New Method for Measuring In-Place Density of Soils and Granular Materials

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Conventional methods of measuring the in-place density of soils and granular materials are time-consuming and oftentimes subject to considerable error. Presently used methods, such as measuring volumes by use of oil or calibrated sand, have one or more of the following shortcomings: (1) suitable only for application to a small range of hole sizes, (2) subject to considerable error when surface of ground is rough, (3) accuracy affected by vibration or temperature, (4) cannot readily check densities of successive lifts by merely extending depth of same hole, and (5) require lengthy calculations and correction factors for final answer.

In an attempt to overcome these deficiences, the Washington Densometer has been developed. The basic principle of the instrument is the same as that used in some other methods, namely that of inflating a rubber balloon with fluid until it fills the excavated hole and measuring the volume of the hole by measuring the amount of fluid so required. However, to the authors' knowledge, the apparatus is unique in the method of application of this principle.

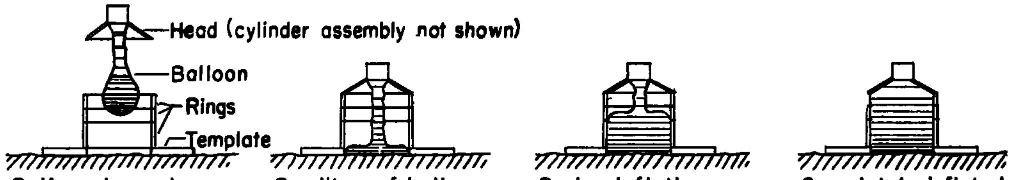
The device uses a closed system with a cylinder and piston to activate inflation and deflation of the balloon. This permits extremely rapid operation, plus the direct reading of volumes in cubic feet from the calibrated piston rod. By the inclusion of known-volume rings, rapid and accurate measurements of holes varying from 0.000 cu. ft. up to 0.500 cu. ft. can be made.

● THE need for a fast, accurate means of determining the field density of in-place granular base course and surfacing materials, as well as of subgrade soils, has become critical in recent years in the highway-construction field. Widespread application of moisture-density specifications to insure uniformity of roadbed construction requires that field methods be sufficiently rapid that control data can be made available to the engineer and the contractor during the compaction process and without causing delay to the progress of the job.

This is particularly critical in projects utilizing equipment-train methods of construction, such as soil-cement or cement-stabilized-base projects, where each phase of operation is integrated in time and order with other operations. The rapid progress of such projects does not allow sufficient time for determining field densities during the compaction phase using presently accepted methods. This has resulted in actually running "control" tests _after_ a section of road is completed; the data serving primarily as a record to serve as a guide in future work. Often, the end result is a considerable waste of rolling time for compaction equipment, or in some cases, the need to disrupt the progress of the job because of the necessity of reprocessing a completed section.

Other phases of highway work have also been curtailed by the inadequacies of presently accepted standard field density test methods. In the field of research, this department has begun a long-range program of investigation of base-course and surfacing materials. A considerable number of pavement failures can be explained only in terms of failure of the granular surfacing materials and base courses. To determine what correction steps are required, it is necessary first to determine whether the deficiencies are in the materials themselves, or a result of the manner of placement or alteration of physical characteristic due to traffic. Extensive field studies will be required to find the correct answers, and one phase of these field investigations involves de-

A.



Balloon being lowered into rings for initial reading. Approximately 1 liter of fluid in balloon.

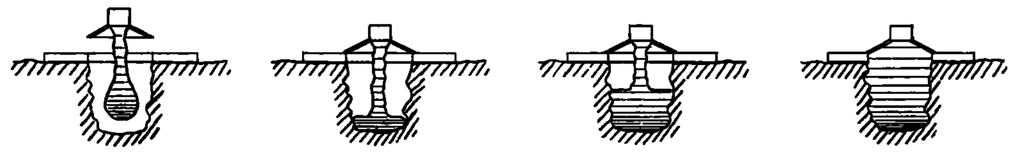
Condition of balloon with apparatus clamped in place prior to inflation.

During inflation. Note how balloon fills from bottom up.

Completely inflated. Record initial reading (IR). Deflate balloon and remove Densometer from rings.

B. Remove rings, dig hole, and leave out ring or combination of rings whose volume most nearly equals the estimated hole volume. Sum of volumes of rings left out = ring constant.

C.



Balloon being lowered into hole. Rings not on template.

Condition of balloon prior to inflation. Fluid in balloon causes bottom of hole to be filled without trapping air.

During inflation, filling from bottom allows balloon to fill voids displacing air upwardly and out vents.

Hole and head completely filled. Record final reading (FR).

D. Calculate volume: (FR + ring constant) − IR = volume of hole.

Note: The sketches above show a hole volume of approximately 0.2 cu. ft. and all rings were omitted for the final reading. For smaller holes, one or more of the rings would be used during the final reading. The purpose of the rings is to cause the balloon to be inflated to approximately the same degree for both the initial and final readings.

Figure 1. Sequence illustrating characteristics of densometer during operation.

termination of field densities both during the construction period and after various periods of traffic. The large volume of such data required dictates the need of field equipment that is both accurate and rapid. Presently accepted methods are not suitable for such studies for the reasons stated below, and this is one of the primary reasons the Washington Densometer was developed.

STUDY OF EXISTING METHODS

In 1952 this department reviewed the several existing methods generally accepted by various agencies for determining field densities, and found that each method possesses one or more of the following shortcomings: (1) required too much time for operation, exclusive of time required to dig hole; (2) suitable only for application to a small range of hole sizes close to the size of hole for which the apparatus is calibrated; (3) do not provide for initial surface reading, which introduces appreciable error when surface of ground is rough; (4) accuracy seriously affected by outside influences such as vibration, humidity, temperature; (5) will not permit checking densities of successive lifts by merely extending the depth of the same hole; (6) require frequent recalibration to insure accuracy; (7) require a level surface for successful operation; (8) not suitable for use in clean granular materials; (9) danger exists of trapping air in bottom of holes dug in fine-grained soils; and (10) require lengthy calculations and correction factors for final answer, which increases the possibilities for errors.

DISCUSSION OF WASHINGTON DENSOMETER

With these deficiencies in mind, development of the Washington Densometer

was started. Successive improvements in design resulted in a device that has none of the shortcomings listed above. The schematic drawing shown in Figure A illustrates the basic features of the apparatus. The principle utilized is the same as that used in some other methods; namely, that of inflating a rubber balloon with fluid until it fills the excavated hole and measuring the amount of fluid so required to determine the volume of the hole. However, to the writers' knowledge, the apparatus is unique in the method of application of this principle. The use of a closed system with a cylinder and piston activating the inflation and deflation of the balloon permits extremely rapid operation and the direct reading of volumes in cubic feet from the calibrated piston rod. The inclusion of known-volume rings permits the use of a large-size balloon for both small and large holes without loss of accuracy. The purpose and use of these rings are illustrated in Figure 1.

In summary, the following features and advantages are found in the densometer method of measuring hole volumes:

1. Operation time is sufficiently short that "wet densities" can be determined in from 10 to 20 minutes depending on the time required to dig the hole. Of the total time consumed, only about 3 minutes are required for setting up the densometer and making the necessary readings.

2. An initial reading that will account for variations in roughness of the original ground surface at the hole site is taken, which increases the accuracy of the determination.

3. Volumes of holes from 0.000 cu. ft. to 0.250 cu. ft. can be measured with equal accuracy. (Actually, this volume can be doubled by recharging the cylinder during the operation). The large capacity of the device makes it applicable for determining densities in coarse, granular materials as well as in fine-grained soils.

4. The balloon membrane is very thin, and the size of the balloon is such that it fills the excavated hole without being stretched appreciably. These features,

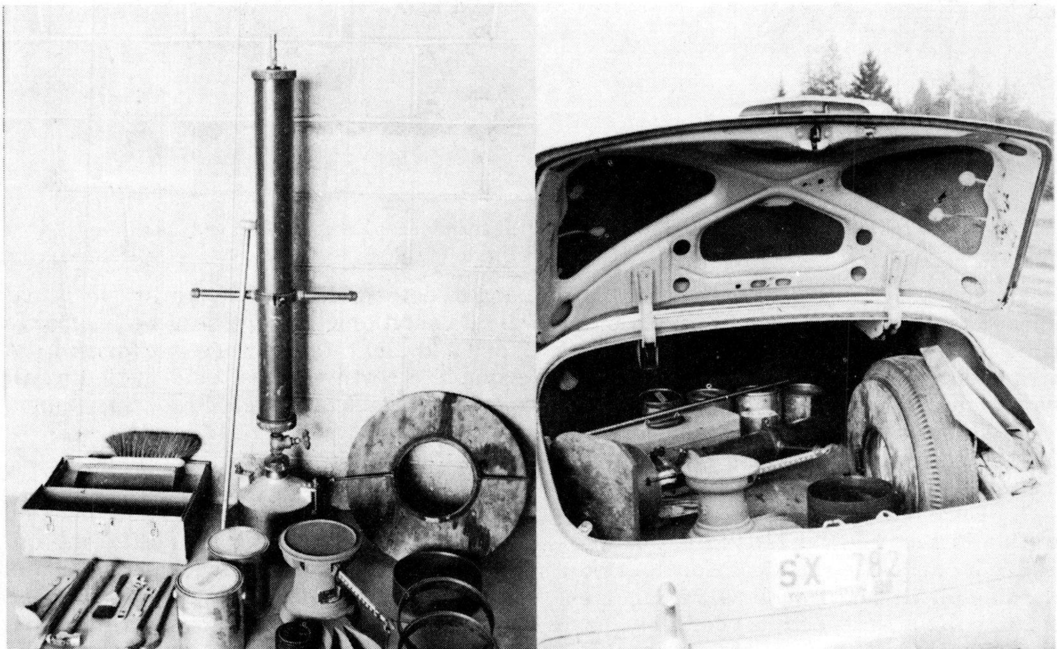


Figure 2. Complete field kit for Washington Densometer; (left) including tools and equipment for field maintenance and operation; (right) loaded for transport in trunk of passenger car.

coupled with the fact that the balloon is lowered into the hole in such a manner that the hole is filled from the bottom up, insure that air is not trapped and that practically all pits and voids in the hole walls are filled.

one man can carry it with no difficulty (see Fig. 2).

RESULTS OF EXPERIMENTS

To verify the accuracy of the densometer

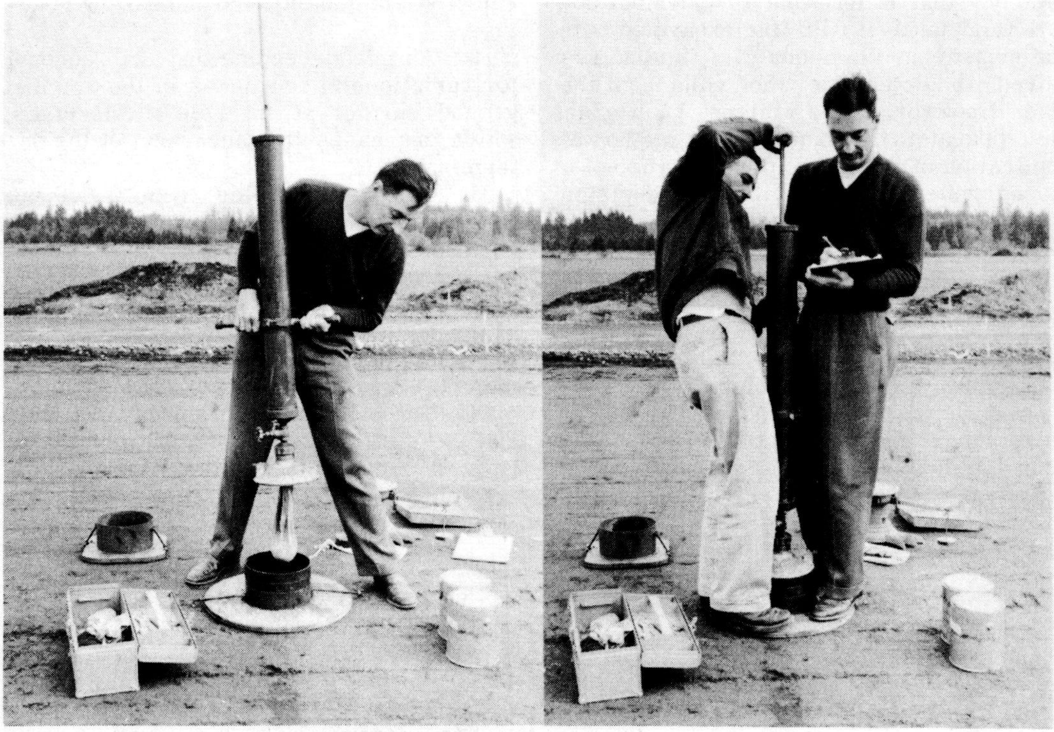


Figure 3. Lowering balloon into rings and template (left) and taking initial readings (right).

5. Successive determinations on any number of thin layers can be made in the same hole. Holes up to 18 inches in depth have been tested; however, the anticipated maximum depth of hole is about 22 inches.

6. Results obtained are of equal or greater accuracy than those obtainable by presently accepted standard field methods.

7. Once calibrated, no further calibration is necessary. Little field maintenance is required, except for periodic bleeding off air and occasional replacement of the balloon. These procedures have been simplified to a point where very little operational time is lost.

8. Readings are made directly in cubic feet, which greatly simplified calculations.

9. The apparatus is of such size that it can be carried in the trunk of a passenger car, and is sufficiently light that

and to determine its adaptability to actual field conditions, a series of both laboratory and field tests were performed. A complete review of the tests including all pertinent data is appended to this paper.

LABORATORY EXPERIMENTS

1. A series of readings was made on the same hole site by two different operators. It was found that the apparatus exhibits a definite stopping point when the piston is depressed; that an operator will repeat his determinations accurate to less than 0.0002 cu. ft.; and that two different operators can repeat each other's determinations with equal accuracy.

2. A container whose volume was accurately determined by precise water-filling methods was checked with the densom-

eter. The volume determined agreed exactly with the true volume on two trials, and varied 0.0001 cu. ft. on one trial. Different operators were used for the third trial. This accuracy greatly exceeds that required for field density tests.

comparative results were obtained. The densometer consistently gave slightly larger hole volumes for the same hole, and the difference increased as the roughness of the hole surface increased. This indicates that the densometer more-com-

Figure 4. Balloon, flexible suction tube and tapered sleeve, carrying base, head, lock ring, wrench. Upper right shows balloon slipped over suction tube and sleeve and being placed in head. Lower left shows head clamped to carrying base and lock ring being tightened to seal balloon in place. Lower right shows cylinder in position on head and being tightened with special spanner wrenches.

3. A series of parallel tests was run with the sand-volume method and the Densometer. It was found that if extreme care was used in calibrating and operating the sand-volume apparatus, and if an initial ground-surface reading was made with the sand-volume apparatus, close

pletely fills the voids than does the sand.

FIELD EXPERIMENTS

1. The densometer was used for field control of compaction of cement-treated and granular base materials on five dif-

P SH No. 9 Cont. No. 4490 Section Bogachiel to Hoh River

Inspector Humphres - Gadbois Date Aug. 12, 1953

Test Hole No.	7						
Station	723+00						
Reference to ℄	5' Left						
Reference to Grade	C.T.B.						
DENSITY DETERMINATION							
Can No.	1						
Densometer Final Reading "A"	0.1712						
Ring Constant "C"	0.1500						
Sum of Final Reading plus "C"	0.3212						
Densometer Initial Reading "B"	0.1923						
Vol. of Hole-Cu.Ft.(A+C-B)	0.1289						
Wt. Wet Soil from Hole + Can	19.87 lb						
Wt. of Can	1.49						
Wt. Wet Soil - lbs.	18.38						
Wet Density - lbs./cu.ft.	142.6						
Dry Density - lbs./cu.ft.	134.3						
Max.Density - lbs./cu.ft.	136.1						
% of Max.Density-lbs./cu.ft.	98.7						
MOISTURE DETERMINATION							
Wt. of Damp Soil + Tare	4.38						
Wt. of Dry Soil + Tate	4.25						
Wt. of Moisture	0.13						
Wt. of Tare	2.15						
Wt. of Dry Soil	2.10						
% Moisture	6.2						

$$\text{Wet Density} = \frac{\text{Wt. of Wet Soil}}{\text{Vol. of Hole}}$$

$$\text{Dry Density} = \frac{\text{Wet Density}}{\frac{1+\%\ \text{Moisture}}{100}}$$

$$\%\ \text{Max.Density} = \frac{\text{Dry Density} \times 100}{\text{Max. Density}}$$

$$\%\ \text{Moisture} = \frac{\text{Wt. of Moisture} \times 100}{\text{Wt. of Dry Soil}}$$

1 Gram = 0.0022 lbs.

1 lb. = 453.6 grams

Remarks: #7 Hole 6" deep in cement-treated Base Course. Rolled for 1-hr w/ pneumatic roller and two 10-Ton tandem steel-wheeled rollers. Appearance - excellent

Figure 5. Suggested form with sample data for field density test report.

ferent projects. On one project parallel determinations were made with the sand-volume method. On this project results of the two methods agreed closely (±0.0004 cu. ft. for holes approx. 0.10 cu. ft. in volume) except occasionally when construction equipment working nearby vibrated the ground while running the sand-volume determination. Differences then increased to a maximum of 0.0015 cu. ft. Intermittent checks made on the other projects gave similar results. Speed trials using the two methods showed that it was possible to complete two determinations of wet density using the densometer while completing one with the sand. The trials included the time required to clean the hole and refill it with fresh cement-aggregate mix and the time required to calculate results.

An alcohol-burning method of drying the samples was correlated with oven-drying, and was used on the grade to determine moisture content in conjunction with the densometer. With two men and using this procedure, it required approximately 10 to 15 minutes to determine the wet density, and an additional 5 minutes to determine the dry density. At no time was it necessary to delay the operations of

the contractors for density information. It was consistently possible to check at least one density, and sometimes two or three densities in each 400-foot to 800-foot section of roadway before the rollers were needed on the next section. It was found possible to complete a wet-density determination for each pass of a roller when the sections were over 600 feet long without interfering with the roller operation.

On one of the above projects, it was necessary for one man to work alone temporarily. Using the densometer and the alcohol-burning method of drying, he was able to make six complete dry density determinations in 3 hours. These tests were made in an 8-inch lift of 1 inch of clean crushed gravel. On several occasions on this project, tests were made on successive 4-inch layers in the same hole with excellent results.

2. The densometer has been used to check the densities of crushed stone surfacing, top course. Three densities were taken at each of several sites at different offsets from centerline. The alcohol-burning method was used for determining moisture content. Moves at about 3,000 feet were made between test sites. It was possible to make up to 30 complete determinations per 8-hour day under these conditions. Results were very consistent and logical. Occasional comparisons with the sand-volume method gave good results and verified the accuracy of the densometer.

SUMMARY

In actual field use, the Washington Densometer has proven itself to be considerably faster, equally or more accurate, and extremely more versatile than other existing accepted types of equipment designed for measuring in-place hole volumes in soils.

The accuracy, versatility, and speed attainable with this equipment have greatly increased the practical degree of actual control possible on controlled-compaction projects. The range of material types for which control can be considered practical has been broadened considerably, and the effectiveness of various types of rollers on thin or thick lifts of soil can now be readily investigated.

Maintenance requirements of the equipment during use has proven to be practically negligible. The balloon mortality rate is lower than anticipated, with replacements being required only after the equipment has been stored unused for considerable time.

Reception by field inspectors, resident engineers, and contractors has been favorable.

Appendix A

DESIGN AND OPERATION PROCEDURE

The schematic sketches and section-plan drawings (Figs. A-D) show the physical arrangement and dimensions of the apparatus. It is designed to handle hole volumes up to approximately $\frac{1}{4}$ cu. ft. without recharging the cylinder, or up to approximately $\frac{1}{2}$ cu. ft. or more with recharging. Tests to date have been confined to $\frac{1}{2}$ cu. ft. and less, so no statement of satisfactory performance at volumes above that can be made at this time.

The piston is designed to move freely in the tube, and yet give a sufficiently tight seal to allow the fluid to be sucked upward into the tube without loss of seal. The leather seals were selected after trying several materials and have worked very well. They tend to freeze temporarily on setting unused for long periods, but can be freed by light tapping on the handle, or by turning the rod with a wrench, and will then work freely and smoothly.

The balloon used was selected primarily for its size, which allows digging holes of about 9 inches in diameter, a desirable size for granular materials. It has a thin wall, and a high stretch ratio, which allows it to conform to small irregularities in the hole surface. Being a standard weather balloon, it is commercially available at low cost.

Soluble oil, the type used by machinists to make cooling water, is added to the water used in the apparatus to avoid rust and corrosion, and to lubricate the cylinder walls. Other fluids, such as hydraulic brake fluid, could be used, but the water-oil solution is inexpensive and satisfactory.

The detachable handle is calibrated in divisions of 0.001 cu. ft., and readings

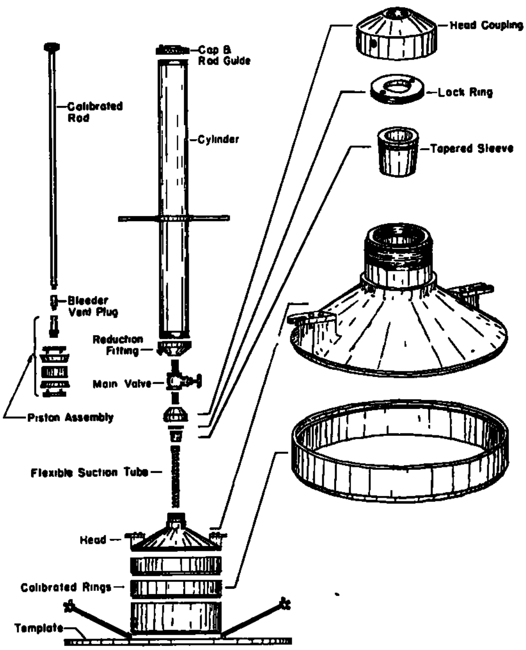


Figure A. Schematic assembly sketch.

accurate to 0.0002 cu. ft. are made by interpolation between divisions. With the handle removed, the Densometer will fit easily into the back seat or trunk of a car. The carrying base is clamped to the head to protect the balloon during transportation, and also serves as a stand for the

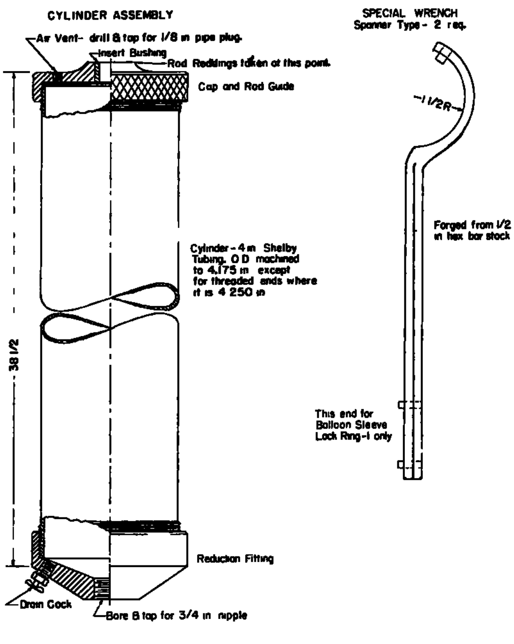


Figure B.

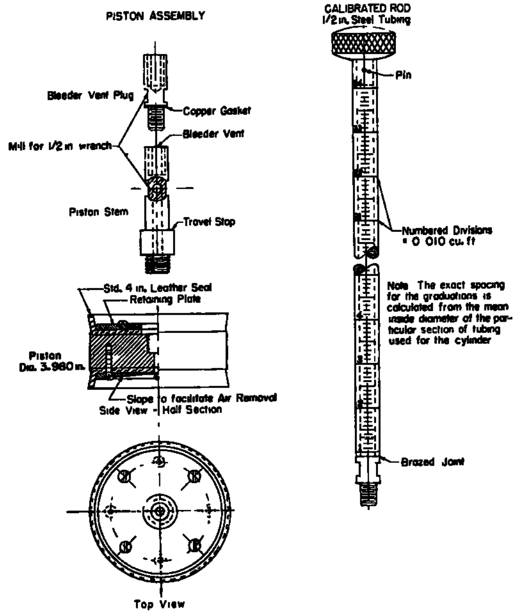


Figure C.

apparatus between readings during operation (see Fig. 2).

The calibrated rings are machined as closely as possible to volumes of 0.0500 cu. ft., and 0.1000 cu. ft., the actual volumes, both singly and in various combinations, being established by careful check with water or other precise methods. Once calibrated, these volumes are established as constants for the apparatus and so marked on the respective rings. Change of the ring volumes due to normal tempera-

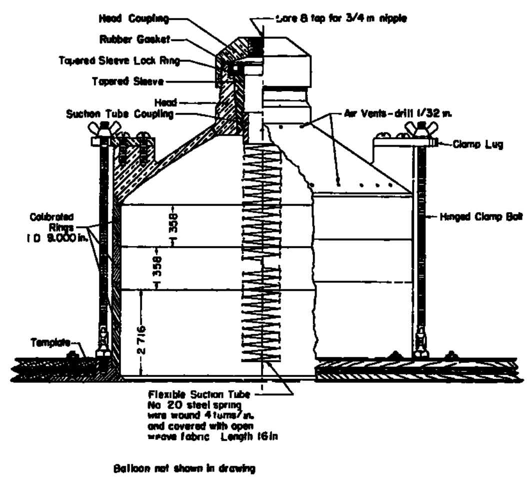


Figure D. Head assembly, side view of half section.

ture fluctuations are not of sufficient magnitude to introduce appreciable error in final results. However, if the apparatus is to be used in areas where extreme temperature changes are common, it would be good practice to establish a volume-temperature calibration curve for the device. It has been established that temperature fluctuations of less than 30 F. have no noticeable effect on final results. Further investigative work of temperature fluctuations is contemplated.

OPERATING PROCEDURE

A. Assembly and filling with fluid. (Necessary occasionally when balloon is replaced).

1. Remove head from cylinder at joint below main valve and remove tapered balloon sleeve and flexible suction tube (Fig. 4).

2. Slip neck of balloon over tube and tapered balloon sleeve until flare of balloon neck is flush with bottom of tapered sleeve.

3. Trim off neck of balloon at or slightly below groove near top of balloon sleeve. Lower deflated balloon through opening in head until the tapered sleeve is firmly seated.

4. With head clamped to carrying base, place tapered sleeve lock ring in position and tighten, forcing tapered sleeve into final seated position.

5. Place head gasket in head coupling and connect the upper cylinder to the head.

6. With densometer clamped to carrying base, and piston removed, open main valve and fill with fluid until about 6 inches of fluid raises in cylinder. Rock gently to facilitate passage of air bubbles from balloon and head upward into cylinder.

7. Insert piston, bleeder vent open, and push down until fluid raises in vent hole. Close piston bleeder vent with calibrated rod and raise piston, sucking fluid from balloon into cylinder. Leaving approximately 1,500 cc. of fluid in balloon, close main valve.

8. Remove piston. (If piston is too low in cylinder to allow removal by opening piston vent, open drain valve at bottom of cylinder while pulling up piston). Adjust fluid level to within about 3 inches of top and replace piston. Cover top of piston with enough fluid to cover the leather seals, install bleeder vent plug and cylinder cap.

9. Inflate balloon in carrying case several times by opening main valve and operating the piston to insure removal of all air from balloon. After last run, close main valve and exert a strong upward pull on piston to de-air the fluid in the cylinder.

10. Remove bleeder vent plug and press piston down until fluid raises to top of vent. Replace plug. The apparatus is now de-aired and ready for use. (This step should be repeated whenever Densometer has not been in use for some time).

Although the above assembly operation appears quite involved, it is quite simple in practice, and can be completed in approximately 10 minutes.

B. Field Density Determination:

1. After selecting site, smooth ground sufficiently so that template sets solidly. Do not attempt to level surface that will lie within center area of template. Place rings on template.

2. Place Densometer on template and rings, and clamp in position (Fig. 3). With two men standing on template for rigidity, open main valve and apply gentle pressure to calibrated rod. Sufficient pressure should be used to cause piston to lower at a constant, medium rate. When the balloon fills the rings and head, a definite shock will be felt. Maintaining slight pressure on handle, note reading on rod at top of cylinder cap. Repeat three times by lifting and depressing piston about 10 inches to ascertain that no air is trapped and apparatus is functioning properly. This will be shown by the consistency of the readings. (No trouble has been experienced from this source to date). Record reading as "Initial Reading". Note: One man can operate Densometer if heavy bag of dirt is used to balance load on template.

3. Evacuate fluid from balloon by lifting piston, close main valve, remove Densometer, and set on carrying base.

4. Remove calibrated rings from template, and, being careful not to move template, dig hole as for other methods. Save all material in a sealed can to avoid loss of moisture. The excavated hole should be as smooth as possible, avoiding small radius holes or extreme undercutting of the template.

5. Upon completion of hole, leave out whatever number of calibrated rings are estimated to most nearly equal the

volume of the hole, and clamp Densometer to template. (Care should be taken to lower balloon into hole in such a position that it will not be twisted when the Densometer is seated.) Repeat Step 2, and record reading as "Final Reading". Repeat Step 3.

6. Add volumes of rings left out in Step 5, and record as "Ring Constant". Determine volume of hole by following formula:

(Final reading + Ring Constant) - Initial Reading = Vol. of hole in cu. ft.

7. Weigh wet soil taken from hole and calculate wet density:

$$\frac{\text{Wt. wet soil (lb.)}}{\text{Vol. of hole (cu. ft.)}} = \text{Wet density (lb./cu. ft.)}$$

8. Determine moisture content by accepted means and calculate dry density.

C. Determination of volume of holes larger than 0.230 cu. ft.

For such holes, it is necessary to recharge the piston to furnish sufficient fluid to fill the hole. The following procedure may be used:

1. See B-1 above.
2. See B-2 above.
3. See B-3 above.
4. See B-4 above.
5. Upon completion of hole, leave out all of the rings and clamp Densometer to template. Open main valve and allow fluid in cylinder to pass into balloon until piston is just short of extreme lower position. Close main valve and record reading as F.R. No. 1.
6. Open drain valve to allow air into cylinder, and raise piston to extreme top position. Close drain valve, remove handle, bleeder vent plug, and cylinder cap, and remove piston from cylinder.
7. Fill cylinder with additional fluid, replace piston, de-air and reassemble cap, plug and handle. Record reading as I.R. No. 2.
8. Open main valve and complete filling of holes as in step B-2 above. Record final reading as F.R. No. 2.
9. Fluid is evacuated as in step B-3 above, except that excess fluid is eliminated through the drain valve into a container.
10. Calculate hole volume as follows: (See Fig. 5).

(F.R. No. 1 - I.R. No. 1) + (F.R. No. 2 - I.R. No. 2) + 0.2000 = Vol. in cu. ft.

Note: Minor modification of the apparatus to include a filling tube connected to the bottom of the cylinder and rising along the side will permit recharging the cylinder without removing the piston. Details of this modification are now being worked out and will be published as an addendum to this report when completely tested.

Appendix B

RESULTS OF EXPERIMENTS

1. Check for consistency of readings.

Initial readings taken with all three rings in place. Final reading taken after removal of specified ring. All readings taken at same position on smooth, flat concrete slab.

Note: Volumes indicated are slightly smaller than true volume of ring removed because balloon is not inflated to same degree for both readings.

Series No. 1 (Ring No. 1 removed for final reading)

I.R.	0.1862	0.1860	0.1862	0.1861
F.R.	0.1366	0.1364	0.1365	0.1365
Vol.	0.0496	0.0496	0.0497	0.0496 cu. ft.

Bled air before start of second series.

Series No. 2 (Ring No. 2 removed for final reading)

I.R.	0.1970	0.1969	0.1969	0.1970
F.R.	0.1475	0.1475	0.1474	0.1474
Vol.	0.0495	0.0494	0.0495	0.0496 cu. ft.

Series No. 3 (After setting in sun 1 hr., temp. 86 F.; Ring No. 2 removed for final reading)

I.R.	0.1954	0.1953	0.1953	0.1953
F.R.	0.1458	0.1458	0.1458	0.1458
Vol.	0.0496	0.0495	0.0495	0.0495 cu. ft.

Bled air before start of series 4.

Series No. 4 (Ring No. 3 removed for final reading)

I. R.	0. 2233	0. 2233	0. 2233	0. 2233
F. R.	0. 1238	0. 1238	0. 1238	0. 1238
Vol.	0. 0995	0. 0995	0. 0995	0. 0995 cu. ft.

Series No. 5 (Rings No. 1 and 2 removed for final reading)

I. R.	0. 2244	0. 2244	0. 2244	0. 2244
F. R.	0. 1254	0. 1254	0. 1254	0. 1254
Vol.	0. 0990	0. 0990	0. 0990	0. 0990 cu. ft.

CONCLUSION: Apparatus exhibits a very definite stopping point which will repeat itself consistently. Variations of 0. 0002 cu. ft. are possible in making individual readings due to human variations in interpolating the scale. When initially filled with water, air should be bled frequently, as a small amount of air will separate each time fluid is pulled into piston. This effect becomes practically negligible after several runs. Normal temperature changes do not appreciably affect the accuracy of the apparatus.

2. Calibration of rings: Rings were calibrated by a careful, exact water-volume method. One ring was sealed to a rubber base, leveled, and filled with water, using a glass plate to establish when full. The other rings were then added, the joints being sealed with tape, and their volumes determined successively, the procedure was then reversed to establish the volume of the bottom ring. Three checks were made, and temperature corrections were included. The following volumes were determined:

Ring No. 1 = 0. 0498 cu. ft.
Ring No. 2 = 0. 0500 cu. ft.
Ring No. 3 = 0. 0998 cu. ft.

By volume of rings in pairs, it was established that each joint increased the volume 0. 0002 cu. ft., and:

Rings No. 1 and 2 = 0. 1000 cu. ft.
Rings No. 2 and 3 = 0. 1500 cu. ft.
Rings No. 1 and 3 = 0. 1498 cu. ft.
Rings No. 1, 2, and 3 = 0. 2000 cu. ft.

For practical purposes, the constants used were established as 0. 0500 cu. ft. for each small ring, and 0. 1000 cu. ft. for the large ring.

3. Check of Known Volume: A cylindrical metal container with a rounded bottom joint was used, and its volume determined by the water method. Initial readings were taken on a smooth, flat concrete surface with the densometer, and then the template was set on the container, rings No. 2 and 3 removed, and the final reading made after filling the container. Cylinder was bled between each trial to give different set of readings. Established volume of container = 0. 1675 cu. ft.

	Trial 1	Trial 2	Trial 3
F. R.	0. 2127	0. 2175	0. 2230
Ring Constant	0. 1500	0. 1500	0. 1500
Sum	0. 3627	0. 3675	0. 3730
I. R.	0. 1952	0. 2001	. 2055
Vol.	0. 1675	0. 1674	0. 1675

CONCLUSION: The device will accurately determine the volume of a hole. Operators were changed for each of the above trials, and part of the fluid was bled out of the cylinder to avoid repetition of readings. The trials show that excellent results are obtainable independent of the operators.

4. Comparison to sand cone method (California large sand-volume apparatus) in actual field conditions: In these tests, it was found imperative to use extreme care in making the sand cone determinations to get consistent results. The cone was calibrated by the water method, and the sand was calibrated frequently during the tests. To eliminate error due to uneven ground surface, initial readings were made, using a template and a thin rubber membrane (dental dam) so the sand could be recovered and weights were determined accurately to 0. 01 lb. Parallel determinations were made on the same hole with the sand cone and the Densometer. The following results are typical of this series of tests:

Vol. (Sand Cone)			
1	2	3	4
0. 0906	0. 1120	0. 0878	0. 1057 cu. ft.
Vol. (Densometer)			
1	2	3	4
0. 0907	0. 1124	0. 0880	0. 1058 cu. ft.

Note: The Densometer consistently gave slightly large hole volumes for the same hole, and the difference increased as the roughness of the hole surface increases. This indicates that the Densometer fills the small pits and irregularities more completely than does the sand.

Occasionally it was not possible to avoid

having construction equipment working nearby. On these occasions, the volume determined by the sand cone was consistently larger than that determined by the Densometer. The degree of error caused by vibration of the sand is indicated by the following typical results:

	1	2	3	
Vol. (Sand Cone)	0.1192	0.1289	0.1692	cu. ft.
Vol. (Densometer)	0.1180	0.1277	0.1674	cu. ft.
Error	0.0012	0.0012	0.0018	cu. ft.

5. Time trials: Actual operation of the Densometer including set-up time, but excluding hole digging time is about 3 minutes. Under actual field conditions, where it was necessary to clean up the hole and re-fill with compacted soil, approximately two complete determinations could be made with the Densometer while making one with sand-volume apparatus.

Including average hole digging time, wet density determinations require from 10 minutes to 15 minutes under actual field conditions. The density of 2-inch to 4-inch layers of crushed stone surfacing was determined on several projects during construction. The alcohol-burning method was used to determine the moisture content, and it was possible for a two-man crew to make as many as 30 complete dry density determinations in an 8-hour day. Three tests were made at each location, and moves of about 1,000 feet were made between locations.

On one project, density determinations were made in an eight-inch lift of clean crushed gravel base course material. One man working alone was able to complete six dry density determinations in three hours.

6. Measuring Large Holes: Two holes were dug 17 inches and 18 inches in depth respectively. The volume of each was checked with the Densometer and by the sand-volume method using the large California sand-volume apparatus. Careful calibration of the sand apparatus was made for each determination. Initial readings were taken with both types of equipment.

	Hole #1 (17" deep)	Hole #2 (18" deep)
Densometer	0.4853 cu. ft.	0.5081 cu. ft.
Sand Cone	0.4830 cu. ft.	0.5060 cu. ft.
Difference	0.0023 cu. ft.	0.0021 cu. ft.

Results show good agreement and difference would affect a normal density less than 1 lb./cu. ft. The slightly larger volume shown by the Densometer indicates more complete filling of the voids.

Discussion

ALFRED W. MANER, Highway Research Engineer, Virginia Council of Highway Investigation and Research — The authors are to be congratulated for developing a piece of equipment that permits rapid and accurate determination of field densities. With the Washington Densometer they seem to have overcome to a great extent the deficiencies of the more-common methods of measuring field densities.

Of prime importance is the reduction of time for operation. Undoubtedly we shall someday have equipment that will measure moisture and density in a very few minutes without disturbing the soil or other material, but to have a device now that is fast enough to permit control during the rolling operation is a big step forward.

It is particularly interesting to learn that the volume of relatively large holes can be determined with the Washington Densometer. During the past year we had occasion, in Virginia, to determine the relative densities of two sections of waterbound macadam compacted by two different methods. Taking a cue from North Carolina we used a heavy, 15-inch-diameter ring as a guide in digging the hole, a 100-lb. bag of Ottawa sand for measuring the volume, large buckets and platform scales for weighing, in addition to other necessary equipment. We would have welcomed a device like the densometer at that time.

In using the densometer for determining the density of different layers in the same hole, it seems that extreme care must be exercised in order not to change the volume of the hole in the upper layers when digging in the lower layers. It would be easy to change the volume of the hole after the determination has been made and thus give erroneous results in succeeding layers.