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IN SITU FIELD TESTING OF MECHANICAL PROPERTIES

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Abstract

The ability to measure the mechanical properties of materials through in situ field testing is being investigated. Three portable devices are being used at road construction sites in Minnesota to determine which devices could be best implemented into the design and construction process of roads. The three devices are the Loadman portable falling weight deflectometer (PFWD), Humboldt GeoGauge, and the dynamic cone penetrometer (DCP). Using these devices a material's stiffness can be estimated and compared to other methods such as the falling weight deflectometer (FWD) and compaction tests. It has been found that each device gives similar results and has promise, but that there needs to be some modification to the devices and the existing empirical correlation equations.

Introduction

Over the past two years, the Minnesota Department of Transportation (Mn/DOT) has been experimenting with several devices used for in situ field testing of aggregate bases and subgrade soils to determine their mechanical properties. In order to implement mechanistic-empirical pavement design, material properties like strength, stiffness, and their uniformity are needed. Traditionally, engineering knowledge and expertise supplemented by soil classifications and index tests have been used to determine the quality of a material during design and construction. Mechanistic properties allow geotechnical performance to be estimated during design and then measured during the construction process. The current use of density tests and qualitative observations need to be enhanced by the use of more sophisticated yet practical in situ field testing equipment.

The ability of three devices to measure mechanistic properties is being studied. These devices are the Loadman portable falling weight deflectometer (PFWD), Humboldt GeoGauge, and the dynamic cone penetrometer (DCP). This equipment is being tested and compared to current methods, which include the falling weight deflectometer (FWD), sandcone density, and the nuclear density gauge. All of these tests require training and need to be executed with precision. Any mishaps could result in an inaccurate measurement and require a retest. The nuclear density gauge also requires a license to

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operate. Values of density from sandcone and nuclear gauge are compared to the standard Proctor density to determine levels of compaction. Using the PFWD, GeoGauge, and DCP values of an elastic deformation modulus are estimated and these moduli values can be compared to the values used for design.

Road construction sites throughout Minnesota were visited and tests performed during 1998 and 1999. The road construction that took place at MnROAD in 1999 will be the focus of this paper. At each project, tests were performed at numerous locations with each device. The results were then used to estimate an elastic modulus so that the devices could be more easily compared to each other. Many issues are being investigated in this study with the goal of selecting a device that will be used to aid in the design and construction of roads throughout Minnesota.

Test Equipment

A more detailed description of each device and the associated procedures can be found in (Al-Engineering 1997, Humboldt 1998, Siekmeier et al.1999, Tayabji 2000). Pictures of all three devices can be seen in Figures 1 and 2.

The GeoGauge is a portable device that applies small stresses and calculates the in situ stiffness of the material from the measured force and deflection. The deflection results from small forces that occur due to vibration of the device. Sensors are used to measure the deflections and forces applied. The GeoGauge is able to eliminate false values caused by vibration from outside disturbances such as vehicle traffic.

The PFWD is a device that measures the deflection resulting from a falling weight and estimates an in situ modulus. The device has a mass that is dropped from a known height and uses an accelerometer to determine the deflection. Besides the deflection, the bearing capacity modulus, time of loading impulse, and an approximate rebound deflection are also displayed on a screen on top of the PFWD.

The DCP, which has been used in by Mn/DOT for several years, measures in situ shear strength, which is used to estimate the modulus using existing correlations from (Webster 1992 and 1994) and (Powell 1984). The DCP consists of a weight that is dropped from a set height and drives a steel rod with a cone attached at the bottom into the ground. A penetration index with units of (mm/blow) is recorded.

The FWD is a Dynatest model 8000 that is trailer mounted and pulled by a van. It is a non-destructive testing (NDT) device that has become a standard for MnDOT and others around the world. This impulse loading device is capable of producing wide ranges of loads. Geophones located at specified distances from the load plate measure velocities caused by the falling weight. These velocities form a deflection basin, which is used to determine an elastic modulus for the material.

Site Locations

The road construction sites were selected based on their location, material type, and availability. A 100-mile radius from the home office was set as a limiting distance to prevent long drive times to perform minimal amounts of testing. The type of material was not as important as the thickness in some cases. A minimum of 6-in was set for aggregate bases to allow for certain analyses to be performed at various depths. Finally, there were only certain days that tests could be performed and the construction schedules only allowed for small time periods where testing would be allowed. Testing was typically performed in both wheel-paths at two areas approximately 100-ft apart. This made it possible to analyze both the longitudinal and transverse differences and similarities across the grade.

Test Procedures

General procedures were developed for testing, but were often altered to accommodate the testing area or time frame. Below are the typical methods and order of testing. In general the least destructive tests were completed first.

The GeoGauge test was performed four times at each designated station. When placing the GeoGauge it was necessary to make sure the device was in complete contact with the surface. To seat the device properly, it was pushed down lightly and rotated back and forth about 90-degrees in each direction. One test was run and the results recorded. Then the device was lifted off the surface and reseated for the second test. After the second test the GeoGauge was set aside and the PFWD was used. After running the PFWD, the GeoGauge was performed again to determine whether the PFWD had changed the results in any way.

As stated above, the PFWD was performed in between two sets of GeoGauge tests. A total of five PFWD tests were performed at each location. All values are recorded however the first two tests are used as seating drops and are not used in the calculations. The last three are averaged to determine the modulus. When testing with the device it is important to make sure that the device is plumb so that that the weight falls freely. While gripping the top of the PFWD, the drop button was pressed quickly to release the weight.

The DCP requires two people when the penetration for each drop is needed. An operator to run the test and a recorder. The operator places the device in the same location as the PFWD and GeoGauge and taps the rod down so that the cone has penetrated the surface. The recorder then takes down the initial reading. The weight is dropped from the full drop height and the penetration recorded. This is done until a minimum of 6-in (150-mm) depth is reached. The recorder calls out the depth after each drop so the operator knows when to stop.

The FWD testing depended on the area tested and the procedure had to be altered at each location. Generally, the FWD was used at each location, but not each wheel path.

FWD tests were performed prior to the location of the other tests, in between the two sections, and after the other testing. This allowed for greater analysis of the grade longitudinally to determine uniformity.

MnROAD Testing

For the purpose of this paper the results from the testing that occurred during the 1999 reconstruction at the MnROAD research facility are used. The reconstruction took place during August and September of 1999. Five test sections, 27, 28, 33, 34 and 35, all located on the low volume roadway were reconstructed. Each test section's pavement surface and granular base were removed leaving the subgrade in place. Testing was performed on the subgrade for the five test sections and then on the Cl 6 Sp aggregate base for test sections 33 – 35 when it was placed and compacted.

The outer wheel paths in both lanes were tested. Each test section has a set of ten FWD stations that are located 50-ft apart and are tested routinely throughout their life. The PFWD, GeoGauge, and DCP tests were conducted in an alternating pattern. The reason for testing in this manner was to save on time and to get test results both longitudinally and transversely across the grade. For example, in test section 33, the outside lane (offset –9.5-ft) FWD stations 1.5, 3, 5, 7, and 9 were tested and on the inside lane (offset 9.5-ft) stations 2, 6, and 10 were tested. This method of testing was used for each test section. Any changes to this method were due to the station being inaccessible due to the installation of sensors nearby. A diagram of a typical test section can be seen in Figure 3.

The results from the subgrade tests on test sections 33 – 35 are included here and discussed in detail. These three test sections give an adequate amount of results and also had the greatest variety of tests performed on them. The other tests performed include nuclear density, sandcone density, standard Proctor, plastic and liquid limits, grain size distribution, R-value, and laboratory resilient modulus. It is hoped that these additional tests will allow existing empirical correlations to be verified or new correlations to be developed.

A set procedure was developed for the MnROAD site in order to normalize the data collection process. The following is a list of tests and how the tests are performed.

1. Falling Weight Deflectometer (FWD): tests run at each FWD station
2. GeoGauge: 2 tests at designated stations
3. Loadman (PFWD): 5 tests at designated stations
4. GeoGauge: 2 tests at designated stations
5. Dynamic Cone Penetrometer (DCP): 1 test to > 6-in (150-mm) depth

After the FWD, GeoGauge, PFWD and DCP tests were completed, sandcone density, nuclear density, and samples were collected at select locations in each test section. One standard Proctor was performed for each test section. The sandcone density tests were performed in general accordance with ASTM D1556-90 Standard Test Method for

Density and Unit Weight of Soil in Place by the Sandcone Method. The Nuclear tests are performed according to ASTM D2922-96 Standard Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth). The equations to estimate elastic modulus for each device are taken from (Siekmeier et al. 1999).

Results and Discussion

The subgrade from the test sections is classified as a sandy lean clay according to the Unified Soil Classification System using the gradation, liquid limit, and plastic limit obtained from the laboratory tests. The table below shows the results from tests sections 33, 34 and 35.

Table 1: Soil Classification for Test Section 33, 34, and 35

Grain Size Distribution	Test Section		
	33	34	35
	% passing	% passing	% passing
1 1/2	100	100	100
1	100	100	100
3/4	100	100	100
3/8	100	100	100
#4	100	100	100
#10	96	97	95
#20	na	na	na
#40	85	89	85
#100	63	66	63
#200	52	56	52.5
Liquid Limit	27	34	29
Plastic Limit	17	19	18
ASTM	CL	CL	CL
Proctor Density (lb/ft^3)	111.4	109.9	117.3
Opt. Moisture (%)	15.7	16.8	13.0

The gradation, plastic limit, and liquid limit are very similar for the three test sections with test section 34 having slightly more pass the #200 sieve and having a higher liquid limit. Therefore the three sections were expected to have very uniform Proctor results, however test section 35 has a slightly higher Proctor density and a lower optimum moisture. This has an affect on the compaction levels.

Nuclear density is plotted versus sandcone density in Figure 4. A relationship between the two can be seen here. The sandcone density tests are time consuming and only performed once for each test section. The nuclear gauge was performed at each location where the other devices were tested. Therefore, the density measurements from the nuclear gauge will be used for analysis.

Similarly, the moisture results from the nuclear gauge and the sandcone are plotted in Figure 5. A relationship is evident here between the two results. The moisture from the nuclear gauge is used for analysis.

Using the results from the nuclear gauge, the density is plotted versus stationing throughout test sections 33 – 35 in Figure 6. The density varies between 120 and 125-lbs/ft^3 throughout the sections. This shows that it is not perfectly uniform and in distances of only 100-ft, density can vary somewhat, but it is minimal.

The nuclear moisture is also plotted versus stationing to show the variation throughout the test sections in Figure 7. The moisture contents range from 10 – 12-%.

In Figure 8, the Proctor density is plotted versus test section. The Proctor is used to determine the compaction levels so it is important to determine how it compares to the nuclear density throughout the test sections. A Proctor was performed at only one station per test section. Proctor densities from test section 33 and 34 are similar about 111 and 110-lbs/ft^3 respectively. The Proctor from test section 35 is different with a density of 117-lbs/ft^3. This is a 6 – 7-lb difference or about 5-%. This is going to be substantial when determining the compaction levels. The result is lower levels of compaction for test section 35.

Proctor optimum moisture is plotted versus test section in Figure 9. Similar to before, test section 35 is different. Test section 35 has a lower optimum moisture than 33 and 34 by about 3-%.

The compaction, which is the nuclear density divided by the Proctor, is used when determining if a material is ready to be paved. The compaction is plotted versus stationing in Figure 10. As stated above the compaction in test section 35 is about 7-% less than in 33 and 34. Even though the material is expected to be uniform throughout, it is not. The variability in Proctor test results also needs to be considered.

The compaction versus the moisture is plotted and a range in moisture from 9 – 12-% can be seen Figure 11. This is lower than the optimum moisture of about 16-% that compaction should be performed at. The tests were performed when moisture contents were lower because of the inability to get on the material earlier due to problems getting the material toleranced to the appropriate grade.

The modulus results from the DCP at 6-in, GeoGauge, PFWD, FWD and the compaction are plotted against stationing in Figure 12. An overall picture of how the devices and the compaction levels follow similar trends is evident here. It is here where the correlation can be made between the commonly used compaction criterion and the in situ mechanical properties. When the compaction level is high, the modulus values are higher. This relates the stiffness of a material to the compaction.

Figure 13 shows modulus results for the GeoGauge, Loadman, DCP and FWD versus the FWD modulus. The FWD modulus was used as a comparison device since it has been used the longest and is the recognized standard by many road authorities around the world. All three devices measure higher modulus than the FWD and a linear relation is used to show this. The Loadman has the strongest correlation and the least amount of variance as shown in the R-squared value. The Loadman is the only device that does not have an offset, so when the FWD measures low modulus so does the Loadman. The fact that it is twice as high needs to be examined further, but is likely due to the fact that the Loadman does not measure the load applied. Both the GeoGauge and DCP are initially offset by a value of 60. The GeoGauge is about a one-to-one ratio, but has the initial offset. This offset is most likely caused by a slight crust at the top layer of the subgrade that the device measuring. The DCP, similar to the GeoGauge, is about three times as high as the FWD and has the initial offset.

The relationships between modulus for the devices are shown in Figures 14. The modulus from the GeoGauge, PFWD, and DCP are plotted versus stationing. A trend can be seen in that when the modulus is higher for a location for one device it is higher for the other devices. Generally the PFWD and GeoGauge reasonably close. The DCP results are typically twice as high. A possible reason for this could be that the existing empirical equation gives too high of an estimate of modulus. Another common factor is the difference from the DCP at 3-in and at 6-in. The estimated modulus at 3-in is higher in every case. A reason for this is a crust that is formed on the top inch or two of the clay subgrade. This crust is harder and stiffer and requires more DCP blows to penetrate.

Conclusions

The moduli values from the GeoGauge, PFWD, and DCP are not identical since each device estimates modulus in different ways, however they do follow the same trend. It has been determined that each device has different levels of accuracy and precision, which are controlled by several factors. For example, placement is critical and can vary the results considerably and therefore standard procedures must be followed. Overall the results show reasonable agreement between the three devices in many cases. The stress dependency of some of the tested materials was apparent from the difference in modulus results and the stresses applied by each device. The PFWD and GeoGauge gave similar results throughout the study. However, the modulus that was estimated from the DCP was generally greater than the PFWD and the GeoGauge in fine-grain materials, but lower for unconfined granular materials. A solution would be to improve the correlation equation to give results that more closely resemble those of the FWD, PFWD, and GeoGauge.

The DCP is also beneficial in determining changes in material's strength at different depths. This is evident in the difference in DCP results at 3-in and at 6-in. A change in material, for example from base to subgrade, can be determined along with the depth. In general, the DCP allows the user to analyze a material with depth, and at greater depths than the PFWD and GeoGauge. The DCP is also relatively easy to operate and is inexpensive. Mn/DOT has nine additional DCPs, which are available for loan to public and private organizations in Minnesota. The loan program is intended to overcome the cost of manufacturing the DCP device, which is an obstacle that deters interested organizations from trying the DCP. It is anticipated that once an organization has had the opportunity to use the loaned DCP and become familiar with the device that they would be willing to purchase their own DCP for future use.

The PFWD needs to be modified so that the load applied can be measured. Currently only the deflection is measured and the load is estimated. The estimated load is used to determine the modulus. As seen in Figure 13 the modulus is twice as high as the FWD. The actual load could be twice as high the estimated load, which would result in too high of a modulus. If the load could be measured using a load cell, the modulus would be more accurately estimated, and would possibly fit with the FWD. Mn/DOT is presently looking into developing a PFWD that would measure load and result in a more accurate characterization of materials.

The GeoGauge seems to be sensitive to the top few inches of material. If the device would provide more of a force when measuring it could measure to deeper depths. This needs to be investigated more deeply.

The PFWD and GeoGauge show promise and are intended to measure to depths of about 6-in, but this depth is not certain. Also, it is not possible to determine if the material is uniform throughout the measured depth. The GeoGauge and PFWD produce relatively similar results for the tests presented here. Both the GeoGauge and the PFWD are easy to operate and do not require much training. However, more investigation needs to be done to determine their accuracy and how to correlate them to levels of compaction.

It is recommended that the transition to mechanistic design continue and for the GeoGauge, PFWD, DCP or a similar device be implemented into the design and construction process. First more research needs to be done to determine an appropriate device. Then a standard procedure for in situ mechanical testing needs to be developed to aid the designer so information like stiffness and uniformity may be better known. With this information, engineers will be able to utilize materials and equipment more efficiently to construct higher quality roads.

New Specification

The following minimum shear strength requirement for aggregate bases is now part of Minnesota's "Standard Specifications for Construction." "The full thickness of each layer of classes 5 or 6 shall be compacted to achieve a penetration index value less than or equal to 10-mm per blow." "...must be tested and approved within 24 hours of placement and final compaction. Beyond the 24 hour limit, the same aggregate can only be accepted by the Specified Density Method" (sandcone and standard Proctor).

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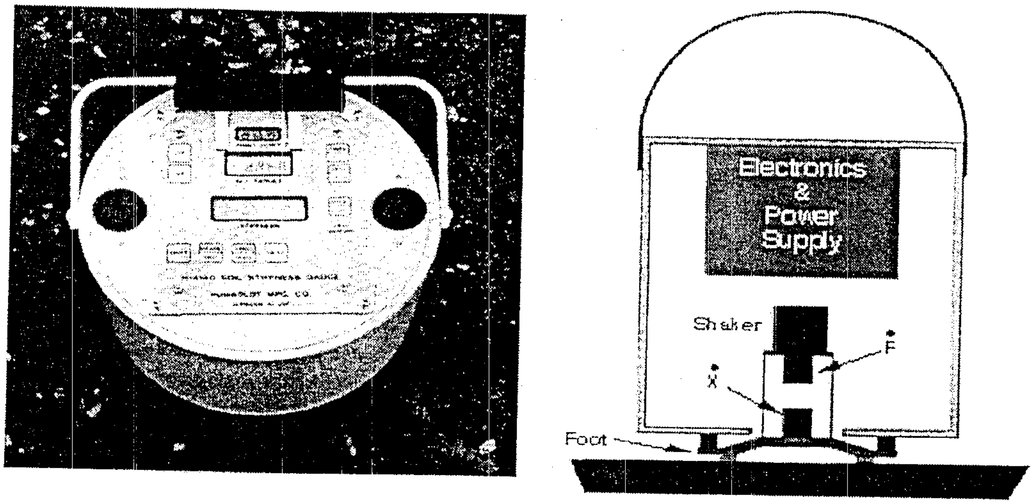

Figure 1: Humboldt GeoGauge

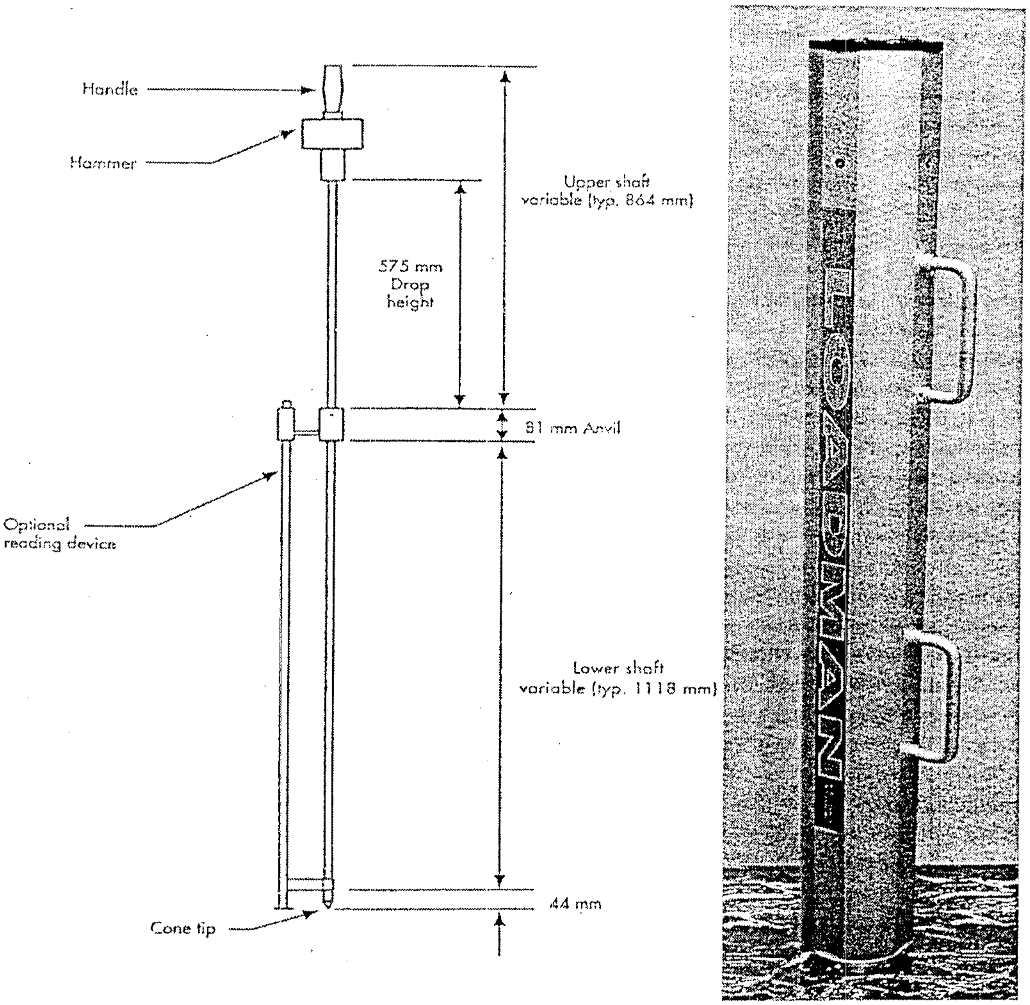

Figure 2: Dynamic Cone Penetrometer (DCP) and Loadman Portable Falling Weight Deflectometer (PFWD)

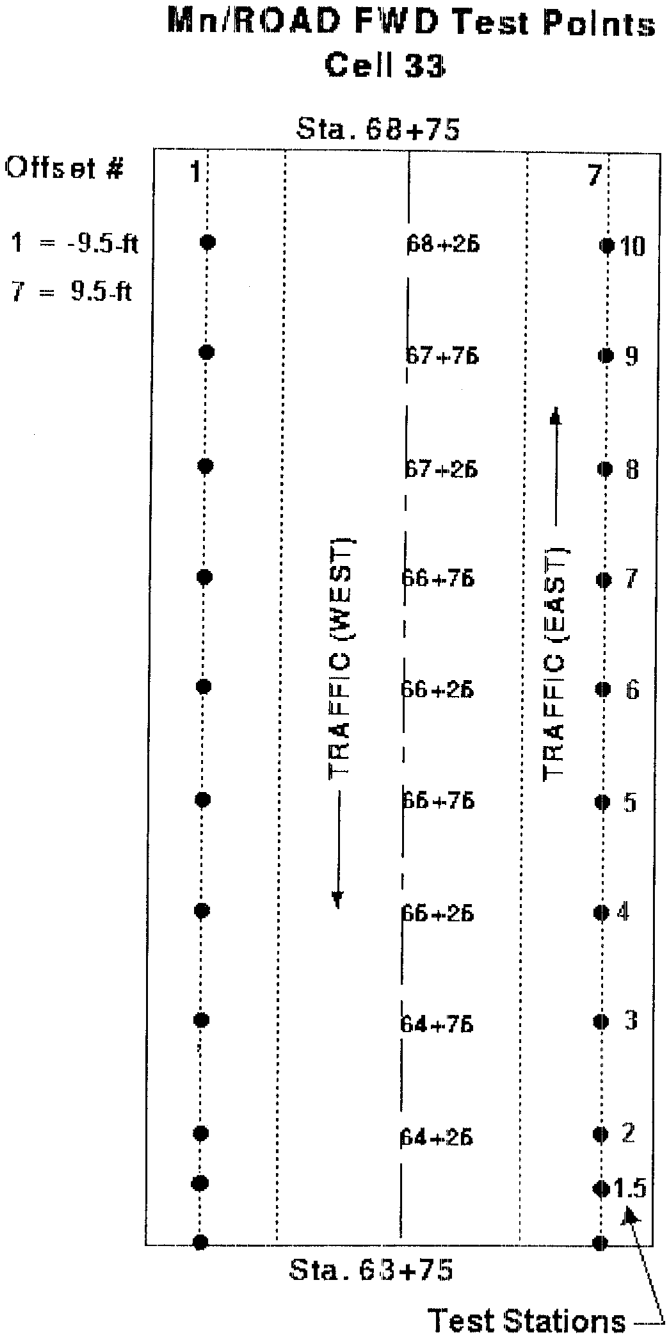

Figure 3: Test Section (Cell 33)

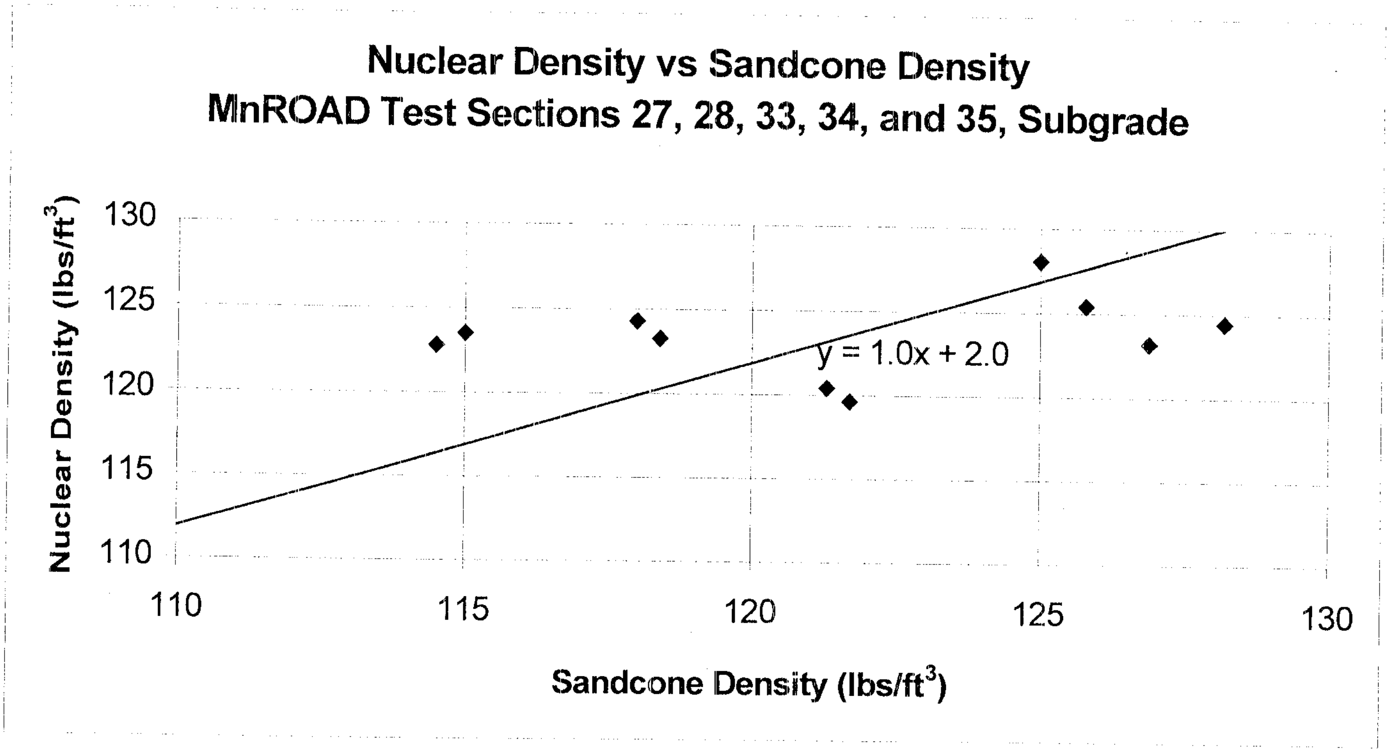

Figure 4: Nuclear Density versus Sandcone Density

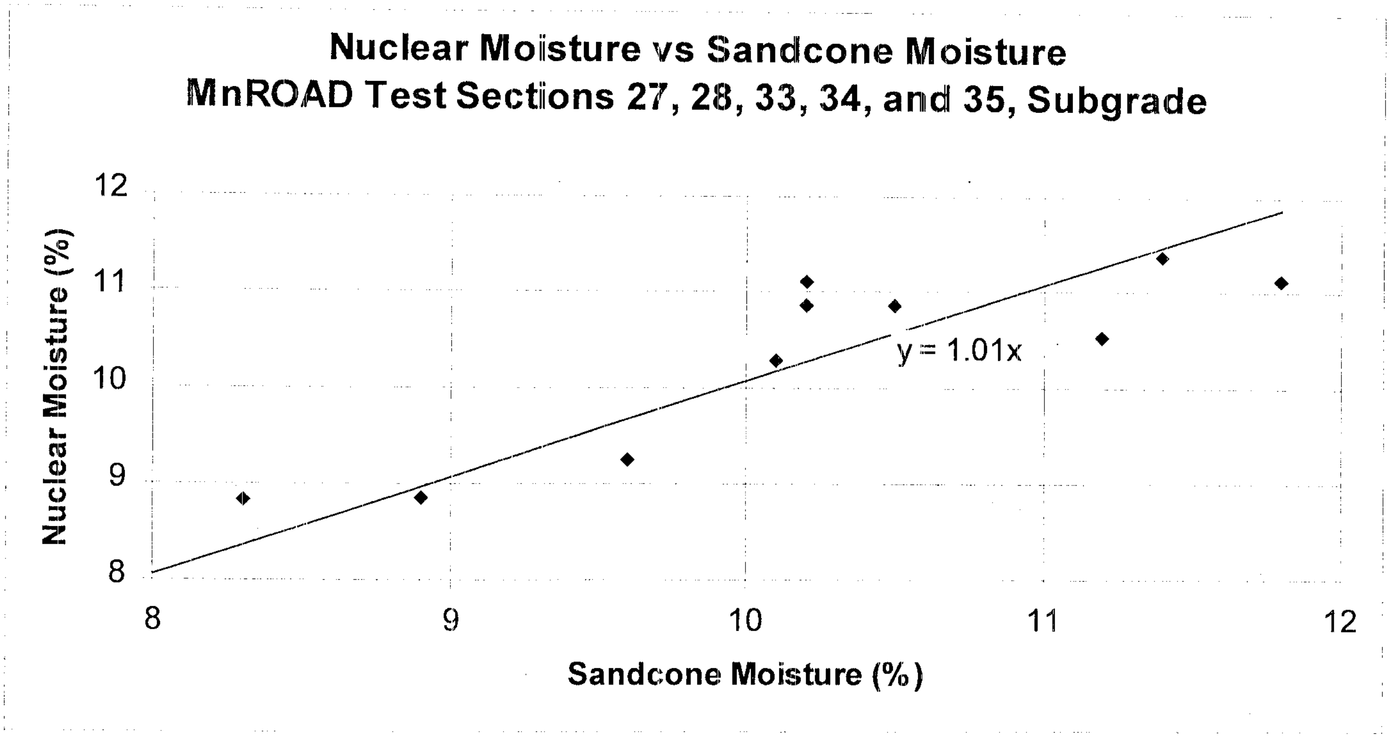

Figure 5: Nuclear Density versus Sandcone Moisture

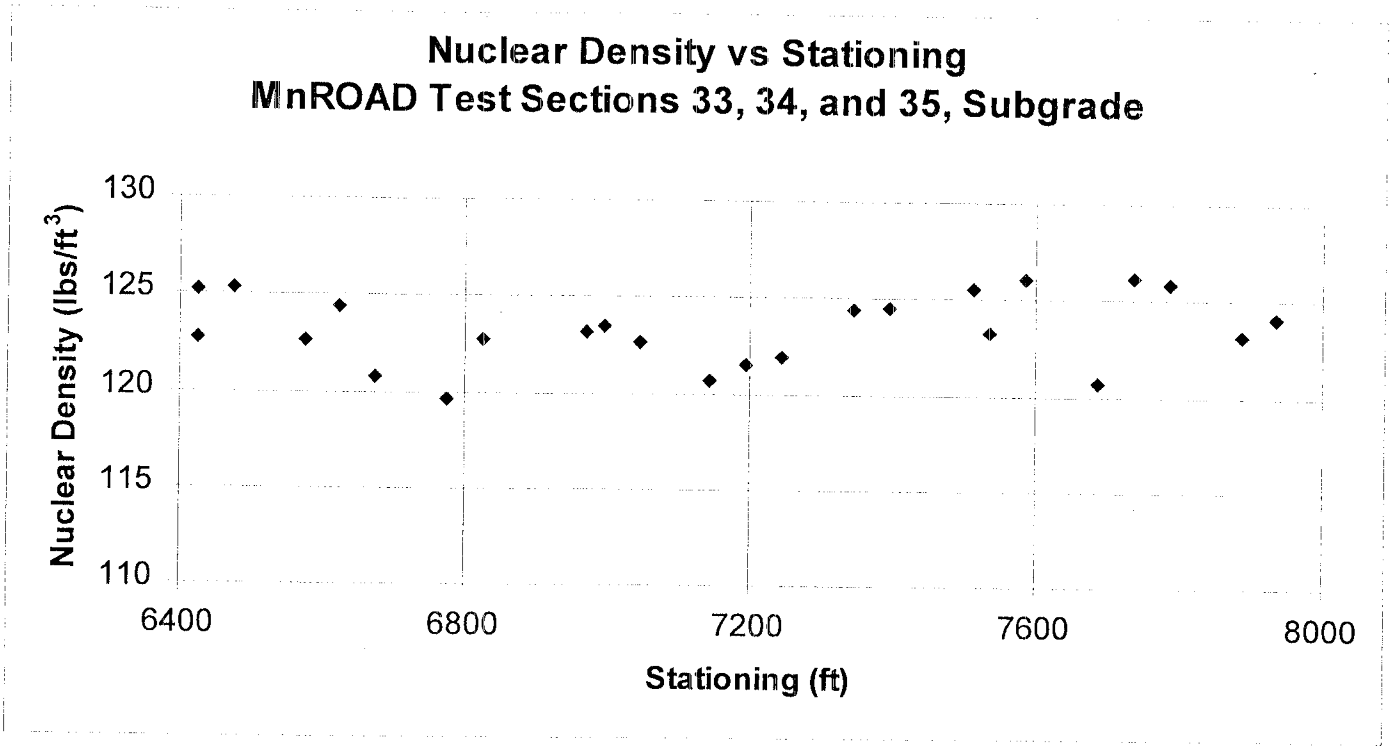

Figure 6: Nuclear Density versus Stationing

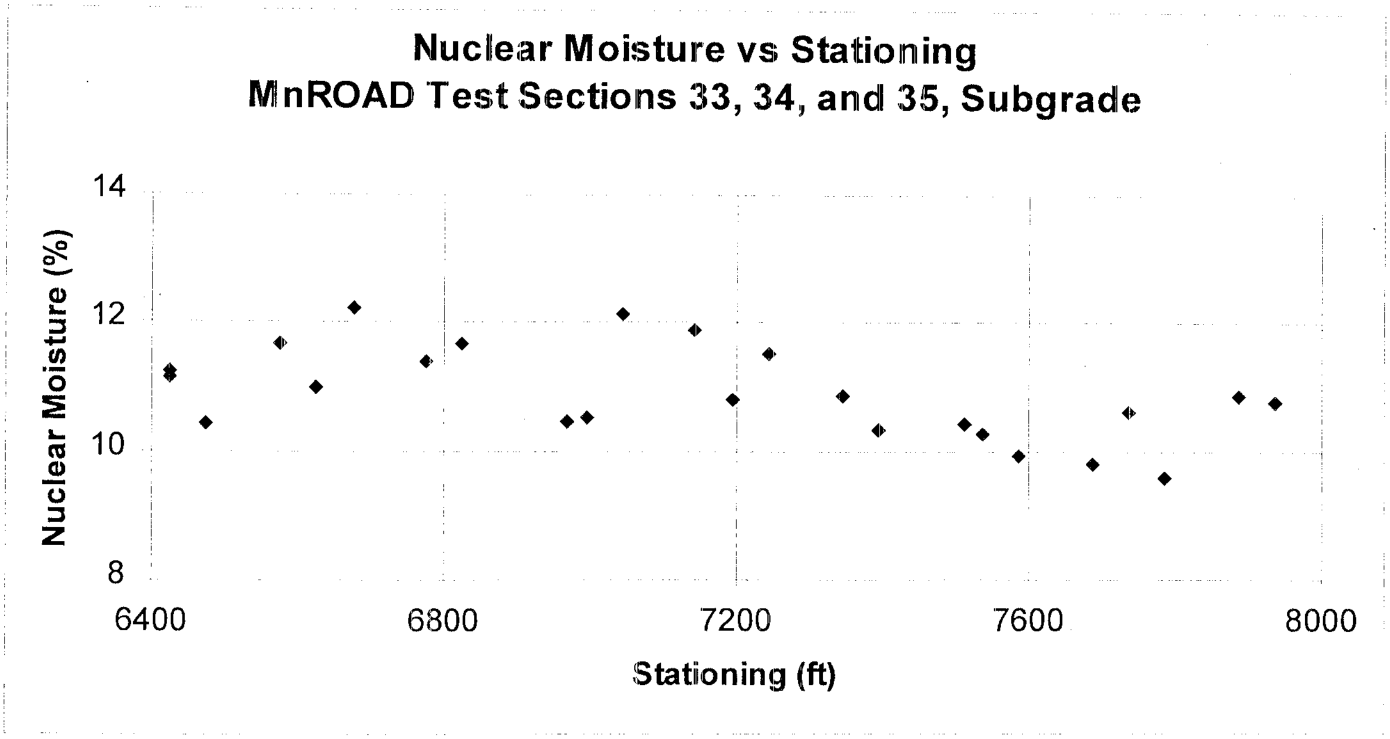

Figure 7: Nuclear Moisture versus Stationing

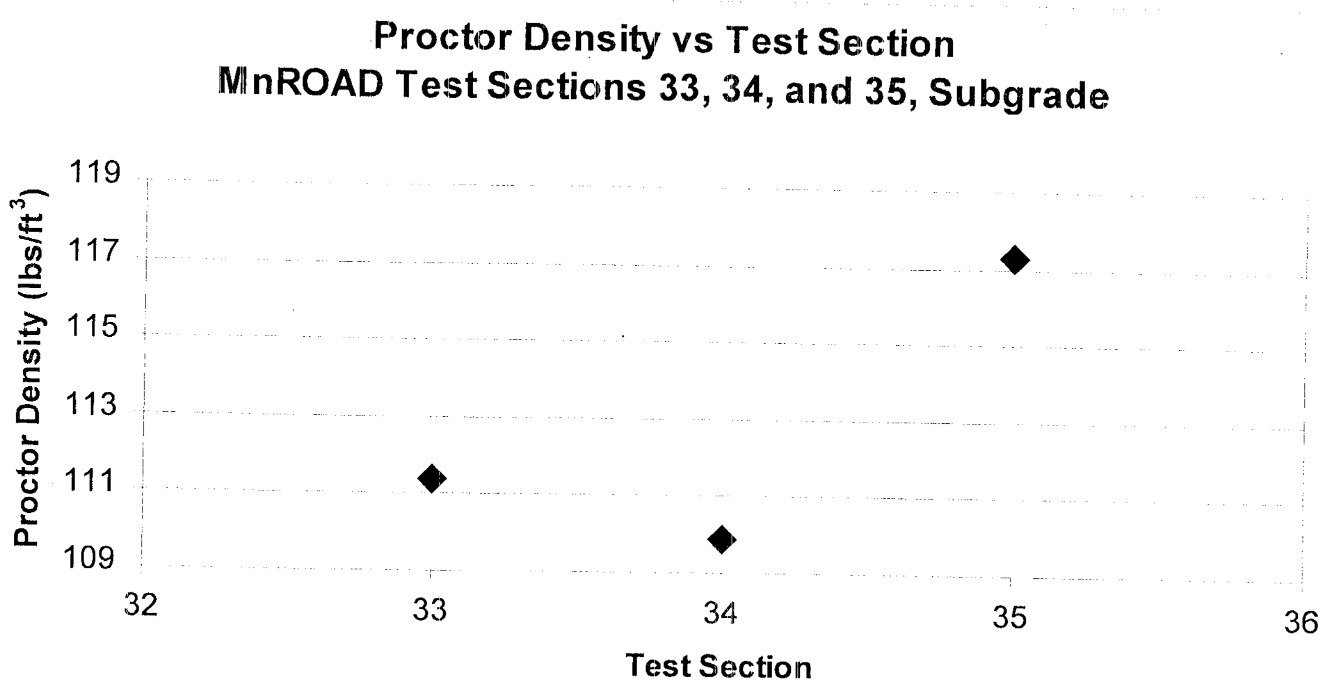

Figure 8: Proctor Density versus Test Section

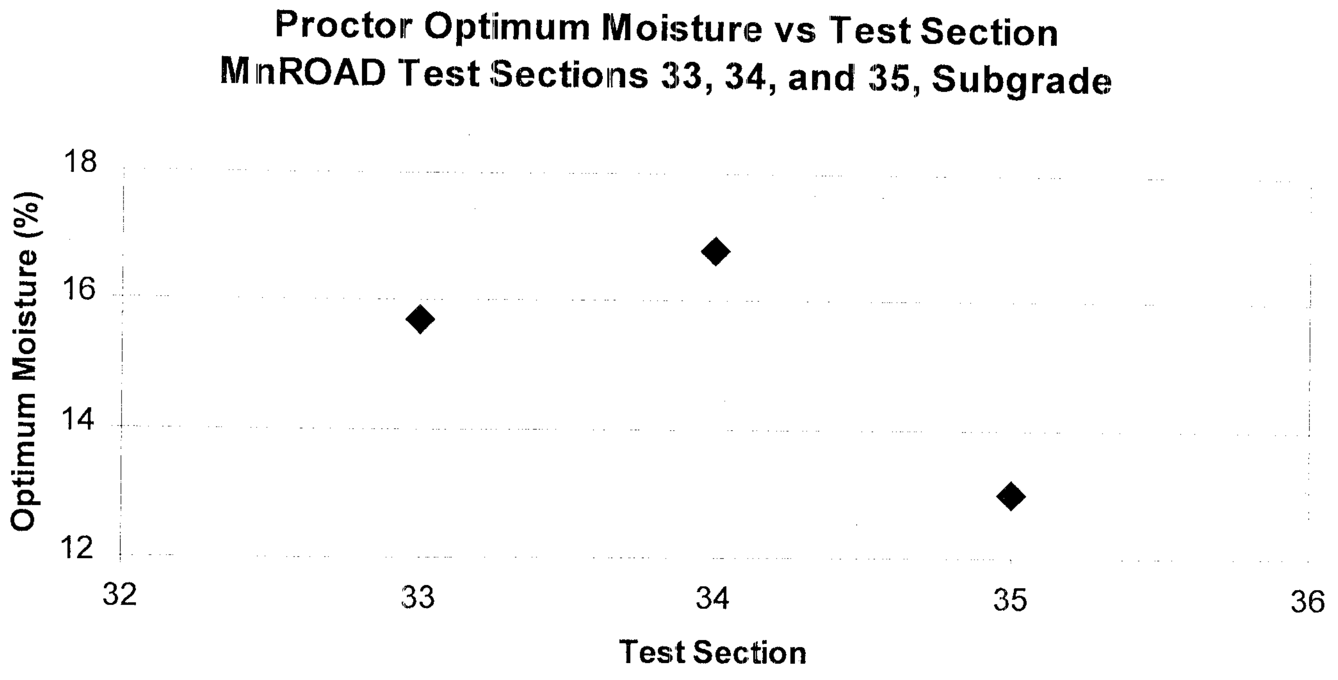

Figure 9: Proctor Moisture versus Test Section

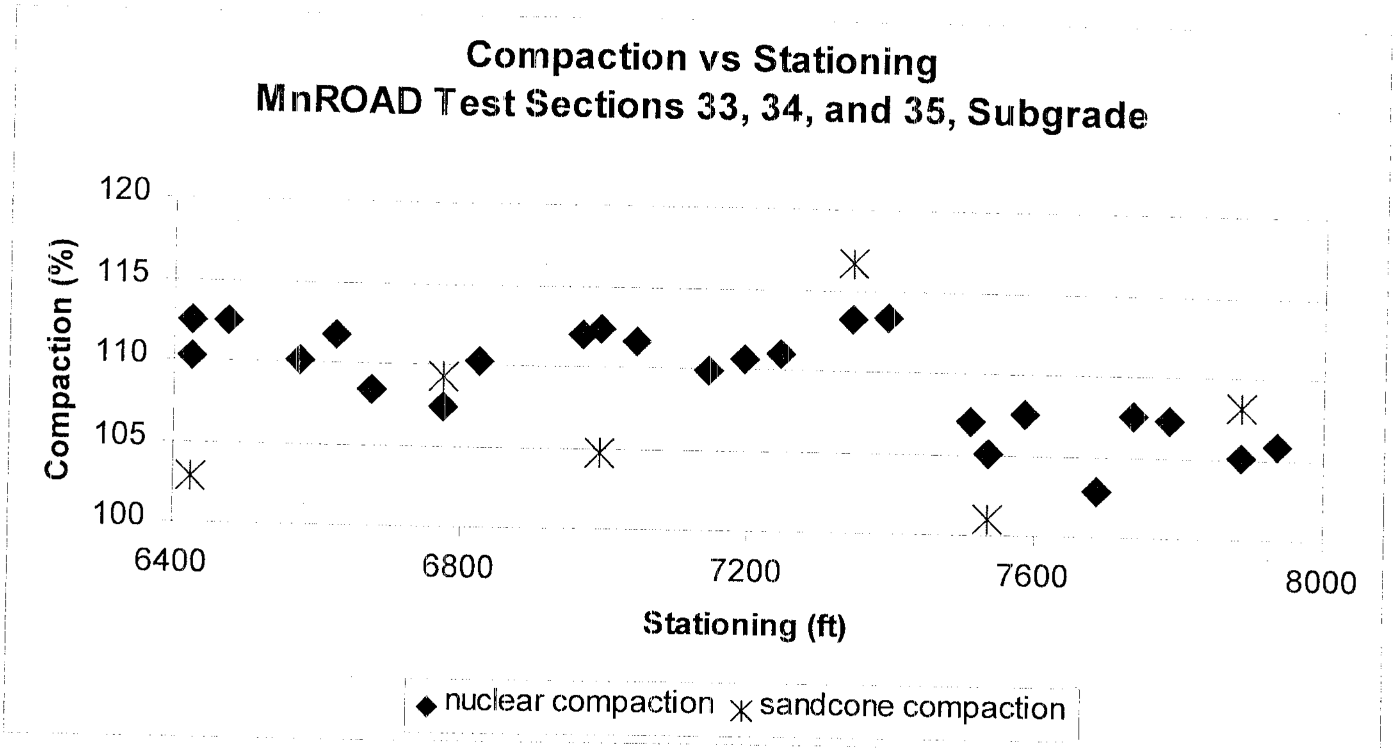

Figure 10: Compaction versus Stationing

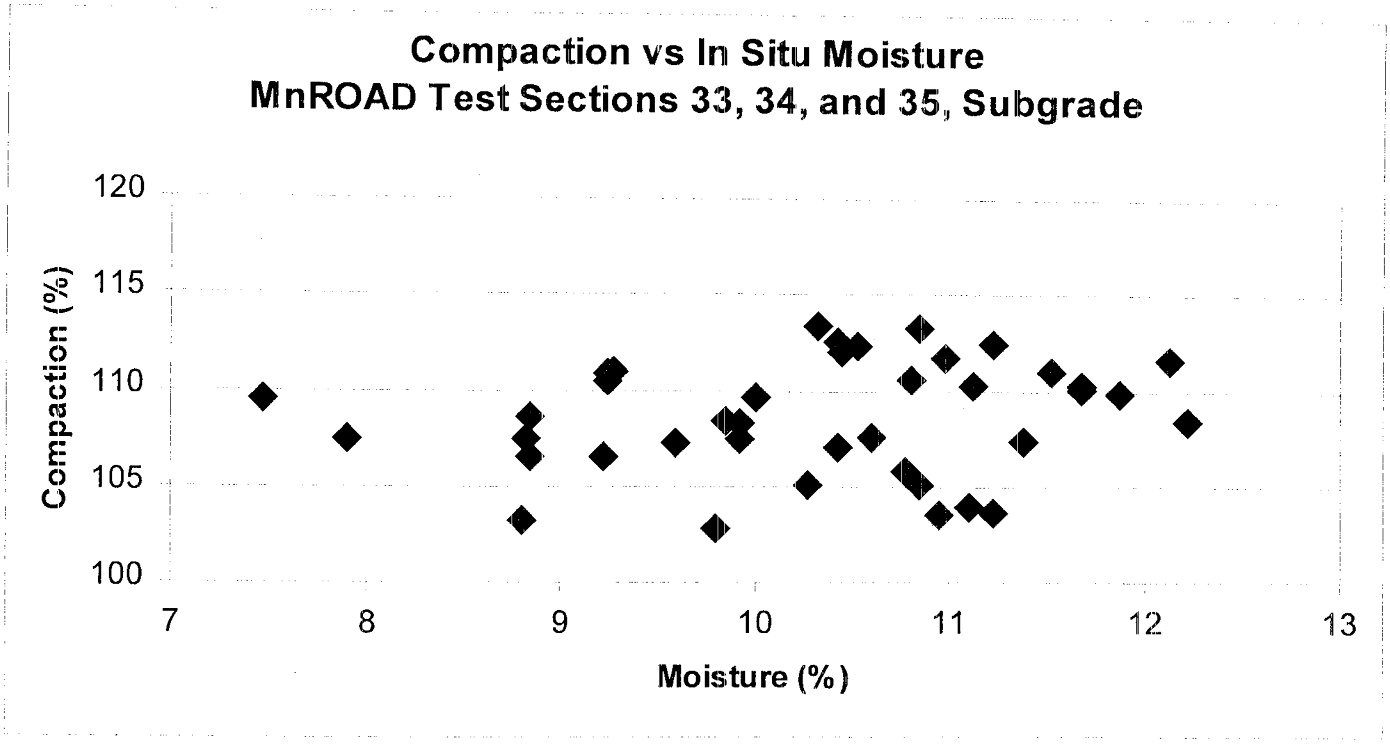

Figure 11: Compaction versus In Situ Moisture

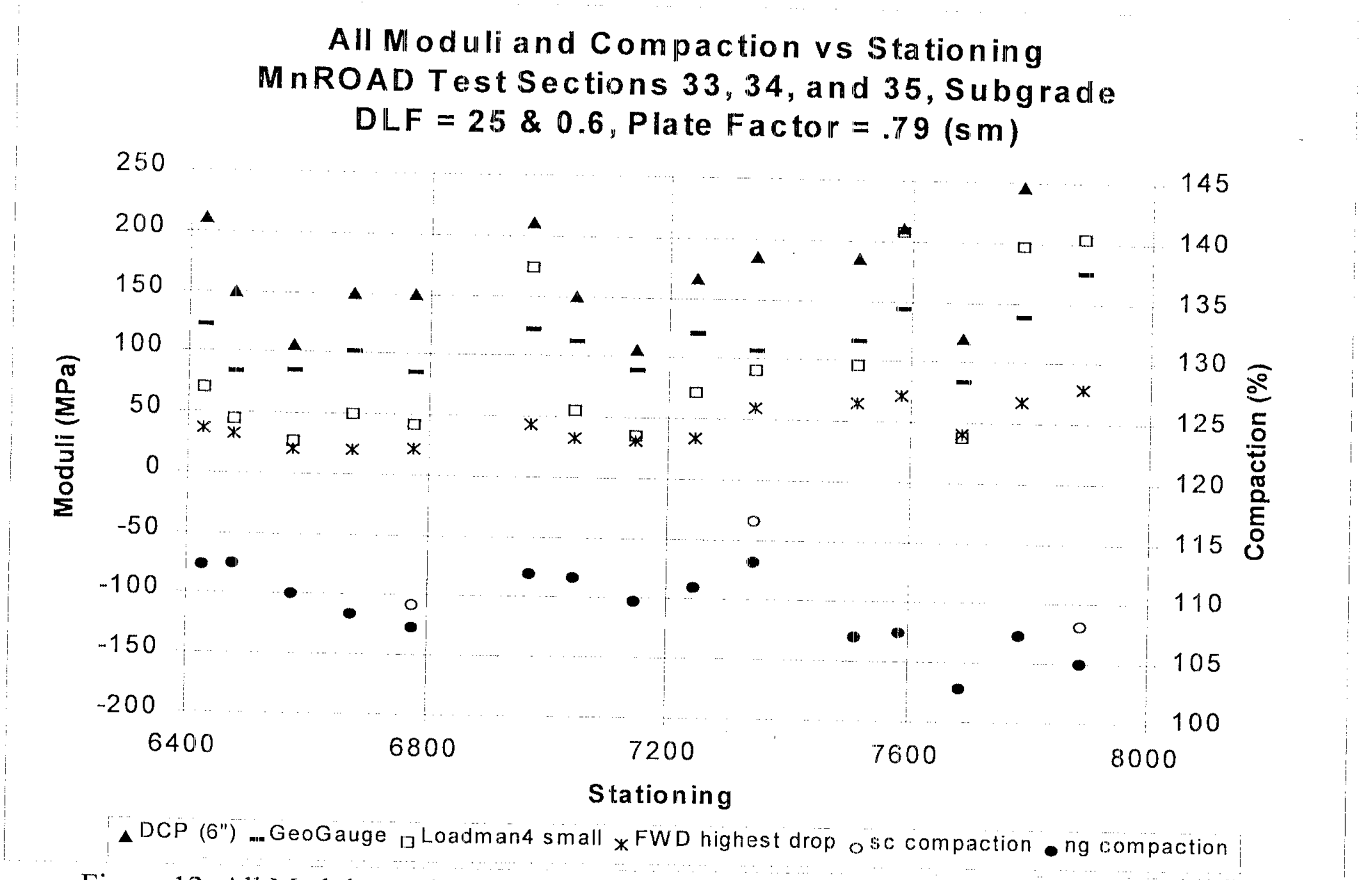

Figure 12: All Modulus and Compaction versus Stationing

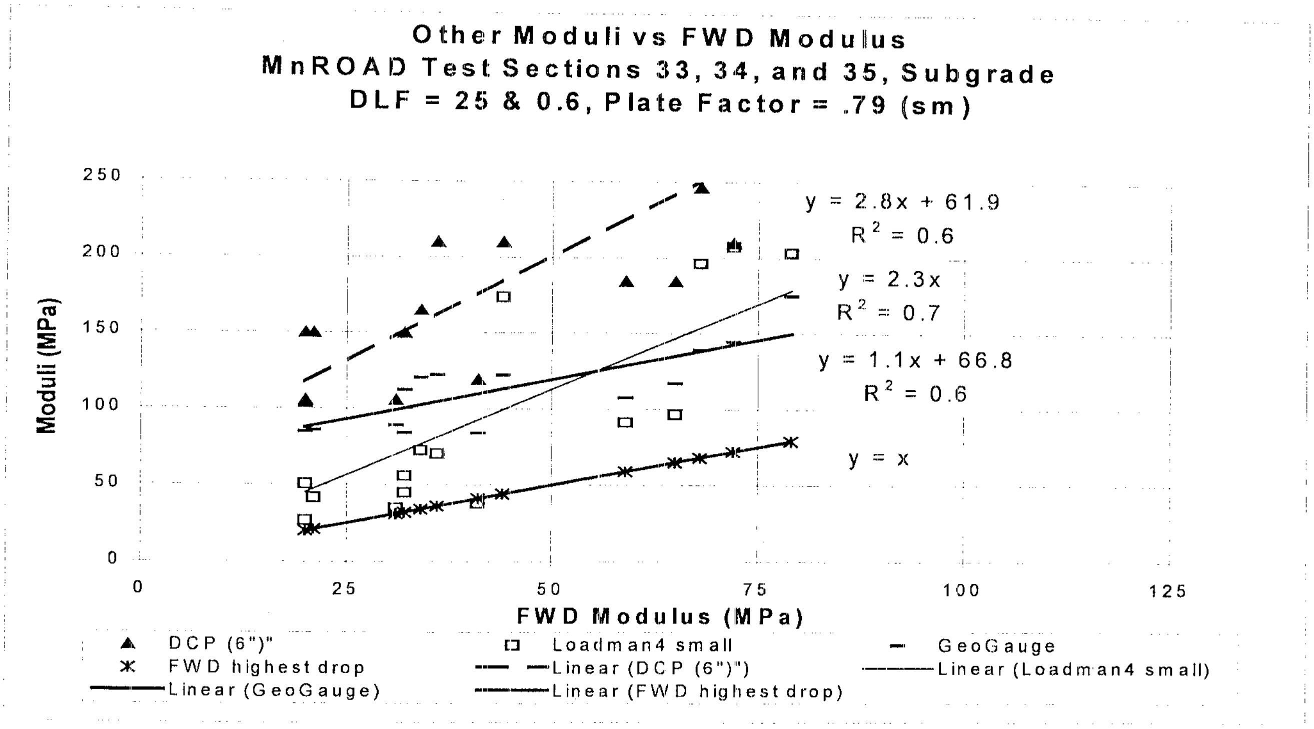

Figure 13: Other Moduli versus FWD Modulus

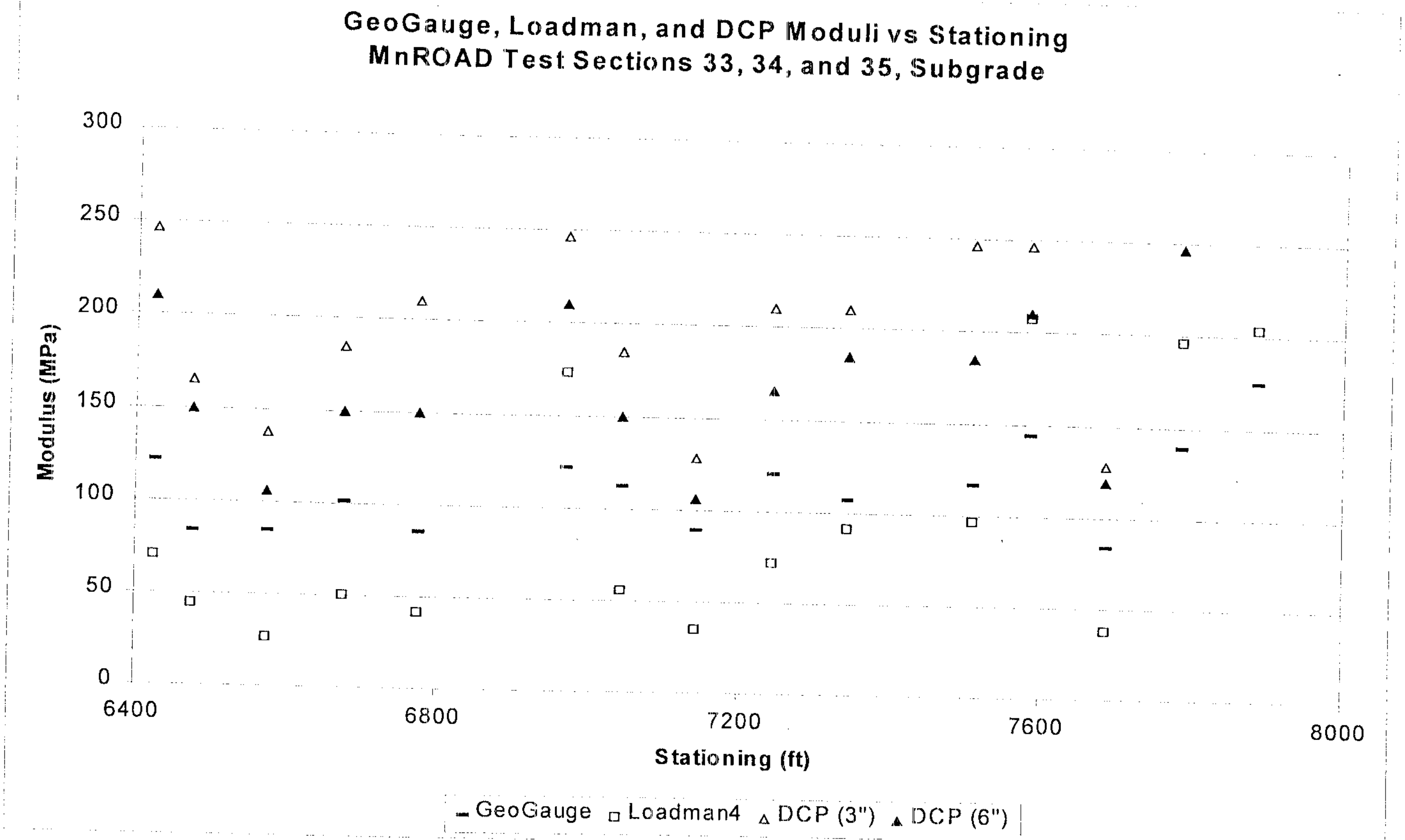

Figure 14: GeoGauge, Loadman and DCP Moduli versus Stationing