An Investigation of Moisture Changes and Soil Structure in Earth Dams

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SUMMARY.- The results of field and laboratory work during construction of several earth and rockfill dams are presented to demonstrate that optimum moisture content is not constant under uniform compaction but varies with the initial moisture content of the soil before the compaction test. Furthermore, moisture content itself in sealed storage is not absolutely constant. The validity of the standard compaction test as a determinant of certain soil properties is considered.

I.- INTRODUCTION

In the construction of earth dams optimum moisture content (OMC) is an accepted value governing soil placement moisture limits. It is also used during the materials investigations to determine the moulding moistures for testing.

In research into engineering behaviour and structure of soils, moisture contents are frequently reported in relation to OMC. In some cases, OMC is quoted as being the moisture which governs the behaviour of compacted soils and thus marks a boundary between soil structures. Reference is made to works of Aitchison et al (Ref. 1), Leonards and Narain (Ref. 2), Clegg and Paul (Ref. 3), Lambe (Ref. 4 and 5) and Seed and Chan (Ref. 6) and others.

Most workers, with given soil, compaction and water, assume OMC constant. It will be demonstrated here that such an assumption is invalid. In small earth structures the changes may not be significant and probably escape unnoticed. On large dams, for instance, accurate pore pressure prediction is of considerable economic value and thorough knowledge of all factors affecting it is necessary.

II.- FIELD EXPERIENCE

On various dams of the Snowy Mountains Hydroelectric Authority involving detailed soil investigation and stringent construction control, it has been found that discrepancies existed between the values of soil properties recorded during and immediately after placement and those measured later in the laboratory. In particular, differences were noted in the values of OMC and the soil moisture content. Whilst the latter changes were attributed, at the time, to either drying of soil samples during storage or to ingress of moisture during handling in a humid room, no satisfactory reasons were found to explain the apparent changes in OMC. The matter was not pursued in depth as long as the changes, though mathematically significant, had no known effect on the engineering properties of soils in the embankment. On some projects it was found, however, that the changes caused considerable pore pressure variations necessitating, in some cases, a complete review of the placement moisture content.

During construction of Jindabyne Dam the behaviour of compacted core departed markedly from that anticipated. The pore pressures were much lower than expected. In fact, instead of positive pressures expected from the placement moisture content, large negative pressures developed and suction values of up to 2.8 pF were measured. Comparison of field and laboratory results showed that after several weeks storage of soil samples from the embankment the measured OMC increased by approximately 2.5 per cent. This increase indicated that the actual placement moisture content which, as is usual in dam construction was related to OMC, could have been too low. Empirical calculations suggested uniform increase of placement moisture content to bring the pore pressures to the desired level. This was done and positive pore pressures quickly developed and reached the predicted values. No cause of the phenomena was suggested at the time.

During construction of Talbingo Dam the pore pressures in the earth core were considerably higher than anticipated. After an extensive series of checks of all placement and testing procedures which ruled out some simple reason for the excess pore pressure, it was found that there was an apparent difference of about 1.5 per cent between the OMC determined under field conditions and that measured later in the laboratory on soil samples from the embankment. The field OMC appeared to be always higher than the laboratory one. A flat decrease of placement moisture content was applied and the pore pressures were reduced.

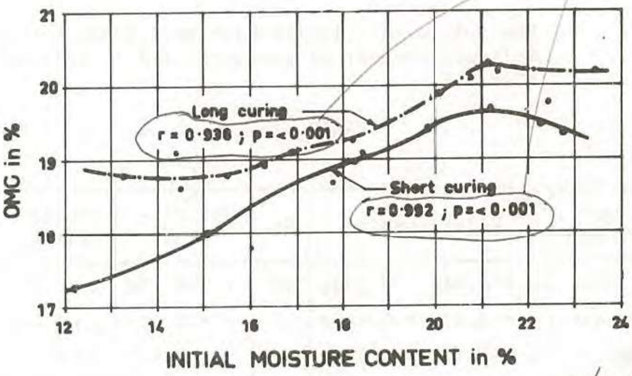
III.- INVESTIGATION AT BLOWERING

(a) Procedure

During construction of Blowering Dam a relatively large scale field investigation of factors affecting compaction test results was carried out. A testing programme was set out to establish the effects of a different initial moisture content and the length of curing time on compaction results. In addition, the influence of maximum particle size was studied. The soil was taken from the impervious core of the dam after compaction by an average of eight passes of a heavy sheepsfoot roller. Thus it was ensured that breakdown of soil particles would have already occurred before laboratory compaction tests. The soil was broken down by hand and passed through a 1 in BS sieve. The sample was then mixed and quartered until a final sample was obtained. The soil was divided into 100 lb subsamples and stored in plastic bags inside metal containers. Compaction tests were carried out under conditions of controlled temperature and humidity using a mechanical compactor to eliminate human error, as much as possible. Compaction was done by 25 blows of a 5.5 lb hammer falling 18 inches on three layers of soil in a 1/20 cubic foot mould. Testing was performed using soil at different initial moisture contents. In one series of tests, moisture was introduced into the soil in carefully measured increments, normally at actual moisture content plus two, four and six per cent. Testing was then done after varying periods of curing ranging from one hour to several weeks. Another portion of the soil was first dried out on electric dryers and then conditioned by adding measured amounts of water. Varying periods of curing were again allowed. In all, over 1,000 tests were carried out with at least three repetitions at each initial moisture content and curing time. Moisture contents were determined using the whole of each compacted specimen subdivided into three subsamples of approximately 2 lb each, and the dry density of soil determined. Classification tests were performed for each 100 lb subsample.

(b) Results

The average results of all classification tests are shown on Table I. The compaction test results, in simplified form, are shown on Figure 1. At least five points were used for each OMC-maximum dry density determination as well as results from the three point rapid method (Ref. 7). Whilst the maximum particle size had a significant effect on compaction results, only the corrected resultant variations of OMC are shown here. It can be seen that OMC changed with change in initial moisture content. The upper limit, however, was not conclusively established because the apparent levelling of the curve could be partly attributed to errors arising from testing soil with an excess of water. The observed change of OMC was most marked after curing time of up to about 24 hours. The soils cured for longer periods showed lesser OMC movement but still significant enough to affect the behaviour of an earth core. The time dependent OMC changes were studied further and, after analysis, it was concluded that the actual moisture content (w) of soil also changed during curing. In general, the moisture content remained relatively constant after conditioning for a period of about 24 hours. During longer curing the moisture content became progressively less. The change was most marked within a certain overall range of initial moisture content. Below and above this range the moisture changes diminished (Fig. 2).



Regression analysis data.

Figure 1

4% imc causes 1% change in omc.

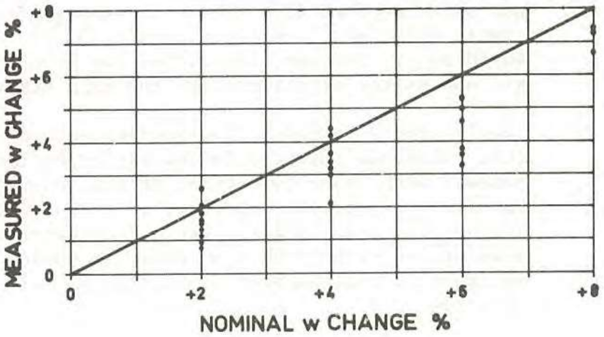


Figure 2

TABLE I

CLASSIFICATION TEST RESULTS

W_L	W_P	I_P	LS*	G	PERCENTAGES PASSING BS SIEVE 1"	3/4"	3/8"	3/16"	7	14	25	52	100	200	CLAY
45	23	22	8	2.75	100	99	96	90	89	80	74	68	62	55	30

* LS = LINEAR SHRINKAGE

IV.- INVESTIGATION AT TALBINGO

(a) Procedure

During the construction of Talbingo Dam an investigation was made of moisture content and OMC movement during storage of soil in airtight containers. One hundred and ten samples were taken. Moisture content and OMC were determined during placement and after varying time intervals. Moisture contents on sampling and testing were compared. In moisture content subsampling losses were inevitably associated with the removal of the rock fraction. These were evaluated by specially controlled tests on 17 samples. A study was also made of changes in OMC using 24 of the 110 samples mentioned above.

(b) Results

The following relationships were found between moisture content of placement and at testing (Table II):

TABLE II

Age (days)	Relationship	No.	Correlation	Significance
0-40	$y = 4.960 + 0.590x$	58	$r = 0.718$	$p < 0.001$
40-80	$y = 3.632 + 0.666x$	22	$r = 0.639$	$p < 0.001$
80 +	$y = 5.143 + 0.628x$	30	$r = 0.570$	$p < 0.001$

where y = moisture content at testing and x = moisture content at placement. The relationship for samples aged more than 80 days was shown by Student's t test to be significantly different from those aged 0-40 and 40-80 days. However, the latter two groups did not differ significantly from each other.

The 17 specially controlled samples showed that, although moisture losses caused by rock removal were about two-thirds of the observed variation in moisture content, they could not account for the changes alone. Furthermore, similar losses must have occurred in taking moisture content subsamples at the time of sampling.

The relationship between OMC at the time of placement and OMC tested after storage in the laboratory (y and x respectively) was:

$y=1.740+0.833x \quad r=0.939 \quad p < 0.001$....(1)

Furthermore, there was an association with the difference between OMC and moisture content at placement, and the change in OMC during storage. Relationships for samples wet of OMC differed from those dry (Table III):

where y = increase in OMC during storage and x = difference between moisture content and OMC at the time of placement. There was no relationship for samples within 0.5 per cent of OMC.

TABLE III

Relation to OMC	Relationship	No.	Correlation	Significance
Over .5% Dry	$y = 1.090x - 2.262$	7	$r = 0.854$	$p < 0.01$
Over .5% Wet	$y = 0.535x - 1.012$	34	$r = 0.722$	$p < 0.001$

V.- SPECIAL INVESTIGATION

(a) General

As each layer of soil was placed at four selected sites at Talbingo Dam, quadruplicate samples were taken in airtight jars. The places were marked with plastic markers. Sampling was repeated for each layer through a rise of about 5 feet. Sampling times were recorded. Afterwards excavations were made and a corresponding series of samples taken from the same places. Embedment varied from 1½ hours to several weeks. The fourth site was in finer plastic soil. A fifth site was selected for soil structure studies. Only one level was sampled but undisturbed samples were taken.

(b) Moisture Content

Moisture content changes, other than those within experimental error, were in the same direction in the embankment as in storage. Changes in the embankment always exceed those in storage. These remarks apply equally to 105°C and 200°C moisture contents.

For 38 routine control samples from Talbingo, 105°C and 200°C moisture contents were very significantly related:

$y=1.84+0.978x \quad r=0.892 \quad p < 0.001$....(2)

where y = 200°C and x = 105°C moisture content.

For 70 specially controlled samples from the special investigation, changes in 105° and 200°C moisture contents were very significantly related:

$y=0.781x-0.173 \quad r=0.758 \quad p < 0.001$...(3)

where y = 200°C and x = 105°C moisture content changes during storage.

The change in 105°C moisture content was very highly significantly related to "adsorbed" (105°C-200°C) moisture for 69 points:

$y=1.552-0.504x \quad r=0.628 \quad p < 0.001$...(4)

where y = adsorbed moisture, x = 105°C moisture content change on storage.

Soils stored after a period of embedment behave in the same way during storage as those sampled immediately on placement.

For the specially controlled samples there was a significant relationship between the change in 105°C moisture content and time of embedment. This did not apply to longer periods than 75 hours.

(c) Differential Thermal Analyses

Differential thermal analyses (DTA) were made to check that adsorbed moisture was driven off at 200°C. The DTA showed that there was a significant loss of material between 105°C and 200°C. This material was collected and shown to be water.

(d) Exchangeable Sodium Percentage

A relationship was considered (Ref. 1) between exchangeable sodium percentage (ESP), soil moisture electrolyte concentration and soil structure. Some adsorbed cations and soluble salts determinations were made so that structural changes could be investigated.

Changes in ESP after embedment were slight and random. Electrolyte concentration of soil moisture had more variation but did not show a recognisable trend. Results did not indicate structural change.

(e) Specific Surface

Specific surfaces of soil crumbs passing No.7 BS sieve were determined to ascertain whether structural changes could be detected this way but embedment did not produce any recognisable trend.

(f) Base Exchange

For Site 4 samples, base exchange capacity was found. It was highly significantly related to moisture content change on storage. The correlation was sufficiently close to enable moisture content change to be estimated from base exchange capacity. The relationship was:

$y=0.0600x-0.98 \quad r=0.8 \quad p<0.001$......(5)

where y = % moisture change at 105°C,
x = base exchange capacity in milliequivalents per 100 grams.

However, all the soils were from one place, and only eight results were available from which to compute the relationship.

(g) Microscopy

Slides were made from the two undisturbed samples from Site 5 by the method used in CSIRO (Ref. 8). These were used both for optical and electron microscopy. Optical examinations revealed nothing of soil structure, but electron micrographs of cracks in the slides permitted examination in depth. Maximum magnification was 2000. Stereoscopic pairs showed conclusively that no structural change had occurred during 45 hours embedment. This agrees with the observations of other workers (Ref. 9,10).

Moisture changed by 0.9 per cent.

VI.- DISCUSSION

(a) Moisture Interchange

Whatley (Ref. 11) after considerable investigation, demonstrated also that both moisture content and OMC are not constant during storage. He believed that changes in both moisture content and OMC resulted from changes from flocculated to deflocculated soil structure. This, he considered, caused interchange between adsorbed and free moisture, the former being that driven off between 105°C and 200°C. The results (equations 2, 3 and 4) demonstrated that no such interchange occurred as increases in 105°C moisture content were matched by equivalent increases in 200°C moisture content.

(b) Movement Toward Equilibrium

Since no structural change had been found, consideration was given to the concept of an equilibrium moisture content related to the Thornthwaite Climatic Index (Ref. 12). It appeared possible that the soil moisture content could tend toward such an equilibrium and thus explain the observed moisture movements. Unfortunately, the necessary climatic data for computing the Index were not available at the site.

(c) Source of Adsorbed Moisture

From the adsorbed cations tests, using published figures for ionic and hydration shell radii (Ref. 13), the amount of hydration shell moisture was computed. The published radii are based on transport experiments and are not a direct measure of the dimensions at rest. Clay thixotropy and some published work (Ref. 14) suggest that shells may slide over each other more readily in rapid motion. Dimensions could be greater at rest. If computed hydration moisture is plotted against adsorbed moisture for Sites 1, 2 and 3, all points lie close to a line whose slope is 1 : 5. This would be explained if hydration shells have five times the volume at rest as in transport. The relation certainly suggests that hydration shell moisture is associated with 105°-200°C moisture.

Soils from Site 4 did not conform. These contained abundant expanding lattice clay. Adsorbed moisture there was less than the relationship would suggest. The deficiency was related to base exchange capacity, which was highly significant. The base exchange capacity could reflect the proportion of expansive clay, in which case the interlayer hydration water may be removed at 105°C, whereas other hydration water may not.

VII.- CONCLUSIONS

From the foregoing results it may be concluded that OMC of soil tested under uniform compactive effort changes with the initial moisture content. The magnitude of the change is greatest within a certain initial moisture range and also dependent, to a degree, on curing time. Accompanying changes of the actual soil moisture content during curing were also observed.

The implication of these findings is considered to be of practical importance for the design and construction of projects where a small change of placement moisture content, even of the order of one half of a per cent could have serious economic and engineering repercussions.

The present work was carried out by Snowy Mountains Authority, an organisation which does not carry out fundamental research but undertakes investigations only to a point required by current construction needs. Thus, although the reasons for the observed changes remain unknown, from the available results it appears that changes of OMC are not caused by structural rearrangement and consequent transfer between adsorbed and free moisture. The possibility of movement toward equilibrium is worthy of further investigation.

With more frequent construction of high earth structures, testing procedures must be constantly updated to keep pace with more refined design requirements. It appears that the standard compaction test, which for decades has remained basically unchanged in concept, may now require a review. In the meantime, construction of trial embankments during investigation, where the design and the size of a project warrants it, remains as the only means of accurate assessment of soil properties.

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