"THE ROLE OF SUCTION IN THE PERFORMANCE OF CLAY FILL"

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Abstract

Plastic clay is commonly used as fill. Proper placement is the key to the performance of the fill. Improperly placed clay can either settle or heave, dependent upon compactive effort and relative moisture used at the time of placement.

Clods in clay fill have a high "transient" shear strength as a result of high matrix suction. Point to point contact between clods, coupled with low compaction energy, results in large voids within the fill. A decrease in matrix suction by addition of moisture results in loss of strength of the individual clods and subsequent collapse.

Gross settlement of 7 to 13 percent of the depth of fill has been observed in clay fill. Moisture-density relationship (ASTM D-698) curves were plotted along with the results from suction and relative strength tests, to evaluate the field performance and observed post-settlement condition of the fill. X-ray analyses on the fill before and after collapse as well as laboratory-prepared samples illustrating the macro-structure of the fill are presented.

The paper illustrates that simple field verification of the condition of the fill is possible using a pocket penetrometer in conjunction with moisture and density tests.

Introduction

Performance of clay used as fill has been the subject of an extensive body of literature. As early as 1933, Proctor (1933a, 1933b, 1933c, and 1933d) addressed the relationship between moisture and density and compaction procedures in a series of articles published in *Engineering News-Record*. This series of articles are as relevant today as they were in 1933 and deserve rereading.

The purpose of this paper is not to reinvent the wheel, but rather to reintroduce and update the concepts presented by Proctor. Specifically, this paper addresses compaction of moderate to highly plastic clay relative to the potential for post-construction settlement. Extensive literature is available addressing heave of over compacted clay, and is therefore not addressed here.

One of the fundamental principles addressed by Proctor in his classic series was that soil moisture in conjunction with compactive energy determined the relative density of the compacted soil. Proctor advocated testing to confirm the compacted condition of fill. Two tests were proposed and used extensively on large earthen dams, the Standard Proctor moisture density relationship with corresponding field densities, and a less known "plasticity-needle" penetration resistance test.

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Proctor illustrated that the penetration resistance for a clay varied with the moisture. His tests illustrated that clay compacted below optimum moisture had a higher strength then clay compacted above optimum moisture.

The purpose of the present paper is to explore the relationship between optimum moisture, transient strength observed by penetration resistance, and suction. For the purpose of this discussion, transient strength is defined as the apparent strength attributable to suction pressure. (As suction pressure increases, the effective pressure increases with the corresponding increase in strength).

A brief case study is then presented to illustrate application of the laboratory results.

Laboratory Study

Moisture density curves on expansive clay are performed routinely throughout the world. By the addition of a simple penetrometer-moisture curve, a significant amount of information can be developed to aid both the technician performing the field confirmation tests and the reviewing engineer.

The results of ASTM D-698 moisture-density relationships on three moderately plastic clays are shown on Figs. 1 through 3. For each relationship, the soil sample was divided into five sub-samples. A quantity of water was added to each sub-sample, mixed thoroughly, bagged and allowed to hydrate for a minimum period of 24-hours. The moisture-density relationship was then established in accordance with ASTM D-698.

Prior to drying each sample to obtain the test moisture, the samples were cut lengthwise. Penetration resistance was obtained at multiple locations to confirm uniformity.

Two representative samples were also taken from each test point for evaluation of soil suction. Total soil suction was obtained by using both filter paper in accordance with ASTM D-5298, and using the WP-4 device manufactured by Decagon Instruments. Two replicate samples were tested using each method. The results presented on the Table 1 represent the average values of the two replicate tests. The ASTM calibration curve was used for the filter paper suction values.

Two additional curves are shown with each of the three standard moisture-density curves; pocket penetrometer resistance versus moisture, and variation in soil suction versus moisture. The soil suction curves shown in Figs. 1 through 3 are based on the results of the WP-4 tests. The total suction measured using the filter paper procedure showed similar trends, although the values were significantly higher. A comparison of measured suction using filter paper versus the WP-4 for each sample is provided in Table 1, 2 and 3.

Analysis of Figs. 1 through 3 illustrates a decrease in the penetration resistance with increase in moisture and corresponding decrease in soil suction. Particular attention is drawn to the penetration resistance curves. In each case, the resistance exceeded the maximum of the penetrometer where the sample was compacted below optimum. In other words, given identical unit weights and volume of voids, the penetration resistance for samples compacted below optimum was notably higher then where the sample was compacted above optimum. This loss of strength can be directly attributed to the decrease in suction and corresponding decrease in effective stress.

This variation in penetration resistance above and below optimum moisture can be used as a reliable check on the results of field moisture and density tests using a nuclear density device. If the test results indicate that the fill is above optimum moisture, then the corresponding penetration resistance should be a value generally less then 4.0 tons per square foot, dependent upon the specified moisture. If the penetration resistance does not correspond to the penetration/moisture curve, it is an indication that the moisture density curve or test is not valid for that particular portion of the fill.

The suction/moisture relationship indicates the role soil suction plays in the apparent strength of moderately to highly plastic clay. Since points of equal unit weight above and below optimum moisture represent an equal volume of voids, the apparent strength gain below optimum moisture must be due in large part to the increase in suction or effective stress.

In addition, since points horizontally opposite of each other on the moisture density curve have an equal volume of voids, no significant variation in the settlement characteristics of either sample would occur upon saturation. In fact, the classic paper by Holtz and Gibbs (1954) illustrated that, for samples of equal unit weight, samples compacted below optimum swelled relative to samples compacted above optimum.

The practical application of the proceeding information is presented in the following discussion.

Field Application of Penetration Resistance

This paper has been generated as a result of observation of settlement of utility trenches where plastic clay was used for backfill. Typical examples of settlement of utility trenches are shown in Figures 4 and 5. A case history of the settlement observed in Figure 5 was presented at the Fall Meeting of Texas Section ASCE Fall Meeting in 2000 (Reed and Phipps, 2000)

Settlement shown in Figs. 4 and 5 occurred with no applied load other then overburden. The settlement occurred despite the fact that both utility ditches were reportedly compacted to 95 percent Standard Proctor density.

This type of gross settlement is sometimes erroneously attributed by engineers to the post construction addition of water. Some have even coined the phrase “hydro-compaction”, meaning upon saturation, the fill lost strength with corresponding settlement.

A general analysis of the moisture density curves in Figs. 1 through 3 indicate that fill compacted to 95 percent density should perform in a similar manner whether compacted above or below the optimum moisture. If anything, the fill should swell if compacted below optimum. An extensive body of literature supports the conclusion that clay compacted below optimum moisture swells with a gain in moisture.

Why then would clay backfill undergo excessive settlement? To settle approximately 10 percent, a significant decrease in the volume of voids must occur.

Analysis of the suction/moisture relationships shown in Figs. 1 through 3 illustrates that at moisture contents below optimum, the total suction increases. The increase in suction results in an increase in effective stress, which in turn increases the shear strength.

For in-situ plastic clay existing at moisture below optimum, the clay exhibits a high suction value and high shear strength. Excavation of dry clay results in relatively dense, hard clods principally because of the existing high internal strength associated with soil suction.

If the dry clay clods are then compacted to 95 percent Standard Proctor density, one would expect the sample to heave, or, at a minimum to have similar settlement characteristics of a clay compacted to 95 percent density above optimum. This conclusion is based on the fact that both samples at 95 percent density have an equal volume of voids. One would then conclude that either all clay compacted to 95 percent density settles approximately 10 percent under overburden loads, or, error occurred in the measurement of the field density. The first conclusion is not supported by either the extensive body of literature or by practical experience.

Field density tests conducted on the trench backfill shown in Fig. 5 reported that the fill had been compacted to a minimum of 95 percent Standard Proctor, at a moisture content of one to two percentage points above optimum.

After isolated settlement of the roadway shown in Fig. 5 was noted, sample borings were drilled to evaluate the relative condition of the fill. Two conditions were investigated, areas exhibiting significant settlement, and areas where no settlement had occurred at the time of the field investigation. Samples of the fill where no settlement was observed were hard, with penetration resistance exceeding 4.5 tons per square foot (tsf). Where settlement had occurred, the penetration resistance varied from 0.5 to approximately 2.0 tsf.

A significant variation in the moisture was also noted. A plot of the moisture content at locations exhibiting and not exhibiting settlement is provided as Fig. 6. The relative moisture reported with the field moisture/density tests are also plotted on Fig. 6.

Examination of Fig. 6 indicates that fill which has not undergone settlement is at moisture contents 1 to 4 below the optimum moisture. Fill within the areas of collapse are 3 to 5 percentage points above optimum.

The large gain in moisture and subsequent loss of strength of the fill is not in itself a problem, however, fill at 95 percent Standard Proctor density should not undergo significant settlement. It can be concluded, because of the settlement, that the fill was not, in fact, compacted to 95 percent of maximum density.

As part of the investigation, samples from collapsed and non-collapsed locations were submitted for x-ray analysis. This analysis was done in accordance with ASTM D-4452.

A photograph of the x-ray conducted on the collapsed fill is provided in Fig. 7. The analysis indicates the fill contained relatively dense clods within a softer, less dense, matrix.

A photograph of a sample of clay fill compacted above optimum moisture is shown in Fig. 8. Note the absence of dense clods in Figure 8 compared to Fig. 7.

Application of the penetration tests during the field moisture and density testing could have alerted the field technician or reviewing engineer that the field moisture and density was suspect. Because of the dense, hard clods, the penetration resistance would have indicated very hard (penetration values of 4.5 tsf) soils. For moisture above optimum, penetration resistance of 2.5 to 4.0 tsf would be anticipated.

Conclusions

In clay, penetration resistance varies with moisture. At above optimum moisture, there is a significant reduction in the resistance, attributed in part to the decrease in effective stress associated with a decrease in suction.

The addition of a simple penetration test during development of the ASTM D-698 moisture density laboratory curve can be utilized as an additional check on the validity of field tests. Field tests where the measured or reported moisture is above optimum, but the resistance is 4.5 tsf or greater should be suspect.

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Table 1. Comparison of Soil Suction values from Filter Paper and WP-4 Methods (Soil Sample A)

Moisture Content (%)	**Total Soil Suction Filter Paper (tsf)**	**Total Soil Suction WP-4 Method (tsf)**
10.8	14.4	4.19
13.5	7.7	3.88
15.4	7.4	3.70
18.0	4.9	3.11
19.2	2.1	1.71
21.5	2.8	1.71

Table 2. Comparison of Soil Suction values from Filter Paper and WP-4 Methods (Soil Sample B)

Moisture Content (%)	**Total Soil Suction Filter Paper (tsf)**	**Total Soil Suction WP-4 Method (tsf)**
12.7	12.4	4.17
14.5	5.45	3.88
16.4	4.8	3.25
18.9	2.1	1.71
20.1	1.0	1.71

Table 3. Comparison of Soil Suction values from Filter Paper and WP-4 Methods (Soil Sample C)

Moisture Content (%)	**Total Soil Suction Filter Paper (tsf)**	**Total Soil Suction WP-4 Method (tsf)**
13.2	18.2	4.11
15.6	5.4	3.99
17.7	5.0	2.89
19.7	2.8	1.71
21.9	2.5	1.71

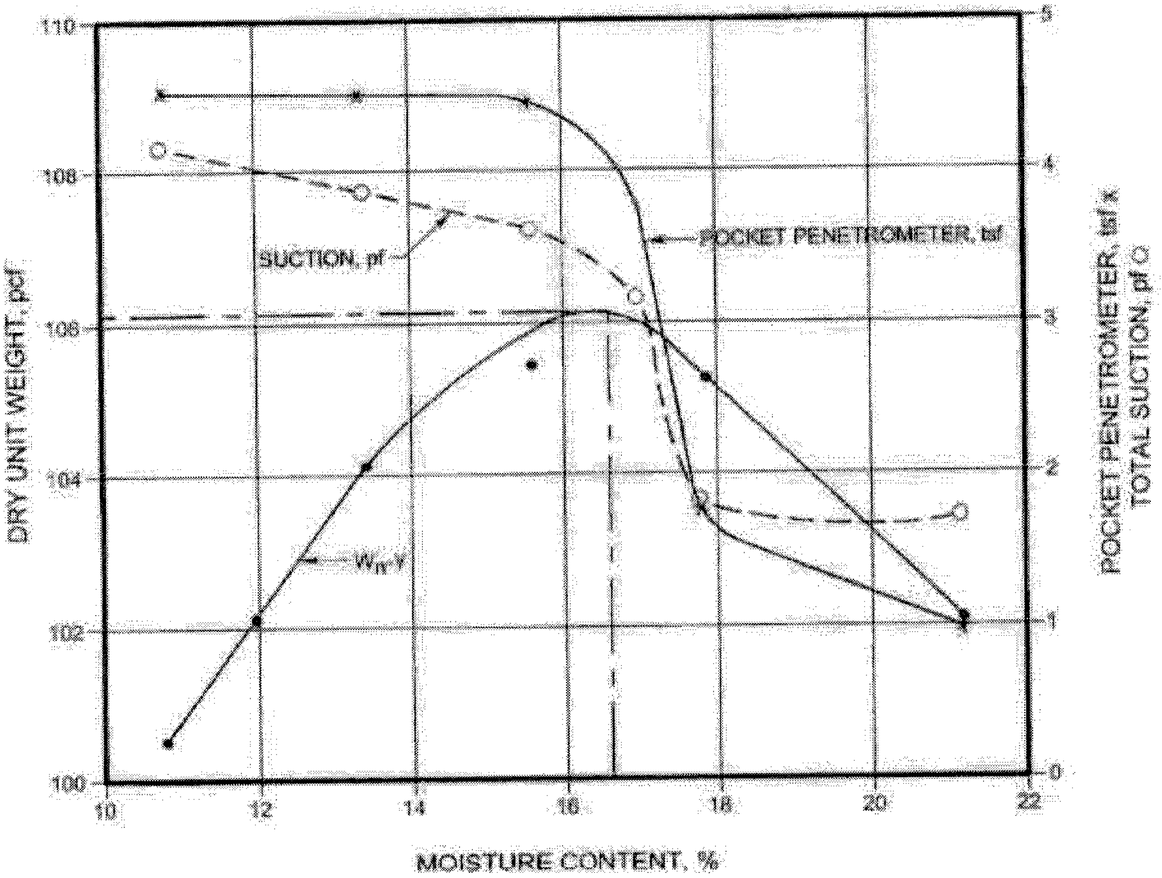

Fig. 1 Variation of pocket penetrometer resistance, suction, and dry unit weight with soil moisture (Soil Sample A)

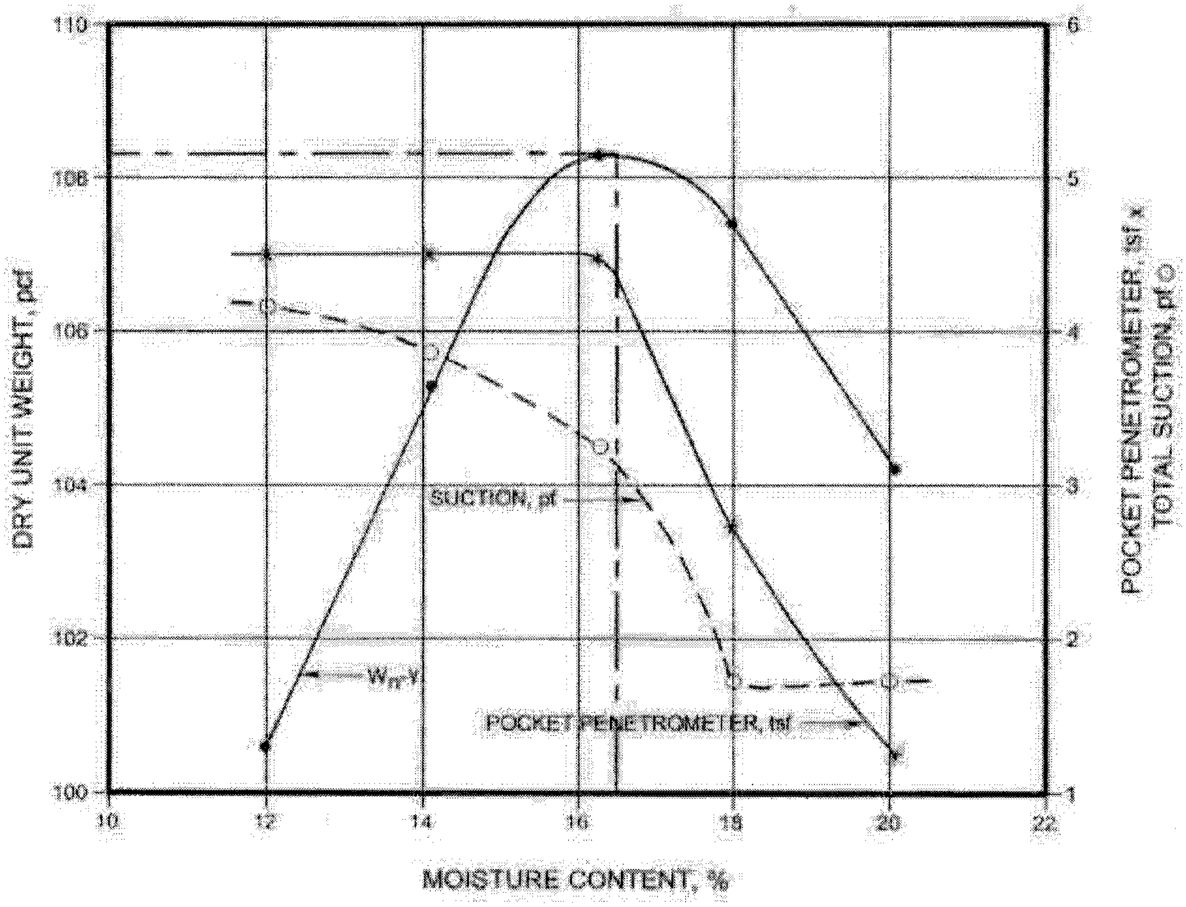

Fig. 2 Variation of pocket penetrometer resistance, suction, and dry unit weight with soil moisture (Soil Sample B)

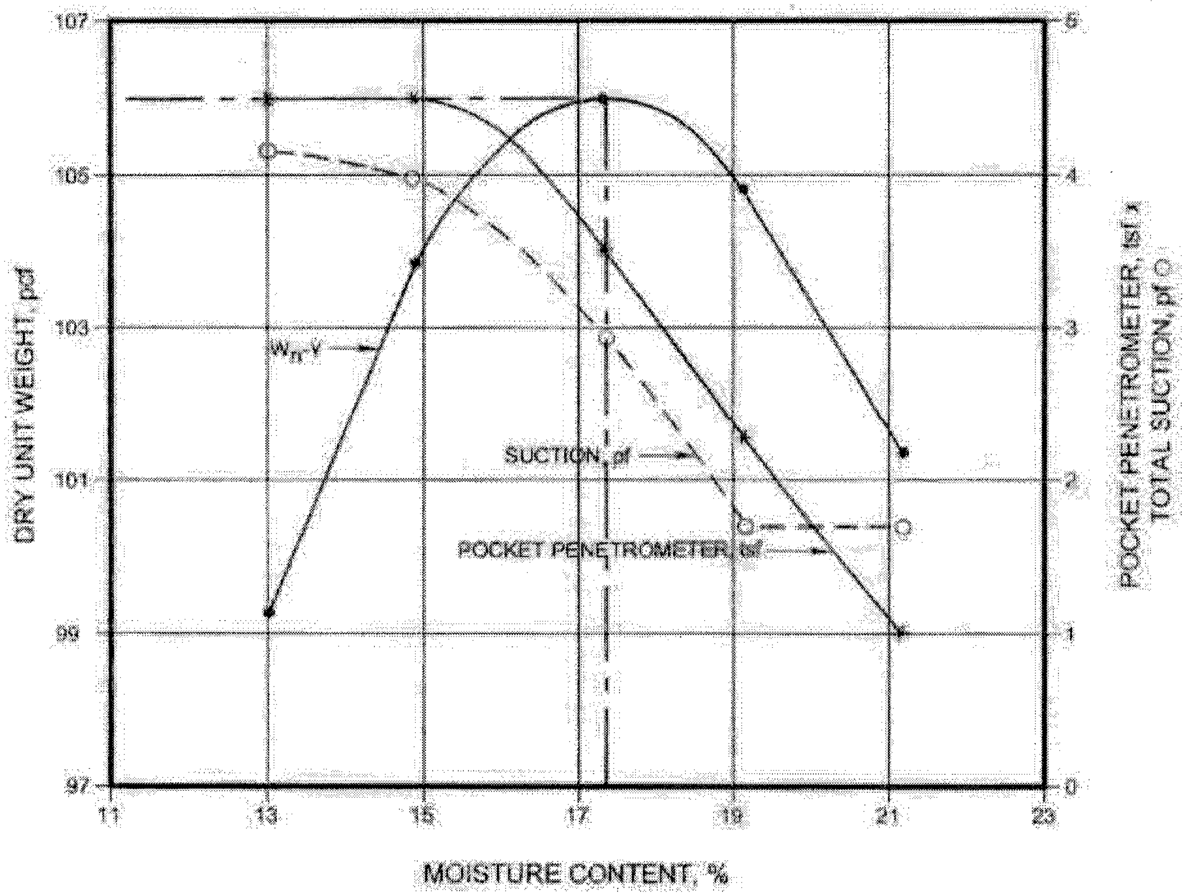

Fig. 3 Variation of pocket penetrometer resistance, suction, and dry unit weight with soil moisture (Soil Sample C)

Fig. 4 Post construction settlement of utility trench backfill.

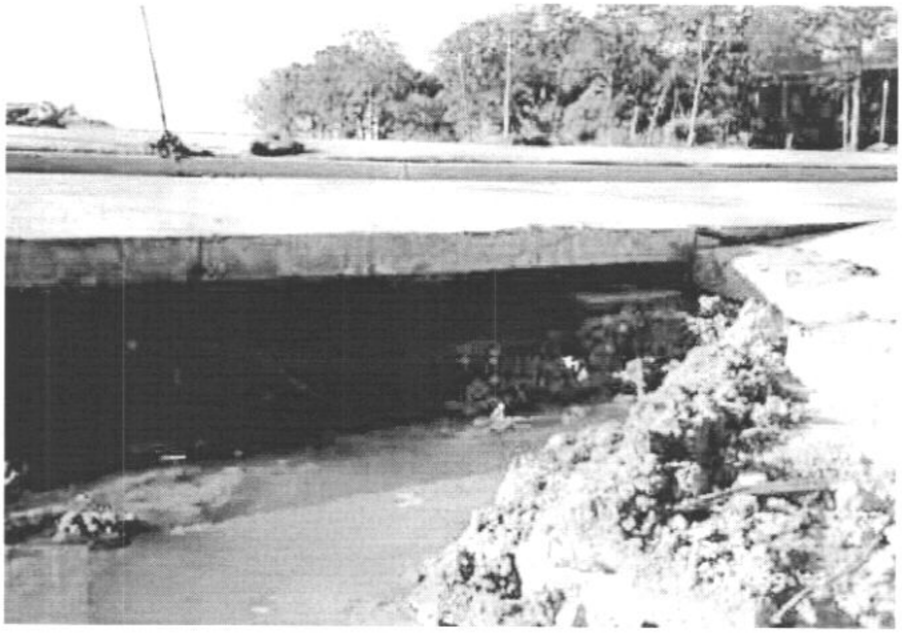

Fig. 5 Post construction settlement of utility trench backfill. Note the resulting void beneath the pavement section.

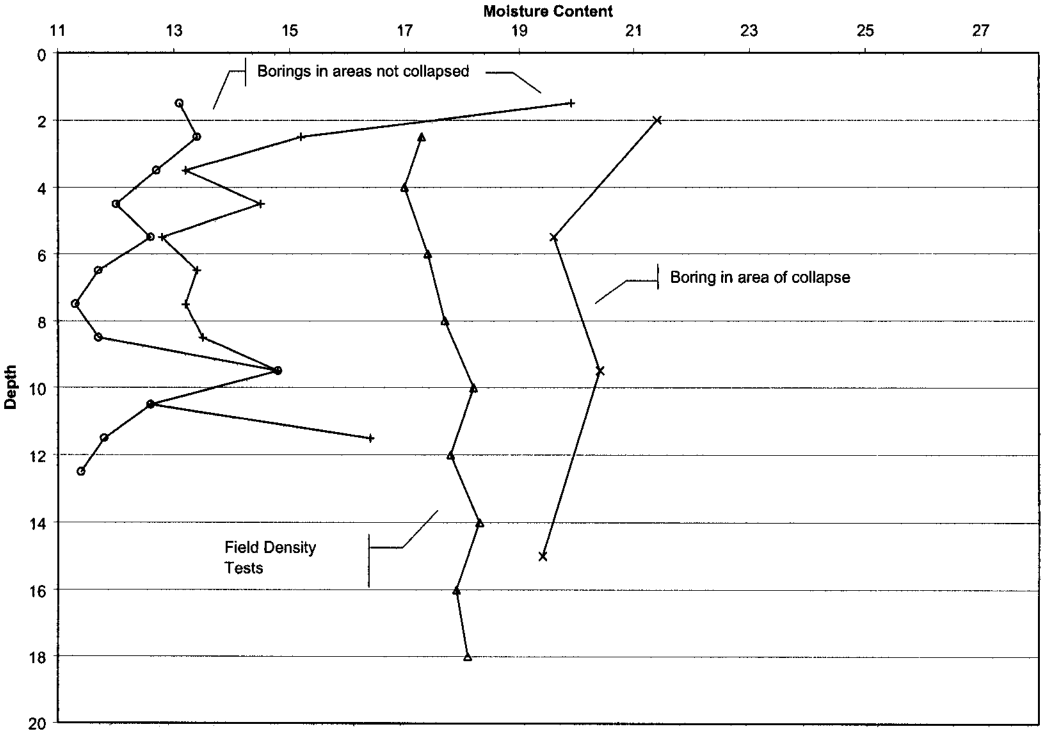

Fig. 6 Soil moisture vs depth for soil sample borings from the location shown in Fig. 5.

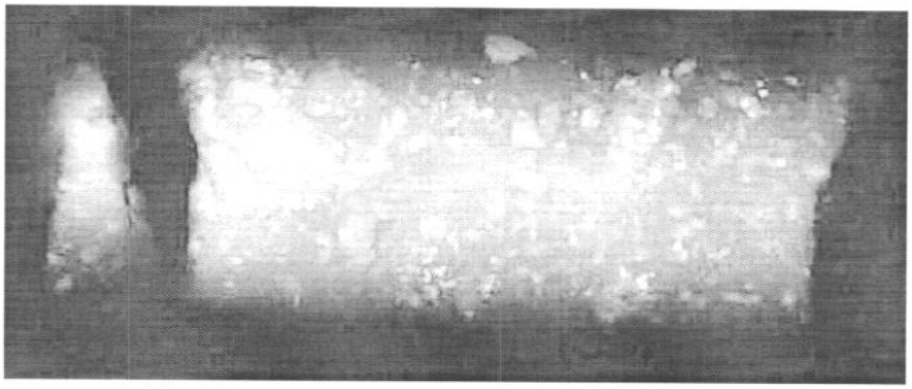

Fig. 7 X-ray of soil sample obtained from utility trench (location shown in Fig. 5). Note the soil clods within sample.

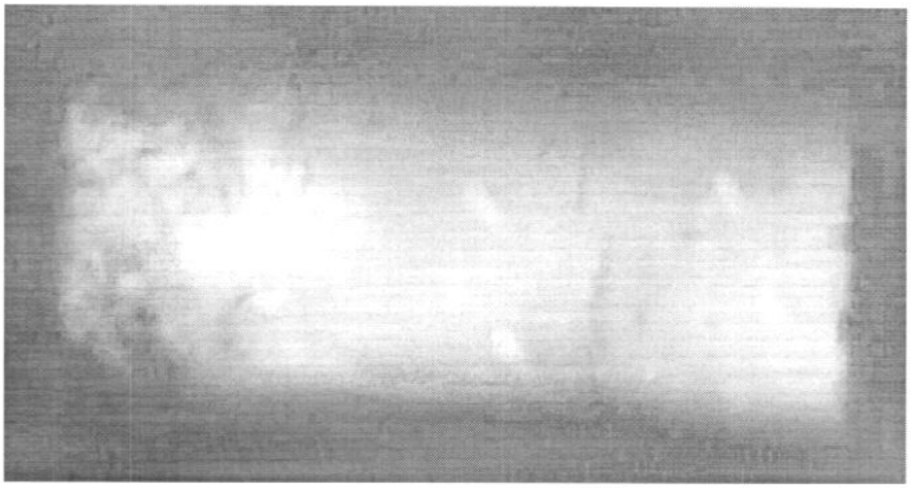

Fig. 8 X-ray of sandy clay fill placed at above optimum moisture content. Note relatively fewer soil clods compared to sample in Fig. 7.