PAPER No. 269

Soil compaction as applied to Airfield Construction and Stability of Runway Slabs in High Spring Level Areas

By

C. L. Handa, I.S.E.

INTRODUCTORY

This note is based on investigations done in the field as well as in a small scale laboratory in connection with the construction of concrete runways involving 4 inches thick cement concrete slabs laid on compacted soil without the provision of any soling. In this design, on an operational site, 4,500 tons of materials are saved for every inch of soling thickness, the place of which is taken by compacted soil which by actual tests, has been found to provide an adequately safe and stable foundation. The information given in this note embodies the results of field experiments covering the successful completion of 80 lacs sq. ft. of Runway and Taxi Track surface which is equivalent to 150 miles of 12 ft. wide road. The earth work compacted consisted mostly of a six inch layer and in cubical contents aggregated to 50 lacs. The nature of soil met with was of very varied composition and each of the constituents ranged between wide limits as given below :—

Clay from 8 to 47 per cent.

Silt from 4 to 57 per cent.

Sand from 11 to 81 per cent.

The dry bulk densities of the soil in its natural state varied between 1·6 and 1·3 and these were generally improved to an average figure of 1·85, thus securing an improvement of 15 per cent to 40 per cent respectively. The bearing capacity of the natural soil varied between 1 and 3 tons per sq. ft. and this was improved respectively up to 3 tons and 7 tons per sq. ft. representing, an increase of from 200 per cent to 130 per cent. The attainment of the requisite standard of compaction without retarding the progress of construction at a rush pace, became possible through continued experiments in the laboratory co-ordinated with field tests involving about 100 complete analyses of soils and 1,000 tests on D. B. density and 300 tests on bearing capacity of soils. A study of these results has failed to give any set formulae or simple code for the compaction of soils but the more important of these results are presented for what they are worth, in the hope, that these will be of interest to the Engineer, who has a long way to tackle before the complex of soil qualities can be reduced to the exactness or discipline of a science.

Laboratory Equipment

This comprised :—

(1) Analytical balance, capable of weighing accurately up to milli grams.

(2) Electric shaker worked by a 1/4 H. P. Motor for dispersion of soil samples.

(3) Modified Proctor's compaction apparatus.

(4) Roller compactor (Improved adoption of item 3 above).

(5) Chaino Hydrometer.

(6) A Still (for distillation of water).
(7) An oven for drying soil samples.
(8) A Descicator.
(9) Cylinders – 1 dozen.
(10) Evaporating basins – 2 dozens.
(11) Pippettes 50 c. c. – 2.
(12) Pippettes 10 c. c. – 2.
(13) Litre Flasks – 2.
(14) 250 c. c. bottles. 24.

Field Apparatus

(1) Sampling wedges.
(2) Drying pans.
(3) Measuring cylinders 250 c. c.
(4) Khurpies.
(5) Angithies.
(6) Country balance.
(7) Cloth bags.
(8) Apparatus for testing bearing pressure up to load intensity of 10 tons per sq. ft. on 6 inch square base.

The cost of all the laboratory equipment was approximately Rs.1,000 and the field equipment for each site Rs.100.

The laboratory was in the charge of an experienced M.Sc. Research Assistant and he also controlled the Field Test Staff consisting of Observers and Samplers who were specially (but quite easily) trained.

Special Features and Difficulties

Paper No. 256 by Mr. S. R. Mehra and Papers No. 257 (and 260) by K. B. S. I. Mahbub read before the 1942 and 1943 session of the Punjab Engineering Congress dealt with the subject of soil stabilisation and densification of canal banks and these interesting and instructive papers embody the fundamental theory and methods of compaction as per standard works on the subject and as studied or applied by these authors in their field and laboratory research. While use has been made of their experience and findings, only such facts are given in the present note where either the differences as to soil treatment for the achievement of maximum compaction are material, or fresh ground had to be covered for the solution of difficulties caused by the special features and necessities of the work. These are enumerated below :—

1. *Higher standard of soil strength required for landing grounds, i.e*, a dry bulk density of about 1·80 and a bearing capacity of 7 tons per. sq. ft. in the case of clayey soils and 3 tons per sq. ft. in the case of sandy soils or high water table area. The maximum settlement allowed under these load intensities was not to exceed 0·06 of an inch. These specifications

are much higher than what is aimed at for compacted canal banks where 10 per cent in excess of natural D. B. density of excavated soil is accepted in respect of densification and a bearing capacity of only 1 ton per sq. ft. is aimed at.

2. *Presence of high spring level.* Extensive compaction had to be done in an area where spring level ranged from 5½ ft. to 2 ft. below natural surface representing a new and an important aspect of compaction methods which can be applied to road making in waterlogged areas.

3. Speed and progress of compaction in so far as it was apart from merely the strength of labour or multiple organisation.

Whereas no theoretical explanations have been attempted or empirical formulae recommended, the above special features and difficulties have been coped with, through experiments and trial and error in the field and the laboratory. And solutions in almost all cases have been found to be strikingly simple and effective. These are summarised below :—

(*a*) **Laboratory experiments on optimum moisture.** These formed the real nucleus and foundation on which the field work was based, and the results actually obtained in the laboratory were accepted for guidance in preference to any known or published formulae. As a result of these experiments optimum moisture percentage was found to be not merely a function of the soil composition in terms of sizes of particles, as is generally held. This inference is supported by the large number of experiments involving soils of varying compositions carried out from field samples which were analysed and compacted in the laboratory (see Appendix Table I). An attempt was first made to standardise the optimum moisture percentage with reference to the sand content but it was found that in most of the cases the laboratory results, subsequently confirmed by work in the field, gave a wide variation from the formula proposed in Paper No. 257 *viz.*

$W = 24 - 0{\cdot}14S$ ....(1)

Where W = optimum moisture percentage

S = sand percentage

[*Classification of sizes.*

Sand. Particles above ·05 m.m. diameter

Silt. Particles between ·05 and ·005 m.m. diameter

Clay. Below ·005 m.m. diameter]

It was seen that this formula could be used only in the case of soils in which there was a predominance of sand (over 50 per cent). In the case of soils with a predominance of silt (over 35 per cent) the above formula was not only not a rough guide but was actually misleading, as the variation between moisture percentage actually needed and that given by the formula was so large as to be out up to 40 per cent. A few instances are given below :—

Site.	Composition			Optimum moisture		Difference.	Percentage variation.	Optimum moisture as per formula W=24 − ·14s − ·1Si.	Remarks.
	Clay	Silt	Sand	Determined in Lab. and confirmed by field work.	As given by formula W=24 − ·14S.				
1	2	3	4	5	6	7	8	9	10
B S800 T	17·6	57·8	24·6	15·0	20·6	5·6	38%	15·3	Formula in
C 250 T	22·0	63·6	14·2	16·0	22·0	6·0	38%	16·2	Column (9)
C 2150 sec.	29·0	48·0	23·0	16·0	20·8	4·8	30%	16·5	discussed
C 700 sec.	28·8	45·2	26·0	16·4	20·3	3·9	24%	16·3	below.

One obvious fact in this connection is that it is not sand content alone that governs the moisture percentage but silt also plays an important part. In the case of above and similar compositions, more approximate results are given in column 9 and these have been derieved from the following formula :—

$$W = 24 - \cdot 14S - \cdot 1Si \quad \ldots\ldots\ldots(2)$$

where W = optimum moisture percentage.

S = sand percentage.

Si = silt percentage.

The formula (2) was no doubt a better guide in the case of predominantly silty soils as compared with Thal soils, yet this formula also was accepted with considerable reserve as in certain instances, the moisture percentage of samples with similar silt content was considerably different. One reason for this would be the difference in the relative clay and sand contents but what appears to be the safest conclusion is that the optimum moisture content, besides being related to the composition dependent on size of soil particles, is also closely related to the nature of the constituents, chemical or colloidal, the exact analysis of which is not yet covered or allowed for in our study of soil science. Hence the only criterion for success in the field would be the tests carried out in the laboratory by trial and error and the main focus of stress should be the reproduction and application of laboratory results in the field, the main requisites of which are discussed below.

(*b*) **Rigid moisture control in the field.** Whereas the determination and knowledge of the optimum moisture percentage has its value, a matter of greater importance is the attainment and control of the desired moisture percentage in the field. The method of flooding the actual area of work was altogether undesirable in case of soil in which clay predominated. With flooding, the area got too wet and working conditions were not available for several days. The better alternative was to water the area of borrow pits and bring the excavated earth across in an over-moist state. During transit and in the process of spreading it went on losing moisture and rolling was started while the moisture content was on the higher side. The process of rolling brought moisture to the top which kept evaporating away, thus it was ensured that the soil got rolled before the moisture content could fall below the optimum. However, the duration in which the soil possessed optimum moisture content was too small to permit of the completion of the rolling required and in order to extend this period, we had to resort to provision of additional moisture through sprinkling. Throughout the process, twice-daily (forenoon and afternoon), observations of moisture content were carried out by the field Samplers and Observers and in accordance with these results the sectional overseers were able to regulate both moisture and the working of rollers. Dry bulk density tests were also carried out simultaneously and practically the same D. B. density was attained as in the laboratory.

In the case of sandy soils the area of work gave better results with flooding after the earthwork of filling had been laid to complete the profile. The interval between flooding and starting of compaction depended on the permeability of the soil due to its clay content but flooding much in advance generally resulted in excessive loss of moisture, and in cases of low clay percentage (under 15 per cent), it was found desirable to do the flooding only about twenty-four hours in advance. In such cases the soil brought from the borrow pits was not previously watered.

In the case of high spring level area, the process was materially different and is dealt with separately.

(*c*) **Rolling**. The experience gained as to type and size of rollers to be employed for various soils and conditions is as follows :--

1. *Clayey soils*. Toothed concrete rollers (width 4 ft., weight 1·3 tons, knobs 3 inches high, size of knob 6 inches at base to 4 inches at top) were found to be very effective. As the area of knobs is only 1/7th of the total roller area, these rollers exert a pressure equivalent to a 9 ton plain roller, on the portion of soil trodden under the teeth. Hence this type of roller was even more effective than a six-tons steam road roller which was therefore used only in the final stages of work after first compacting the sub-grade with the requisite number of rollings with the toothed rollers. If this was not done, clods of soil persisted in spite of rolling with the steam road roller. Dry bulk density of 1·80 to 1·95 was generally attained in the case of clayey soils by rolling them at optimum moisture with 12 to 16 rollings of a 1·3 ton toothed roller followed by 4 to 6 rollings of a 6-ton steam roller. With the latter, the rule observed was that the narrow hind wheels should have covered every portion of the soil at least once in the longitudinal direction. After this, one or two cross rollings were generally found sufficient. At this stage the soil answered also to the required standard of bearing capacity which was tested up to a load intensity of 7 tons per sq. ft. on 6 inch square base and gave settlement of less than ·06 inch provided the moisture content was below 10 per cent. This figure incidentally was always lower than the optimum moisture for maximum dry bulk

density. The bearing tests were done with a speical but simple apparatus (for details see Plate II).

2. *Sandy soils.* These are quite the reverse of clayey soils so far as the type of rollers is concerned as with the toothed rollers the surface of the formation got continually ripped up instead of being kneaded into a compact mass. This was caused by lack of adequate cohesion in the soil particles due to the smaller percentage of clay. Thus maximum compaction could not be attained with the toothed rollers as in the case of clayey soils. On the other hand two-ton plain rollers were quite effective in the initial stages of compaction. Any clods in such soil were more friable and were easily pulverised by plain rollers which, however, could not produce the maximum D. B. density without being supplemented by steam rolling. Generally quite high dry bulk densities were obtained ranging from 1·8 to 1·9 but considerable difficulty was felt in obtaining the requisite bearing capacity due to the absence of the same amount of cohesion as was come across in the case of clayey soils. For this reason sandy soils with clay less than 10 per cent had to be faced with a 3 inch layer of clayey soil carried from the nearest source available within 10 to 15 chains lead. During the process of flooding the clay was washed into the pores of the sandy soil and the resulting admixture when rolled to highest D. B. density had also higher bearing capacity than if clay had not been admixed. In this case the bearing capacity developed, generally ranged from 3 to 5 tons per sq. ft. The number of rollings required for this kind of soil ranged between 12 to 16 rollings of a two-ton plain roller followed by 4 to 6 longitudinal and one to two cross rollings with a six-ton steam roller.

It will thus be seen that for attaining a high bearing capacity (over 3 tons per sq. ft.) we require firstly a high dry bulk density (1·7 or over) and at the same time a certain minimum clay content 15 to 20 per cent, without which the soil will not develop the necessary cohesion. While speaking of the high bearing power on an unconfined and unweighted soil it is understood that at the time of test the moisture content in the soil is not in excess of 10 per cent by weight. As regards compacted soils which have higher moisture content, but which are confined and enclosed due to being superimposed with concrete slabs as in a runway, the matter is dealt in detail subsequently.

(*d*) **Speed and Progress.** In the case of both clayey and sandy soils and in as far as spring level was not closer than 8 ft. from natural surface, the work of compaction proceeded apace and provided the earthwork of the sub-grade up to formation level was completed, the progress on compaction was generally 25,000 sq. ft. per day at each job. Serious interference was however experienced due to the effect of rainfall in irrigated tracts, whereas in non-irrigated tracts the main difficulty was scarcity of water and rainfall was welcome. In the former case a lot of time was saved by providing adequate drainage to the formation in the incomplete stage, during the process of compaction, and again when the sub-grade was finally compacted. This prevented rain-water from forming pools and the compacted surface escaped permanent damage as most of the rain-water got drained off and the soil resumed working conditions in comparatively shorter time. This drainage question proved a very important factor in the long run and its importance was soon realised after some unfavourable experience, during which work had to be suspended due to excessive moisture and pools of water that formed after a moderately heavy rainfall, thus rendering the soil unworkable.

In a non-irrigated tract, every occasion of rainfall was made use of, as it was the most suitable time to roll the soil, and all available rollers used to be put to work. On two occasions the rollers were supplemented by lorries carrying materials and this proved, within limits, to be the quickest method of compaction in which a natural dry bulk density of 1·45 was improved to a figure of about 1·7. The lorries had to be driven at slow speed (10 miles an hour) and their track was successively confined to different sections across the width of the formation. Simultaneously with this process the decreasing moisture content of the sub-grade was kept up by means of a watering lorry which sprinkled water over the formation.

While discussing speed and progress, it is emphasised that the main factor contributing to this was the strict collaboration between the work in the field with that in the laboratory. A sample of the Observers' daily report made from each field site to headquarters will be of interest (see Appendix Plate III).

One important precaution before commencement of rolling was that all earth put into the formation had previously been cleared of all grass, roots or vegetation with scrupulous care. This was effected by scraping the top 3 inches before laying the borrow-pits and subsequent hand picking. Before laying the first layer of earth to be compacted, the natural surface underneath was ploughed over three times and cleared of roots, grass, etc. by hand picking. But for this precaution, the mass of soil, even though temporarily compacted to high standard, would deteriorate, due to the organic matter decaying and leaving voids in its place.

Compaction work in high spring level areas. In the case of both clayey and sandy soils, and provided the spring level was not within five feet of the natural surface, the requisite standard of dry bulk density (1·8) and of bearing capacity (5 to 7 tons per sq. ft.) was achieved and remained intact till the sub-grade was covered with concrete slabs. There, was, however, one job in the writer's charge in which the water table was initially high due to the land being a rice growing area. An unusally heavy monsoon made matters worse and spring level rose from five feet to within two feet of the natural surface. These conditions were altogether peculiar and the moisture content in the sub-grade ranged from 20 to 25 per cent and due to excessive wetness, did not yield to the usual compaction treatment described so far. Here the use of toothed bullock rollers or steam rollers rather than compacting the soil produced quaking conditions in patches and the rollers would get bogged. It was therefore doubted whether such a site could at all give a safe landing ground. In what follows, the writer has given the special methods used for the treatment of this soil and also the results of acutal experiments on full scale slabs, which were loaded to an intensity of twenty tons per sq. ft. on 6 inch test area and have neither settled nor cracked. A fuller description of the conditions is given as it is considered that special interest attaches to this site.

Mr. F. F. Haigh, Chief Engineer, inspected the job at the end of September 1942. To get over the dead-lock, the following alternatives were considered :—

1. Increasing thickness of concrete slab.
2. Admixing sand or ballast in the sub-grade soil.
3. Compaction of the sub-grade with light rollers, but increased number of rollings to produce a dry bulk density of 1·65 or over and a bearing capacity with not more than ·06 inch settlement under a load intensity of 3 tons per sq. ft.

While going over the area and examining the conditions at different portions of the runway with a view to hit on a solution, the writer had noticed certain tracks and paths over which traffic had gone on for some time on account of camels carrying bricks and cement.

These tracks had automatically got compacted to a high dry bulk density in spite of the facts that the soil composition at these places was similar and high sub-soil water conditions were identical.

This process was in fact analogous to the application of light rollings on the sub-grade applied discontinuously after brief intervals so as to avoid any continuous and heavy rolling strain on the soil in its over-moist state. As however high dry bulk density and bearing pressure had been attained in these local pathways, this method was suggested by the writer and was approved by Mr. Haigh.

This simple alternative had the great advantage of practicability without extra cost, as 1 inch extra thickness of the slab would have involved about 1,100 tons extra material equivalent to $1\frac{1}{2}$ lacs of rupees besides loss of valuable time.

Subsequently the work was executed adopting the third alternative, after attaining the prescribed conditions on the sub-grade and adhering to the 4 inch thick slab in 1 : 2 : 4 stone ballast concrete. The runway slabs were tested after 28 days curing under a load intensity of 10 tons per sq. ft. Neither any cracks nor settlement appeared. As a result of these tests, it was accepted that no modification in the design was called for and the runway could be regarded safe.

The job was again inspected by Mr. Haigh in January 1943, and he suggested a further study of the stability of this runway in view of the relatively high spring level (2 ft. to 3 ft. below natural surface), and the effect that this might have on the accumulation of moisture in the sub-grade due to its having been covered with concrete slabs thus reducing evaporation.

For this purpose, a number of holes were left in the runway slabs for observations which have now been carried on for 7 months. These results are given in the appendix (see Table IV).

During this period a special full scale experiment has also been conducted and it can now be stated with confidence that the periodic variation of spring level from 5 ft. to 1·5 ft. below natural surface will not take away from the stability of the concrete runway, which will therefore be safe under all conditions for the designed load intensity produced by aircraft. These experiments were considered necessary before any definite assertions could be made. The presence of such a high water table so close to the concrete slabs certainly raised doubts as to the scope of the runway, and in any case it would be better to limit and restrict the use of the runway during certain months when the sub-soil water level is too high, rather than risk the safety of landing aircraft.

The following points have been studied :—

(1) Whether there was any concentration of moisture in the compacted sub-grade below the concrete slab, and how far it was related to the rise of spring level and in what way would the sub-grade be affected.

(2) What would be the effect of (1) above on the bearing strength of the slabs.

This was arranged through a full scale field experiment in which three slabs of sizes (15′ × 15′, 30′ × 15′ and 15′ × 15′) hereafter called respectively Nos. I, II, and III were constructed in a pit excavated in an area adjoining the runway keeping the slabs respectively 2 ft., 3 ft. and 4 ft. below the natural surface. The spring level at the time (June 1943) was about the lowest 5·3 ft. below natural surface. The thickness of the slab being 4 inch, the top of the sub-grades under the slabs was respectively 3 ft., 2 ft., and 1 ft. above the spring level. With the help of these slabs, the worst possible conditions for the runway have been anticipated and up to August 1943, the bottom of the lower most slab is only 6 inch clear of the spring level.

The soil in the sub-grade under these slabs was mechanically analysed and had a composition of clay 20 per cent, silt 45 per cent and sand 35 per cent. It was compacted with light rollers so as to give a dry bulk density of 1·75, which is about the same as was attained generally for the runway. A number of holes were left in all the slabs for observation purposes.

At the beginning of the experiment and before the slabs were laid, or compaction done, distribution of moisture and natural dry bulk densities in the soil under the three slabs were observed down to water level. These are given in the table below and will be seen to range near about 1·50 :—

(Table A Spring Level 5·4 ft. below Natural Surface).

	Depth below N. S. in Feet.											
	0 – ·5	·5 – 1	1 – 1·5	1·5 – 2	2 – 2·5	2·5 – 3	3 – 3·5	3·5 – 4	4 – 4·5	4·5 – 5	5—5·5	5·5—6
Natural D.B. density	1·55	1·5	1·52	1·52	1·49	1·54	1·49	1·56	1·55	1·46	...	...
Moisture percentage.	12·5	13·1	20·3	18·0	15·6	19·3	18·6	16·3	21·5	26·9	25·3	27·0

During the process of compaction, the quantitative improvement in dry bulk density of the sub-grade under the slabs with different number of rollings was observed and is tabulated below :—

Slab No. 3. Spring Level 1′ below top of sub-grade.

	No. of Rollings.										
	0	7	14	21	28	35	42	49	56	63	70
Dry bulk density with plain roller.	1·57	1·60	1·64	1·69	1·72	1·74	1·77	1·77	1·78	1·76	1·77

With a light plain roller weight 1·5 tons, 55 rollings had to be given to raise the dry bulk density to 1·77.

The slabs were then laid with hand mixed concrete using 1 : 2 : 4 mix., of which test cubes gave a crushing strength of 2,900 lbs. per sq. inch at 28 days.

Observations regarding the distribution of moisture under all the slabs were taken and these are tabulated below :—

Slab No.	Date of Observation.	Depth of spring level below bottom of slab.	Moisture percentage of soil at various depths (Feet) below Slabs No. 1, 2 and 3.							
			0—·5	·5—1	1—1·5	1·5—2	2—2·5	2·5—3	3—3·5	3·5—4
1 Concreted on 4-6-43	4-6-43	3·0	10·2	17·9	18·9	18·5	20·4	22·7	24·4	26·3
	18-6-43	2·9	15·0	15·5	17·6	20·4	18·5	21·9	23·0	23·8
	21-6-43	2·7	15·2	16·3	18·5	19·7	20·9	21·2	23·3	24·9
	4-7-43	2·9	13·3	15·6	17·0	18·8	19·4	21·2	22·3	24·0
	12-7-43	2·9	14·2	16·6	17·8	18·4	18·5	21·3	22·5	23·8
	21-7-43	2·9	16·9	18·5	19·2	20·9	22·8	23·0	25·7	26·3
	29-7-43	3·0	16·1	18·0	20·4	22·2	23·1	23·6	25·8	26·8
2 Concreted on 4-6-43	4-6-43	2·0	12·3	19·1	21·8	20·2	23·8	26·5	26·5	29·6
	19-6-43	1·9	15·2	17·4	21·1	22·8	23·5	25·3	30·7	33·0
	26-6-43	1·7	15·3	17·1	21·9	22·9	24·0	26·8	30·4	33·2
	10-7-43	1·9	16·6	20·3	21·6	23·5	24·2	27·0	27·5	35·3
	20-7-43	1·9	15·9	18·1	21·9	23·9	23·5	31·5	33·1	31·7
	25-7-43	1·8	18·2	20·4	22·6	23·0	23·6	33·7	31·8	36·4
	30-7-43	1·8	18·6	21·0	21·8	22·3	23·3	25·7	28·2	30·2
3 Concreted on 1-7-43	1-7-43	1·0	18·0	23·5	24·5	25·4	27·8	28·4	30·0	35·0
	18-7-43	0·9	18·5	23·7	26·4	30·4	30·4	30·4	30·4	35·7
	26-7-43	0·9	18·8	20·8	23·9	27·6	29·5	35·8	38·8	37·0
	6-8-43	0·8	18·8	24·8	28·8	30·0	32·5	34·0	35·5	36·2

It will be seen that in the case of the two upper slabs, the moisture content under the slabs was nearly 12 per cent at the time of the start of the experiment in June 1943, whereas in the case of the lower most slab the moisture content was 18 per cent at the very start.

The observations so far made reveal the variations in the moisture content. During this period the spring level rose by 6 inches, thus producing very critical conditions on the lower most slab, where the bottom of concrete was only 6 inches clear of the spring level. It further appears that the moisture content in the sub-grade increased progressively in the case of the upper two slabs (1 and 2), whereas in the case of slab No. 3 there was no appreciable variation in the percentage (18 per cent) which was first observed at the time of concreting. This suggests that there is a maximum moisture content in compacted sub-grade which may be regarded the saturation point for that degree of compaction and is not further affected, with the rise of spring level, even as near as 6 inch from the bottom of the slab. This depth corresponds to the thickness of the compacted layer.

Load tests have been carried out on all the slabs up to an intensity of 10 tons per sq. ft. using a 6 inch square test area and there has been no settlement or crack.

Simultaneously the sub-grade under the slabs has also been tested under load which was applied through the observation holes. The settlements obtained are given in the table below :—

Slab No.	Moisture Percentage.	Settlement in Inches at tons sq. ft.					
		1	2	3	4	5	6
1	16·4	·052	·128	·190	·243	·353	...
2	15·9	·066	·150	·257	·391	·550	·687
3	16·5	·07	·136	·220	·294	·402	·562

The above table shows that by itself the compacted sub-grade is not capable of withstanding the specified load intensity and undergoes considerable settlement due to the decrease in bearing capacity caused by the increase in moisture content. Bearing tests on the compacted sub-grade before putting the slabs showed that under an intensity of 3 tons per sq. ft., the settlement was not more than ·06 inch in the case of the upper two slabs. In the case of the lower most slab however, the bearing capacity was visibly lower as the moisture content never fell below 18 per cent.

The lowest slab however withstood a load intensity higher than the specified 7 tons per sq. ft. This indicates that there is no subsidence of the sub-grade, and therefore the slab does not come under tension. The probable explanations for this can be :—

1. The load intensity dispersed through the slabs at 45° though in excess of the bearing capacity of the moist sub-grade by itself, is, less than the bearing resistance which the sub-grade develops by virtue of its having been compacted and then being covered by the concrete slabs.

2. The sub-grade under the slabs being effectively covered and enclosed, is so circumscribed that it is not capable of lateral displacement or of heaving up. As such it resembles a flexible but incompressible medium. This property is ensured because of the original compaction treatment which lends homogeneity to the soil surface and mass and therefore minimises the risk of local subsidence.

3. The pressure applied on the slab presumably does not cause a re-arrangement of the particles and the excess of moisture does not in any way impair the dry bulk density which has been previously attained. As such the moist sub-grade exercises the same function as comparatively dryer sub-grade, so long as the soil is confined. This is corroborated by the fact that in an experiment on the lower most slab, a load intensity of 17 tons per sq. ft. produced failure at one of the corners following a settlement ·05 inch after which the slab cracked

with a loud noise, the plane of rupture clearly showed that failure was due to tension. This very slab was however also tested under a greater load intensity (24 tons per sq. ft. on 6 inch base) at the centre, where sub-grade though in an identical stage as regards moisture was more confined. Neither any settlement nor any crack appeared.

Along with the results of these experiments in high spring level area, data regarding compaction of soil, variation of optimum moisture with soil composition, and the maximum dry bulk density obtained in different specimens have been collected. This is given in the Appendix in the form of tables and curves which have been derived from experiments to study soil properties so far as they bear on compaction and maintenance of compacted sub-grade.

Attention is invited to the use of the Roller Compactor (see sketch in Appendix) which was specially devised during the course of the work and is a great improvement on the modified Proctor Compaction apparatus.

The laboratory was on a modest and by no means elaborate scale, but it is considered that results though necessarily approximate are substantially and fundamentally indicative.

The results collected in the field for about a year have been compiled on the suggestion of Mr. F. F. Haigh, I.S.E., Chief Engineer and Mr. James L. Roy, I.S.E., Superintending Engineer whose interest in the subject and helpful suggestions were a great encouragement to the writer.

DISCUSSION

While introducing the Paper, Mr. **C. L. Handa,** wanted to draw the attention of the house to the importance of recognition of soil as a structural material. Concrete Engineers had until recently been content on designing earthwork on foundations with traditional methods based on judgment and experience and had not inquired too closely into the complex of the behaviour of soil. The reason for this was firstly, lack of pressing need and then the fact that soil varies very much in composition and characteristics and this factor rendered useful work difficult. The speaker said that in the Paper being presented to the house, he had recorded the results of an attempt to understand solid behaviour and to take advantage of the results in the execution of a large work rapidly and at least cost.

Continuing, the speaker said that the problem of soil compaction and of the behaviour of soil under loaded slabs had been particularly considered under conditions in which the spring level was high and rose to even within 2″ of the runway slabs.

The main conclusions were that the difference in composition of soil as to size of particles and then the nature of the soil content was so varied that it was best to attack a problem in soil with experiments rather than with any rules of thumb. These experiments were simple enough and yielded reliable results in preference to any theoretical or empirical formulae.

Continuing the Author said that the best definition of soil compaction which a layman might understand was " The amount of soil which could be forced into a given volume. " For any soil, there was an optimum moisture content at which a given amount of work would produce maximum compaction.

The speaker further drew attention to the fact that compaction was entirely due to the reduction in the percentage of air voids. Hence the moisture content present limited the compaction possible in every case. A further limitation was the size of compaction equipment and mechanical energy that could be expended.

Whereas optimum moisture content was of great importance, it was to be remembered that it was not a property of the soil in the sense that it could not be varied. In such cases where the aim was not to obtain the maximum dry bulk density but to be content with a somewhat lower figure say a dry bulk density of 1·6 or so against a maximum dry bulk density of 1·9, it was a great advantage to use a moisture content which was up to 5 % in excess of the optimum moisture required for max imum. density. The advantage of using a higher moisture content was that lighter rollers could be employed and thus we could obtain the required density of 1·6 with a smaller expenditure of mechanical effort. It was, however, to be clearly borne in mind that this procedure had the limitation of not yielding the highest density of which the soil was capable. The analogy of using 1 : 4 : 8 concrete against 1 : 2 : 4 concrete where higher strength was not required was quoted by the speaker.

Earth work was a problem mainly of the practicing Engineer. Hence soil research should not only be confined to the special Research Workers but the Engineers must examine the subject from a practical and a field point of view. In the Paper presented before the house, it was desired to record the result of such an attempt which became possible because of the opportunity that the speaker had in having to deal with various soil conditions for a programme which involved an expenditure of about 80 lakhs of Rupees and a paved area of 80 lakhs sq. feet.

The Author concluded by saying that it was a most interesting problem to find out the extent to which compacted earth retained its properties or high density and high bearing power under changing conditions as such variations in soil moisture as well as in the age of the compacted specimens were unavoidable. Although a lot of work had been done in laboratories on the subject of soil compaction, its co-relation with the requirements of large scale operations still offered a big field for further experiment and research and the Paper before the house had been put forward as an effort in that direction.

Mr. **G. K. Vij**, remarked that Mr. Handa's Paper dealt principally with the site where he was in charge. At this particular place the sub-soil during the monsoon of 1942 was as high as 1′ from the natural surface and the problem was not merely to construct the landing ground but even the carriage of material presented considerable difficulty. No road could stand the heavy traffic of the lorries and even the collection of material could not be done. Actually the difficulties became so acute that it was under consideration whether this site could at all be fit for a landing ground from the structural point of view, because even if it could be constructed, the question was still there whether it would be safe enough for all future times. At this stage, however, it was also to be considered that since the aerodrome sites were selected by the Defence Department in view of certain tactical considerations, a site very near that area would be necessary even if that particular site was abandoned. Since the spring level condition in that *ilaqa* was similar throughout, the problem could not entirely be solved and some method of building a landing ground even under such conditions had to be considered and made feasible.

Actually during this dilemma, they were held up entirely for nearly six weeks from doing any kind of work inspite of the fact that the war situation at that time required the completion of the work at the earliest possible time. Fortunately, however, a camel track directed his thoughts in a new direction and he started seeing the possibility of the solution.

He found that the actual problem had resolved to this, that they could get the necessary dry bulk density by light but repeated rollings although they might not get the necessary bearing strength. It was expected, however, that when the sub-grade dried later on, the necessary bearing strength would be attained and so long as they could obtain the necessary dry bulk density, they could more or less safely carry on the concreting work. The Chief Engineer had given specific orders that the minimum specifications to be adhered to where dry bulk density of 1·65 and a bearing strength of 3 tons per sq. ft.

Since the condition of moisture in the sub-grade after concreting was a matter which was vitally connected with the future suitability and the safety of the landing ground, observation holes were left in certain slabs.

These observations revealed, as stated by Mr. Handa, that the moisture percentage changed very very gradually even if the sub-soil went down considerably and if the sub-soil rose very high or even higher than the level of the sub-grade, this moisture percentage in the compacted soil rose to a certain maximum of about 20% and then stopped. The full scale experiment carried out corroborated this fact.

Summing up, he said, that he found that a landing ground on a high spring level with a thoroughly compacted sub-grade was even stronger and safer than another where the sub-grade was likely to be dry and wet alternatively, for a sub-grade with no room for any voids was not capable of being further compressed and thus offered an incompressible medium which could bear enormous weight from all sides while a sub-grade which had dried up from a wet state offered scope of further local compression, causing a possibility of local settlement and thus involved the possibility of failure of the slab.

The subject of compaction had undoubtedly got enormous scope for further investigation and universal utility.

K. B., S. I. Mahbub speaking on Mr. Handa's Paper said that Mr. Handa had mentioned that the approximate formula given by him (Mr. Mahbub) for optimum moisture content in his Paper presented to the Congress two years back, *viz.*, $W = 24 - .14\ S$, was applicable to sandy soils only and did not hold good in the case of silty soils. The optimum moisture content denoted the state when there was sufficient free water in the soil to act as a lubricant and facilitate a more compact re-arrangement of the soil particles under pressure. The quantity of water in this case was just below the limit which would cause swell or further separation of the soil particles. As different soils would need different lubrication, the optimum moisture depended not only on the particle size, and its chemical or colloidal condition as mentioned by Mr. Handa but also on the grading and range of the soil particles. Any formula which took into account only the quantity of one or more constituents could, therefore, be at best a very rough approximation and could have a limited application only for that particular type of soil. On the same analogy better lubrication or more moisture was required with light rollers than with heavy rollers.

Mr. Mahbub then invited attention to another point, *viz.*, the limit to which the weight of the roller could be reduced for attaining a certain compaction.

The dry bulk density increased with increase in the number of rollings up to a certain limit beyond which a heavier roller had to be used to get a higher compaction. The roller used should be able to exert a greater pressure than the maximum pressure to which the soil had to be subjected. This would indicate that there was a definite lower limit up to which the weight of the roller could be reduced for attaining a certain compaction.

Mr. Handa had given densities obtained by using a light roller, on page 10, but there was no mention of the depth to which the results related. Presumably these pertained to the top 6″. It would be interesting to know how the dry bulk densities were affected below a depth of 6″, *i.e.*, how far down did the effect of the light roller extend.

Mr. **R. R. Handa** speaking on Mr. C. L. Handa's Paper congratulated the Author for taking all the trouble that he had done in order to lay down for the guidance of the Engineer, the number of rollings necessary for different conditions of moisture content. The compacting sub-grade underneath the slabs had a great future and he would recommend its trial even under the metalled roads in substitution of the soling coat. The object of the soling was to provide a footing for metalling. If the runways and taxi tracks had been successfully constructed without soling coats, there was no reason why the roads which had to carry far less heavier loads than the runways should not be constructed merely of a thickness of metalling over compacted sub-grade. This would result in a considerable saving of a coat. In the case of cement concrete slabs, it had been proved that compacted surface was sufficient to carry heavy loads, because tests carried out at the ends of individual slabs on the runways showed no cracks what to say of settlement. He suggested that tests be done to find out if with suitable modification, compaction of the sub-grade could not be applied to the ordinary macadamised roads.

The old method was to leave the formation for one monsoon season before metalling was done. In the consideration of strategic roads, it was not possible always to spare so much time. Substitution of compaction was, therefore, an advantage in that respect.

Mr. **R. R. Handa** also endorsed the Author's conclusions from his personal knowledge and experience of the construction of an aerodrome. He had given orders that he would not permit the masonry works on the taxi track to start until the whole of the earthwork and compaction was completed. After earthwork had been done, they had rains. The contractor's labour had also to be kept engaged as soon as rains were over. The heavy rollers were marooned and so they started work with light rollers. The result was that the dry bulk densities of compacted soils on the taxi track were anything of the order of 1·8 to 1·9 against 1·2 to 1·3 for natural soil.

The Paper would also be very useful for the Military High Command in as much as, it was brought to their notice that there was no difficulty in constructing cement concrete runways, when the sub-soil water level was high. The compacted surface helped in the laying of the slabs after which the whole of the surface acted like a raft in distributing the pressure underneath it.

The compactor shown in Plate II gave a very good indication in the aboratory of the approximate number of rollings required. In course of time, when compaction had been accepted as a substitute for soling in road making, it would find a good place in the economy of road construction.

In the job he had to construct, he had ordered that immediately after rain, light rollers should start work. The result was that very high dry bulk densities were obtained. His conviction was that the more the rolling, the more should the sub-grade improve. The curve in Plate No. VII however showed that after about 55 rollings, the dry bulk densities tended to fall.

While discussing the Paper, Dr. **Vaidanathan** remarked that Mr. Handa had made an original contribution to the subject of compaction of soils in this Paper. It was a credit to have been able to compact wet oils and bring them to a high density of nearly two, as had been mentioned in the Paper. The method which he had adopted for doing this was by a slow process of consolidating the soil by light pressure and then slowly increasing the load until full compaction was obtained.

When a saturated clay mass was loaded, the whole pressure was first taken up by the pore moisture and by applying gradually increasing pressure. Mr. Handa had been able to drive off all excess moisture, and finally bring the mass of soil particles together. The slow process had also helped in the orientation of the soil particles. The trend of consolidation depended on the permeability of the soil. He had by slow compression decreased the permeability, brought the soil particles together and oriented them as favourably as possible for getting high densities.

Mr. **Haigh** who had been keenly interested in the problem of soil compaction, had later on suggested to them that this method might be used for preventing seepages from canal beds. At present, the Dr. observed, they were employing this method for berms and beds of canals. In one case an experimental tank made in the Institute compound gave a seepage of 15 cusecs and after compaction, the seepage reduced to about 1 cusec. This was very remarkable. But after two or three months, it was found that the compaction had somewhat deteriorated. These experiments were still in progress.

Mr. Handa's roller compactor, was also an improvement on the old apparatus which was giving an impulse to the soil mass and not a continuous pressure. The process of giving an impulse for soil compaction and then trying to find the optimum moisture had a fundamental error in it which Mr. Handa had now corrected in his new apparatus.

Recent theories of soil compaction also took into account many of these factors which had been experimentally verified by Mr. Handa.

Lt.-Col. Blench raised the point that the Military were popularising the work of compaction which had a very great potentiality in so far as it saved considerably in the quantities of materials which would otherwise be needed for providing the soling coat. He further raised the point as to how for soils once compacted could be preserved in that condition, and pointed out that the results given in the Paper had a far-reaching application.

Mr. **Harris** said that soling coat had been used previously by the Buildings and Roads Branch but now in their programme of widening of roads they considered that only the wearing coat was sufficient provided it was laid on compacted earth. Such roads, he said, were giving satisfactory performance under the loads to which they were subjected.

Mr. **C. L. Handa** in his written reply acknowledged the important part that had been played by Mr. Vij, Sub-Divisional Officer-in-charge of the high spring level airfield mentioned in the Paper. Mr. Vij had carried out various experiments under his supervision and his contribution to the results was characterised with great care and insight. The opinion that " an airfield founded on a high spring level area with compacted sub-grade is even stronger and safer than another where the sub-grade was likely to be dry and wet alternately " was however in the opinion of the Author an extreme view because excess of moisture could not but take away from the bearing capacity of the soil. There was, however, no doubt that the problem of high spring level could be satisfactorily got over by adopting modified compaction methods as had been suggested in the Paper.

In reply to K. B., S. I. Mahbub, the Author agreed that the moisture content was a function not only of the quantity of sand present in a soil's specimen but also on the grading and range of the soil particles. Hence the formula $W = 14\ S$ was certainly a close approximation for predominantly sandy soils. A still nearer approximation for silty soils was the formula $W = 24 - {\cdot}14\ S - {\cdot}1\ Si$ which had been suggested in this Paper as a result of further experiments. It was, however, admitted that such formulae could only be rough approximations and therefore the Author advocated that wherever it was possible, field experiments were the best guide.

Regarding the second point raised by Mr. Mahbub that the weight of the roller could be reduced only up to a certain limit for attaining a certain compaction, the Author was again in full agreement. It had not been suggested in the Paper that light rollers were superior to heavy rollers in all circumstances because this would amount to getting better compaction with less mechanical work and would therefore be unaxiomatic. What had been suggested was that if their aim and design was for rather lower dry dulk densities, then they could afford the use of light rollers and the process was considerably expedited and cheapened if lighter rollers were used. The essence of the suggestion was that the practical Engineer working in the field should take pains to find out the optimum roller weight and moisture combination for a particular dry bulk density.

Regarding the third point raised by Mr. Mahbub, observations were certainly made by the Author regarding the improvement in dry bulk density by taking samples upto a depth of 2′ below natural surface. These results showed that the effect of the light rollers definitely travelled to lower than 6″ but the improvement in dry bulk density at depths lower than 6″ was less than would have been the case if toothed roller were used. For a light plain roller, the depths of layers had to be 3″ or so as against 6″ and therefore toothed rollers were definitely superior to light rollers subject to the requirements of the case as discussed above in detail.

Subsequent to the writing of the Paper presented to the house, the Author had worked out nomograms for various soils and various moisture contents from which it was possible for the field engineer to anticipate as to what number of rollings would be required for the attainment of various densities. In addition to this the improvement that took place in the bearing capacity of soil for various dry bulk densities had also been ascertained. The roller compactor had been further improved and was now in use in the Irrigation Research Institute in order to co-relate laboratory work with field work for the Thal lined Canal Construction which was in hand. These results were not incorporated in this discussion but had been separately presented to the Central Board of Irrigation where these were discussed in the 14th Meeting of the Research Committee held at Simla during August, 1944.

PLATE I.

RESULTS OF EXPERIMENTS ON OPTIMUM MOISTURE CONTENT FOR SOILS OF VARIOUS COMPOSITIONS AS DETERMINED IN THE LABORATORY AND CONFIRMED IN THE FIELD.

Sr. No.	Site on Airfield.	Size Composition of Soil.			Optimum moisture percentage observed in the Laboratory & confirmed in the Field.	Dry Bulk Density before compaction.	Dry Bulk Density after compaction.	Percentage improvement.	Remarks. (see foot-note.)
		Clay.	Silt.	Sand.					
1	2	3	4	5	6	7	8	9	10
	Predominantly sandy soils (50% and above sand)								
1	A 1000 Pr	8·0	10·4	81·6	13·0	1·56	1·67	7·0	A.
2	C 5275 T	15·2	3·4	81·4	14·8	1·63	1·89	13·4	X.
3	A 1000 T	13·8	5·8	80·4	15·6	1·31	1·70	29·8	X.
4	A 2000 Pr	9·6	11·6	78·8	14·0	1·53	1·68	9·8	A.
5	C 2400 Sec	11·3	9·6	78·6	13·0	1·60	1·86	16·2	A.
6	C 5250 T	16·4	5·4	78·2	12·0	1·63	1·80	10·4	X.
7	C 2000 Sec	12·0	10·8	77·2	13·0	1·44	1·82	26·9	A.
8	A 1500 Pr	10·0	14·2	75·8	10·0	1·53	1·77	15·7	X.
9	A 1000 Sec	15·9	8·9	75·2	13·0	1·54	1·67	8·6	A.
10	A 500 T	16·8	8·6	74·6	14·4	1·65	1·86	12·8	A.
11	C 2100 Pr	11·3	15·7	73·0	14·0	1·60	1·80	12·5	A.
12	C 1600 Sec	12·2	17·2	70·6	12·6	1·43	1·95	36·4	B.
13	C 6250 T	20·6	10·2	68·2	14·0	1·53	1·90	24·2	A.
14	A 2000 T	16·4	21·6	62·0	14·0	1·40	1·80	28·7	B.
15	A 500 Sec	15·6	23·2	61·2	15·0	1·52	1·65	10·5	A.
16		21·0	15·2	60·8	15·0	1·54	1·92	24·7	A.
17	C 100 Sec	17·8	25·2	57·0	13·6	1·54	1·90	23·4	B.
18	C 1600 Pr	18·8	24·8	56·3	14·0	1·65	1·80	9·1	B.
19	C 200 Pr	14·5	30·5	55·0	14·0	1·63	1·83	12·3	B.
20	C 600 Sec	19·2	26·2	54·6	14·0	1·53	1·80	17·6	B.
21	A 150 Sec	23·0	23·6	53·4	16·0	1·54	1·68	9·1	A.
22	A 3500 Sec	14·0	33·0	53·0	12·0	1·50	1·76	17·3	B.
23	C 1400 Pr	20·6	28·8	50·6	16·0	1·65	1·80	9·1	A.
24	C 3000 Sec	24·4	25·0	50·6	11·0	1·55	1·980	28·6	X.
25	A 4500 Pr	23·0	27·0	50·0	14·0	1·41	1·83	29·7	B.
	Predominantly silty soils (35% and over silt)								
26	C 250 T	22·0	63·6	14·4	16·6	1·31	1·70	29·7	B.
27	B 5800 T	27·6	57·8	24·6	15·0	1·50	1·72	14·7	B.
28	B 1000 T	24·0	57·4	18·6	13·6	1·52	1·87	23·1	X.
29	B 1400 T	28·2	57·2	14·6	14·4	1·47	1·78	21·1	X.
30	B 400 P	31·4	57·0	11·6	14·8	1·60	1·80	12·5	X.
31	B 5000 T	21·2	56·2	22·6	14·0	1·50	1·80	20·0	B.
32	B 1200 P	32·8	56·0	11·2	14·8	1·52	1·80	18·4	X.
33	B 1000 T	29·2	54·2	16·6	14·5	1·65	1·80	9·9	X.
34	B 2100 P	29·2	54·0	16·8	14·0	1·50	1·83	14·0	X.
35	B 4500 T	24·8	54·0	21·2	14·0	1·50	1·84	22·6	X.
36	B 1600 T	33·0	54·0	13·0	14·0	1·61	1·80	11·8	X.
37	B 3000 T	33·6	54·0	12·4	11·2	1·42	1·72	21·1	X.
38	B 2500 T	29·8	54·0	16·2	14·0	1·47	1·80	22·5	X.
39	B 5500 T	25·0	53·6	21·4	14·0	1·52	1·78	17·1	X.
40	B 2000 P	32·0	53·0	15·0	15·2	1·45	1·88	29·7	X.
41	B 1800 T	36·6	52·8	10·6	14·4	1·43	1·88	31·8	X.
42	A 3000 S	18·7	51·9	29·4	15·0	1 54	1·85	20·1	B.
43	A 1500 T	35·6	51·2	13·2	16·0	1·70	1·74	2·3	B.
44	B 2000 T	30·6	51·0	18·4	12·8	1·47	1·88	27·9	X.
45	B 1500 T	32·0	50·8	17·4	17·0	1·65	1·90	15·2	B.
46	C 2250 T	30·4	50·6	18·6	16·0	1·46	1·68	28·8	B.
47	C 750 T	32·0	49·6	18·4	16·0	1·61	1·80	11·8	B.
48	B 200 P	30·6	49·0	20·4	13·0	1·49	1·88	12·2	X.
49	C 1750 S	34·2	48·2	17·6	16·0	1·49	1·94	30·2	B.
50	C 2150 S	29·0	48·0	23·0	16·0	1·52	1·76	15·8	B.
51	A 500 P	29·8	47·6	26·6	12·8	1·56	1·85	18·6	X.
52	C 1400 S	35·6	47·4	17·0	14·0	1·54	1·80	10·3	X.
53	B 800 T	33·0	47·2	19·8	14·8	1·52	1·83	20·3	X.
54	B 3500 T	29·8	47·0	23·2	13·0	1·56	1·88	15·4	X.
55	C 1200 P	26·6	46·2	27·8	14·0	1·38	1·82	32·0	B.
56	A 4500 S	16·0	45·8	38·2	14·0	1·52	1·78	17·1	B.
57	C 1750 T	31·0	45·4	23·6	16·4	1·4	1·8	12·5	B.
58	C 700 S	28·8	45·2	26·0	16·4	1·42	1·80	22·2	B.
59	A 3500 T	20·8	45·0	34·2	18·0	1·32	1·82	39·0	X.
60	A 2500 P	16·8	45·0	38·2	12·0	1·52	1·78	13·4	X.
61	B Zero T	34·8	44·8	20·4	17·0	1·52	1·80	18 4	B.
62	B Zero P	34·8	44·8	20·4	14·4	1·52	1·80	18·4	X.
63	C 1250 T	29·8	44·6	25·6	13·6	1 55	1·78	14·8	X.
64	A 3500 T	13·8	44·0	42·2	14·0	1·32	1·82	39·4	B.
65	B 600 T	23·8	43·4	32·8	14·0	1·60	1·85	15·6	B.
66	C 4000 T	38·8	42·8	18·4	15·0	1·44	1·78	9·6	B.
67	C 1800 P	15·1	41·6	43·3	12·0	1·59	1·80	18·3	X.
68	A 3000 P	35·0	40·2	24·8	13·0	1·46	1·92	31·5	X.
69	A 7280 T	32·4	40·2	27 2	16·0	1·66	1·82	9·6	B.
70	C 4750 T	30.6	38·8	30·6	14·0	1·50	1·77	18·0	B.
	Predominantly clayey soils (30% and above)								
71	A 3000 T	47·6	34·0	18·4	17·0	1 32	1·82	37·8	B.
72	C 600 P	47·5	27·9	26·4	12·0	1·41	1·70	20·5	X.
73	C 400 P	47·0	32·4	20·6	16·0	1·41	1·78	26·2	X.
74	A 1500 T	45·8	35·0	19·2	16·8	1·70	1·74	2·3	X.
75	A 400 T	45·2	31·4	23·4	16·4	1·46	1·82	24·6	B.
76	A 4500 T	41·0	42·0	17·0	16·0	1·46	1·82	24·6	B.
77	C 1050 S	41·0	40·6	18·4	17·6	1·54	1·76	14·2	B.
78	A Zero P	40·8	45·6	13·6	12·0	1·60	1·92	20·0	X.
79	A 5000 T	38·6	23·4	38·0	15·0	1·46	1·88	28·3	X.
80	C Zero T	38·6	36·4	25·0	13·6	1·64	1·80	9·7	X.
81	C 1000 P	36·1	37·4	26·5	14·0	1·47	1·78	21·0	X.
82	A Zero T	35·7	30·1	34·2	15·0	1·29	1·80	39·4	B.
83	C 3750 T	33·4	23·8	42·2	16·8	1·44	1·77	22·9	B.
84	A 7000 T	31·2	35·8	23·0	14·8	1·30	1·79	37·7	X.
	Neutral soils (no single constituent predominates)								
85	C 3250 T	27·0	24·2	47·8	18·8	1·51	1·90	25·3	X.
86	A 6500 T	29·0	31·0	39·6	12·0	1·48	1·86	25·6	X.
87	C 350 S	20·4	30·8	48·8	14·0	1·54	1·86	20·7	B.
88	A 2500 T	18·4	33·2	48·4	16·4	1·59	1·89	15·2	A.
89	A 1500 S	23·2	27·2	49·6	14·0	1 50	1·69	12·6	B.

Note.—1. This table sums up optimum moisture percentage results determined in the laboratory and confirmed by compaction in the field.

2. Optimum moisture is governed by the predominant constituent (Sand, Silt or Clay), present in the soil composition. For predominantly sandy soils, marked "A" approximate results are given by the formula W=24 – ·14S.

This formula does not hold for predominantly silty soils marked "B" which fit in better with the formula W = 24 — ·14S – ·1Si (W optimum moisture percentage, S sand percentage, Si = Silt percentage).

3. There are a good number of exceptions to the above presumably on account of the difference in the *nature* of the constituents. These cases have also been included in the table. (Marked X.)

4. In clayey soils, none of the above formulae holds and actual experiment is the best guide. The same is also the case in what may be called "Neutral" soils where no constituent predominates.

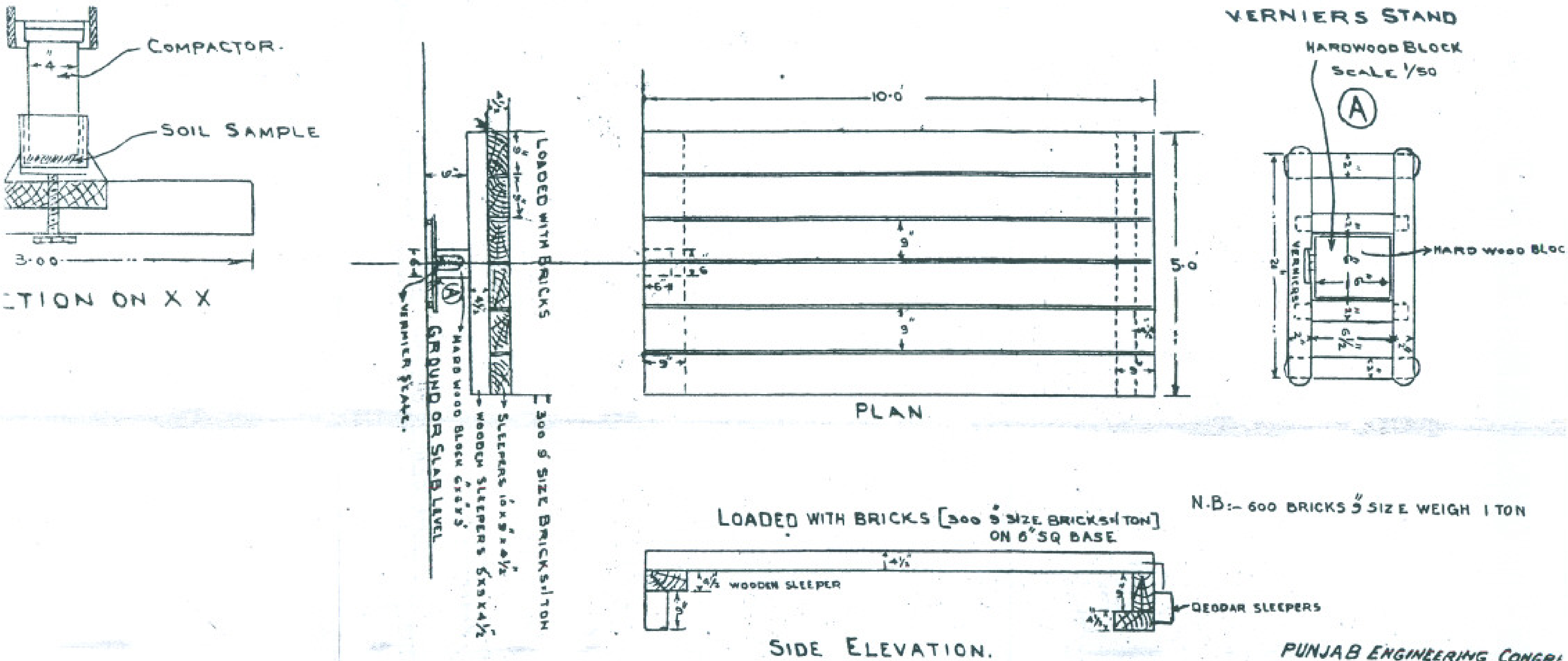
5. In the above predominantly sandy soil means 50% or more sand, predominantly silty soil 35% or more silt and predominantly clayey soil 30% or more clay.

APPARATUS FOR BEARING PRESSURE OBSERVATION

SCALE=1/20

PLATE II

PAPER NO. 269



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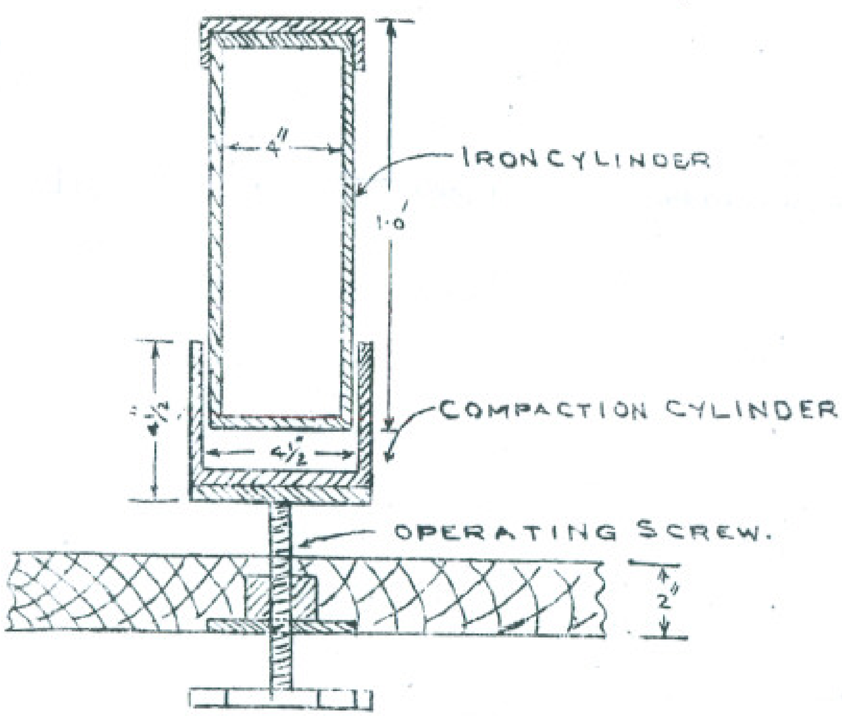
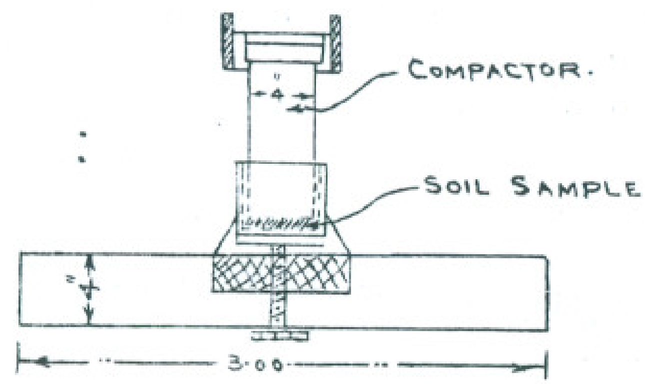
DETAILS OF COMPACTOR (A)

SCALE 1/50' = 1 INCH





SECTION ON X X

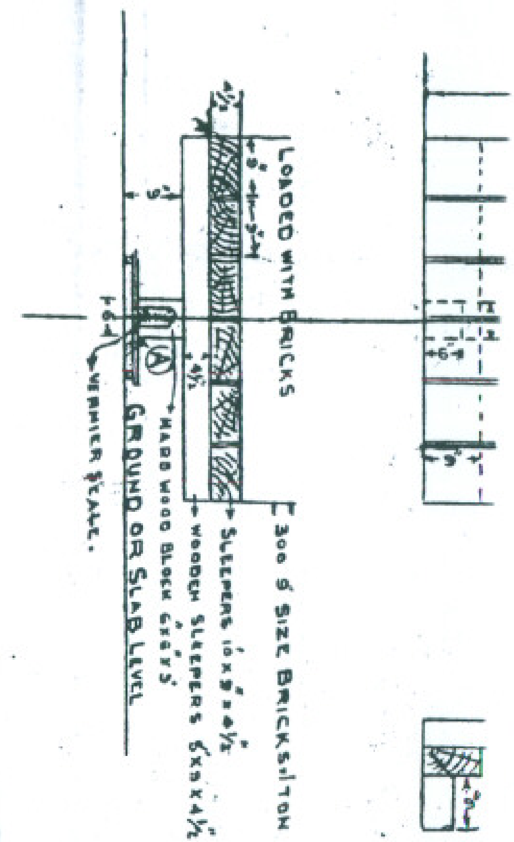


PLATE III.

PAPER No. 269.

JOB No.

OBSERVER'S REPORT ON COMPACTION OF SUB-GRADE.

Site.	R. D.	Distance from centre line.	Optimum moisture percentage.	Moisture before rolling.	Dry bulk density attained.	No. of rollings.	Moisture % after rolling.	Settlement at 3 tons per sq. ft. at 6" sq. test block.	Settlement at 7 tons per sq. ft. on 6" sq. test block.	Moisture at the time of settlement.	Remarks.
											T = Toothed 1·3 tons roller. S = 6 tons steam roller.
Secondary Runway	883	58′ L	15·0	16·2	1·72	T 16 S 4	15·3	0·19″	·45″	15·3	Excessive settlement to be re-compacted and tested afterwards.
	903	Centre 30′ L.	15·0	15·7	1·85	T 16 S 4	14·7	0·08″	·18″	14·3	Excessive settlement due to high moisture content will improve after drying a bit.

Submitted to the Sub-Divisional Officer, II Aviation Sub Divn. for information.

DHARAM CHAND

PLATE IV.

PAPER No. 269.

PROGRESSIVE VARIATIONS OF MOISTURE UNDER SLABS OF PRIMARY RUNWAY AT AN AIRFIELD IN HIGH SPRING LEVEL AREA.

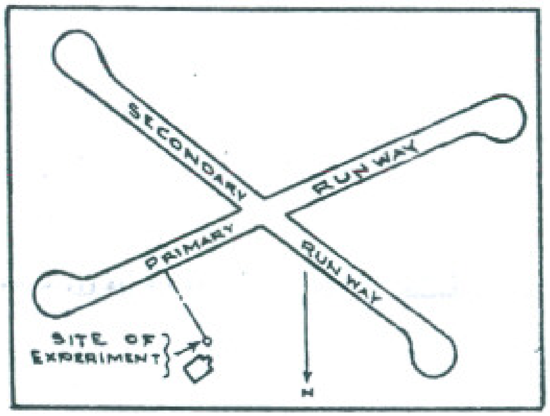
Slab No.	Date of concreting.	Date of observation.	Moisture percentages at depths.				Spring level below N. S.	Remarks.
			0 – ·5′	·5′ – 1′	1′ – 2′	2′ – 3′		
A	7-2-43	6-2-43	*23·0	20·7	20·0	19·9	3·3	
		27-2-43	*22·2	18·9	18·5	18·5	4·2	
		26-5-43	16·3	16·2	17·8	17·0	5·2	
		19-8-43	14·7	16·9	18·6	18·1	5·0	
G	7-2-43	7-2-43	*20·0	16·0	16·3	20·7	3·3	
		27-2-43	18·9	14·3	18·5	18·5	4·2	
		9-6-43	16·5	13·4	16·9	15·6	5·3	
I	7-2-43	7-2-43	*21·0	18·4	17·6	20·7	3·3	
		3-3-43	14·3	20·0	14·3	18·5	4·2	
		30-5-43	12·4	15·2	15·0	18·8	5·2	
J	7-2-43	7-2-43	16·3	17·6	18·4	16·3	3·3	
		7-3-43	16·1	17·1	18·5	18·5	4·5	
		19-5-43	19·8	12·0	15·6	18·6	5·1	

*These readings are high due to the effect of rainy weather.

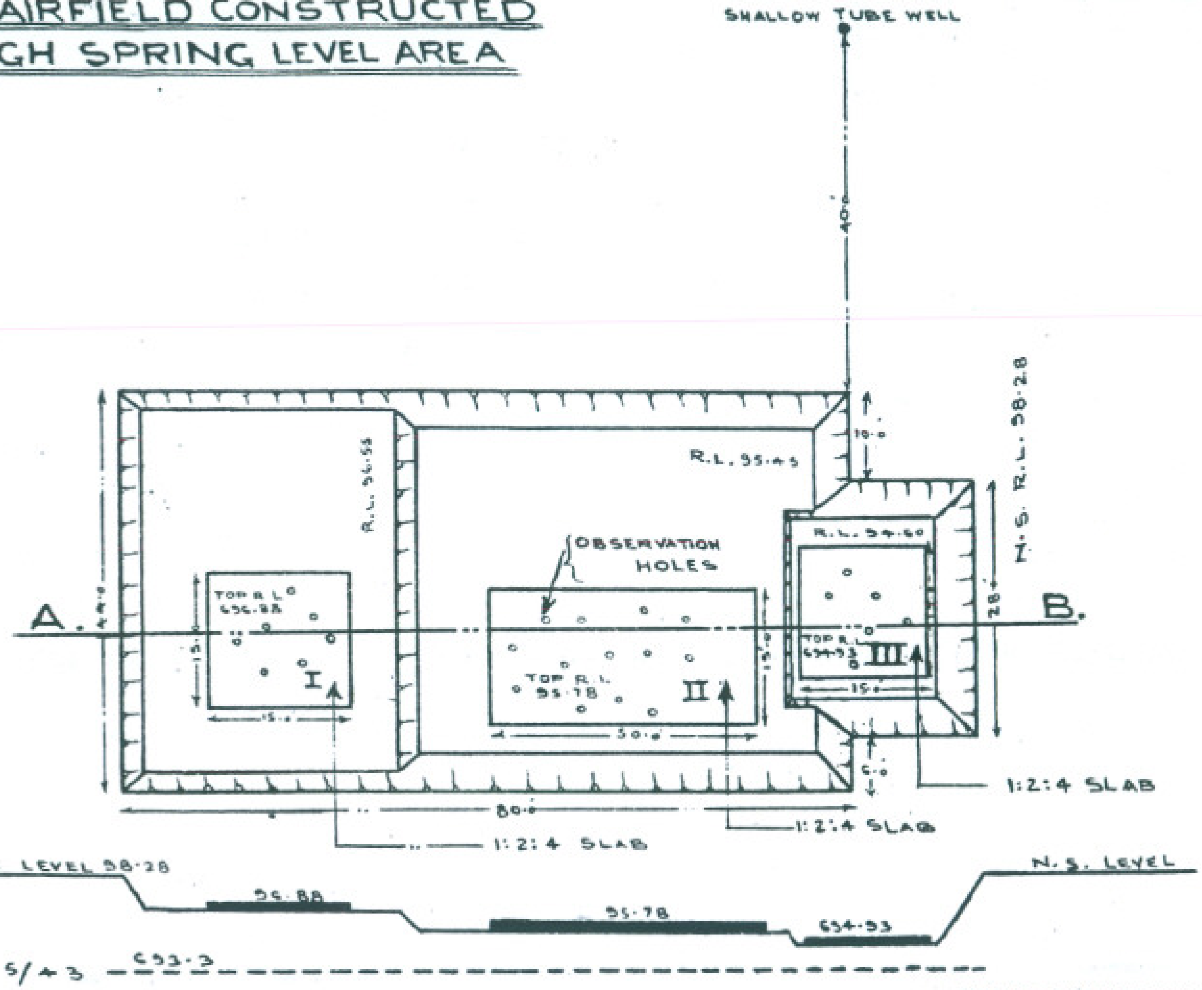
Note.—1. These observations show that during six months after the concreting of slabs, there has been no concentration of moisture in the sub-grade. In this period spring level has on the average been 4·2 ft. below the bottom of the slab. These observations pertain to the actual Runway.

2. In the case of experimental slabs constructed in a pit, the spring level ranged from 1 ft. to 3 ft. below the bottom of experimental slabs made at different levels and there was a rise of 6″ in the spring level in two months (see separate graph attached).

LAYOUT PLAN OF EXPERIMENTS AT AN AIRFIELD CONSTRUCTED IN HIGH SPRING LEVEL AREA



INDEX PLAN



SECTION ON A.B

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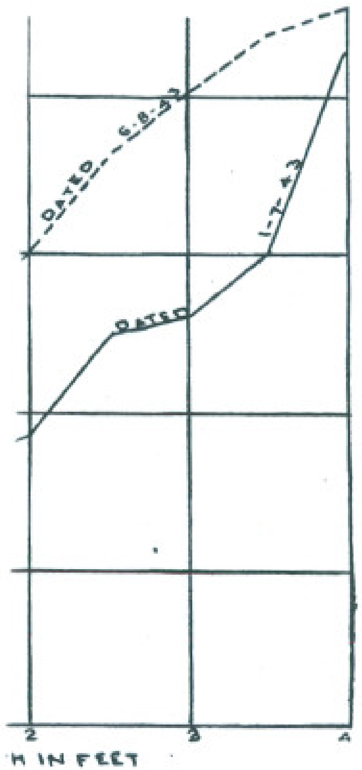
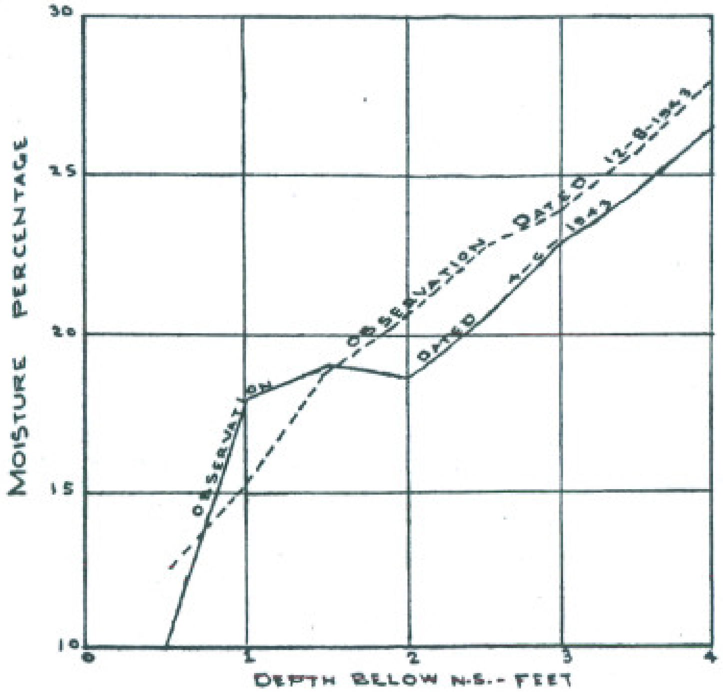
MOISTURE PERCENTAGE IN UNCOVERED AND UNCOMPACTED SOIL NEAR SLAB No. 1

PLATE VI

PAPER No. 269



(3 FEET ABOVE SPRING LEVEL)



NOTE:—1. The first three graphs show the moisture percentages in the compacted soil below slabs No. 1, 2 and 3 for a depth down to four feet below the bottom of the slab. The interval of time is approximately two months and in the case of slab No. 3 conditions appear to have become steady.

2. In the fourth graph the variation of moisture has been studied for exposed natural and uncompacted soil. It will be seen that the maximum rise in over two months has been from 10 % to about 12 % only and the concentration due to high spring level and subsequent rise is very little.

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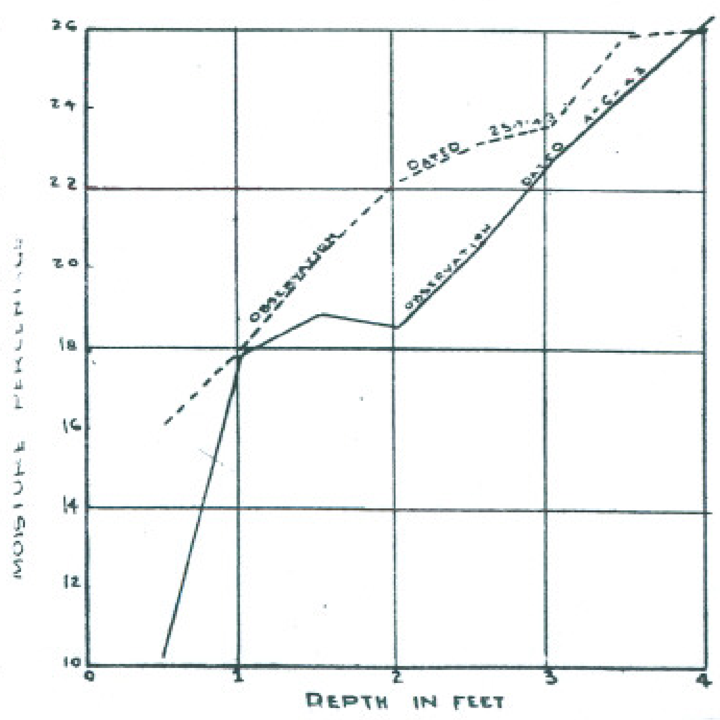
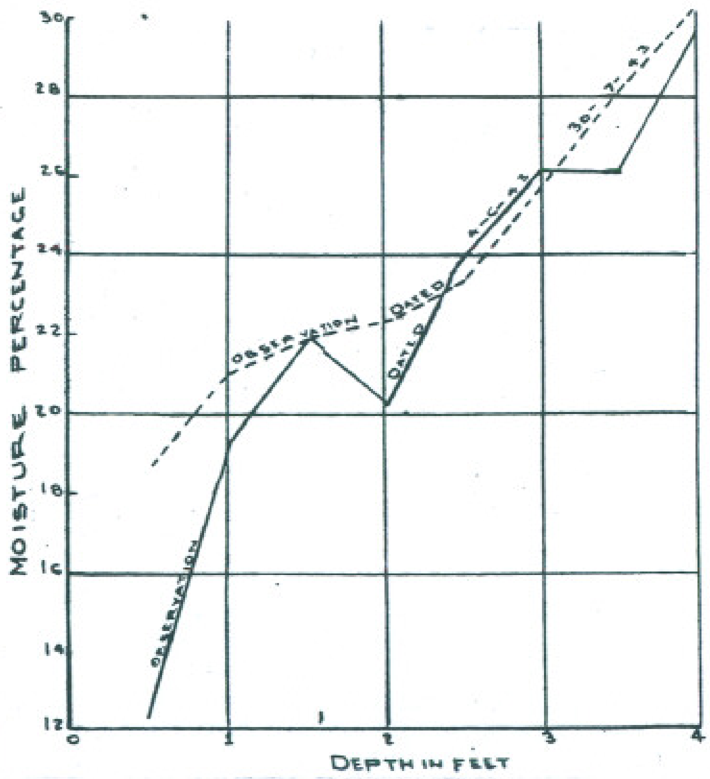
MOISTURE PERCENTAGE OF SOIL AT VARIOUS DEPTHS

BELOW SLAB No 1
(3 FEET ABOVE SPRING LEVEL)



BELOW SLAB No 2
(2 FEET ABOVE SPRING LEVEL)



BELOW SLAB N
(1 FEET ABOVE SPRING

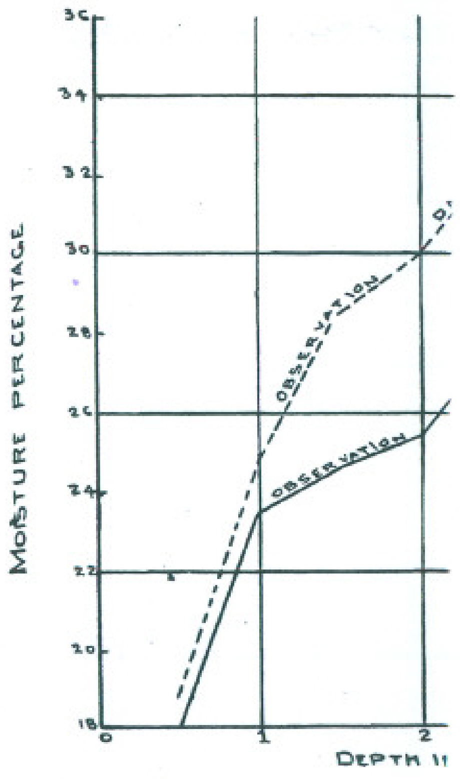


PLATE VII

COMPACTION OF SOIL UNDER HIGH SPRING LEVEL CONDITIONS

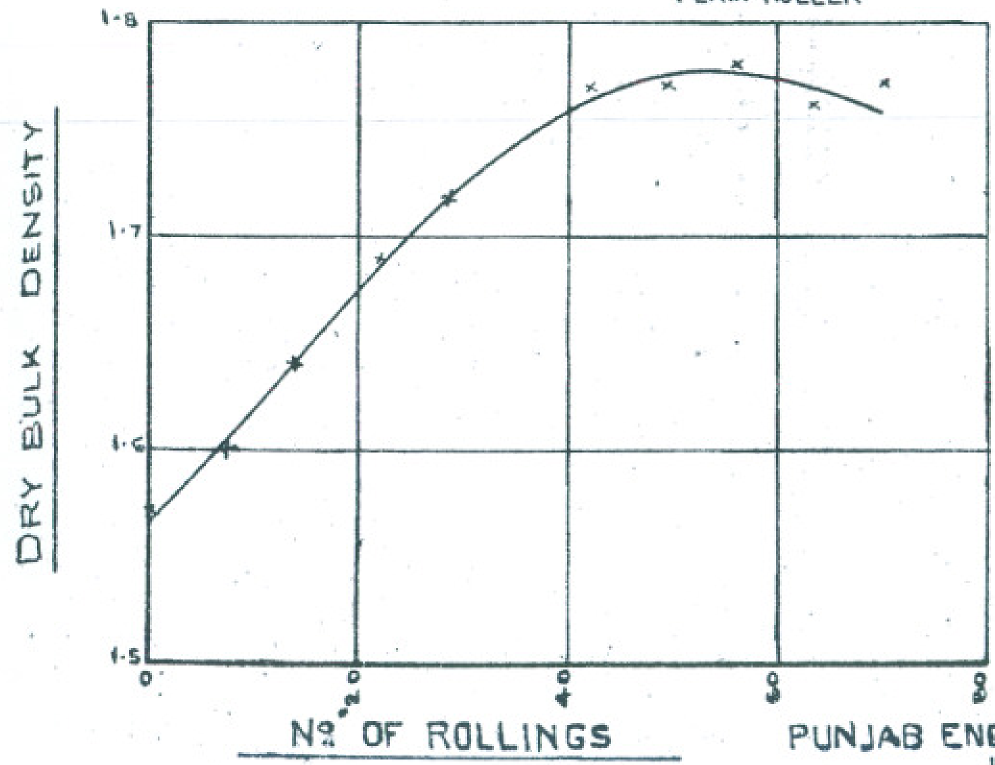
PAPER No. 269

IMPROVEMENT IN DRY BULK DENSITY WITH LIGHT ROLLERS AT MOISTURE CONTENT HIGHER THAN THE OPTIMUM

ACTUAL MOISTURE = 18 %
OPTIMUM MOISTURE = 14 %

WEIGHT OF ROLLER = 1·5 TON PLAIN ROLLER

SOIL COMPOSITION
CLAY = 20%
SILT = 45%
SAND = 35%



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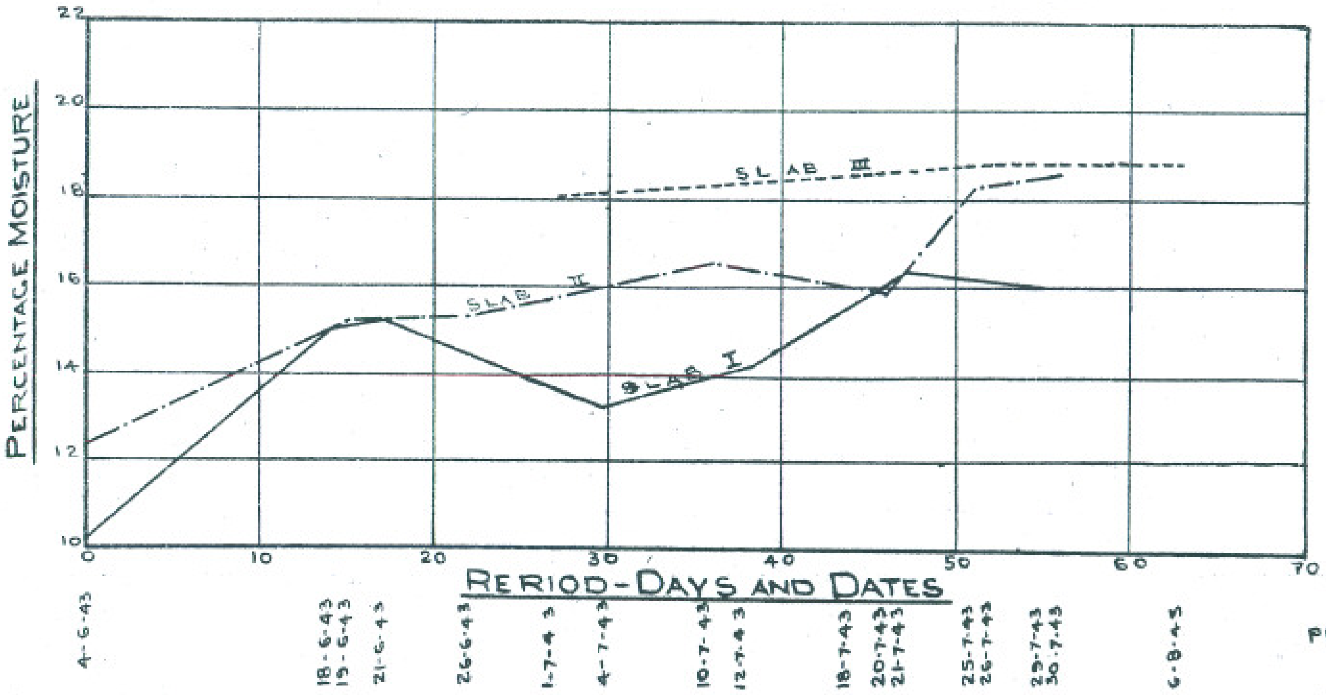
PROGRESSIVE CONCENTRATION OF MOISTURE BELOW SLABS

PL
PAPE



Note —I. These graphs s
variation of m
6" depth of co
immediately b
2. When slab No.
4th June, 1943
respectively 3
bottom of slat
the next two m
3. It will be see
No. 3, there h
increase in mo
spring level
bottom of the
that the mois
near the satu
beginning of

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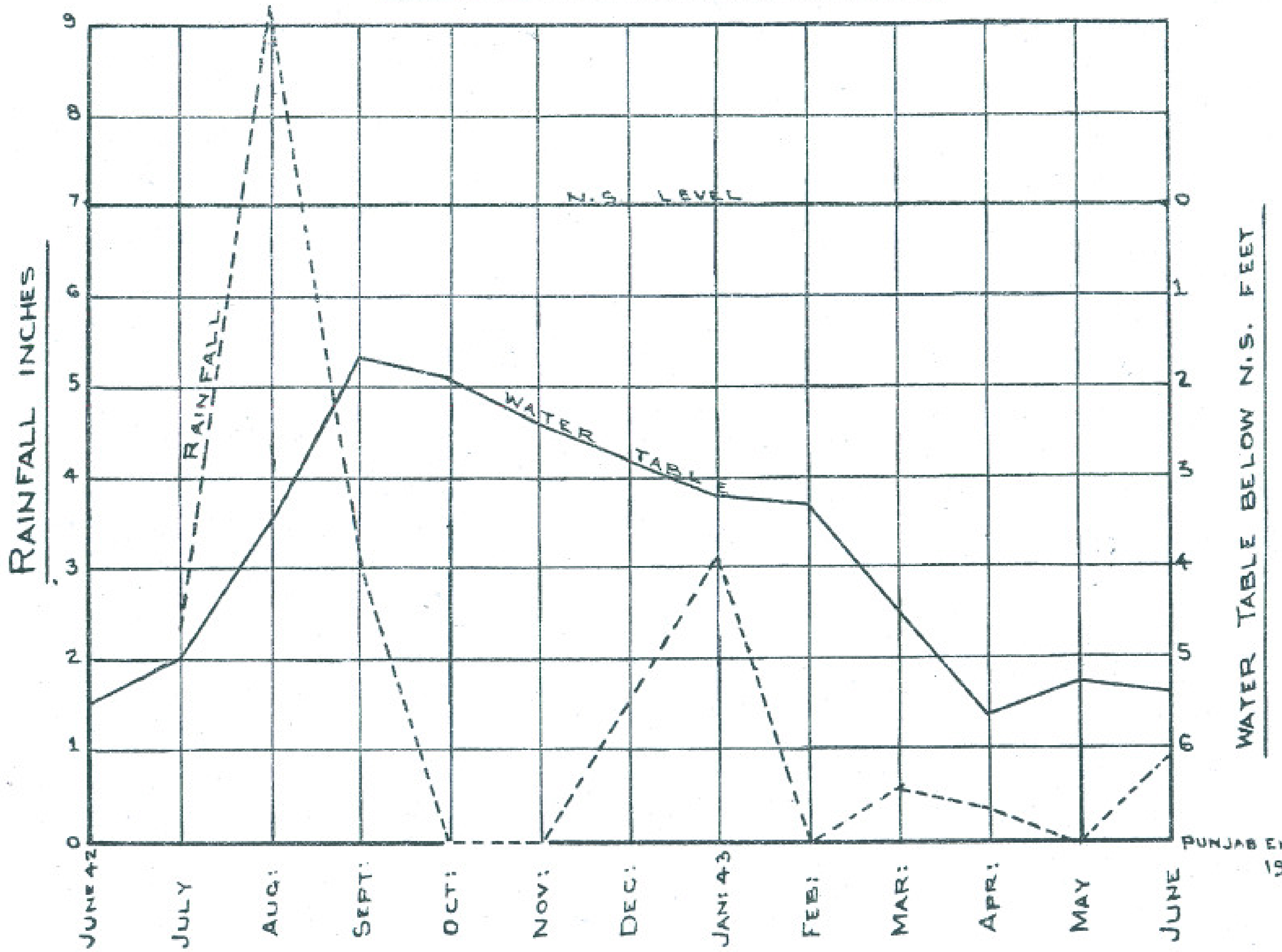
PLATE IX

PAPER No. 269

SPRING LEVEL VARIATION & RAINFALL AT SITE OF AIRFIELD CONSTRUCTED IN HIGH WATER TABLE AREA



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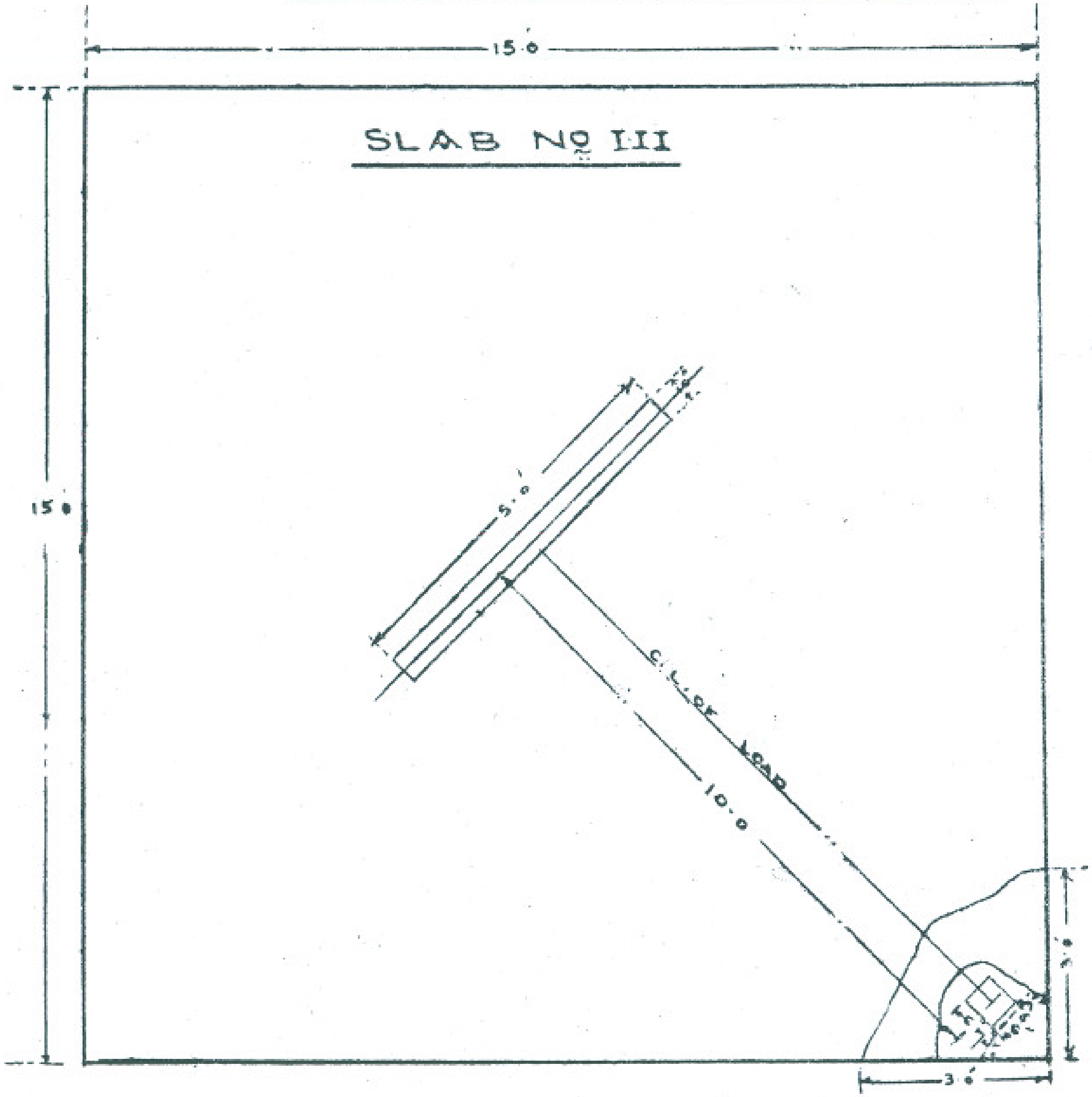
PLAN SHOWING FAILURE OF SLAB No. III
UNDER $17\frac{1}{2}$ TON/SQ: FT: LOAD



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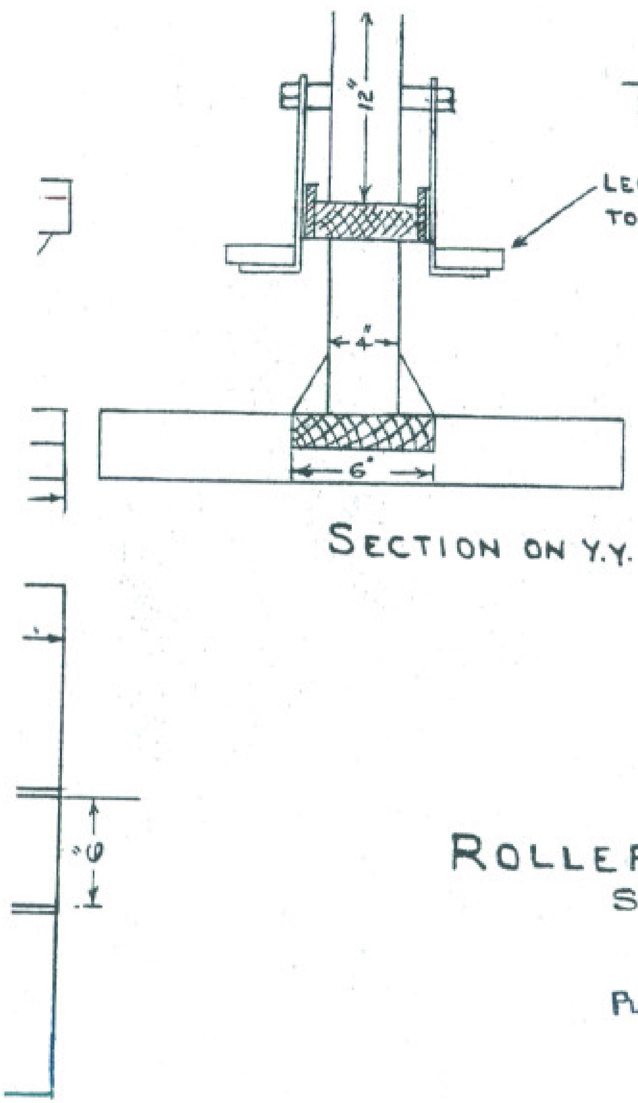

This apparatus is an alternative to Proctor's modified compaction apparatus. In the latter the soil is compressed with a ramming action and the results cannot be easily correlated with the number of rollings that have to be given to the soil to obtain the desired compaction. In the Roller Compactor, a miniature representation of a Roller in the Field is obtained and the improvement in Dry Bulk Density for various rollings can be very quickly worked out. The weight of the roller can be varied by placing additional weights in the legs suspended from the roller axle. A vernier scale attached to the compaction cylinder records directly the reduction in the volume of the sample, from which Dry Bulk Density can be easily calculated as the area of the cylinder is constant. Two per cent additional moisture was added to the soil with a graduated pipette for successive tests and the optimum moisture was found for any particular soil within an hour. It is found that the Proctor's apparatus gives higher Dry Bulk Densities than can be obtained by rolling in the field and the results with the roller compactor approximate more to the actual.

ROLLER COMPACTOR

SCALE 1/100 = 1 INCH.

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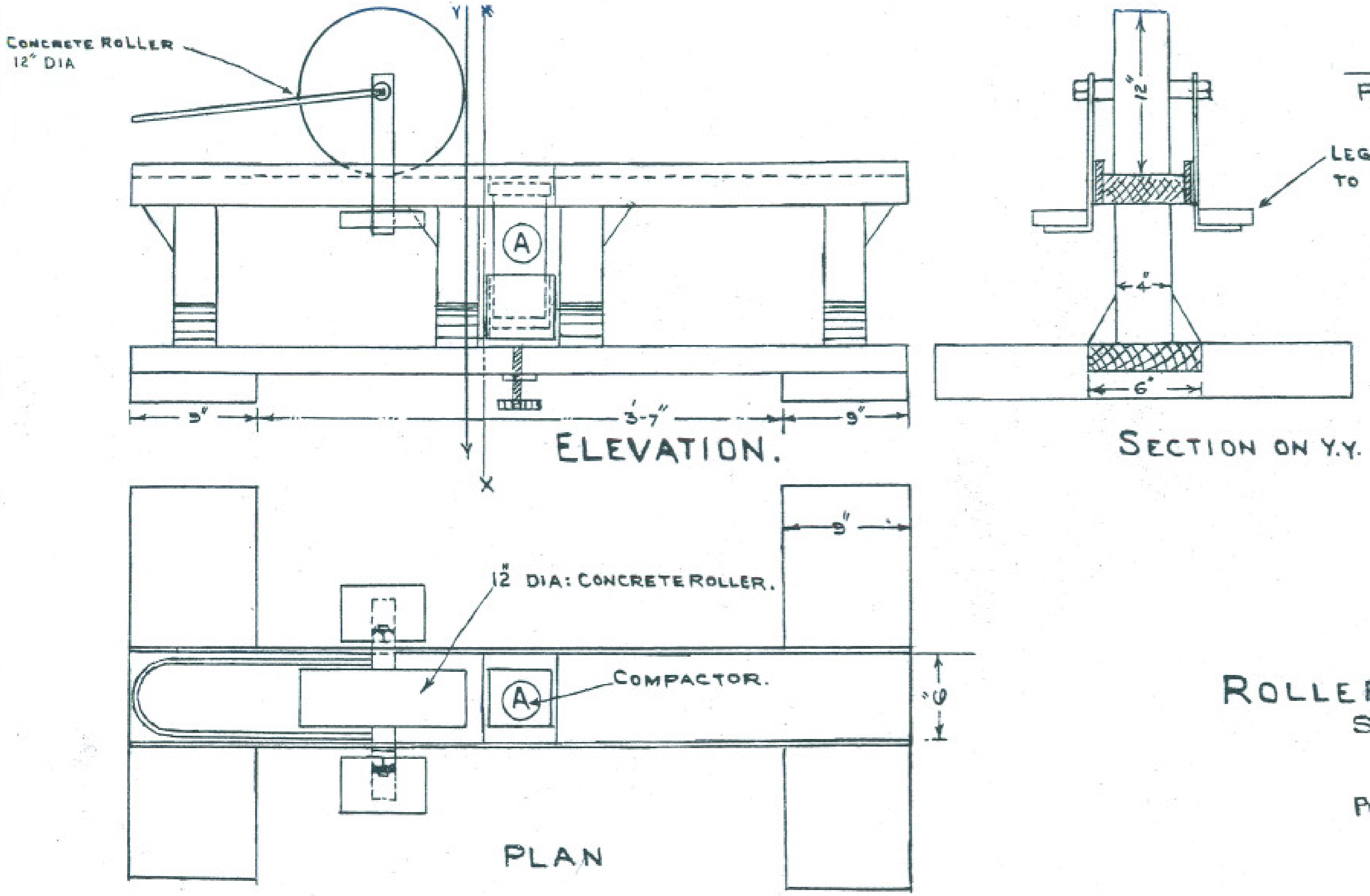

PLATE XI

PAPER No. 269

ROLLER COMPAC

SCALE 1/100' = 1 IN

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