No. RW/RD/R-25(1)/81-NHVI *Dated the 17th December, 1986*

To,

All Chief Engineers of States and Union Territories dealing with Roads

Subject : Circulation of selected extracts from the literature survey and the State of the Art Report for selection of field compaction equipment and compaction procedures relevant to Indian conditions.

Compaction is one of the principal means available to the Highway Engineers for substantially increasing the strength of material used in construction of roads. Since the need for mobilising and retaining the strength of material has always remained a key point in the technique of highway construction, the interest in different compaction techniques, equipment and compaction characteristics of materials is almost never ending. All developed countries and many developing countries spent a large sum of money on research in this direction. In the past the Indian Roads Congress had brought out a State of the Art Report on a similar subject in 1978 i.e. Special Report No. 3, IRC-36. Since then a large number of new sophisticated equipments have been added to the list of compaction machineries and new information and research data are also available. This Ministry had, therefore, sponsored a research scheme R-25 for selection of field compaction equipments and compaction procedures relevant to Indian conditions. The first phase of the work which consists of literature survey and preparation of a State of the Art Report has been completed by the Indian Institute of Technology, Kharagpur under the guidance of Dr. C. Subbarao and Dr. A.N.R. Char.

2. The report is at present under consideration of the Planning and Implementation Group for this Research Scheme and the Ministry is also trying to get the same published for wider circulation among practising engineers. Meanwhile, some relevant extracts from the report are enclosed for advance information and general guidance. It is hoped that these will be found useful to field engineers engaged in construction of highways.

Encl. to letter No. RW/RD/R-25(1)/81-NHVI dated the 17th December, 1986.

EXTRACTS FROM THE STATE OF REPORT ON MINISTRY'S R&D SCHEME NO. 25 SELECTION OF FIELD COMPACTION EQUIPMENT AND COMPACTION PROCEDURES FOR SANDS RELEVANT TO INDIAN CONDITIONS

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7. COMPACTION PROCEDURES FOR SANDS

7.1 Experience in India

7.1.1 A study by Larsen and Toubro

Poorly graded sand

A study on techno-economic viability of vibratory roller was carried out by M/s Larsen & Toubro Ltd. The experiments on soil compaction on an embankment were carried out with 10 T static roller and 8.5 T vibratory roller (Model TT 900. Ref. Appendix A-II, Item 2). The compactive performance of the two rollers is given in Table 7.1.

The 8.5 T vibratory roller could give 100 per cent standard proctor compaction with 4 passes on 30 cm thick layer of poorly graded sand (BP) whereas the 10 T static roller could attain only 95% compaction after 8 passes with 20 cm thickness of the poorly graded sand.

By using vibratory roller 100 per cent compaction was obtained even at moisture content ± 5 per cent from the optimum moisture content whereas while using non vibratory roller the optimum moisture content was required to achieve acceptable level of compaction. Vibratory roller could not be used effectively for compaction of poorly graded sand, however, this problem was overcome by blending 10 per cent soil with sand. This aspect will be discussed later in section 7.2 and 7.3.

7.1.2 **A study by IAAI**

Chief Engineer, International Airport Authority of India has given data on number of passes required to achieve 95% modified AASHO compaction on different types of soils with 8 tonnes and 6 tonnes vibratory rollers, Tables 7.2. Frequency 1800 vihr/min. and amplitude 1.2 mm. For a sand (OMC modified AASHO, 7 per cent), the 8 tonnes roller required 3 passes to compact 30 cm thick layer and the 6 tonnes roller required 4 passes to compact a 20 cm thick layer.

7.1.3 **A study from Tamil Nadu**

Natarajan studied the performance of different types of rollers in compacting different types of soils in Tamil Nadu. Table 7.3 gives the properties of the soils. A comparison of the performance of a 8-10 ton roller, 4 ton tandom rollers and 5 ton vibratory roller on a silty sand and a clayey sand are made in Tables 7.4 and 7.5. Thickness of loose layer of soil 225 mm.

While it was not possible to compact silty sand (Table 7.4) with 8-10 T conventional (static) roller, the 4 T tandem roller and 5 T vibratory roller were able to achieve more than 100 per cent compaction (Proctor standard) at 4 passes. They are therefore more suitable than a conventional three wheeled 8-10 T roller.

On clayey sand (Table 7.5) even though none of the three rollers used were able to achieve 100 per cent compaction the 8-10 T roller and 4 T tandem rollers were found to be more suitable than the 5 T vibratory roller, since compaction was 97 per cent, with 4 T tandem roller and 98 per cent with 8-10 T three wheeled roller after 8 passes.

It may be noted that the light weight of 4 T tandom roller and 5 T vibratory roller were adequate for compacting a cohesionless soil, silty sand (PI = O), where as higher weights are indicated for better results on soils with cohesion, i.e. clayey sand (PI = 6).

7.1.4 **Experience in Rajasthan**

Fine dune sand

Soil compaction data received from Shri M.C. Sharma, Chief Engineer (Roads), PWD Rajasthan is given in Appendix A-IV. The data pertains to compaction of fine dune sand. To obtain more than 95 per cent compaction, 5 to 6 passes of tractor tyring and 6 to 8 passes of 8-10 T smooth wheel roller were required to compact this sandy soil at optimum moisture content. A pneumatic tyred roller was not found suitable for the compaction of road embankment as its turning for forward and backward movement posed problems. For another soil, a sandy clay loam, 5 to 6 passes of tapered sheepfoot roller and 6 to 8 passes of smooth-wheeled roller were required.

7.2 **Experiences Abroad**

7.2.1 **A Study by D'Appolonia et al**

Poorly graded sand

Full scale experiments for sand compaction by vibratory rollers for a land reclamation project in USA were reported by D'APPOLONIA et al. Poorly graded fine sand (mean particle size 0.18 mm) was compacted at fill moisture content, 3.3 to 4.2 per cent (Degree of saturation 15 per cent), by 6 ton towed vibratory roller, 2 feet thick lifts could be compacted to give 75 per cent relative density. However, 1.5 feet (0.55 m) thickness was recommended. It was observed that top 6 to 12 inches (15 to 30 cms) of each layer was poorly compacted. However, this was not a set back as this poorly compacted top would be densified enough when next layer is compacted. Speed of roller 3 km/hr.

7.2.2 **Australian Experience**

The performance of a 15 T vibratory roller is compared with that of a 200 T super compactor (static roller) in Table 7.6. Medium size Botony sand of maximum dry density 1.76 gm/cm^3 was equally well compacted by both the machines as shown by the density gradient in the Table 7.6. However, the vibratory roller was much more efficient, gave higher output and was economical.

7.2.3 **TRRL, UK, Experiments**

Toombs describes an investigation into the performance of a caterpillar 17 T self propelled tamping roller in the compaction of a heavy clay, a sandy clay, a well graded sand, a gravel-sand-clay and a uniformly graded fine sand. The results show that a satisfactory state of compaction is likely to be achieved after 4 to 7 passes on 250 mm thick compacted layers of the cohesive soils and the uniformly graded fine sand at a roller speed of 2.5 km/h. With the cohesive soil and well-graded granular soils the thickness of "loose mulch" at the surface of the compacted layer tended to decrease with successive passes of the tamping roller. However, with the uniformly graded fine sand, the feet completely penetrated the soil at all stages of the compaction process.

Sometimes the site conditions warrant compaction in stages, first by a tracklaying tractor and then by a roller. This is particularly applicable for poorly graded sand with a low bearing capacity. Light vibratory equipment, with smaller outputs, such as plate compactors and vibrating tampers, have been found suitable to compact uniformly graded sands, whereas power rammers are unsuitable to compact uniform sands.

7.3 **Difficulties in Compacting Poorly Graded Sands**

Data in this section, so far, show that poorly graded fine sands and uniformly graded fine sands are difficult material to compact. FORSSBLAD observes that, on uniformly graded sand, it is difficult to obtain a high degree of compaction close to the surface of a layer. Down to a depth of 10 to 15 cms, the compaction achieved with medium or heavy vibratory or static rollers is lower than at greater depths. The reason is the low shear strength of the uniformly graded soils. Material is pressed up behind the roller drum and the surface layer then obtains a comparatively low density. In practice this is usually not of great significance. When a fill is placed in several layers, the previous top layer is compacted when the next layer is rolled. However, the difficulty of compacting the surface layer should be kept in mind, when performing field compaction tests.

7.4 Dry Compaction

Many areas of the world have a semi-arid or arid climate, where water is often both difficult and expensive to supply. In desert regions, where sandy soils dominate, dry compaction is a method that is both technically and economically advantageous. In recent years several organisations, the United Nations Development Programme among others, have studied this subject.

Efficient compaction of water saturated soils is possible for soils containing less than 5 to 10 per cent of silt (Ref Section 1). Dry compaction allows a higher content of silt, which in this case should be less then 20 to 30 per cent.

On the basis of the laboratory test results, the Dynapac Research Department also performed full-scale compaction tests using a 135 kg CM 13 vibratory plate compactor and a 10 ton CA 25 self-propelled vibratory roller. In both cases compaction was performed on sand :

A. With a water content between a dry and saturated state

B. Completely water saturated

C. Completely dry

As expected, the completely water saturated sand was compacted to a higher density than the sand with a lower water content. More unexpected was the finding that compaction in a completely dry state, gave the highest dry density, both at the surface and at depth. The diagrams, Fig. 7.1 and 7.2 also indicate that the layer thickness can be increased for dry compaction which, coupled with the fact that watering is not necessary, can result in considerable cost savings.

The compactability can, however, be influenced by other factors than the content of fines expressed in per cent. One factor can be the presence of small amounts of active fine-grained material that binds the sand particles together ("cemented" types of soil). The presence of soluble salts in the sand can also result in a higher density at compaction at the optimum water content than at dry compaction, Fig. 7.3. The reason is that the salts are dissolved in water.

The decision whether a certain sand is suitable for dry compaction must therefore be decided from case to case, on the basis of compaction tests performed at different water contents. The laboratory tests should be made by vibratory compaction.

Possible alternatives are :

— Vibrating table method developed by the U.S. Bureau of Reclamation, designation E-12 and also nominated as ASTM D 2049.

— Vibrating tamper method developed by Dynapac, apparatus type TE 10.

— Vibrating hammer method developed by the Transport and Road Research Laboratory, nominated as British Standard, BS 1377, Test 13.

— Test method developed by the United Nations Development Programme, using a Cobra drilling machine, Fig. 7.4.

This method is especially suited to field conditions.

For further details of the test procedures, see. Section 2.

Practical Experience

Practical experience has confirmed the results of the related compaction tests. Dynapac 10 ton self-propelled vibratory rollers with pneumatic drive wheels as well as tow type vibratory rollers have been used with very good results on highway construction projects in hot and dry climate conditions. Uniformly graded dry sand has been effectively compacted in layer thickness up to 1.0 m. Degrees of compaction up to 100 per cent modified Proctor have been achieved in the upper section of the fill. The CA 25 D, with drive on both wheels and drum, was found to have a good traction, even on uniformly graded sand. A driven vibrating roller drum also gives a somewhat higher density than a non-driven drum with the same linear load, frequency and amplitude.

Quite often sand may contain a certain amount of water, even very near the surface. In such cases, it is sometimes possible to dry the material in the sun.

The Italian contractor Furlanis Construzioni Generali S.P.A. used CA 25 vibratory rollers for dry compaction of uniformly graded fine-sand (0.5 mm) in 0.3 to 0.5 m layers in a highway construction project in Saudi Arabia. A relative density of 70 per cent was required, which is equivalent to about 95 per cent modified Proctor.

Comprehensive investigations of the compaction of dry soil, to start with in connection with the construction of Trans-Sahara highway, have been conducted by the United Nations Development Programme. A detailed report of compaction tests performed in Gao, Africa is published.

After initial investigations, a 2 km long test section was laid. A 200 to 300 mm thick base course consisting of laterite with 20 per cent of the soil passing through sieve No. 200 and with water contents between 1.5 and 4 per cent was compacted using the following schedule :

— 8 passes using a Dynapac CA 25 D, large amplitude

— 2 passes using a Dynapac CA 25 D, small amplitude

— 2 runs with a water tanker, distribution 4 litres/m^2

— 8 passes using a lightweight pneumatic-tyred roller

— 2 passes using a Dynapac CA 25 D, static.

An average degree of compaction of 95.5 per cent modified Proctor was achieved. It was found to be advantageous to use a large amplitude in respect of the compaction of lower parts of the base course while compaction nearer the surface was better using a small amplitude. A double surface treatment was laid as surface course.

Conclusions

Laboratory tests and practical experience have shown that, to achieve the most effective result at dry compaction, the water content should not exceed 1.0 to 1.5 per cent. Not as good, but still acceptable compaction results have been obtained at water contents up to about 5 per cent.

An important factor to be considered is the possible effect of a small amount of fine-grained particles which bind the particles together. The possible effect of soluble salts must also be considered.

Laboratory compaction tests by vibration on the fill material are recommended before dry compaction of sand is attempted on a large scale in field.

Special caution is necessary in the application of dry compaction for fills which later can be water saturated, for example fills under buildings where watering of gardens and leakage from water and sewage conduits will cause water infiltration of the ground.

It is noted that sand with water content 3.3 to 4.2 per cent was compacted in USA (Sec. 7.2.1).

7.5 Confinement of Sand, Use of Soil Reinforcement

Sand when unconfined possesses no shear strength. Moist or saturated sand can be compacted in embankments without external confinement. If dry sand is to be compacted, it would need flooding with water if no external confinement is provided during compaction. In desert areas it is difficult to fetch enough water and it is impossible to retain slopes of embankments when water flows out and the sand dries up if there is no confinement. Rarely if boulders could be imported to the site then confinement may be provided with boulders and dry compaction (described in previous section) can be resorted to. Another alternative is providing confinement by soil reinforcement.

7.5.1 Use of Soil Reinforcement

Reinforcement may be added to sand in embankment to perform one, or all, of three main functions Fig. 7.5.

(a) Superficial slope reinforcement and stiffening

(b) Major slope reinforcement involving reinforcement

(c) Reinforcement of weak embankment foundations.

The use of superficial slope reinforcement was pioneered by the Japanese, and particularly the Railway Technical Research Institute of Japanese National Railways. Reinforcement used by the Japanese is generally in the form of short lengths of Netlon, a polyolefin net, placed in horizontal layers near the face of the slope, Fig. 7.5a. Such reinforcement gives resistance to surface erosion and vibrations as well as permitting heavy compaction plant to operate close to the shoulder of the embankment, so effecting good compaction in the sensitive area. Netlon is now available in India.

7.6 Control Standards

From the experiences described in this chapter it is observed that standard Proctor density, modified Proctor density and relative density have been used in different countries to control state of compaction of sands. In Libya fine dune sands have been compacted to about 110 per cent of standard Proctor density i.e. to more than 100 per cent modified Proctor density. Indian specifications so far have demanded upto 102 per cent of standard Proctor density only. USBR specifies relative density as criterion for compaction control of cohesionless soils. Speed of vibratory rollers was 3 km/hr or less in most of the field compaction operations and in field compaction tests.

7.7 Output and Cost

Table 7.1 shows that the output of the vibrating roller was 253 cum/hour and that of the three wheel static roller was 30 cum/hour. Cost of compaction of cubic meter of sand by vibrating roller amounted to Rs 1.10 and that by the static roller to Rs 1.85. Thus the advantage of unit cost and huge output of a vibratory roller is undeniable.

8. COMPACTION PROCEDURES FOR CLAYS

8.1 Experience in India

8.1.1 Experience in Maharashtra

Data received from Maharashtra Engineering Research Institute (MERI) gives information on compaction of clays for Warna and Kanher Projects. The data is reproduced in Appendix A-V. Statement I of the Appendix A-V gives results of field and laboratory tests on some of the soils. For soils in Plot No. I, liquid limit and plasticity index were about 50 per cent and 20 per cent respectively. Dry density obtained after 4 to 6 passes of sismopactor (static weight 8.5 T) was about 1.42 g/cm^3. Statement II gives values of field wet density for different number of passes of sismopactor. Fig. I of the Appendix A-V shows that sismopactor was capable of attaining modified Proctor density on casing material with 10 to 12 passes and standard Proctor density with 6 passes. On hearting material which can be expected to contain more of clay fraction, the sismopactor required 6 to 8 passses (Fig. III, Appendix A-V) to attain standard Proctor density and about 20 passes to attain modified Proctor density. The indication is that a heavier vibratory roller would be more efficient in attaining modified AASHO density.

Fig. II of the Appendix A-V is bizarre. It shows the performance of an ordinary (smooth) roller of 5T. A roller is inadequate if it requires more than 12 passes to attain a desired density. The sheepsfoot roller which required 22 passes (Fig. IV, Appendix A-V) to compact hearting material to standard Proctor density was inefficient and inadequate for the purpose whereas sismopactor (Fig. III same Appendix) was successful.

8.1.2 Experience in West Bengal

GUPTA et al described experiences of soil compaction for N.H. 6 and for a Bye-pass to NH 2 near Calcutta. Though the project provided for sheepsfoot rollers as well as flat tyred diesel rollers, the only type of compacting machine available with the organisation for works covered by the paper was 8 tons smooth three-wheeled diesel roller. Desired densities (about 95% of standard Proctor) were generally attained by 8 passes of the roller when the field moisture content of the soil was from 1 to 3 per cent above or below optimum moisture content for silty sand type clays (PRA classification being A4 to A6). However, at some places the field densities fell short of desired densities. The difficulties encountered in compaction of such soils are listed in Appendix A-VI. The Appendix A-VI describes also the effect of heavy earthmoving machines on compaction.

Road and Building Research Institute, West Bengal, conducted field tests to compact a clayey silty soil. The properties of the soil were : Liquid limit = 48 per cent, plasticity Index = 23 per cent, silt content = 82 per cent, and clay content = 16 per cent. Maximum dry density and optimum moisture content in standard Proctor test were 1.665 g/cc and 18.4 per cent respectively. The maximum dry density and optimum moisture content in modified AASHO test were 1.875 gm/cc and 13.3 per cent respectively. Laboratory CBR values of the soil tested at standard Proctor and modified AASHO parameters were 2.11 per cent and 3.35 per cent respectively.

3-wheeled static rollers of 8 T and 6 T capacity were used in field tests. The field data in the Reference 43 showed that 12 passes of rear wheel of 8 T roller gave 100 per cent standard Proctor density while the front wheel could not give even 95 per cent density with 12 passes. The 6 T roller was unable to give 100 per cent standard Proctor density. The rear wheel of 6 T roller required 18 passes to give about 95 per cent density and the front wheel gave still less. Neither of the rollers was adequate to produce modified AASHO density in the field tests. A list of smooth 3-wheeled diesel rollers manufactured in eastern India as appended to the Reference 43 revealed that all the manufacturers produced the road rollers with same or similar specifications and dimensions

8.1.3 IAAI Experience

IAAI reported data on compaction of a heavy clay (Liquid limit = 48 per cent, plasticity index = 24 per cent) to achieve 95% modified AASHO density by 8 T and 6 T vibratory rollers, Table 7.2 section 7.1.2. The 8 T vibratory roller required 9 passes to compact 30 cm thick heavy clay and the 6 T vibratory roller required 10 passes to compact 20 cm thick layer.

8.2 Experience Abroad

8.2.1 Dynapac Experience

Clays have plastic properties. The compaction characteristics are highly dependent on the water content. When the water content is low, the clay is hard and firm. Above the optimum water content, the consistency becomes more and more plastic when the water content is increased.

To obtain the specified density, the water content should not diverge too much from the optimum water content and the main problem in clay compaction is very often to adjust the water content to the optimum. The addition of water to a dry clay material by using water tanks, harrows, pulvimixers (soil stabilizers), etc. is time consuming and expensive. Water infiltration in the borrow pit is another alternative. The drying of a wet clay material can only be done in a dry and warm climate, even then using harrows or pulvimixers. A prolonged rolling operation with sheepsfoot rollers is sometimes used to dry a wet soil.

Clay materials with a high plasticity are avoided and seldom used as fill materials due to high compressibility, low shear strength (low stability) and difficulties with water content-density control. A rule is that the liquid limit of a clay fill should not exceed 50 per cent. Clays of type MH and CH (H = high compressibility) are therefore avoided as fill materials.

Even at the optimum water content, clay requires a considerable compaction effort and a lesser layer thickness compared to non-cohesive soils. The compactors must exert relatively large compressive and shear forces.

It is, however, necessary for vibratory rollers used for clay compaction to have a rather high static weight. With sheepsfoot and padfoot drums it is possible to further increase the forces acting on the surface and to break the more or less hard lumps of a clay fill.

To compact a clay soil the contact pressure applied to the soil must overcome the shear resistance of the material. Pneumatic tyred rollers produce a maximum surface pressure of 6 to 8 kg/cm^2. This contact pressure makes it possible to compact clays with low or medium strength (unconfined compressive strength below 2 kg/cm^2). As previously mentioned, clays with a water content above the optimum, have a comparatively low strength and can therefore be compacted with light or medium weight pneumatic tyred rollers. Heavy, towed pneumatic tyred rollers with weights of 40 ton and more have been rather widely used for clay compaction on dam and airfield constructions. They need a heavy tractor for towing and are not very manoeuverable.

Compaction of clay or clayey soils with a high strength requires the use of static or vibratory sheepsfoot or padfoot rollers to generate the necessary pressure. Vibratory sheepsfoot rollers, were first introduced around 1960. The largest single application for this roller type was the Ludington water storage reservoir in Michigan, USA constructed between 1969 and 1972. Over 16 triple hitch combinations of Dynapac 5-ton vibratory sheepsfoot rollers were used after comparative tests with static sheepsfoot rollers, and 30 ton pneumatic tyred rollers.

Towed rollers have to a large extent now been replaced by self propelled rollers. Another trend has been that sheepsfoot rollers have been replaced by padfoot rollers. The padfoot rollers normally have a larger capacity in m^3 per hour than sheepsfoot rollers. They also compact the surface layer to higher and more uniform density than sheepsfoot rollers.

Static padfoot rollers, also called tamping rollers, have static weights in the range of 15 to 40 ton and static linear drum loads between 30 and 80 kg/cm. The heavier models allow a layer thickness up to 0.3 m. They operate at high speeds and can in this way obtain high capacities. They are equipped with levelling blades and are efficient in spreading the fill material and to break the often large and hard lumps obtained at excavation of clay.

Self-propelled vibratory padfoot rollers with a drum module weight of around 7 ton (total static weight around 11 ton), have a static linear load of the padfoot drum of around 30 kg/cm. With this type of roller it is possible to compact clay materials at water contents around the optimum in layers of up to 0.3 m (after compaction) to densities between 95 and 100 percent standard Proctor.

Heavier vibratory padfoot rollers, with a drum module weight of 10 ton, have a static linear load of around 50 kg/cm. The layer thickness can be increased up to 0.4 m. Vibratory tandem rollers with two padfoot drums are now introduced and represent a further alternative for large clay compaction jobs.

Vibratory padfoot rollers are able to compact thicker layers than static padfoot rollers. They are also more versatile with regard to the type of soil, due to the combination of the static and dynamic forces.

In practice, a combination of a static padfoot roller (tamping roller) used to spread and pre-compact the material, and a 10 or 15 ton vibratory roller has proved to be suitable and economical. For this application, heavy vibratory smooth drum rollers are also used with good results.

A question often raised is if vibratory clay compaction is characterised by other relationships between water content and density compared with static compaction. The Australian test result shown in Fig. 8.1 indicate that the compaction curves follow the same pattern for vibratory compaction, static compaction and laboratory tests.

The specified density for clay fills is normally between 95 and 100 per cent standard Proctor. During recent years some authorities and consultants have specified 95 per cent modified Proctor for motorway embankments consisting of clay. For a clay material this roughly corresponds to 105 per cent standard Proctor and requires a large compaction effort. The water content of the soil becomes even more critical factor and veriations greater than maximum 2 per cent from the optimum water content value can normally not be accepted.

8.2.2 Wet Clays (U.K.)

Wet clays can be compacted in considerably thicker layers than dry clays. In the field, water content often greatly exceeds the OMC. A wet clay, which is more or less plastic can be compacted with a limit effort into a homogeneous mass having an air void content of not more than 5 to 10 per cent. The water content of the clay cannot, however, be reduced more than marginally, even by extended compaction. When the water content is substantially higher than the optimum, the degree of compaction will be comparatively low, even though the air void content has been reduced to a low level.

In conntries with a constantly wet climate, the U.K. for example, clays in embankment fills are compacted at higher water contents than the optimum without serious future settlements due to consolidation. Investigations in the U.K. have shown that water contents upto about 1.2 times the plastic limit can be accepted. Above this water content the traction conditions for scrapers, trucks and compactors become more and more difficult which also is a hindering factor for the use of wet clays as fill materials. Vibratory compaction of wet cohesive fill materials, or natural cohesive soils with a high ground water level, may cause a water migration to the surface of the fill and an increased plasticity of the material. Under such conditions, the use of vibrations should therefore be avoided or reduced. This also applies for the first layers placed directly on top of a wet cohesive material.

When wet clays have to be used as embankment fills, alternatate layers of clay and sand can be used to get a more rapid reduction of water content and a more stable fill i.e., a sandwich construction can be used.

8.3 Difficulties and New Techniques

Information in this section and in the Appendix A-VI bring out the difficulties encountered in compacting clays. When the moisture content is on the dry side of OMC more effort is needed. If a compactor is found inadequate a heavier compactor will be required. Padfoot rollers and medium to heavy vibratory rollers are suitable to compact clays near OMC.

8.3.1 Treatment of Wet Clay Fill

Some of the problems of wet clays are highlighted in section 8.2. The wetness of a clay fill and its corresponding low undrained shear strength may present difficulties in both the design of an embankment and its construction. There are a variety of solutions to these problems. Where stability is a problem, an embankment can be redesigned with flatter slopes.

In many cases it may be economic to reduce the moisture content of the clay fill and hence increase its undrained shear strength. Other methods are treatment with lime and sandwich construction.

8.4 Treatment of Existing Uncompacted Clay Subgrade

With increasing frequency it is necessary to build structures and roads on sites where there is a considerable depth of uncompacted clay. It might be economic with a fill of shallow depth to remove the fill and replace it with thin layers with adequate compaction. For deeper clay fills, preloading with surcharge of fill or stone column technique may be useful to increase the strength of the sub-soil.

8.4.1 Dynamic Consolidation

In dynamic consolidation, deep compaction of soils is attempted by repeated impacts of a heavy weight on to the ground surface. The Menard system of dynamic consolidation as it has been applied at clay fill sites in U.K., has typically involved dropping a 15 T weight from heights of upto 20 m. Primary tamping has usually consisted of repeated impacts at a number of points on a fairly widely spaced grid. At the clay fill sites in U.K., dynamic consolidation seems to have had significant effect on the fill down to depths of 5-6 m. Sometimes it may be necessary to import granular fill on to the site to form a working platform.

8.5 Control Standards

IRC has given specification requirements for embankment soil compaction based on laboratory maximum dry density (Table 6.3). The information in this section shows that 95 per cent of standard Proctor density is stipulated as a minimum density requirement by and large. 95 per cent to 100 per cent modified AASHO density has been required for some projects abroad. Bose and Dasgupta observed that "CBR tests of compacted clay fill should find a place in standard specification as moisture content and density checks do not depict the actual picture of the strength of soil". They also observed that in wet areas clayey soil should be compacted at or slightly above OMC but never below OMC. It may be noted that Swiss norms (Table 6.2) have included CBR values in the standards.

Suitability of Wet Clays

According to British specifications, a clay having liquid limit more than 80 per cent or plasticity index more than 55 per cent is to be treated as unstable material for earth fills. Also a wet clay at moisture content more than 1.2 times its plastic limit is an unstable material. The later criterion was contested at conference on clay fills. The plastic limit test itself was found to be unreliable. Arrowsmith finds it to be more logical to use shear strength criterion for suitability directly rather than through the ratio of moisture content to plastic limit.

The trafficability of earth moving plant was not originally a problem as caterpillar tractors and scrapers were able to excavate and place any material that could be compacted. However, as self-propelled rubber-tyred scrapers were introduced and became progressively larger, the shear strength requirements of the soil to support them became more critical. From observations on M6 (UK), the following minimum shear strength requirements emerged :

Caterpillar tractors and scrapers	— .35 kg/cm^2
Large rubber-tyred scrapers	— .50 kg/cm^2

A direct undrained shear strength criterion was advocated by Dennehy, as it relates to the functional limitations of plant and the immediate stability of embankments.

Dennehy gave undrained shear strength limits as 0.4 kg/cm^2 and 0.6 kg/cm^2 respectively for tyre pressure ranges of 2.4 to 3.1 kg/cm^2, and 3.4 to 3.8 kg/cm^2.

9. COMPACTION PROCEDURES FOR OTHER SOILS AND MATERIALS

9.1 Indian Experience

9.1.1 Experience in Gujarat

Data received from the Director, Gujarat Research Institute is reproduced in Appendix A-VII. The data comprises results of compaction trials at Ukai dam and at Kadana dam.

Compaction trials at Ukai

The soil was more or less a uniformly graded clayey to sandy silt which could be classified as CL, ML, SM and occasionally as CL — ML groups. Laboratory test results of these soils are given in Appendix A-VII. CL type soils could be compacted to the required standard by normal sheepsfoot rollers, though with some difficulty and after applying 2 to 4 more passes as compared to normal 8 to 10 passes. However, the feebly plastic to non-plastic silty soils proved to be the most difficult to compact. Compaction trials with sheepsfoot roller, 8 to 10 T smooth static roller, 4 T vibratory roller and pneumatic tyred roller showed the unsuitability of the equipment. The shear strength of the soil in the as-laid loose state was significantly low. Finally a low foot pressure roller was developed by welding 20 cm x 10 cm steel plates to the feet of an ordinary sheepsfoot roller and the equipment was called 'Elephant-foot-roller'. The pressure intensity at the foot of the roller could be brought down to 8.8. kg/cm^2. This roller gave the best relative performance with a pressure intensity of 10.3 kg/cm^2. The summary of typical rolling trials is presented in Table I of the Appendix A-VII. There was no mention of any trials with a combination of crawler tractor and vibratory roller.

Compaction trials at Kadana

At Kadana, the soils compacted were gravel-sand mix, river gravel and an impervious soil in the hearting zone. Equipment used were 3.6 T vibratory roller, crawler tractor, sheepsfoot roller drawn with tractor, and smooth static roller as stated in Tables II and III of the Appendix A-VII.

Compaction for highway construction in Gujarat

An experimental study has been carried out in Gujarat for comparison of a pneumatic wheel vibratory roller of 10 tonne dead weight and a three wheel static roller of 8 to 10 tonne dead weight for compaction of embankments of silty clay soil of plasticity index of 14 to 17 per cent, M.D.D. : 1.77 gm/cc and OMC 17 to 18 per cent. The details of the two rollers used are given below :

Three wheel static roller :

(i) Total weight (unballasted)	: 8 tonnes
(ii) Total weight (ballasted)	: 10 tonnes
(iii) Line Pressure (ballasted)	: 578 N/cm
(iv) Rolling width	: 1675 mm
(v) Prime mover	: 33 H.P. diesel engine at 1500 r.p.m.
(vi) Cost	: Rs. 2.00 lakhs

Pneumatic wheel vibratory roller

(i) Number of rolls	: One
(ii) Number of tubeless tyres	: Two
(iii) Dead weight (unballasted)	: 10.131 tonnes
(iv) Static rolling pressure	: 260 N/cm
(v) Frequency	: 2300 vibrations/min
(vi) Cost	: Rs 7.5.lakhs

It was found that :

(i) The soil could be compacted to satisfactory density with the vibratory roller in thicker lifts and with less number of passes. This increased the output of work achieved by the vibratory roller.

(ii) The compactive effort in the case of vibratory roller was twice that of the three wheel static roller of the same dead weight.

Tables 9.1 to 9.3 give the comparison of performance and economics of the two rollers.

9.1.2 Experience in Tamil Nadu

The study from Tamil Nadu, reported in Section 7.1.3, included results of performance of the three types of rollers on a red earth (properties in Table 7.3), with plasticity index 8 per cent. 4 ton tandem roller and 8-10 ton conventional roller gave hundred percent standard Proctor compaction after 6 passes and the 5 ton vibratory roller required 8 passes to give the same standard of compaction.

The 8-10 ton conventional three wheeled roller has been successfully used in Tamil Nadu, for almost all soils. Experience has shown that waviness and uneven finishes are often produced, when this roller is directly used on loose layer of cohesive soil at high moisture content, warranting the use of a light roller like sheepsfoot or pneumatic tyred roller first.

A field experimental study on the use of modified AASHO compaction was made on Bhavani Komarapalayam Bye-pass, forming part of National Highway 47, on a small stretch of 200m. The soil at the experimental site was of black cotton variety with plasticity index value of 41 per cent and CBR of 3 per cent with lump size ranging from 10 to 15 cm. The modified method of compaction of embankment construction, over subgrade soil using a fill material having plasticity index of 17 per cent was used. A sample of fill material was subjected to modified Proctor compaction for determining OMC and dry density.

With a view to find out the performance of 4 Ton Tandem roller and 12 ton 3 wheel roller in achieving the higher density (modified Proctor's density) in the field, an experimental stretch with equal lanes was marked out and the soil at (OMC — 1%) and lump size not exceeding 15 cm was spread uniformly to proper camber and grade of the road. 12 Ton roller, 4 Ton Tandem roller (with or without vibrations) were used to compact the respective lanes and the performance of these rollers was assessed in terms of in-place dry density measured at the end of every two passes of the rollers. In another stretch, the effect of the change of moisture content was also studied.

From the values of field dry density, it was observed that the 4 Ton Tandem roller (with or without vibration) required 6 to 8 passes to give 95 per cent modified Proctor density and it could give about 97 per cent density after 12 passes. The 12 ton three wheel roller achieved hundred percent modified Proctor density after 8 passes. The need for use of a heavier vibratory roller was indicated. It was also observed in the case of this fill material, better compaction was achieved, when compacted at a moisture content slightly over and above the OMC compared to dry of optimum.

9.1.3 A study by Larsen and Toubro

The study on techno-economic viability of vibratory roller carried out by Larsen and Toubro (details: ref. Section 7.1.1) included tests on silty clay, sandy clay and a sandy gravel. The results of field experiments have been presented in Table 7.1. The 8.5 T vibratory roller could give hundred per cent standard Proctor density with all the three types of soils whereas the 10 T static roller could give about 95 per cent density. The vibratory roller could compact thicker layers with less number of passes than the static roller could. The outputs of the vibratory roller were higher than those of the static roller. The cost of compaction per cubic metre of fill by the vibratory roller was about half of that of the static roller (Table 7.1).

9.1.4 CRRI study

A study was carried out at the Central Road Research Institute, New Delhi for determining relative efficiency of a 4 T tandem vibratory roller as compared to an 8 T standard three wheel static roller.

The specifications tried were:

(a) Soil sub-grade (properties of Delhi Soil, Appendix A-VIII).
(b) 150 mm thick stone soling,
(c) 75 mm thick water-bound macadam,
(d) 25 mm thick bituminous concrete,
(e) 20 mm thick premix carpet, and
(f) single coat surface dressing.

The following broad conclusions were arrived at:

(i) While 4 to 5 passes of the 8 T three wheel static roller were generally needed, 6 to 8 passes of the 4 T vibratory roller were sufficient to give the same compactive effort for most of the specifications.
(ii) For compaction of stone soling layer, the 4 T tandem vibratory roller was not so efficient as the 8 T three-wheel static roller.
(iii) Good compaction could be obtained by using the vibratory roller in the case of bituminous surfacing such as single coat surface dressing, 20 mm thick premix carpet and 25 mm thick bituminous concrete layer.
(iv) Soil subgrade and water-bound macadam layer could be compacted satisfactorily by using the vibratory roller.

9.2 Silts

Silt are non-plastic fines. A special problem with very fine sand and silts is that the material at high water content and under influence of traffic or vibrations, is rapidly transformed to a more or less fluid state due to the pore water pressures generated by the mechanical work (liquefaction). Silts are also very susceptible to frost heaving.

Silt and silty soils are, as all fine-grained soils, to a high degree dependent on the water content during compaction which should not diverge too much from the optimum water content. Drainage of the borrow pit is one possible way to reduce the water content. At optimum water content silt and silty soils are comparatively easy to compact. Silty sand as well as pure silt have low cohesion and can be compacted in rather thick lifts, 0.7 to 1.0 m when using heavy vibratory rollers with 10 to 15 ton drum module weight.

Silty soils which contain a certain amount of clay may have a considerable cohesion and will have compaction properties similar to those of clayey soils. Consequently silty soils have rather varying compaction properties covering the range between non-cohesion materials and pure clay soils.

9.3 Fly Ash

Fly ash has similar compaction properties as silt and can be well compacted by vibratory rollers with a low or medium static linear load. Compaction is achieved to 95 to 98 per cent standard Proctor density at a moisture content slightly below OMC. The side slopes of embankments are usually covered with an earth fill of suitable thickness to prevent erosion and environmental pollution. Fly ash has been used for bulk fill in a number of highways in UK and USA, including motor ways and expressways. Cinder, another waste material from industries, has been successfully used in construction of high banks on some highways in India.

9.4 Compaction by Blasting

In the treatment of saturated loose cohesionless soils by blasting, buried explosives are used to cause liquifaction followed by expulsion of pore water and densification. This ground improvement technique does not require compaction equipment. It is cheaper than vibroflotation method when deep compaction of saturated cohesionless foundation soils is required along highway alignments. LYMAN reported effectiveness of the blasting method in silty soils. An under water fill at Luni bridge approach on NH 15 in Rajasthan was densified by blasting.

9.5 Diversification of Equipment Use

Vibratory plate compactors and vibrating tampers (section 4.4.) which are useful in highway construction can be used to compact fills below floors and in trenches. Vibratory rollers are useful in compacting asphalt concrete. Heavy vibratory rollers are used to compact rock fill.

9.5.1 Roller compacted concrete

The use of vibratory rollers instead of internal vibrators to compact mass concrete was primarily investigated and tested by U.S. Army Corps of Engineers and the Tennessee Valley Authority. The concrete used has a low cement and water content. Vibratory rollers with static linear load of 20 to 30 kg/cm are suitable. Vibratory plate compactors or smaller models of vibratory rollers can be used to compact concrete laid close to sheet-pilings and concrete constructions.

9.6 Appropriate Technology

The extensive variety in properties of the materials to be compacted with great differences in job, site and weather conditions makes it more or less impossible to state a few simple and general rules for the choice of equipment.

9.6.1 Equipment for rural works

It is difficult to provide vast and remote rural areas with modern compaction equipment. Central Road Research Institute has developed appropriate animal drawn compaction equipment for use in construction of rural road works. Two inexpensive road rollers (cost approximately Rs 3000/- to Rs 4000/-) and two water bowsers (cost about Rs 1500/-) have been designed and fabricated by CRRI.

9.6.2 Equipment for slow jobs

Smoothwheel static rollers and sheepsfoot rollers, whose outputs are lower than those of vibratory rollers, will go a long way in serving jobs for less important roads, where time schedules are not tight.

9.6.3 Equipment for major works

The versatality of vibratory rollers is obvious from various case histories cited in this report. Though initial capital cost of vibratory roller is high there is gain in energy consumption and time. High outputs of the roller yield low unit cost of compaction. It is desirable to have two weight ranges of vibratory rollers for immediate use in India :

(a) 4 to 6 T tandem vibratory roller for metropolitan and medium works.
(b) For large projects 8 to 10 T dual drum vibratory roller with facility to exchange with padfoot rollers and with the following characteristics :

Frequency range :	1800-2400 vibr/min.
Double amplitude, ranges :	0.4 to 0.8 mm and 1.0 to 1.5 mm.

10 SELECTION OF EQUIPMENT, RESEARCH METHODOLOGY AND RESEARCH AREAS

10.1 Selection of Field Compaction Equipment

The choice of suitable compaction equipment is sometimes made by the contractor on the basis of earlier experience and existing range of equipment. In some cases the type of soil material and or the specifications are decisive. Information in Sections 3, 4, and 9.6 is of some use in preliminary selection.

In many cases, however, there are several alternatives. It is always very important to choose compaction equipment which is not only suitable for the type of material to be compacted but also well adapted to the hauling and spreading operations as well as to other work-site conditions.

The following checklist can be used as a guide :

Factors influencing the choice of compaction equipment :

1. Type of soil and water content.
2. Compaction specifications (specified degree of compaction in standard or modified Proctor, specified layer thickness, specified types of compaction equipment).
3. Methods of hauling and spreading the material. These factors, to a high degree, determine the suitable layer thickness.
4. Need of drying or watering of the soil.
5. Traction conditions for the compaction equipment.
6. Necessary compaction capacity in m^3/h. Are filling operations going on at different sections?
7. Climatic conditions.
8. Transportation of the machines to the site and between different sections on the work site.
9. Possibilities to standardize the compaction equipment.
10. Facilities available for repairs and service.

One example of a possible standardization is when a 10 ton selfporpelled vibratory roller with a smooth drum is used for sub-base and base compaction on a road project in combination with the same roller type with padfoot drum for compaction of the embankments consisting of clay. Asphalt versions of the same basic design are also available. The advantages with regard to spare part supply, repairs, and service are obvious.

Another example is to use a heavy vibratory roller with a smooth drum for rock and gravel fills, as well as on filter materials on a dam project. With a vibratory padfoot roller used on the core, the entire compaction job can be done with the same roller type.

Sometimes a joint operation of rollers of different types is favourable. The possible combination of a self-propelled static pad-foot (tamping) roller with levelling blade to spread the material and to crush big lumps and a vibratory roller is one such example.

The compaction effect obtained with a combination of different roller types is a question which requires further basic study and practical experience.

10.2 Methodology for Field Compaction Tests

The soils to be compacted and the working conditions are never the same from one site to another. At the start of a large compaction job, it is therefore common practice to make several field compaction tests, sometimes with different types of compactors, to determine suitable layer thickness, roller speed and number of passes.

To obtain as accurate as possible field compaction test results, the following points should be kept in mind :

1. The layer on which the test is performed should be spread on top of a compacted layer of the same material. The density of the underlying layer should be at least the same as that intended for the test fill.
2. The test area should be compacted with at least three roller lanes side by side, Fig. 10.1. Overlap between the lanes should be about 10 per cent of the roller width. All three lanes should be rolled with the same number of passes and density tests should be made in the centre lane. Outside the compacted area there should be a shoulder, with at least the width of the roller, to avoid lateral movement of the material.
3. The roller speed should be determined before the tests and carefully checked. A suitable rolling speed for a vibratory roller operating on soil or rock fill is 4 km/h. Difficulties to reach the specified density may require further tests with a somewhat lower speed or vice-versa.
4. The suitable number of passes after which the density tests should be made are normally 4, 6 and 8 passes. Especially on fine-grained soils, the roller passes should not follow each other too close in time. Higher densities will be obtained if the soil can "consolidate" for at least an hour between the roller passes. In silty soils some air can be pressed out during such rest periods by the pressure built up during compaction.
5. For most types of soil, it is very important that the water content in the test material is near the optimum (±2 per cent) when the test is performed.
6. Density tests are normally performed with the sand-replacement or water-baloon methods, but other testing methods may also be used according to special requirements. Tests should be done at selected spots on the surface and at 150 mm intervals down through the layer. At low surface density, e.g. in uniformly graded sand or when sheepsfoot rollers are used, the tests have to be made at some depth below the surface.
7. The suitable layer thickness varies according to the size of the roller and the type of material. Indications as to layer thickness for various types of compaction equipment can be found in Table 10.1 or 6.1. It will often be suitable to try two or three different layer thicknesses. At base compaction, vibratory compaction is usually performed on a layer thickness equal to the total thickness of the base.
8. It is sometimes suitable to use a test area where the layer thickness varies rectilinear, Fig. 10.2. Tests are made at different sections. The maximum layer thickness can be determined from the results of the density tests.

General Advice

If the specified density is not reached in a compaction test, the applied compaction energy per unit volume must be increased. This can be done by :

* Increase of number of passes
* Decrease of roller speed
* Decrease of layer thickness

Table-7.1

	Type of soil	Silty clay CL	Sandy Clay SC	Sand SP	Sandy Gravel SC
	Type of roller				
Lift Thickness Loose (cm)	Static	22.5	22.5	20	30
	TT-900	60	45	30	60
No. of passes	Static	6	7	8	6
	TT-900	5	4	4	3
Time taken (Sec.)	Static	584	422	490	734
	TT-900	221	106	108	148
Percentage Compaction	Static	95.02	95.97	95.20	96.00
	TT-900	100.00	100.00	100.00	100.00
Output per hr (Cum/hr)	Static	46	40	30	62
	TT-900	413	395	253	684
Cost/cum (Rs.)	Static	1.20	1.39	1.85	0.89
	TT-900	0.67	0.70	1.10	0.40

Table-7.2 : Number of Passes Required to Achieve 95% Modified AASHO Compaction on Different Types of Soil with 8 Tonnes and 6 Tonnes Vibratory Rollers.
(Frequency — 1800 Vibrations/min. and Amplitude 1.2 mm)

Nature of soil	L.L. per cent	P.L. per cent	P.I. per cent	OMC % Modified AASHO	No. of passes with Static load 8 tonnes roller for 30 cm, thick layer	No. of passes with 6 tonnes roller for 20 cm. thick layer
Sand	—	—	—	7	3	4
Sandy clay	22	14	8	8.5	5	5
Silty clay	24	19	5	9.0	5	6
Heavy clay	48	24	24	12.0	9	10
Granular Base	18	13	5	8.0	5	4
Crushed Rock Base	—	—	—	6.0	6	6

Table-7.3 Properties of Soil

			Index Test				Sieve Analysis				Sedimentation Analysis			Proter Test		C.B.R. @ Proctor density O.M.C.		
Serial Number	Description of soil	Unified soil classification	P.R.A. soil classification	Liquid limit %	Plastic limit %	Plasticity index	Per cent passing 15200	Per cent passing 1540	Per cent passing 158	Specific gravity	Sand %	Silt %	Clay%	Maximum density gm/cc	Optimum % moisture content	Immediate %	After 4 day soaking %	Moisture after 4 day soaking %
1.	Foundation soil (H.R.S. Clay)	CL	A. 6	35	15	20	99	79	52	2.44	35	34	31	1.74	17	8	3	24
2.	Gravel	GC	A.2.6	37	15	22	42	31	23	2.74	47	22	31	2.11	11	19	18	13
3.	Silty sand	—	—				100	74	10	2.52	92	8	—	1.89	11	32	27	12
4.	Clayey sand	SM SC	A.2.4	19	13	6	99	77	26	2.64	76	19	5	2.12	10	16	9	10
5.	Red Earth	—	—	22	14	8	95	71	30	—	—	—		1.93	12	21	10	—

Table-7.4 : Performance of Rollers on Silty Sand (PI-0)

No. of passes	Tandem Roller: Field dry density gm/cc	Tandem Roller: % Compaction	Vibratory Roller: Field dry density gm/cc	Vibratory Roller: % Compaction
2	1.77	94	1.93	102
4	1.95	104	1.93	102
6	1.94	103	1.94	102
8	1.93	103	1.97	104
10			1.98	105

Table-7.5 Performance of Rollers on Clayey Sand (PI-6)

No of Passes	Tandem Roller		Vibratory Roller		Conventional Roller	
	Field dry density gm/cc	% Compaction	Field dry density gm/cc	% Compaction	Field dry density gm/cc	% Compaction
2	1.84	87	1.85	87	1.87	88
4	1.91	90	1.84	87	1.89	89
6	2.05	97	1.90	90	1.95	92
8	2.06	97	1.91	90	2.08	98
10	2.05	97	1.93	91	2.08	98

Table 7.6 Dynamic Vs Static Compaction of sands

Depth metres	Density cm/cm³	
	200 T Static compactor	15-T Vibratory roller
0.30	1.69	1.69
0.60	1.74	1.74
0.90	1.76	1.76
1.20	1.73	1.73
1.50	1.69	1.70

Table 9.1

Type of roller	Lift thickness cm.		No of passes	Time taken, min.	Moisture content, percent	Dry density gm/cc
	Loose	compacted				
Static roller	30	20	7	6.6	19	1.65
Vibratory roller	45	30	3	2.7	20	1.70

Table 9.2

Type of roller	Hours worked	Output cu.m.	Output per hour, cu.m.	Density gm/cc
Static roller	348	19785	56.85	1.65
Vibratory roller	160	20380	127.37	1.70

Table-9.3

Type of roller	Total cost	Cost/hour	Cost/cu.m.
Static roller	Rs. 21,924	Rs. 63	Rs. 1.10
Vibratory roller	Rs. 24,000	Rs. 150	Rs. 1.18

APPENDIX-A-II

List of Vibratory Rollers Manufactured or supplied in India

1. Details of Vibratory Rollers manufactured by M/s Dynapac (Sweden) supplied by M/s Escorts Ltd.

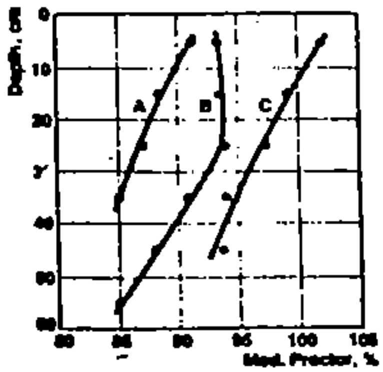
Roller characteristics	Model Designation CC 21	CC 14	CC 14G	CA 25
Number of rolls	Two	Two	Two	One
Number of vibrating rolls	Two	Two	One	One
Diameter of vibrating drum, mm.	1040	900	900	1525
Rolling width, mm	1400	1300	1300	2130
Total weight (static), kg	6600	4350	4250	10400
Load per cm of vibrating roll contact (static), kg/cm, front/rear	22.9/ 24.3	15.8/ 17.7	17.3	28.8
Weight on vibrating roll Kg. front/rear	3200/ 3400	2050/ 2300	2250	5900
Amplitude, mm	0.35/ 0.7	0.35/ 0.7	0.35/ 0.7	0.8/ 0.7
Frequency, vibration/min.	3000	2500	2500	2000-2400

2. **Details of Vibratory Rollers manufactured by M/s Alberst(France) supplied by M/s Larsen and Toubro Limited.**

Model designation	Sismo-pactor TT 900	Sismo-pactor TT 901	Sismo-pactor TT 1600	VM 1203	VM 1204	VA 10 ST	VA 10 DT	VA 10 DV	VA 10 DP	VA 10 SP
Number of rolls	One	One	One	One	One	Two	Two	Two	One	One
Number of vibrating rolls	One	One	One	One	One	One	One	Two	One	One
Total weight (static), kg.	8500	8600	19000	14200	15700	7600/ 8600	8000/ 9000	8800	8400	8200
Weight on vibrating roll (static), kg.	7400	7400	16000	8100	10100	4400	4400	4400	4200	4000
Load per cm of vibrating roll contact (static), kg/cm.	33	33	58	37	46	31.5	31.5	31.5	30	28.5
Amplitude, mm	1.2	1.33	0.83 1.25 1.67	0.66 1.00 1.33	0.66 1.00 1.33	0.36 0.57 0.78	0.36 0.57 0.78	0.36. 0.57 0.78	0.36 0.57 0.78	0.36 0.57 0.78
Frequencies, Vibrations/min.	1380 to 1980	1380 to 2220	1500 to 1980	1500 to 1980	1500 to 1980	1560 to 2700	1560 to 2700	1560 to 2820	1560 to 2820	1560 to 2820
Rolling width, mm	2350	2350	2900	2200	2200	1400	1400	1400	1400	1400
Diameter of vibrating rolls, mm	1200	1200	1600	1500	1500	1350	1350	1350	1350	1350

3. **M/s Jessop & Co. Ltd., in collaboration with M/s Aveling Jessop Ltd. of U.K. are manufacturing vibratory rollers in India. The machine with appropriate modifications can be used for compaction of soils, granular materials and bituminous mixes. Treaded penumatic tyres are interchangeable with steel rolls. Vibratory drum can be replaced by padfoot roll.**

Total weight	10434 kg.
Weight on vibratory roll	5654 kg.
Static rolling pressure	260 N/cm.
Frequency	2300 vibrations/min. (maximum)
Centrifugal force	14515 kg



2

Fig 7.1 *Compaction tests on sand with 135 kg vibratory plate compactor.*

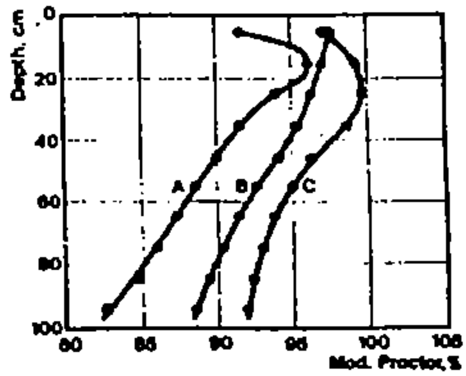


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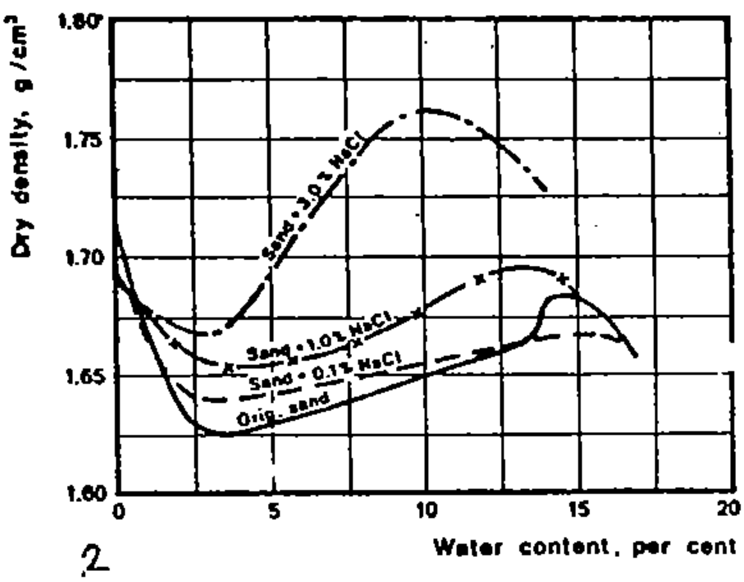
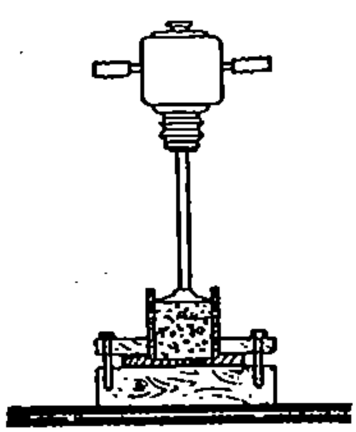
Fig 7.2 *Compaction tests on sand with 10 ton self-propelled vibratory roller.*



2

Fig 7.3 *Laboratory compaction tests with sand containing sol[illegible]e salts.*



2

Fig 7.4 *Laboratory compaction tests with a Cobra Atlas Copco Hammer.*

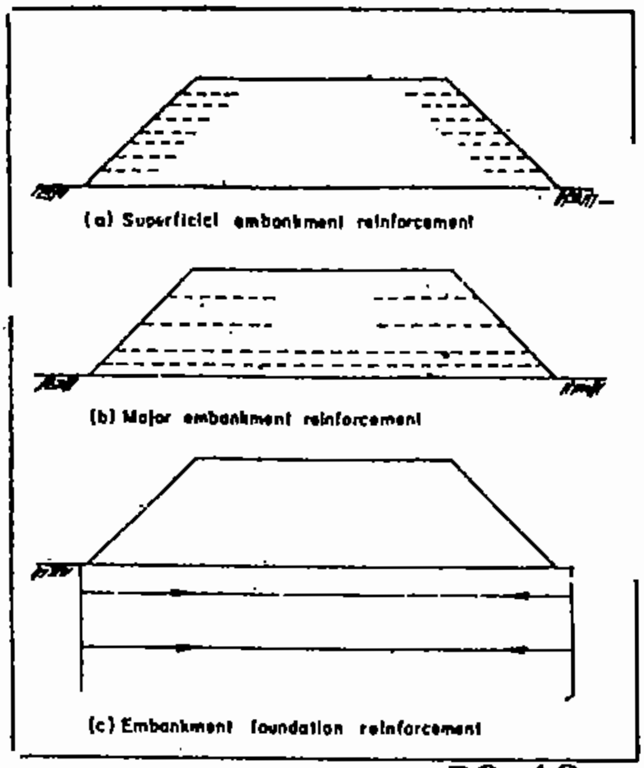


Fig 7.5 Modes of embankment reinforcing [39, 40]

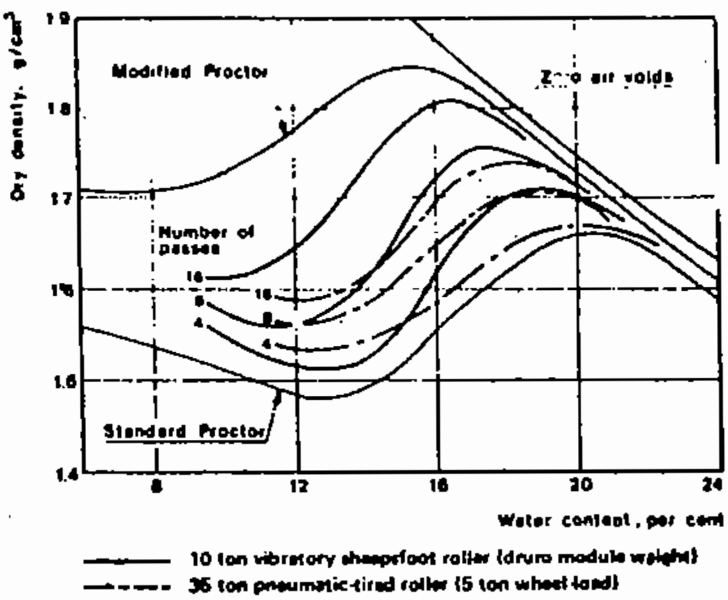


Fig. 8.1 Results of compaction tests on clay made in Australia [44]

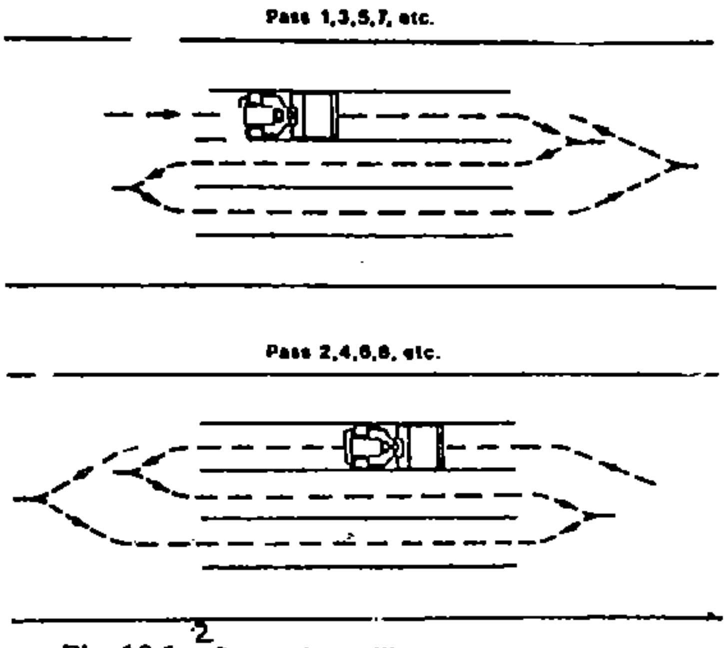


Fig. 10.1[2] *Proposal to rolling pattern on test a ea.*

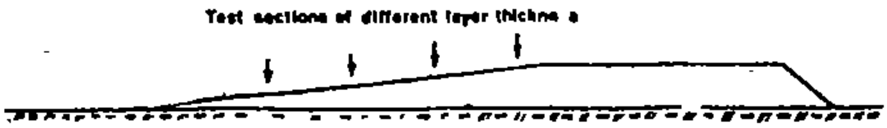


Fig 10.2[2] *Sloping test area.*

Total applied force	20169 kg.
Roll width	2133 mm
Roll diameter	1524 mm
Engine	102 BHP
Speed	0 to 187 m/min. 0 to 375 m/min.
Cost	Rs. 8 lakhs approximately.

4. Details of Vibratory Roller Manufactured by M/s Elektromag Devices Pvt. Ltd., New Delhi

Total weight (Static)	2300 kg.
Rolling width	900 mm
Frequency	4000 Vibrations/min.
Cost	Rs. 1,78,500/-

5. Details of Vibratory Roller manufactured by M/s International Engineering and Construction Co., Calcutta

	Model VR-75 Maximix
Total weight static	1800 kg.
Weight on Vibrating roll	1000 kg.
Rolling width	1000 mm
Diameter of vibrating roll	650 mm
Linear contact pressure (Static)	10 kg/cm.
Linear contact pressure (dynamic)	30 kg/cm.

6. Details of Vibratory Rollers manufactured by M/s Usha Atlas Hydraulic Equipment Ltd., Calcutta.

	Model Designations		
	Vibrol D 60	Vibrol R 91	Vibrol SP 200
Total weight, Kg.	650	1833	10320
Weight on vibrating roll kg.	—	—	5660
Lead per cm of vibrating roll contact (Static), kg.	5.5	—	—
Rolling width, mm	686	914	2100
Diameter of vibrating roll, mm	—	—	1370
Amplitude, mm	—	0.45	1.45
Frequency, Vibrations/min.	4500	4020	2980