Effect of Heating on Bearing Capacity of Highway Subgrades

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•MOST OF Brazil's territory lies in tropical and subtropical regions. Throughout the country the soil layers compacted in highway construction are exposed—mainly in summer—to intense natural heating, frequently for prolonged periods of time. The daytime air temperature often reaches 39 to 41 C (102 to 106 F) and it is not uncommon that in some areas this temperature will remain unchanged during the night. Hence, the temperature of the bare soil attains values around 45 to 60 C (113 to 140 F) according to its composition, color, surface condition, etc. Therefore the evaporation tends to be very important (especially during the dry days) in compacted subgrades before they are covered with the pavement.

Such considerations inspired the author to investigate in the laboratory the degree of influence of preliminary drying on the future bearing capacity of compacted subgrades. It was worthwhile to study the effects of drying by heating of compacted non-saturated soil samples and the repercussions on the strength after wetting.

In spite of some well-known shortcomings—such as the difficulty in reproducing specimens of similar characteristics, and low accuracy in the penetration test—the CBR method was selected to determine the strength because it is the most widely used procedure for pavement design in Brazil as well as abroad and because it was the most convenient method available to the author in establishing the effect of drying.

However, the author wishes to emphasize that neither the conventional CBR method chosen for carrying out the experiments nor the program of laboratory tests were able to reproduce the slow and complex phenomenon of moisture change that occurs in the subgrade from the end of construction until moisture equilibrium develops. This equilibrium probably is achieved only after several drying-wetting-drying cycles, and the traditional CBR method does not consider such a complex approach. The heating action before soaking was the only modification introduced in the CBR test by the author.

REVIEW OF THE LITERATURE

Pioneer work on the effect of heating on soaked strength was done by McDowell (1). Since 1946 McDowell has emphasized the eventual benefits of the so-called dry curing, after having tested several types of soils—coarse- and fine-grained, and from low to medium plasticity. The strength was obtained after dry-curing and subsequent soaking (by capillarity) by (a) the unconfined compression test for the coarse soils and (b) the modified bearing value (MBV, i. e., a test with equipment resembling the CBR) for the fine soils.

The coarser soils ("crushed stone-soil flexible base material mixtures," according to McDowell) were oven-dried at 60 C (140 F) for 8 hours. The finer soils ("minus 40-mesh soils") were submitted to the most severe conditions of drying, which reduced the moisture content practically to zero.

The strengths McDowell obtained for his dried-soaked samples were 2 and 1.5 times (coarse and fine soils, respectively) the strengths that the standard test indicated. Such a large influence must have been due to the extremely severe cure conditions adopted by McDowell, specially for finer soils. Although the results may not be easily analyzed because of the great variety of parameters, McDowell has given us a general picture of dry-curing effects on soils of different types and of several energies of compaction.

TABLE 1
SOIL CHARACTERISITCS

LL	PL	PI	Percent Passing Sieve No.				Standard AASHO		CBR (55 blows)			Classification		Activity
			10	40	200	0.002 mm	γ_{dmax}	w_{opt}	γ_{dmax}	w_{opt}	Expansion, percent	HRB	Unified	
34	25	9	95.2	79.0	42.0	7.6	1,790 g/cm³	16.5	1,976 g/cm³	11.8	0.3 to 1.0	A-4(1)	SM	1.18

Even if his significant values for each type of soil at a given energy of compaction are rather few—which does not allow a detailed consideration of the heating effect—McDowell's concept, research, and conclusions have been very useful to the highway engineer.

In a more recent paper, Zalazar (2) also considered the dry-curing effect based on his experience in highway construction in Argentina. He investigated with three kinds of laboratory test: (a) CBR of statically compacted samples, (b) Hveem stabilometer, and (c) triaxial compression. His samples were also oven-dried at 60 C (140 F) and, in order to reduce the molding moisture content to pre-established values (a percentage of PL or of w_{opt}), he controlled the curing period. In the CBR test he used immersion as the means of soaking. The CBR values, in accordance with the soil type, increased between 0 and 60 percent, while the stabilometer values decreased in general and the triaxial values increased slightly.

The small number of samples used by Zalazar (two for each soil and each test—one for the standard procedure and another for dry-curing) do not encourage a deeper analysis of pre-heating effect.

EXPERIMENTATION

Soil

In order to prevent detrimental effects such as cracks during drying, the author chose a soil relatively fine-grained but of low plasticity: a purple reddish highly silty sand with clay, a residual material of weathered gneiss, found in abundance in the mountains encircling Rio de Janeiro. This soil was given preference also for its characteristics (see Table 1), which guarantee thorough soaking during the 4 days of standard CBR procedure.

Technique

After having experienced great difficulty in obtaining exact duplication (moisture content and density) of specimens, the author turned to a more feasible procedure, i.e.,

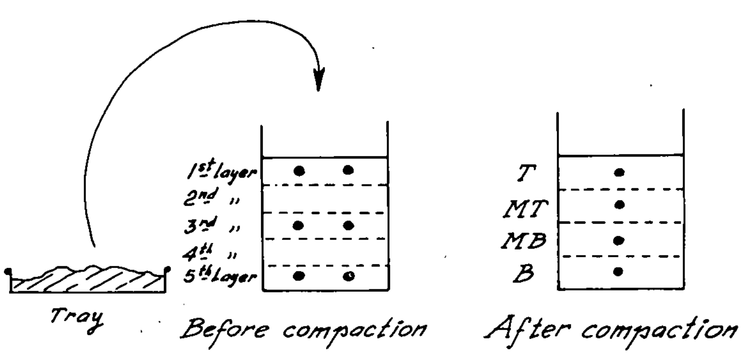

Figure 1. Location of samples for moisture content determination.

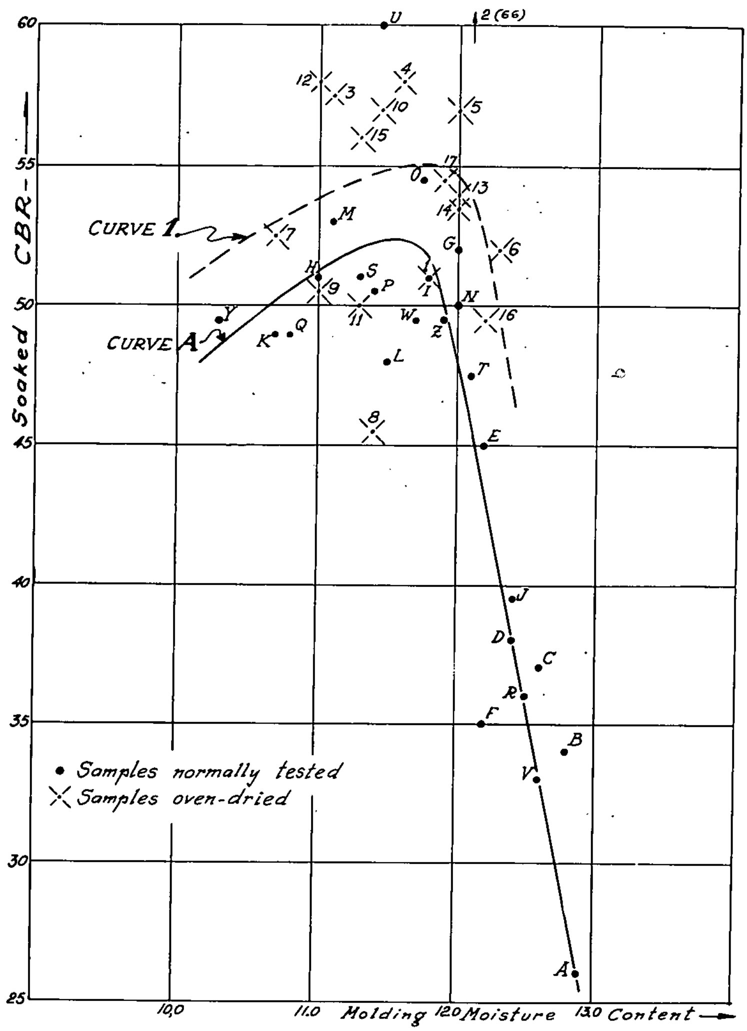

Figure 2. Variation of CBR strength with molding moisture content.

molding a large number of samples so that the desired comparison could be achieved. The step-by-step process was as follows:

1. Compaction of a great number of samples in the CBR mold, in 5 layers, 55 blows per layer, using a 10-lb hammer and stroke of 18 in.;
2. Provision of molding moisture contents from 10 to 13 percent, i.e., around the optimum value;
3. Testing of the compacted specimens in two ways: (a) employing the standard CBR method, i.e., 4 days soaking, measuring expansion subsequent to the penetration test; and (b) 3-hour oven-drying at 40 C (104 F) immediately after compaction and then testing the usual way;
4. Determination of the molding moisture content from samples taken at the exact moment of compaction when the moist soil was spread in the mold—two measurements were made from every first, third, and fifth layer, totaling six per sample (Fig. 1);
5. Determination of the after-soaking moisture content as soon as the penetration test ended, making one measurement for every quarter of each sample, i.e., four measurements per sample (Fig. 1).

The author established the temperature of 40 C as a reasonably representative value of average normal summer conditions to which the upper layers of subgrades of Brazilian roads are subjected.

Preliminary experiments indicated that 3 hours in the oven (at 40 C) was the necessary minimum to affect appreciably the initial moisture content. Moreover, a longer period of drying might have upset the routine of the laboratory where the tests were performed.

The drying of samples while in the molds was carried out in the oven, placing them with their flat surface in a vertical position so that they were exposed equally to heat and consequently dried uniformly and in the shortest possible time.

The process of soaking was performed by means of thorough immersion.

RESULTS AND ANALYSIS

The results of principal importance are shown in Figures 2 and 5. Figure 2 shows, through two curves, the variation of CBR strength with molding moisture content: Curve A shows samples A, B, C, etc., tested according to standard CBR methods (hereafter these samples are referred to as "A-samples"); curve 1 shows samples 1, 2, 3, etc., oven-dried and then tested according to standard CBR methods (referred to as "1-samples").

In spite of the relatively light heating conditions imposed on the samples it remains clear that the preliminary drying increases the bearing support of the soil. We can observe also that this increment tends to be smaller (around 6 percent) on the dry side and larger (around 15 percent or more) on the wet side of optimum moisture content.

It is a well-known and accepted fact that drying increases the effective pressure, even in nonsaturated compacted soil. Lambe (3) explains this phenomenon in terms of

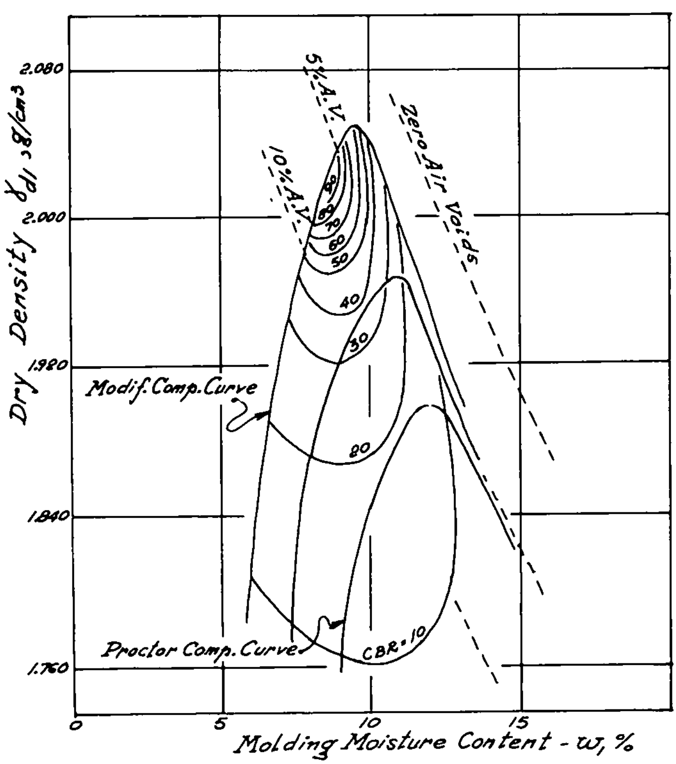

Figure 3. Variation of soaked CBR with the energy of compaction—after Kleyn (6), in Wooltorton (9).

increase of water deficiency involving, as a necessary circumstance, the negative increase of pore pressure. Structure of soil permitting, the drying process is accompanied by shrinkage and, consequently, increase in density.

The experience of Jervis and Eustis (4), Seed, Mitchell and Chan (5), and Kleyn (6) proves that—supercompaction excluded—the strength (after soaking) increases with the growth of energy of compaction when dealing with a given molding moisture content (Fig. 3). Therefore, the increase in strength caused by pre-heating corresponds to an increase in the original energy of compaction E_1 (55 blows, etc.) to E_2,

$$E_2 = E_1 + \Delta E \tag{1}$$

where ΔE is the "heating effect" measured in terms of energy of compaction or compacting effort.

Figure 4 shows a schematic representation of the probable mechanism of the drying and wetting process for a nonsaturated soil, based on British experience at the Road Research Laboratory (7). A compacted sample of high degree of saturation (sample X, Fig. 4) tends, when submitted to drying, to follow a trajectory that approximately coincides with its corresponding line of constant degree of saturation (at least when the drying is of little intensity). A sample of low degree of saturation (sample Y, Fig. 4), in contrast, loses water and simultaneously lessens its degree of saturation; in other words, it shrinks less or may not shrink at all. On the other hand, when wetting, the curves for drying-wetting are not so steep, denoting that the absorbed volume of water is much bigger than the growth of the voids volume.

Taking into consideration both Figures 3 and 4, we must conclude that the representative points for preliminary drying have undergone a dislocation to a "new" curve of compaction (of energy $E_1 + \Delta E$), displaced upwards and to the left of the orginal curve (of energy E_1). Consequently, the soaked CBR values of the "new" curve are larger

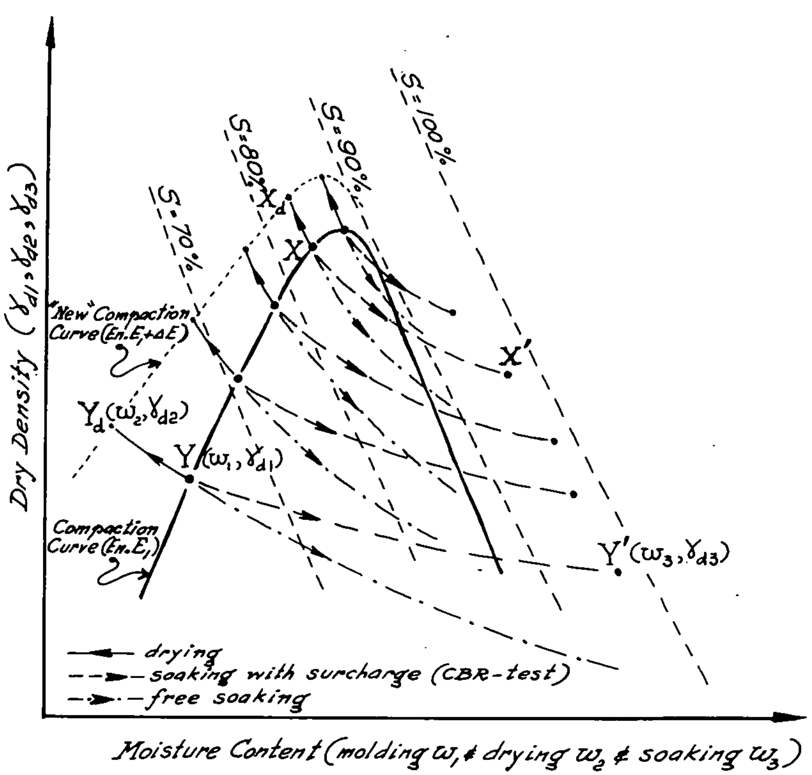

Figure 4. Schematic representation of drying and wetting mechanism of nonsaturated soil.

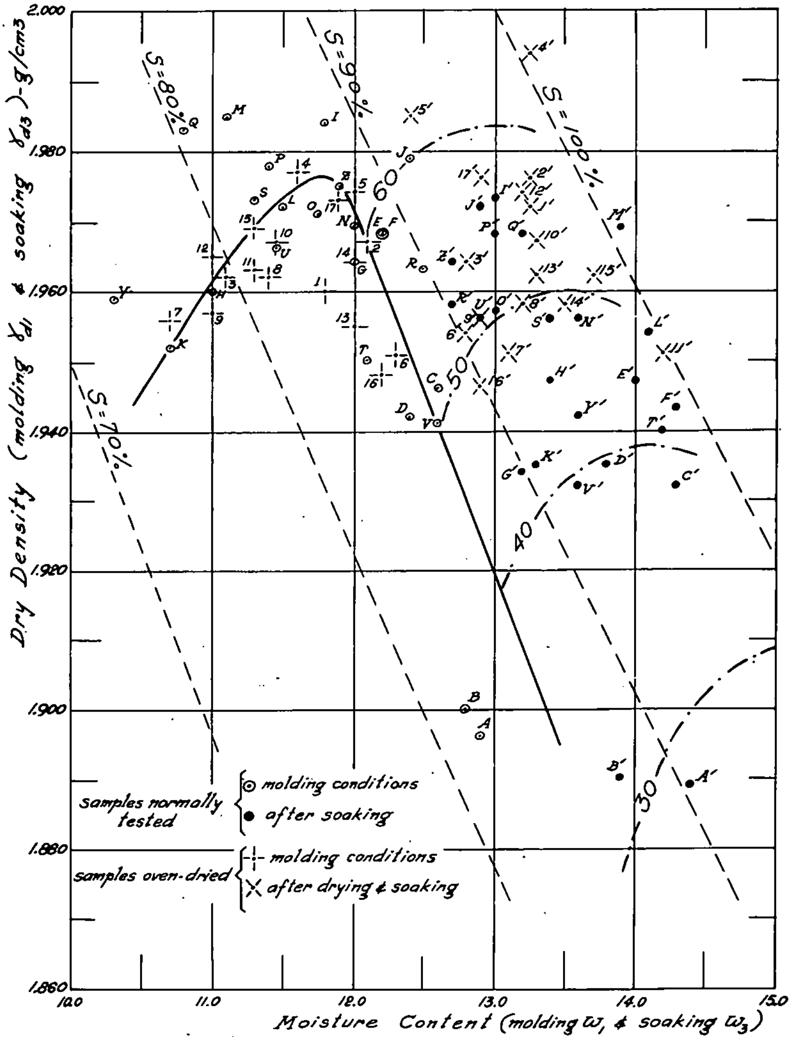

Figure 5. Conditions before and after soaking for normally tested samples and oven-dried samples—iso-CBR curves related to conditions after soaking.

than those from curve E_1. It is worth noting that the dislocation of the points mentioned varies in accordance with their initial degree of saturation. The increase ΔE of energy is not constant along the original curve—it varies with the original degree of saturation of each point. In other words, the "new" curve of compaction does not correspond exactly to a normal curve of constant energy.

If the following symbols are used:

	Molding Conditions	After Drying	After Soaking
Dry Density	γ_{d_1}	γ_{d_2}	γ_{d_3}
Moisture Content	w_1	w_2	w_3

Figure 5 shows (a) the compaction curve obtained for all samples investigated, i.e., the correlation curve of the dry density against the molding moisture content w_1, for A-samples and for 1-samples; (b) the location of points (γ_{d_3}, w_3) representing the conditions after the 4-day soaking, for A-samples and 1-samples (note that the moisture axis is valid for w_1 and w_3); and (c) iso-CBR curves related to the conditions after soaking (γ_{d_3}, w_3).

The dry density γ_{d_3} was calculated differently for A-samples and for 1-samples. For A-samples, γ_{d_3} was determined from the expansion E_S:

$$\gamma_{d_3} = \frac{\gamma_{d_1}}{1 + E_S} \tag{2}$$

For 1-samples, the calculation using the formula

$$\gamma_{d_3} = \frac{\gamma_{d_2}}{1 + E_S} \tag{3}$$

would require determination of the density γ_{d_2} resulting from drying and shrinkage. However, because the direct determination of γ_{d_2} was quite difficult due to the test conditions, the author decided to calculate γ_{d_2} from the consideration of tri-dimensional shrinkage:

$$\gamma_{d_2} = \frac{\gamma_{d_1} \cdot (1 + e_1)}{1 + e_1 - \dfrac{G_S \cdot \gamma_w}{w_d} \cdot \Delta V_v} \tag{4}$$

where e_1 is the initial (molding) void ratio, G_S is the specific gravity of solids, W_d is is the dry weight of the soil mass, γ_w is the unit weight of water, and ΔV_v is the change in volume of voids by shrinkage. Taking into account what has been said before about the probable mechanism of the drying process of nonsaturated soil, the author advanced the following hypotheses:

1. That the volume reduction (shrinkage by heating) is uniform throughout the sample. Such a hypothesis is acceptable if the drying period is compatible with the sample dimensions and type of soil tested. Only in the initial moment is there a tendency for the surface layers to dry faster than the center, because they are in more direct contact with the hot surroundings; as time goes by the moisture content tends toward homogeneity throughout the sample, since the moisture of the center flows toward the surface layers. Hallaire (8), in describing his experiments, says "desiccation starts throughout the sample as soon as the surface is subjected to evaporation." It is important to observe, moreover, that when the author opened at least two CBR samples (No. 14 and No. 50) immediately after oven-drying, he obtained the results given in Table 2, which indicate that the central part had dried and that there was reasonable homogeneity. However, in view of the small difference between W_2 and W_1 of these two samples, it is possible that the observed results could be a consequence of drying during the molding operation or an error in moisture determination. To clarify this point the author performed a different type of moisture determination (before compaction, from the tray; immediately after compaction, by quartering the CBR samples) on three samples (24, 29, and 56-A in Table 2). The moisture content of sample 56-A was smaller after the compaction than before it, which seems logical, although samples 24 and 29 showed just the opposite, which was difficult to explain.

TABLE 2

CBR TEST RESULTS

Samples No.	Time in Oven at 40 C (hours)	Molding Moisture Content Before Compaction[a] (w_1%)				Molding Moisture Content After Compaction[b] (w_1%)					Moisture Content After Drying (w_2%)					Loss of Water[c] (cm^3)
		First Layer	Second Layer	Third Layer	Average Value	T	MT	MB	B	Average Value	T	MT	MB	B	Average Value	ΔV_w
14	2	12.40 12.10	12.70 12.60	12:30 12.10	12.35 –	–	–	–	–	–	11.60	11.90	11.70	11.80	11.75	28
50	3	11.30 11.35	11.50 11.45	11.45 11.70	11.45	–	–	–	–	–	10.90	10.80	10.20	10.50	10.60	38
24	0	12.25 12.45	12.05 12.25	12.50 12.35	12.30	12.60	12.60	12.55	12.40	12.55	–	–	–	–	–	–
29	0	12.20 11.80	12.00 12.20	12.10 12.10	12.10	12.00	12.50	12.30	12.30	12.30	–	–	–	–	–	–
56-A	0	11.60 11.15	11.70 11.25	11.75 11.35	11:45	10.95	10.60	10.85	10.90	10.80	–	–	–	–	–	–

[a]Determined from the tray.
[b]Determined by quartering the sample.
[c]Calculated from $\Delta V_w = \frac{W_s}{\gamma_w} \cdot (W_1 - W_2)$.

2. That the volume reduction (shrinkage by heating) occurs with permanency of the initial degree of saturation S_1 (as molded). Such a hypothesis is valid exclusively for samples of high S_1 (above 70 percent, perhaps)—in which it is possible to admit that water is mainly in the void space around the contact points—and only under non-severe conditions of drying. This hypothesis implies that the relationship between the volume of water lost by drying and the corresponding change of void volume is equal to the initial degree of saturation, i. e.:

$$\frac{\Delta V_W}{\Delta V_V} = S_1 \tag{5}$$

and therefore, the change of voids is

$$\Delta V_V = \frac{\Delta V_W}{S_1} \tag{6}$$

or in other words, the reduction of voids is greater than the loss of water.

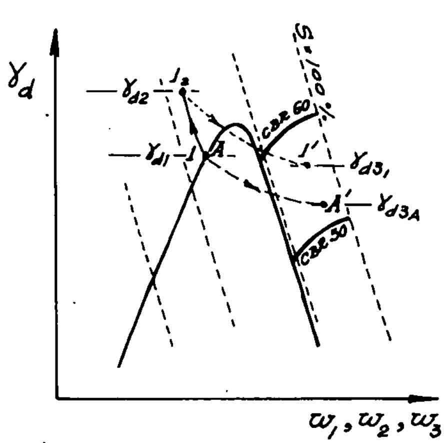

Figure 6. Schematic representation of heating effect.

Then, by weighing the samples before and after drying, ΔV_W was obtained, and it was possible to calculate ΔV_V (Eq. 6), γ_{d_2} (Eq. 4), and finally γ_{d_3} (Eq. 3).

It is worthwhile to consider that Eq. 3, when applied to the 1-samples is not entirely correct, since during the soaking the expansion of these samples is tridimensional in the initial phase. But the error is negligible and does not seriously affect the density.

Figure 6, which is a simplification of Figure 5, shows that, after soaking, the 1-sample tends toward a position in the graph corresponding to a higher CBR value. Therefore, Figure 5 explains why the 1-samples have CBR strengths higher than the A-samples. Furthermore, it allows moderating the results of Figure 2, clearing up whether the eventual scattering of points in this figure is due to intrinsic failure of the CBR test.

CONCLUSIONS

There is no doubt about the positive effect of preliminary heating ("dry curing") on soil strength. Since 1946, McDowell has called the attention of engineers to this matter. However, dry curing has not received the attention deserved and little research has been done on the subject.

It is evident that the problem of natural heating concerns mainly the countries having tropical climates. But the eventual application of moderate artificial heating is of interest to all soil engineers, from tropical countries (in general, less developed) and from temperate and cold countries (more developed) as well.

The present paper pertains to a given type of soil and to restricted conditions of heating (temperature and time of exposure). It seems to the author that it would be important to conduct a broader investigation with other soils and conditions of heating, searching for the benefits from such practice and for the exact limits of technical and economical feasibility.

It is reasonable to assume that sandy and gravelly soils do not show any influence from moderate heating. Otherwise, well-graded soils, with fines of medium to low plasticity, are probably best for preliminary heating to improve bearing support.

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