage, was then carried out on a further 13 calcretes (Tables 9 and 10). In addition to a standard statistical analysis for significance α by a two-sided, paired-sample Student's t -test (15), this table also gives the number of results n that lie outside the 95 percent confidence interval CI and the D2S limits selected from Table 3 as well as the range corrected for these limits.

As part of self-stabilization testing (16), several calcretes were crushed minus 19 mm, compacted into California bearing ratio (CBR) molds, and subjected to up to 20 cycles of wetting and drying; each cycle consisted of 24 h of soaking and 24 h of drying at 105°C to 110°C. In all cases except that of sample 2223, the 4-d soaked CBR was found to increase substantially after cycling in comparison with a CBR

Table 4. Effect of heat on some index properties of calcrete sample 2113.

Property	Value Resulting From Heat Treatment					Deviation From Air-Dried Value		
	Dry			Wet		Maximum		
	Method a (20°C)	Method b (50°C)	Method c (105°C)	Method d (50°C)	Method e (105°C)	+	-	Mean
w_L	36.4	35.0	35.0	34.7	34.7	None	1.7	-1.6
w_p	22.7	21.1	21.3	21.2	23.8	1.1	1.6	-0.9
I_p	13.7	13.9	13.7	13.5	10.9	0.2	2.8	-0.7
V_s^a	27.5	23.4	23.1	24.4	22.9	None	4.6	-4.1
V_s^b	23.0	25.6	25.5	29.7	25.1	6.7	None	+3.5
L_s^a	6.7	7.2	6.7	7.0	6.7	0.5	0.0	+0.2
w_s^a	20.5	21.3	21.4	20.6	21.3	0.9	None	+0.7
w_s^b	13.3	20.0	20.0	17.5	20.0	6.7	None	+6.1
R	1.73	1.71	1.70	1.73	1.71	0.00	0.03	-0.02
I_r	1.0	2.8	2.6	13.4	2.2	12.4	None	+4.3
I_T	13.7	5.0	5.3	1.0	5.0	None	12.7	-9.6
w_a	36.9	40.4	43.0	36.8	36.7	6.1	0.2	+2.3
PD ^a	0.56	0.53	0.50	0.56	0.58	0.02	0.06	-0.02

^a G_s shrinkage limit method.

^b V_s shrinkage limit method.

Table 5. Effect of heat on some index properties of calcrete sample 2116.

Property	Value Resulting From Heat Treatment					Deviation From Air-Dried Value		
	Dry			Wet		Maximum		
	Method a (20°C)	Method b (50°C)	Method c (105°C)	Method d (50°C)	Method e (105°C)	+	-	Mean
w_L	26.2	25.5	24.4	25.7	24.3	None	1.9	-1.2
w_p	16.6	14.9	14.4	15.0	15.7	None	2.2	-1.6
I_p	9.6	10.6	10.0	10.7	8.6	1.1	1.0	+0.4
V_s^a	20.2	19.7	17.3	21.0	14.3	0.8	5.9	-2.1
V_s^b	27.0	21.9	-	25.4	15.4	None	11.6	-6.1
L_s^a	4.9	5.3	4.7	5.3	5.0	0.4	0.2	+0.2
w_s^a	15.6	15.2	15.3	14.8	16.6	1.0	0.8	-0.10
w_s^b	12.0	14.0	-	12.5	16.0	4.0	None	+2.2
R	1.90	19.1	1.91	1.93	1.86	0.03	0.04	0.00
I_r	3.0	3.0	3.6	2.0	3.2	0.6	1.0	-0.1
I_T	3.2	3.5	2.8	5.4	2.7	2.2	0.5	+0.4
w_a	35.4	37.8	40.3	37.3	42.8	7.4	None	+4.2
PD	0.44	0.40	0.38	0.40	0.39	None	0.06	-0.05

^a G_s shrinkage limit method.

^b V_s shrinkage limit method.

determined in the normal way. In some cases, the effect of this treatment on Atterberg limits and bar linear shrinkage was investigated (Table 11).

DISCUSSION OF RESULTS

Statistical Significance of Changes

The precision data in Table 3 for the British soils indicate that single-operator precision expressed as

D2S limits is reasonably constant over the range of properties found. Because these limits for the one calccrete evaluated are in good agreement with these data, it appears reasonable to assume that the single-operator precision for calcrites is similarly constant. The D2S values can therefore be used to indicate the degree to which the individual differences in index properties found after the different heat treatments could be attributable to chance at the 5 percent level. The rounded values of D2S selected are given in the last line of Table 3.

Table 6. Effect of heat on some index properties of calccrete sample 2223.

Property	Value Resulting From Heat Treatment					Deviation From Air-Dried Value		
	Dry			Wet		Maximum		
	Method a (20°C)	Method b (50°C)	Method c (105°C)	Method d (50°C)	Method e (105°C)	+	-	Mean
w _L	23.6	22.9	23.8	23.3	22.6	0.2	1.0	-0.4
w _p	13.3	17.2	16.6	17.4	16.4	4.1	None	+3.6
I _p	10.3	5.7	7.2	5.9	6.2	None	4.6	-4.1
V _s ^a	4.7	5.1	4.8	5.4	2.1	0.7	2.6	-0.4
V _s ^b	8.0	8.6	-	7.5	-	0.6	0.5	+0.1
L _s	0.0	0.7	0.0	0.0	0.0	0.7	0.0	+0.2
w _s ^a	20.9	20.1	21.0	20.2	21.4	0.5	0.8	-0.2
w _s ^b	19.0	18.0	-	19.0	-	0.0	1.0	-0.5
R	1.74	1.76	1.70	1.75	1.72	0.01	0.04	-0.01
I _r	3.6	2.0	4.0	2.0	1.8	0.4	1.8	-1.2
I _r	2.9	2.9	1.8	2.9	3.4	0.5	0.9	-0.2
w _a	43.9	41.9	43.7	42.4	41.2	None	2.7	-1.6
PD	0.48	0.48	0.48	0.48	0.52	0.04	0.00	+0.01

^aG_s shrinkage limit method.

^bV_s shrinkage limit method.

Table 7. Effect of heat on some index properties of calccrete sample 2367.

Property	Value Resulting From Heat Treatment					Deviation From Air-Dried Value		
	Dry			Wet		Maximum		
	Method a (20°C)	Method b (50°C)	Method c (105°C)	Method d (50°C)	Method e (105°C)	+	-	Mean
w _L	31.4	32.8	29.5	32.0	29.3	1.4	2.1	-0.5
w _p	16.0	16.1	15.7	16.4	15.1	0.4	0.9	-0.2
I _p	15.4	16.7	13.8	15.6	14.2	1.3	1.6	-0.3
V _s ^a	19.6	20.3	16.5	18.8	17.5	0.7	3.1	-1.3
V _s ^b	25.2	23.8	22.8	-	24.4	None	2.4	-1.5
L _s	6.0	6.0	5.7	6.0	5.3	0.0	0.7	-0.3
w _s ^a	20.2	21.1	20.1	20.9	19.4	0.9	0.8	+0.2
w _s ^b	17.0	19.0	16.5	-	15.5	2.0	1.5	0.0
R	1.75	1.72	1.75	1.69	1.77	0.03	0.06	-0.02
I _r	1.8	2.2	1.6	2.6	2.0	0.8	0.2	+0.3
I _r	8.6	7.6	8.6	6.0	7.1	0.0	2.6	-1.3
w _a	42.5	48.0	39.2	33.3	51.6	9.1	9.2	+0.5
PD	0.48	0.44	0.51	0.63	0.38	0.15	0.10	+0.01

^aG_s shrinkage limit method.

^bV_s shrinkage limit method.

Table 8. Effect of heat on some index properties of calccrete sample 2493.

Property	Value Resulting From Heat Treatment					Deviation From Air-Dried Value		
	Dry			Wet		Maximum		
	Method a (20°C)	Method b (50°C)	Method c (105°C)	Method d (50°C)	Method e (105°C)	+	-	Mean
w _L	32.7	33.7	32.1	31.7	32.4	1.0	1.0	-0.2
w _p	17.8	21.0	20.2	18.1	19.4	3.2	None	+1.9
I _p	14.9	12.7	11.9	13.6	13.0	None	3.0	-2.1
V _s ^a	15.7	16.2	12.8	14.0	15.1	0.5	2.9	-1.2
V _s ^b	20.2	17.5	16.3	17.6	19.5	None	2.7	-2.5
L _s	4.7	5.3	4.7	5.3	4.7	0.6	0.0	+0.3
w _s ^a	23.2	23.8	24.2	23.2	23.2	1.0	0.0	+0.4
w _s ^b	20.5	23.0	22.0	21.0	20.5	1.5	0.0	+1.1
R	1.65	1.64	1.62	1.65	1.64	0.00	0.03	-0.01
I _r	0.4	2.4	2.2	4.8	0.4	4.4	0.0	+2.1
I _r	37.2	4.9	5.4	2.8	32.5	None	34.4	-25.8
w _a	41.0	41.3	44.5	47.9	45.2	6.9	None	+3.7
PD	0.57	0.58	0.54	0.48	0.51	0.01	0.09	-0.04

^aG_s shrinkage limit method.

^bV_s shrinkage limit method.

The data given in Tables 4 through 8 show that in nearly every case wet or dry heating at 105°C resulted in a lowering of the liquid limits by up to 2 percentage points, the plasticity indexes by up to 4, and frequently in a raising of the plastic and shrinkage limits by up to 3 and 7 points respectively and a lowering of the volumetric shrinkages by up to 12 points. At least half of these maximum values are unlikely to be attributable to chance at the 5 percent level. In contrast, bar linear shrinkage was not significantly affected: The maximum variation from the air-dry value was only 0.7, i.e., less than the D2S limit of 1.0. With a few exceptions, changes in shrinkage ratios, absorption limits, and degrees of

petrification and, to a lesser extent, flow and toughness indexes were generally less marked and erratic and are probably not significant. The effect of heating at 50°C was generally similar to that at 105°C except that the trends were more subdued and the results more erratic, which suggests that the effect of heating at 50°C was becoming subordinate to sampling and testing errors. However, sample 2223 was quite badly affected by heating to 50°C. There was a tendency for the effect of wet heat to be slightly more severe than that of dry heat.

The data given in Tables 9 and 10 show that drying a wet calcrete at 105°C generally caused a decrease in liquid limit and plasticity index by up to

Table 9. Effect of drying at 20°C versus drying at 105°C on some index properties of 18 calcretes.

Sample	Drying Temperature (°C)	w _L (%)	w _p (%)	I _p (%)	I _L (%)	I _T (%)	L _s (%)
2114	20	36.4	22.7	13.7	1.0	13.7	6.7
	105	34.7	23.8	10.9	2.2	5.0	6.7
	Difference	1.7	-1.1	2.8	-1.2	8.7	0
2116	20	26.2	16.6	9.6	3.0	3.2	4.9
	105	24.3	15.7	8.0	3.2	2.7	5.0
	Difference	1.9	0.9	1.0	-0.2	0.5	-0.1
2223	20	23.6	13.3	10.3	3.6	2.9	0
	105	22.6	16.4	6.2	1.8	3.4	0
	Difference	1.0	-3.1	4.1	1.8	-0.5	0
2367	20	31.4	16.0	15.4	1.8	8.6	6.0
	105	29.3	15.1	14.2	2.0	7.1	5.3
	Difference	2.1	0.9	1.2	-0.2	1.5	0.7
2478	20	32.6	19.3	13.3	6.2	2.2	3.2
	105	32.6	19.6	13.0	4.2	3.1	3.3
	Difference	0	-0.3	0.3	2.0	-0.9	-0.1
2479	20	42.2	21.3	20.9	13.4	1.8	5.7
	105	36.5	21.2	15.3	3.8	4.0	5.7
	Difference	5.7	0.1	5.6	9.6	-3.2	0
2493	20	32.7	17.8	14.9	0.4	37.2	4.7
	105	32.4	19.4	13.0	0.4	32.5	4.7
	Difference	0.3	-1.6	1.9	0	4.7	0
6822	20	32.7	19.0	13.7	8.2	1.7	6.3
	105	31.0	18.2	12.8	8.0	1.6	6.0
	Difference	1.7	0.8	0.9	0.2	0.1	0.3
6839	20	26.0	15.8	10.2	6.6	1.6	3.0
	105	24.9	15.0	9.1	6.2	1.6	3.3
	Difference	1.1	0.8	1.1	0.4	0	-0.3
6842	20	20.3	14.0	6.3	3.8	1.7	3.3
	105	20.0	13.5	6.5	4.2	1.6	3.0
	Difference	0.3	0.5	-0.2	-0.4	0.1	0.3
6844	20	33.4	23.9	9.5	5.8	1.6	4.7
	105	29.7	24.5	5.2	5.2	1.0	2.7
	Difference	3.7	-0.6	4.3	0.6	0.6	2.0
6846	20	50.4	27.0	23.4	18.0	1.3	8.0
	105	47.5	27.6	19.9	11.4	1.8	8.0
	Difference	2.9	-0.6	3.5	6.6	-0.5	0
6872	20	-	14.7	NP	-	-	0
	105	-	17.4	NP	-	-	0.3
	Difference	-	-2.7	-	-	-	-0.3
6889	20	25.3	15.9	9.4	5.2	1.8	-0.6
	105	25.9	15.8	10.1	4.2	2.4	3.3
	Difference	-0.6	0.1	-0.7	1.0	-0.6	1.4
6897	20	27.0	15.8	11.2	6.2	1.8	4.2
	105	26.5	16.0	10.5	4.6	2.3	3.7
	Difference	0.5	-0.2	0.7	1.6	-0.5	0.5
6935A	20	33.9	20.0	13.9	9.4	1.5	4.0
	105	33.3	19.1	14.2	6.8	2.1	4.0
	Difference	0.6	0.9	-0.3	2.6	-0.6	0
7088	20	16.2	14.7	1.5	10.2	0.2	0
	105	17.8	15.3	2.5	6.2	0.4	0.7
	Difference	0.1	1.7	-1.6	0.8	-0.4	1.1
7089A	20	22.1	17.8	4.3	6.8	0.6	1.8
	105	22.0	16.1	5.9	6.0	1.0	0.7
	Difference	0.1	1.7	-1.6	0.8	-0.4	1.1

Note: Samples 2114 to 2367 and sample 2493 were tested by operator A on the BS 1377-1961 type of liquid limit device. Other samples were tested by operator B on one ASTM D423-66 type of device.

Table 10. Statistical data for effect of drying at 20°C versus drying at 105°C on some index properties of 18 calcretes.

Statistic	Drying Temperature (°C)	w _L (%)	w _p (%)	I _p (%)	I _r (%)	I _r (%)	L _s (%)
\bar{X}	20	30.1	18.1	11.9	6.5	4.9	4.0
	105	28.9	18.3	10.5	4.7	4.3	3.9
	Difference	1.3	-0.2	1.4	1.7	0.5	0.3
s	20	8.3	3.7	5.4	4.5	9.0	2.3
	105	7.2	3.8	4.4	2.6	7.4	2.3
	Difference	1.7	1.3	2.0	2.8	2.6	0.7
Range	20	16.2 to 50.4	13.3 to 23.9	NP to 23.4	0.4 to 18.0	0.2 to 37.2	0 to 8.0
	105	17.8 to 47.5	13.5 to 27.6	NP to 19.9	2.0 to 11.4	0.4 to 32.5	0 to 8.0
	Difference	-1.6 to +5.7	-3.1 to +1.7	-1.6 to +5.6	-1.2 to +9.6	-3.2 to +8.7	-0.7 to +2.0
n	20	17	18	17	17	17	18
	105	17	18	17	17	17	18
	Difference	17	18	17	17	17	18
α , %	20	-	-	-	-	-	-
	105	-	-	-	-	-	-
	Difference	<0.2	-	0.5	1	-	2.5
95% CI about 0	20	-	-	-	-	-	-
	105	-	-	-	-	-	-
	Difference	±0.9	±0.6	±1.0	±1.4	±1.3	±0.3
n > 95% CI	20	-	-	-	-	-	-
	105	-	-	-	-	-	-
	Difference	9	6	8	7	3	5
n < 95% CI	20	-	-	-	-	-	-
	105	-	-	-	-	-	-
	Difference	1	4	1	0	1	1
Range ± 95% CI	20	-	-	-	-	-	-
	105	-	-	-	-	-	-
	Difference	-0.7 to +4.8	-2.5 to +1.1	-0.6 to +5.0	+0.2 to +8.2	-1.9 to +7.4	-0.4 to +1.7
D2S (Table 3)	20	-	-	-	-	-	-
	105	-	-	-	-	-	-
	Difference	1.5	2.0	2.0	3.0	1.0	1.0
n > +D2S	20	-	-	-	-	-	-
	105	-	-	-	-	-	-
	Difference	7	0	5	3	3	3
n < -D2S	20	-	-	-	-	-	-
	105	-	-	-	-	-	-
	Difference	1	2	0	0	1	0

Table 11. Effect of wetting and drying cycles on some index properties of four calcretes compacted into CBR molds.

Item	Number of Cycles	w _L (%)			w _p (%)			I _p (%)			L _s (%)		
		Before	After	Difference	Before	After	Difference	Before	After	Difference	Before	After	Difference
Sample													
2114 ^a	20	40.4	27.5	12.9	26.1	17.7	8.4	14.3	9.8	4.5	8.0	3.8	4.2
2116 ^a	20	26.1	26.5	-0.4	15.4	18.2	-2.8	10.7	8.3	2.4	6.0	3.0	3.0
2223 ^a	20	24.0	20.2	3.8	17.5	-	-	6.5	SP ^c	5.5	0.6	0.7	-0.1
6935B ^b	5	39.8	34.1	5.7	17.8	19.8	-2.0	22.0	14.3	7.7	6.7	4.0	2.7
Statistical data													
\bar{X}	-	32.6	27.1	5.5	19.2	18.6	1.2	13.4	8.4	5.0	5.3	2.9	2.5
Range	-	20.0-	20.2-	-0.4	15.4-	17.7-	-2.0	6.5-	SP-	2.4-	0.6-	0.7-	-0.1
		40.4	34.1	+12.9	26.1	19.8	+8.4	22.0	14.3	7.7	8.0	4.0	+4.2

^a Testing on material before compaction and after removal from the CBR molds after cycling, soaking, and penetration respectively.

^b Testing on material removed from CBR molds after soaking and penetration and after cycling, soaking, and penetration respectively.

^c Counted as 1.0 in analysis.

6 percentage points and in flow index by up to 10 points. Of this, at least 4 and 7 points respectively exceed the D2S limits and are therefore unlikely to be attributable to chance at the 5 percent level. Significance testing shows that mean changes in liquid limit and plasticity index are significant at the 0.5 percent level or better and changes in flow index and linear shrinkage are significant at the 2.5 percent level or better. Significant individual decreases of more than D2S in liquid limit took place in 7 out of 17 samples (41 percent), in plasticity index in 5 samples (29 percent), and in flow index in

3 samples (18 percent). If the (generally smaller) 95 percent confidence limits are used instead of the D2S limits, about half the samples can be said to have been significantly affected to a slightly greater degree. The plastic limit showed a slight tendency to rise and the toughness index to fall, but relatively few samples were significantly affected and the mean change is not significant. Once again, bar linear shrinkage showed a slight tendency to decrease on heating, but only 3 out of 18 samples (17 percent) showed a significant decrease of up to 1 percentage unit when the D2S limits were used and five (28 per-

Figure 1. Decrease in liquid limit and plasticity index of calcretes after oven drying at 105°C to 110°C versus values after air drying at about 20°C.

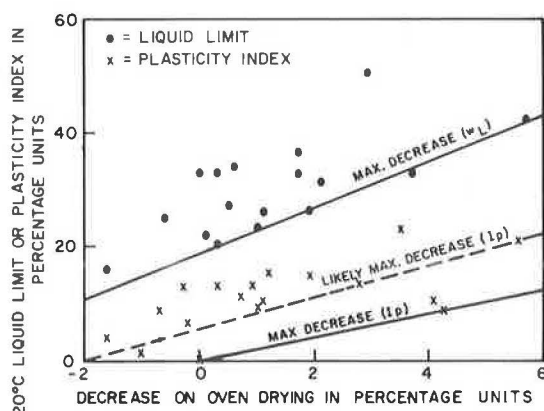
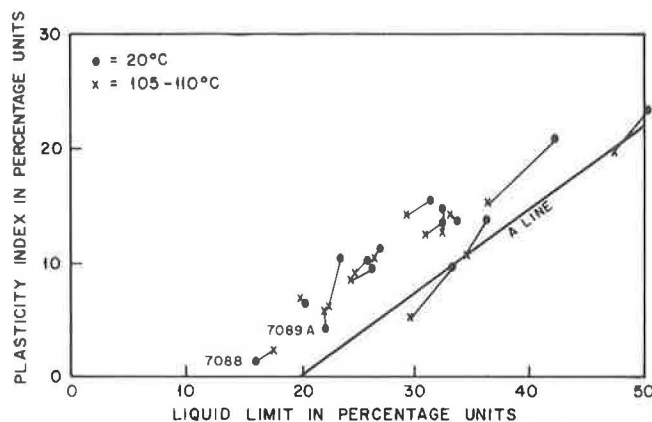


Figure 2. Plasticity chart plot of effect on calcretes of oven drying at 105°C to 110°C versus air drying at about 20°C.



cent) of up to 1.7 units when the 95 percent confidence limits were used.

The results reported here are generally in accordance with those derived from a study of four Indiana soils with air-dried liquid limits of 22 to 39 (17) in which decreases in liquid limit of up to 5 percentage points and in plasticity index of up to 3 points were found for oven-dried material in comparison with air-dried material. For these particular soils, the plastic limit was, however, found to decrease by up to 3 points in contrast with the erratic but more general increase found in this study.

Figure 1 shows that there is a tendency for the samples with the higher liquid limits and plasticity indexes to be affected most and that some useful guide-lines can be drawn. For example, an air-dried liquid limit of 25 is not likely to drop more than 2 points on oven drying and a plasticity index of 6 not at all. Samples 2223 and 6844 are the only serious exceptions in that the plasticity index decreases from about 10 to about 5. Figure 1 also suggests that most of the effects found—even many of those smaller than D2S—are real. When the effect is plotted on the Casa-grande plasticity chart (Figure 2), it is similar to that for organic soils (11), i.e., a downward movement roughly parallel to the A line. Such a plot may also provide a means of distinguishing real from fictitious effects. Thus, the increase in both liquid limit and plasticity index of sample 7088 may be real as it moves parallel to the A line, whereas that of

sample 7089A may not be real as it moves perpendicular to this line.

In all cases, the results of the wet and dry cycling treatment on compacted material in Tables 4 through 8 show a significant, substantial decrease in plasticity index and, in most cases, significant, substantial decreases in both liquid limit and linear shrinkage. These changes are generally greater than the effect of simple drying given in Tables 9 and 10, which suggests that wetting and drying cycles may be of greater importance.

Practical Significance of Changes

Although the effects of drying temperature found in this study are small in comparison with the well-known decreases in liquid limit and plasticity that occur in organic soils (7, 11) and soils rich in montmorillonite (17), mixed layer clays (17), allophane, and halloysite, they are sufficient to contribute to precision, acceptance, and performance correlation problems. For example, judged purely on the basis of the usual plasticity index requirement of 6, samples 2223 and 6844 could be used as either base or subbase depending on whether they had been air- or oven-dried. These problems could be minimized by strict standardization of test methods, which must be the same as those used to derive the empirical material specifications being applied on the works in question. It would be dangerous to use oven drying for quality control if the specifications were derived from the results of tests that used a milder form of drying or none at all, and the reverse procedure would lead to the rejection of good material. Even heating to 110°C, as in the South Africa Department of Transport method DOT A.1(a)-1970, could be safely done provided such heating was standard and not optional and specifications derived from studies on heated but non-heat-sensitive soils were not applied to works that used heat-sensitive soils. A temperature of 60°C is often encountered in road bases in hot arid or semiarid climates and is therefore a reasonable temperature for laboratory drying. Drying at 105°C to 110°C is, however, much more rapid and hence desirable for on-the-job control.

The effects found in this research afford a partial explanation of the higher liquid limits and plasticity indexes apparently allowable in calcrete bases and wearing courses in comparison with most other materials (5). Other explanations include particle porosity (5).

At the time most of this study was carried out, a period of presoaking was included in both the South Africa Department of Transport method (12) and the NITRR method (6) and hence was included in the method used. This requirement has now been dropped from the method of the South Africa Department of Transport. In the absence of presoaking, it is likely that the decreases in liquid limit and plasticity index found would have been larger. The Indiana study (17) found increases in liquid and plastic limits and in plasticity index of up to 3 percentage points after presoaking either air- or oven-dried material for 24 h at about the liquid limit. The finding that bar linear shrinkage was affected relatively little could be of considerable practical value. The effect of air drying on calcretes is unknown. Since most calcretes are found with relatively low in situ moisture contents in arid or semiarid areas, the effect is probably small.

Causes of Changes

The similar effects noted in the Indiana study were ascribed to the presence of mixed layer clays or

montmorillonite. In this study, no mixed layer clays, halloysite, or allophane were found, and montmorillonite was not found in any of the samples most affected, such as samples 6844 and 6846. The contents of organic matter, amorphous matter (present as diatoms), CO_2 (present as calcite or dolomite or both), and FeO and pH do not appear to be significant nor do the results of qualitative tests on air-dried material for easily available ferrous iron (which is not shown). Ion exchange effects should be similar under all drying conditions studied. Heating to 110°C would not cause any decomposition of carbonates although drying a wet material containing carbonates or other more soluble matter could possibly cause slight cementation because of their recrystallization. Such cementation should be lost on rewetting although cementation by the slightly soluble carbonate could build up over a number of wetting and drying cycles to an amount that could not all be redissolved on saturation. This is a likely explanation for the increase in CBR and the decrease in index properties given in Table 11 as well as the tendency of the shrinkage limits to rise after wetting and drying cycles (5, 16). Drying a wet material that contains carbonate could also cause the pH to rise to 10 or more because of the loss of CO_2 from the soil solution and the formation of OH^- ions (5). Amorphous components and clay minerals may be attacked under such conditions. This effect is also likely to be small during a single drying but could build up after a number of cycles. Both effects could take place during service in the road.

Apart from quartz and calcite, a significant component common to all the samples most severely affected by heat is palygorskite. Palygorskite and sepiolite are unique among clay minerals in possessing a nonexpansive amphibole type of lattice. They form hollow, needlelike particles typically matted into a haystacklike structure (18, 19). Up to about 5 percent water by mass can be held in the channels in the needles and about 200 percent between the needles in the haystack structure. Most of the haystack water is readily lost and regained (within minutes) at temperatures only slightly above room temperature (19), but removal of most of the channel water in palygorskite requires up to 10 h at 110°C and causes a slight, reversible collapse of the channels similar to the loss of interlayer water in montmorillonite (20). Palygorskite also loses its selective absorption properties above 88°C and may decrease in surface area above 95°C (18). The reversibility of these changes and the time required for replacement of the channel water have not been stated, but it appears likely that oven drying at 105°C could cause changes that may not be fully reversed in the 24-h rehydration period allowed. Since the Atterberg limits are moisture contents at certain consistency limits, it can be expected that they will be more greatly affected than shrinkage. The behavior of sepiolite can be expected to be similar to that of palygorskite except that channel water is less readily lost and structural collapse less evident (20). Sensitivity to oven drying is therefore probably less marked and probably requires the presence of greater quantities of this mineral, as in the case of sample 2479. The one sample that contained sepiolite (sample 6935) and was subjected to wetting and drying cycles was greatly affected by the treatment although not by simple drying.

It would therefore appear that the presence of palygorskite is the chief cause of the change in index properties observed after oven drying and that montmorillonite, sepiolite, and possibly other clay minerals such as vermiculite (present in sample 2223) probably play a lesser role. The relative importance of the different clay minerals in this respect may be readily determined by experiments on nearly pure clay

minerals. Since palygorskite, montmorillonite, and sepiolite are now known to be common components of calcretes and other soils of arid and semiarid zones (5, 21), many such soils can be expected to be sensitive to oven drying at 105°C . Further work would be required to determine whether drying at 50°C offers any real advantages over drying at 105°C .

The only three calcretes significantly affected in linear shrinkage by drying at 105°C in Table 9 have in common high contents of FeO and soluble salts and frequently a high pH. Oxidation of Fe^{2+} to Fe^{3+} could possibly cause cementation. Salts suggest ion exchange effects, and a high pH suggests the presence of NaHCO_3 or Na_2CO_3 and dispersion and the possibility of an even higher pH during drying and an increased chance of alteration in the clay minerals present.

CONCLUSIONS

1. Approximately half of the 18 calcretes studied exhibited decreases in liquid limit and plasticity index after drying at 105°C of up to 4 or 5 percentage points greater than the 1 or 2 points that could be ascribed to chance at the 5 percent level.

2. As with organic soils, the effect of drying temperature plotted on a Casagrande plasticity chart is to cause the sample to move downward roughly parallel to the A line. In the case of an individual sample, the maximum effect likely is predictable from the liquid limit and plasticity index.

3. Approximately one-quarter of the samples exhibited significant decreases in bar linear shrinkage of up to about 1.5 percentage points more than the 0.3 or 1.0 point that could be ascribed to chance at the 5 percent level. Shrinkage was therefore less affected than liquid limit and plasticity index.

4. Changes were also found in the other index properties studied, but they were generally more erratic and less significant.

5. Changes after drying at 50°C in the five calcretes studied were generally similar to those at 105°C but more subdued or erratic. Further work would be required to establish whether drying at less than 60°C affords any advantage over drying at 105°C .

6. The partial significance of these effects can be minimized by standardization of drying procedure and by the use of the same drying procedure for both the derivation of limiting values for specifications and quality control during construction.

7. The cause of these effects is chiefly the presence of palygorskite and, to a lesser extent, of montmorillonite and sepiolite. It can be predicted from the common occurrence of these clay minerals in such materials that many calcretes and other soils from semiarid and arid zones will be sensitive to oven drying.

8. Even larger decreases in liquid limit, plasticity index, and linear shrinkage were found in compacted materials subjected to wetting and drying cycles, probably because of cementation by recrystallization of carbonate in addition to the heating effect.

9. The effects found provide a partial explanation of the higher liquid limits, plasticity indexes, and linear shrinkages that calcrete bases and wearing courses can apparently tolerate in comparison with most other materials.

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Laboratory Evaluation of Materials and Design Characteristics of PennDOT Underdrain System

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Results of an investigation of the adequacy of Pennsylvania's current design for highway underdrains and of specific materials used in that design are reported. Fine aggregate filter media, types A and B, were examined for their functional capabilities under relatively low hydraulic pressure gradients. Woven and nonwoven synthetic fabrics were investigated to determine the feasibility of using them as a filter medium in the underdrain system. Perforated underdrain pipe was investigated to determine the minimum cross-sectional area of perforation and minimum cross-sectional area of pipe to allow adequate outflow of anticipated inflow. Filter fabric materials appear to have a practical use in drainage systems. Recommendations include (a) further testing to evaluate the optimal combination of filterability versus permeability, the long-range effects on the permeability of filter fabric of contact with fine silt subgrade soils, and the most practical and effective installation procedures;

(b) a minimum perforation area and a minimum pipe diameter; and (c) further investigation into changing subbase gradation specifications to make the material more permeable and eliminating fine aggregate backfill as a filter medium where heads of <0.3 m (<1 ft) are anticipated.

Many kilometers of Pennsylvania's highway drainage systems are being replaced annually because of premature failure, and the functional condition of much of the length of similar systems remains questionable. As a result, some aspects of the Pennsylvania Department of Transportation (PennDOT) highway drainage system design have already been revised. The addition or revision of other system characteristics is