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Comprehensive Subgrade Deflection Acceptance Criteria - Executive Summary

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COMPREHENSIVE SUBGRADE DEFLECTION ACCEPTANCE CRITERIA

EXECUTIVE SUMMARY

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16. Abstract

This executive summary presents a summary of the findings of all study phases conducted to develop recommendations for the development of specifications for subgrade acceptance based on measured deflections. The rolling wheel deflectomter (RWD), portable truck-mounted deflection measurement systems, and dynamic cone penetrometer (DCP) were utilized on numerous subgrade construction projects between the 1998 and 2001 construction seasons. Comparative nuclear density and soil stiffness gauge readings were also obtained at selected locations on many of the included construction projects.

The research findings indicate that deflection test results may be appropriate for identifying areas of poor in-place stability within constructed subgrades. However, deflection testing alone may not provide all of the data necessary to properly differentiate acceptable and non-acceptable subgrade stabilities. It is important to note that deflection test results are related to the moisture-density conditions at the time of testing. Soils that show acceptable results (i.e., low deflections) may subsequently weaken due to changes in moisture content, freezing/thawing, etc. In instances where subgrade acceptance is well in advance of base course application, subgrade moisture changes may result in decreased soil support. For those conditions where soil compaction has been conducted at a moisture state near optimum, surface deflections should be correlated to the achieved level of compaction.

Based on the deflection data gathered during this research study from test areas which were considered as passing based on visual observations, a deflection acceptance threshold of 1.50 inches was selected as reasonable to limit associated acceptance errors. For use within project implementations, this threshold value was recommended for use to identify potentially “failed” test locations. It was recommended that the project engineer retain the right to require corrective actions to improve subgrade conditions based on the magnitude and extent of failed readings.

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WisDOT Highway Research Study # 98-1
SPR # 0092-45-95

by

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for

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1.0 INTRODUCTION

In late 1995 the WisDOT Division of Highways Quality Steering Team (QST) began a detailed process redesign analysis of their current subgrade design and construction process. The charge of the QST was to develop a subgrade design and construction process which would "improve subgrade quality, limit contract change orders, and reduce unplanned program costs." The final report prepared by the QST, dated May 12, 1997, presented a prioritized listing of 21 recommendations aimed at improving both the service to the process customers and the quality of constructed subgrades. The recommended development of specifications for deflection acceptance criteria for completed subgrades to replace all current compaction specifications was deemed essential for process improvement.

In November, 1997, a deflection specification team was established to develop the framework and form for deflection acceptance specifications for subgrade construction. As part of this effort, a research contract was awarded in July, 1998, to the Marquette Center for Highway and Traffic Engineering to provide information and recommendations to the specification development team which would be applicable for acceptance testing of finished subgrades as well as intermediate layers of embankment construction. This contract was amended in 2000 to provide for the development of upgraded test equipment and to broaden the number of field test projects included in the study. A final contract amendment was initiated in 2001 to provide for the conduct of pilot implementations of deflection acceptance test protocols.

This executive summary presents the combined results of all aspects of this research effort which were previously reported in WI/SPR 03-00 [*1*], WI/SPR 02-01 [*2*] and WI/SPR 04-02 [*3*]. The recommendations contained herein are based on results of subgrade modeling studies as well as field test results obtained with subgrade testing equipment developed at Marquette University.

1.1 WisDOT Pavement Performance

In 1997, the WisDOT QST examined the impact of subgrade soil type on pavement performance in Wisconsin [*4*] and concluded that overall pavement performance was not significantly affected by the relative quality of the subgrade. However, it was noted that asphaltic concrete (AC) pavements in areas with soil group 9 (See Table 1.1) showed unusually high levels of distress and warranted further investigation. The Marquette University project team conducted a review of the data to determine if any additional insights could be developed considering the average age of the pavements investigated. The data indicated that the global average PDI accumulation rate for all AC pavements was 3.57 PDI points per year. Using a baseline PDI of 60 to represent an AC pavement in need of repair, the average expected performance life of these pavements is 16.8 years. AC pavements in soil groups 7 and 9 were accumulating PDI at accelerated rates of 4.89 and 4.39 points per year, respectively, representing average service lives of 12.3 and 13.7 years.

Jointed reinforced concrete pavements (JRCP) in soil groups 1, 2, and 7 were also showing marked increases in PDI accumulations rates compared to the overall average trends as were undoweled jointed plain concrete pavements (JPCP) in soil groups 2 and 7. The data base for doweled jointed plain concrete pavements (JPCP-D) was limited to early age pavements and no conclusions on PDI accumulation rates could be made. No service life estimates for the PCC pavements were calculated as these could be misleading based only on average PDI accumulation of these early age pavements. Typically, PDI accumulation in concrete pavements is delayed for a number of years before increasing. Insufficient data was available to determine this offset value for each of these pavement types.

As was concluded in the QST report, analysis of performance trends based on averaged data can be misleading, especially for small data sets. It does, however, appear evident that pavements in soil groups 1, 2, 7, and 9 are performing poorer than other pavements of similar type. For the most part, these relative performance trends are in agreement with the general suitability rankings for the various soil groups, with the exception of soil group 2, which is ranked as the second most suitable subgrade type for construction.

1.2 Subgrade Compaction Considerations

Test rolling and/or proof rolling of constructed subgrades to verify the adequacy of compaction have been utilized for many years. The term proof rolling was first introduced in 1957 by the Corps of Engineers as part of guide specifications for military construction of graded crushed aggregate base courses [*5*]. As originally specified, proof rolling was utilized to increase aggregate density to the range of 103 to 104% of modified AASHTO maximums. Relatively soon thereafter, state highway agencies extended the use of proof rolling to subgrades to check the adequacy of compaction and to correct any deficiencies that may exist. This “correction” was typically aimed at increasing the density of under compacted soils rather than identifying locations where additional compaction, following originally specified procedures, should be completed.

In contrast to proof rolling, test rolling is not intended to significantly increase compacted densities of in situ materials, but rather to confirm that adequate stability has been attained by the compactive effort employed for that material. Test rolling does, however, share an important aspect with proof rolling; namely that the results of the tests are intrinsically tied to the in place density and moisture content of the soil at the time of testing. Unless the moisture-density-strength relationships of the soils being tested are clearly defined, improper inferences from test rolling data may result.

2.0 EQUIPMENT DEVELOPMENT

A variety of test equipment was designed and fabricated at Marquette University and used for field testing of constructed subgrades, including a prototype trailer-mounted rolling wheel deflectometer, portable deflection measuring devices suitable for use with loaded dump trucks, and an automated Dynamic Cone Penetrometer (DCP).

2.1 Rolling Wheel Deflectometer

The prototype rolling wheel deflectometer (RWD) was designed and fabricated at Marquette University during the Summer of 1998. The equipment was designed to 1) provide a rolling platform for a single test wheel load during subgrade deflection testing, and 2) to be easily transported between test sites throughout Wisconsin. A standard open deck trailer frame was selected as the basic structure to provide the required portability between test sites using readily available towing vehicles. Complete details of the prototype RWD are included in WI/SPR-03-00 [*1*].

The trailer frame was originally fitted with four hydraulically actuated outrigger wheel groups to isolate the trailer frame from the deflection basin produced by the rolling test load. The test wheel was selected as a standard, super single G286 truck tire inflated to 110 psi, which matches the steering axle tires commonly used on quad axle dump trucks. The test wheel is mounted on a steel channel frame structure positioned near the central portion of the trailer. The frame structure was originally equipped with steel and polyethylene water tanks which, when filled, produced a test wheel load of approximately 8,000 lb. During the Spring of 2000, the polyethylene water tanks were removed and replaced with steel tanks, increasing the test wheel load to 11,800 lb.

The data acquisition system was originally composed of a STAMP micro-controller interfaced with a palmtop computer. Spatial referencing during testing was achieved by using a proximity switch and magnetic targets epoxied to lug nut covers on the test wheel. The data acquisition software was written to provide for collection of all deflection sensor outputs at each fire of the proximity switch. The subgrade deflections produced by the rolling wheel load were originally measured by a rotational potentiometer mounted to the frame structure of the wheel. The RWD was also equipped with a roller guided steel rack system for measuring permanent subgrade deflections (rutting).

The prototype RWD was reconfigured during the Summer of 1999 to 1) incorporate newer technology for measurement and recordation of subgrade deflections, 2) to provide positive marking of “failed” test locations, and 3) to remove extraneous hardware which was found to be unnecessary during field testing during the Fall of 1998. The direct contact deflection/rutting measuring system originally utilized was replaced by arrays of non-contact, ultrasonic distance measuring senors. The original data recordation system was replaced with an upgraded micro-controller to allow for real-time data processing. The distance measuring instrument (DMI) was modified to include a proximity sensor targeted on the lug bolt studs of the loaded wheel. A dual paint marking system was installed for identifying subgrade test locations where rolling deflection and/or subgrade rutting exceed user defined thresholds. Finally, the four outrigger wheel sets were removed and the trailer was shortened by 4 feet.

2.2 Truck Mounted Deflection Sensors

A prototype deflection measurement system was also developed for use with a loaded dump truck. The system is composed of the same ultrasonic sensors and micro-controller used on the RWD plus a modified, portable DMI system that can be attached to the front bumper of the dump truck. Four separate 3-sensor arrays were fabricated by mounting the sensors on 5 ft aluminum angle bars. Mounting holes were provided to allow for 2 ft and 2.5 ft center-to-center spacing of the sensors. Mounting hardware, used to attach the sensor arrays to the truck, consists of an assortment of 2 inch steel uni-strut lengths, angle brackets, bolts, and clamps. Separate aluminum clamps were specially fabricated to allow for the positioning of single sensors on the front or rear axle of the truck. As developed, this system allowed for the flexibility of instrumenting virtually any quad- or tri-axle dump truck which may be available for test rolling.

Based on the results of quad axle truck testing completed during the 1998 and 1999 construction seasons, a simplified sensor configuration was developed to exclude all instrumentation previously located outside the physical limits of the truck body. This revised configuration included four sensors located below the front bumper and two sensors located on the front axle. Front bumper sensors were located at positions coincident with the center of each front wheel and at positions 2 ft inside of each wheel center. A modified bumper-mounted sensor rack was developed which could easily be field-installed in approximately 10 minutes. Axle mount sensors were positioned 2 ft inside each wheel center, along the same line of the interior bumper mounted sensors. An automated marking system was also fabricated and installed along the front bumper rack. The quad-axle truck used for final field testing was also equipped with an on-board distance measuring device which included positioning targets mounted on the drive shaft. A proximity sensor was mounted to existing bracketing located adjacent to the drive shaft. This sensor provided voltage pulses at approximately 5.5 inch intervals which could be used for spatial referencing of the truck.

2.3 Automated Dynamic Cone Penetrometer (DCP)

An automated Dynamic Cone Penetrometer (DCP) was designed and fabricated during the Summer of 1999. The basic operating parameters, including drop hammer weight, fall height, and cone geometry, are identical to those used for the traditional hand-held DCP. This system was automated by incorporating a chain driven mechanism for raising and releasing the hammer weight, a rotary encoder and proximity sensor for monitoring blowcount and depth of penetration, and a micro-controller for operational control and data recordation. The automated DCP is integrated into a steel assembly which can be vehicle mounted via a 2 inch receiver hitch.

2.4 Deflection Acceptance Criteria

Based on the review of available literature and existing construction specifications, it was deemed most practical to develop deflection acceptance criteria based on in-place subgrade stability as defined by the soil California Bearing Ratio (CBR) value. A soil CBR value of 6 has been shown to represent the lower threshold of soil strength required to provide an adequate construction platform and limit subgrade rutting under construction traffic to ½ inch or less. CBR values in excess of 6 are readily achieved for confined granular soils but may be unattainable for moisture sensitive soils at or near optimum moisture contents.

Computer modeling of subgrade soil response under flexible wheel loads was completed using non-linear elastic and stress-dependent finite element computer programs. This effort was primarily focused on fine-grained, cohesive soils which may not provide adequate stability for construction. These soils are commonly classed as stress-softening as their resilient modulus values typically reduce as load-induced deviator stresses are increased. Subgrade strength properties were varied to represent very soft (CBR = 1-2), soft (CBR=2-3), medium (CBR = 4-6), and stiff (CBR=8-10) cohesive subgrades of varying depth and position below the surface of the subgrade. Single wheel loads simulating the prototype test equipment as well as dual and dual-tandem wheel groups of various configurations were investigated. Maximum surface deflections as well as spatial variations of surface deflections were calculated for each loading case. The deflection trends clearly indicated the significant impact of upper layer strength variations on surface deflections for each load case. Marked increases in surface deflections for soft and very soft upper layers were observed for all load cases but less resolution was evident for transitions between medium and stiff soils. It was also observed that for any given upper layer soil strength, variations in lower layer soils strengths did not contribute to significant maximum surface deflection variations under either load group. Furthermore, as the stiffness of the lower layer decreases in relation to the top layer, greater interaction of the dual wheel loads results in increased surface deflections as compared to the single wheel.

Analysis of spatial variations in surface deflections indicated that when the lower soil layer is stiffer than the upper layer, surface deflections at 24 inches from the center of wheel loading are typically less than 4% of the maximum deflections. For weaker lower layers, surface deflections at 24 inches from the center of wheel loading increase in relation to the maximum deflection, exceeding 20% of the maximum deflection for the extreme case of stiff upper layer over very soft lower layer. However, the deflection difference between 0 and 24 inches from the load center, regardless of soil stiffness variations, were very close for the single and dual wheel loadings. Similar trends can be obtained using equivalent single wheel load (ESWL) analysis techniques developed for CBR based pavement designs. These methods, however, are not applicable for those cases where the upper layers are weaker than underlying materials.

Permanent deformation (rutting or sinkage) of subgrades under pneumatic wheel loads has been related to soil strength. Using the trends illustrated for the Kraft model (80 psi), values of subgrade sinkage where approximated for each soil strength combination and added to the maximum resilient deflection to provide an approximation of the total expected deflection values under single wheel loads similar in magnitude to the prototype deflection equipment. These deflection values are only approximations of the complex interactions between resilient and permanent deflections but they can serve as a general guide for expected field behavior under controlled loadings. The results of these analyses indicated that when upper and/or lower soil layer CBR values are less than 6, estimated total maximum deflection increases to roughly 2 inches or more. The general deflection trends indicate that subgrade deflection measurements under controlled loading conditions may be useful for identifying test locations where in-place upper layer strength is inadequate for construction operations. However, areas with weak lower soil layers may not be as easily differentiated by surface deflections alone. In these areas, more direct layer testing such as DCP testing may be required to quantify in situ soil strength and/or to differentiate layer strength variations.

Deflection testing to date has been conducted primarily on the surface of completed subgrades. Efforts were made to conduct deflection testing on intermediate layers during embankment construction; however, integrating these tests within common construction practices proved impractical. As a result, it is recommended that deflection acceptance testing be conducted only on completed grades and other subgrade tests, such as the standard moisture-density tests, be conducted on intermediate layers.

3.0 FIELD TEST PROGRAMS

3.1 Phase I & II Deflection Testing Program

Subgrade deflection tests were conducted at selected subgrade construction sites in Wisconsin during the latter parts of the 1998 and 1999 construction seasons. For the most part, subgrade deflection tests were conducted over accepted grades. Site clearances were provided by the grading contractors to allow for testing prior to base course applications. The collected deflection and/or penetration data was not used for subgrade acceptance. However, in some cases, corrective measures including additional compaction or excavation below subgrade were requested by project engineers after completion of this field testing.

During the 1998 construction season, subgrade tests were conducted on the following four projects:

1. STH 29 - Wittenberg - State Project ID 1059-16-80
2. STH 31 - Racine - State Project ID 2390-02-71
3. STH 10 - Fremont - State Project ID 1510-08-75
4. STH 29 - Abbotsford - State Project ID 1053-10-72

Subgrade deflection tests were conducted using the prototype deflection equipment along predominantly finished grades on all but STH 29 - Abbotsford. Comparative DCP testing was also conducted at selected locations.

During the 1999 construction season, subgrade tests were conducted on the following:

5. STH 29 - Abbotsford - State Project ID 1053-10-77
6. Golf Road - Waukesha - State Project ID 1065-10-70
7. STH 100 - Oak Creek

Subgrade deflection tests were conducted using the reconfigured RWD on STH 29, Abbotsford. Subgrade deflection tests were conducted using the instrument quad-axle dump trucks on the Golf Road and STH 100 projects. Comparative DCP testing was also conducted at selected locations for all projects.

3.2 Discussion of Phase I & II Field Test Results

The RWD test results obtained during the 1998 construction season generally validated the concept that deflections may be used as an indicator of low in-place soil strength. Surface deflections in excess of 2 inches were measured during 1998 testing at locations where subsequent DCP testing indicated CBR values less than 6 within portions of the upper 24 inches of subgrade. Along STH 29 near Wittenberg, localized high deflections were observed in an area of clayey soils which was previously identified by project engineers as requiring corrective measures. These measures were delayed until after RWD testing to provide a comparative zone of testing over weak soils. DCP testing conducted along STH 31 also indicated numerous areas where in-place CBR values were below 6 for significant depths. Corrective measures were required in these areas based on the results of test rolling, conducted by State inspectors using a loaded quad-axle dump truck, which produced excessive subgrade rutting.

Field data collected in 1999 with the reconfigured RWD was relatively consistent with data collected in 1998. Areas with weak subgrade surfaces to depths of 12 or more inches were readily identified. However, areas with weak subgrades in the depth of 12 to 24 inches below the surface overlain by stiff subgrade materials were not as easily differentiated. Deflection data collected with the instrumented quad-axle truck showed similar trends; however the quantity and quality of this data was low as compared to that collected with the RWD. Truck tests conducted along Golf Road produced front axle deflections and subgrade rutting in excess of 1 inch in an area where State inspectors subsequently required excavation and replacement of the subgrade.

Figures 3.1 and 3.2 illustrate RWD deflection and rutting values versus upper subgrade CBR values using data collected during 1998 and 1999 field testing. Regression analysis of this data provided the following:

RWD Deflection, inch = 3.47 - 3.73 Log CBR + 1.17 $(\text{Log CBR})^2$
n = 36 $R^2 = 0.587$

RWD Rut Depth, inch = 2.00 - 2.56 Log CBR + 0.91 $(\text{Log CBR})^2$
n = 36 $R^2 = 0.632$

The trend line through the data indicates that subgrade areas with upper layer CBR values of 6 or less could be identified by RWD deflections exceeding approximately 1.25 inches or by rut depths exceeding approximately 0.6 inches.

3.3 Phase III Deflection Testing

The primary objectives of Phase III of this study were 1) to supplement the database of subgrade deflection response established during Phases I & II, 2) to determine if deflection testing with an instrumented quad-axle dump truck was a viable alternative to RWD testing, and 3) to provide recommendations for the development of pilot subgrade deflection acceptance specifications which could be incorporated into selected subgrade construction projects during the Year 2001 construction season. To meet these objectives, additional testing was conducted by the Marquette University research staff on selected construction projects during the Year 2000 construction season. Field tests completed by Marquette staff include deflection tests using the re-configured RWD, penetration tests using the automated and hand-held DCP, and deflection tests using an instrumented quad-axle dump truck. During field deflection testing, representatives from WisDOT were present to conduct in-place moisture-density tests using the nuclear densiometer gage. Laboratory tests were also conducted by Marquette staff on soil samples obtained from each project, including standard Proctor compaction tests, laboratory CBR tests using the fabricated Proctor specimens, and unconfined compression tests on smaller-sized compaction specimens.

Subgrade deflection tests were conducted at selected subgrade construction sites in Wisconsin during the Year 2000 construction season. Deflection tests were conducted over previously accepted grades as well as over subgrades purposely placed and compacted in a manner which would generally be considered as unacceptable. These latter tests were conducted to provide deflection data illustrative of subgrade conditions where the upper portions of the subgrade would be considered acceptable but lower portions would not. Site clearances were provided by the grading contractors to allow for testing prior to base course applications. The collected deflection and/or penetration data was not used for subgrade acceptance on any of the included projects.

Subgrade deflection tests were conducted on nine projects during the 2000 construction season as follows:

1. USH 41 - Kaukauna - State Project ID 1131-08-72
2. CTH YY - Menominee Falls
3. STH 164 - Waukesha
4. STH 33 - Beaver Dam
5. STH 60 - Columbus
6. 124th Street - Milwaukee
7. STH 60- Lodi
8. USH 10 - Waupaca
9. STH 57 - Fredonia

Deflection tests were conducted using the reconfigured RWD on all projects with comparative DCP testing conducted at selected locations. Deflection tests were also conducted with an instrumented quad-axle dump truck on STH 57, Fredonia. Nuclear soil testing was conducted by WisDOT staff from representative Districts or from Central Office. Proctor tests were conducted by District staff and Marquette University personnel.

3.4 Discussion of Phase III Field Test Results

The Phase III deflection data indicated a variation of deflection results from the included projects. Figures 3.3 to 3.6 provide summaries of deflection results versus in-place CBR for the variety of soils tested at different subgrade depths. Figure 3.7 provides a summary of the 1998 - 2000 deflection results versus in-place CBR, with all deflection results normalized to a common loading of 12,000 lb. Based on these figures, a deflection threshold of approximately 1.5 inches was recommended for use during pilot implementations to differentiate low strength soils with CBR < 6 in the upper 12 inches. This threshold may not capture every project occurrence of CBR < 6, and in fact may occur where CBR > 6, but it appeared to be the most appropriate selection based on the collected data. During pilot implementations, companion DCP testing was recommended at locations with deflections in the range of 1.0 to 2.0 inches to further clarify the in-place soil strengths and aid in determining the percentage of situations where poor soils would be accepted and/or good soils would be rejected by this threshold. Through a collective effort of the Technical Oversight Committee for this study, involving WisDOT, FHWA, academia, and industry personnel, a draft pilot subgrade deflection acceptance specification was developed.

3.5 Pilot Implementation Deflection Testing

Pilot implementations of the draft deflection acceptance specifications were conducted during the 2001 construction season to supplement the database developed during study Phases I - III and to determine the feasibility of specification implementation as related to the normal sequence of subgrade construction. Subgrade deflections were collected with an instrumented quad-axle dump truck on all pilot implementation projects. Comparative rolling wheel deflectometer (RWD) data was also collected on all but one of the pilot projects. Subgrade penetration tests using the automated and/or hand-held dynamic cone penetrometer (DCP) were also conducted on all projects. During field deflection testing, representatives from WisDOT were present on all projects to conduct in-place moisture-density tests using the nuclear gage. WisDOT personnel also utilized the Soil Stiffness Gauge for data collection on two of the pilot projects. The collected deflection and/or penetration data was not used for subgrade acceptance on any of the pilot projects. However, WisDOT personnel were on site to observe subgrade deflections produced by the loaded quad-axle dump truck and/or the RWD and to identify test locations that were considered unacceptable.

Subgrade deflection tests were conducted on four pilot projects as follows:

1. CTH SS - Waukesha County - State Project ID 1065-04-72
2. STH 57 - Ozaukee County - State Project ID 4015-00-70
3. USH 41 - Oconto County - State Project ID 1152-07-75
4. STH 57 - Sheboygan County - State Project ID 4015-08-71

3.6 Discussion of Pilot Implementation Test Results

The deflection data collected during pilot implementations with the loaded quad-axle dump truck indicated that the shortening of the front sensor rack to ensure that no side extensions exist resulted in a data bias due to swaying of the front bumper. Observation of zeroing runs conducted on most projects indicated an oscillation of the zero readings when the reference deflections measured by the front rack are incorporated into the calculation of wheel deflections. This oscillation was most likely the results of slight side pitching of the body during travel and is essentially removed when only the axle readings are utilized. When compared to RWD deflections measured during comparative testing, deflections computed using only the axle readings are in better agreement.

When viewed in the context of deflection acceptance testing, the use of axle-only deflections inhibit the correction for uneven surface profiles existing prior to actual testing. However, if the subgrade surface is properly bladed and rolled prior to the start of testing, a condition which is specified at the end of each working day, minor irregularities in the subgrade surface should have only localized effects.

Figures 3.8 and 3.9 illustrate comparative plots of calculated CBR versus Soil Stiffness for test projects within District 2. Figure 3.10 illustrates maximum recorded deflections versus Soil Stiffness for these projects. As shown, there is significant scatter in the data sets making useful correlations difficult. Figures 3.11 and 3.12 illustrate maximum recorded deflections vs calculated CBR for all District 2 projects. While there is still considerable scatter in the data, the trending of deflection data is more evident in these plots. Figure 3.13 provides a comparative deflection versus CBR plot for all 2001 pilot projects and previous 2000 test projects. Based on verbal and/or written communication from WisDOT observers of the pilot deflection testing, Table 3.1 was prepared to provide comparative deflection readings obtained in areas considered as “failed”. Provided are both the average deflections and maximum deflections obtained within the “failed” limits. In some instances, the observers noted localized areas which would have been considered as failed but no corrective actions would have been required due to their limited area.

In an effort to develop more meaningful deflection trends from pilot projects tested in passing and failing grade locations, the collected deflection data was further analyzed to develop block average deflection readings obtained over successive 5 foot (1.5 meter) test increments. This block averaging method was selected as a practical means for processing deflection data on test projects. Cumulative frequency plots of collected deflections in passing and failed areas were then developed from the block averages. Figures 3.14 through 3.16 illustrate cumulate frequency plots for the collected RWD deflection data for each included test project. Figure 3.17 provides an overall combined cumulative frequency plot for all collected RWD test data. Figures of this type can be utilized to select a deflection acceptance threshold which limits associated acceptance errors to tolerable values. Due to the overlap in the cumulative frequency lines shown in Figures 3.14 through 3.17, it is not possible to establish a specific deflection threshold which does not include an associated acceptance error, i.e, for any selected deflection acceptance threshold value, some passing grade would be rejected (Type 1 error) and some failing grade would have been accepted (Type 2 Error).

For example, using the results illustrated in Figure 3.17, a selected RWD deflection acceptance threshold of 1.5 inches would imply that approximately 7% of the tested grade which was visually passed would have been rejected and approximately 24% of the tested grade which was failed would have been accepted. Similarly, if a Type 1 error of 10% maximum is selected, the corresponding deflection acceptance threshold would be approximately 1.25 inches and the probability of an associated Type 2 error would be approximately 12.5%.

Figures 3.18 through 3.21 illustrate cumulative frequency plots for the collected quad-axle truck data for each included project. Figure 3.22 provides an overall combined cumulative frequency plot for all collected quad-axle truck data. Based on the results illustrated in Figure 3.22, the associated Type 1 and Type 2 errors were developed for a range of deflection acceptance thresholds and are provided in Table 3.2. Based on the comparative results, particularly those provided in Table 3.2, a deflection acceptance threshold of 1.50 inches for the loaded quad-axle truck was recommended for initial implementation, which equates to a probability of a Type 1 error of 7.7% and a Type 2 error of 42.8%. This initial value was selected to provide an equitable distribution of risk between contractors and WisDOT.

4.0 LABORATORY TEST PROGRAM

Laboratory testing, including Proctor, CBR, and unconfined compression were conducted on soil samples obtained during the conduct of Phase III field deflection testing. For the Proctor and CBR tests, soil samples were oven dried, pulverized, and passed through a No. 10 sieve prior to testing. Compaction and CBR tests were conducted on all minus No. 10 materials using a standard 4-inch diameter mold.

Unconfined compression tests were conducted on the silt soils obtained from STH 33 near Beaver Dam and on the red clay soils obtained from STH 57 near Fredonia. These soils were selected to obtain comparative strength data for two common classes of fine-grained, moisture sensitive soils. The soil samples were oven dried, pulverized, and passed through a No. 40 sieve prior to testing. Compaction and unconfined compression tests were conducted on all minus No. 40 materials.

4.1 Proctor and CBR Analysis

Moisture-density curves were developed for each soil sample by the Marquette research staff. Standard Proctor compaction protocol was followed for all tests. Standard CBR tests were performed on each specimen immediately after compaction. Figures 4.1 and 4.2 illustrate the typical moisture-density and CBR vs moisture relations obtained. As illustrated, the fine-grained soils exhibit typical trends of decreasing CBR with increasing moisture content at compaction. Furthermore, the loss in strength at moisture contents above optimum is most dramatic for silty soils Based on the CBR trends, one may conclude that compaction of silts at moisture contents below optimum would be desirable to provide higher support stability. While this conclusion may be appropriate immediately after compaction, it woefully neglects the fact that moisture gain after compaction can significantly decrease the strength of moisture sensitive soils. This moisture-strength loss effect is best seen by conducting CBR tests after soaking of the compacted specimens, which was done as part of the unconfined compression tests described below.

4.2 Unconfined Compression Testing

Unconfined compression tests were conducted on the silt and clay soils from STH 33 and STH 57, respectively. Specimens were compacted using the Harvard miniature compaction apparatus at selected moisture contents on either side of optimum as determined from the Proctor tests. This Harvard apparatus utilizes a kneading type compaction produced by a spring actuated plunger and results in compacted specimens 1.3 inches in diameter and 2.8 inches in length. Two replicate specimens were compacted at each moisture content with one specimen tested immediately after compaction and the other allowed to soak in water for 48 hours prior to testing.

Table 4.1 provides comparative test data for the soaked and unsoaked specimens. The unconfined compression strengths were used to estimate the CBR of each specimen using the relation:

$$CBR = qu / 4.5$$

where: CBR = California bearing ratio, %
qu = unconfined compression strength, psi

Figures 4.3 and 4.4 illustrate typical compaction and CBR trends for these soils. As expected, for those specimens compacted on the dry side of optimum, the soaking resulted in a significant moisture gain and concurrent strength loss.

A final series of tests were conducted on the STH 33 silt to illustrate the effects of relative compaction on soil strength. Harvard specimens were compacted near optimum moisture content with varying levels of compaction effort to simulate field conditions where moisture content is properly controlled but full compaction is not attained. As shown in Figure 4.5, decreased relative compaction results in a significant loss of strength.

4.3 Discussion of Laboratory Tests

The Proctor/CBR test results clearly indicated the relations between compaction moisture content and resultant soil strength. In normal practice, tests such as these can be used to provide an indication of the expected in-place soil strength after compaction if proper compaction controls are utilized, i.e., full compaction near optimum moisture. For those soils where sufficient stability cannot be attained through proper compaction, select materials can be specified to ensure an adequate construction platform is produced. Furthermore, where laboratory testing clearly indicates a CBR in excess of 6 should be easily attained, consideration should be given to tightening acceptance criteria to ensure that the pavement designer's expectations of soil support strength are realized.

The unconfined compression tests on soaked and unsoaked specimens further illustrate the detrimental effects of moisture gain on fine-grained soils compacted on the dry side of optimum. Combined with Proctor/CBR results, these tests can be utilized to indicate acceptable moisture contents during compaction to ensure that significant strength loss does not occur after grade acceptance. When viewed as a whole, these limited lab tests indicate a need for establishing and controlling moisture contents during compaction. Without these controls, the acceptance of a completed subgrade based on in-placed stability by deflection testing or any other means can lead to erroneous conclusions regarding the long-term performance of the subgrade.

5.0 DEFLECTION ACCEPTANCE CRITERIA

The results of study Phases I through III recommended the development of deflection acceptance criteria based on in-place subgrade stability as defined by the soil CBR value. A soil CBR value of 6 was selected to represent the lower threshold of soil strength required to provide an adequate construction platform and limit subgrade rutting. CBR values in excess of 6 should be readily achieved for many soil types if proper compaction techniques are followed. For these soils, lowering the threshold of acceptability may defeat the purpose of the specifications and result in completed grades with stabilities far below designer's expectations. On the other hand, lower stiffness soils which are expected to have CBR values in the range of 6 - 10 after proper compaction may be considered as better candidates for acceptance testing to ensure the desired minimal strength is achieved.

The trends of deflection versus in-place CBR developed from this study indicate that subgrade deflection measurements under controlled loading conditions may be useful for identifying test locations where in-place strength is adequate for construction operations, provided those operations occur without significant moisture change in the soils. However, unless the moisture sensitivity of the soils has been established and proper moisture controls have been implemented during construction, any soil strength measure can be viewed as transient and adverse changes in strength may result.

The final study recommendations for project implementations of the deflection acceptance specifications indicated that testing should be targeted for projects where moisture sensitive silts and clays are anticipated to be in place within the upper 24 inches of completed grades. A deflection acceptance threshold of 1.50 inches under a standard front axle loading of 24,000 lb (single wheel loading of 12,000 lb) was recommended for use during testing of completed grades.

5.1 Deflection Testing Equipment

Experiences gained during the conduct of deflection testing during the study indicate that the use of a fully loaded quad-axle dump truck is the most practical means for performing deflection acceptance testing. Based on the observed sequencing of construction, the locations of completed grade ready for testing, the availability of access routes to completed grades, and the availability of adequate turn-around locations, the use of the RWD would be problematic in many instances. With only one such system in existence, its limited availability and set-up requirements for water ballasting would also pose significant scheduling difficulties.

While not the case for every data set, the good agreement between deflections measured by axle-mounted sensors on the quad-axle dump truck and the RWD was observable in comparison figures and tables developed from the pilot implementations. For the purposes of specification implementations, it was recommended that the quad-axle truck with the simplified configuration, using only two axle mounted sensors, be utilized. The deflection sensors should be located 2 feet inward from each tire center to provide profile measurements of each wheel track. This would result in an instrumentation configuration which could easily be field-installed in 5 minutes or less. With proper protection from the elements, it is possible to leave the sensors in place during normal usage of the truck so that only protective covers need to be removed prior to testing.

It was further recommended that the marking system used to paint locations where acceptance thresholds are exceeded be configured such that only one mark is applied, representing one or both wheel paths where thresholds are exceeded. This system could be easily adapted to the driver's side step grate, making it more visible to the operator during testing. For the vast majority of cases observed during pilot testing, locations of high deflection and permanent rutting were either similar within wheel paths or easily discernable if differences existed. Furthermore, if conditions were such that differentiation between wheel paths was difficult to identify in the field, the summary printout from the deflection run would clearly identify which wheel path exceeded the acceptance threshold.

It was recommended that implementations of the deflection acceptance specifications utilize the following guidelines for truck instrumentation:

1. The dump truck should be loaded to a sufficient gross load to produce a distributed front axle loading of 24,000 lbs (+/- 500 lb) with the pusher axles raised. Total load as well as front axle loading should be verified by a certified weigh ticket.

2. Front axle flotation tires, which are normally G286 super single tires inflated to 110 - 125 psi cold, should be specified.

3. WisDOT approved deflection instrumentation should be mounted in such a way as to provide recordation of both front tire wheel tracks. A total of two front axle-mounted sensors are required, with sensors mounted 2 ft inward of the centerline of both front tires.

4. A distance measuring device, composed of a proximity sensor and targets, must be provided on the truck to produce pulse voltages of 0 - 5 volts at a travel interval not to exceed 1 ft. The proximity sensor targets may be mounted on the circumference of the drive shaft or on one of the truck tires, provided that the firing interval of the proximity sensor is consistent for all driving surfaces.

5. A positive marking system should be mounted to the front bumper or the step grate to provide surface marks indicating locations where wheel deflections exceed threshold values. The system should apply an easily visible paint or chalk line to the surface of the tested subgrade regardless of subgrade moisture conditions existing at the time of testing.

6. A WisDOT approved data processing/storage device shall be mounted in a location which is readily accessible to the 12 volt DC power source of the truck.

5.2 Deflection Testing Pattern

It was recommended that deflection tests be conducted over the full-width of the constructed subgrade as defined by the edge limits of the proposed pavement shoulders. Tests should be conducted with a minimum of one pass of the loaded truck along each shoulder and proposed driving lanes. For two-lane roadways, this pattern would result in a minimum of four passes (one for each lane and one for each shoulder). Deflection testing should be performed at normal walking speeds not to exceed 5 mph nor be less than 2.5 mph. Deflection testing should be completed with the pusher axles raised during testing, i.e., all load carried only by the front steering axle and the rear tandem axle group.

Deflection testing should be conducted as soon as practical after final subgrade elevation has been reached so that significant moisture loss from the subgrade would not bias the deflection results.

5.3 Deflection Acceptance Criteria

Based on the deflection data gathered during this research study from test areas which were considered as passing based on visual observations, a deflection acceptance threshold of 1.50 inches appears reasonable to limit associated Type 1 and Type 2 errors. For use within project implementations, this threshold value was recommended to identify potentially “failed” test locations. The project engineer should retain the right to require corrective actions to improve subgrade conditions based on the magnitude and extent of failed readings.

Previous study phase reports have indicated the need to conduct DCP testing in failed areas to determine the severity and depth of weak subgrades. While data obtained from this type of testing has been helpful in developing the recommendations contained herein, the use of DCP testing in failed areas should not be required, but rather left to the contractor’s discretion to aid in the development of potential corrective actions.

5.4 Recommended Supplemental Tests

For those projects selected for specification implementation, it was recommended that laboratory testing be conducted for those soils proposed for use in construction to establish moisture-density and compacted strength profiles for soaked and unsoaked specimens. These results would be available for review by WisDOT and contractor personnel to ensure that agency expectations would be clearly enumerated. During subgrade construction, it was also recommended that soil moisture contents be monitored, particularly in the upper 24 inches, to ensure that compaction moisture contents are within acceptable limits of the optimum moisture content for that soil, which is typically +/- 10% of the optimum moisture content. The conduct of the above laboratory tests and soil moisture measurements are not required to implement deflection acceptance testing; rather, these measures are recommended to provide more information to assess the deflection testing process.

6.0 SUMMARY AND RECOMMENDATIONS

This executive summary has presented a summary of the findings of all study phases conducted to develop recommendations for the development of specifications for subgrade acceptance based on measured deflections. The reconfigured rolling wheel deflectomter (RWD), portable truck-mounted deflection measurement systems, and dynamic cone penetrometer (DCP) were utilized on numerous subgrade construction projects between the 1998 and 2001 construction seasons. Comparative nuclear density readings were obtained at selected locations within each project. Comparative soil stiffness gauge readings were also obtained on 2 of the pilot projects

The research findings indicate that deflection test results may be appropriate for identifying areas of poor in-place stability within constructed subgrades. However, deflection testing alone may not provide all of the data necessary to properly differentiate acceptable and non-acceptable subgrade stabilities. It is important to note that deflection test results are related to the moisture-density conditions at the time of testing. Soils that show acceptable results (i.e., low deflections) may subsequently weaken due to changes in moisture content, freezing/thawing, etc. In instances where subgrade acceptance is well in advance of base course application, subgrade moisture changes may result in decreased soil support. For those conditions where soil compaction has been conducted at a moisture state near optimum, surface deflections should be correlated to the achieved level of compaction.

The overall objectives of this research have been met and useful correlations between subgrade deflections and in-place subgrade stability, as measured by the California Bearing Ratio (CBR) or interpreted by visual observations, have been developed. Deflection data collected to date using instrumentation on the axles of loaded quad-axle trucks indicates this data source is adequate for the identification of areas that need further evaluation by WisDOT and contractor personnel to determine if corrective actions are warranted. It was recommended that initial implementations of deflection acceptance testing be conducted on selected projects where moisture sensitive soils are anticipated.

7.0 REFERENCES

1. Comprehensive Subgrade Deflection Acceptance Criteria, Final Report, WI/SPR-03-00, Wisconsin Department of Transportation, March 2000.

2. Comprehensive Subgrade Deflection Acceptance Criteria, Phase III Final Report, WI/SPR-02-01, Wisconsin Department of Transportation, January 2001.

3. Comprehensive Subgrade Deflection Acceptance Criteria, Pilot Implementation Final Report, WI/SPR-04-02, Wisconsin Department of Transportation, January 2002.

4. "Subgrade Design/Construction Process Review," Adamsky, et al., Final Report, May, 1997

5. "Guide Specifications for Military Construction, Graded-Crushed-Aggregate Base Course," Corps of Engineers, Office, Chief of Engineers, CE 807.012, May, 1957.

Table 1.1: Wisconsin Soil Groups

Soil Group	Soil Types	Relative Suitability[1]
1	Silts & silty clay tills of southeastern Wisconsin	6
2	Silts & residual clay soils of southeastern Wisconsin	8
3	Sand plains of central and northern Wisconsin	1
4	Silty clay and clay deposits of eastern Wisconsin	4
5	Sandy to clayey residual soils of western Wisconsin	5
6	Silty clay loam tills of north central Wisconsin	9
7	Sandy loam tills of northern Wisconsin	2
8	Lake Superior clay deposits of northern Wisconsin	7
9	Silty and sandy soils of northeastern Wisconsin	3

(1) Relative suitability for subgrade construction, 1 = best.

Table 3.1: Comparative Deflection Data for Locations Identified as "Failed"

Test Location			Average Deflection, inch			Maximum Deflection, inch		
Site	Date	Stations	RWD	Truck		RWD	Truck	
				Right	Left		Right	Left
CTH SS	5/31/01	20+430 - 20+450 N	na	2.07	1.97	na	4.63	2.87
CTH SS	5/31/01	20+430 - 20+450 S	na	1.32	1.97	na	2.50	5.09
CTH SS	5/31/01	20+560 - 20+580 N	na	2.93	2.63	na	5.64	4.30
CTH SS	6/28/01	36+057 - 36+043 N	na	1.62	1.68	na	2.29	2.22
CTH SS	6/28/01	36+050 - 36+054 S	na	2.15	1.62	na	3.38	2.92
CTH SS	6/28/01	9+71 - 9+82	na	2.27	1.29	na	3.31	2.64
CTH SS	7/11/01	36+035 - 36+045 S	na	.38	.23	na	0.85	0.48
CTH SS	7/11/01	36+055 - 36+065 S	na	.62	.41	na	0.92	0.62
CTH SS	7/11/01	36+115 - 36+130 N	na	1.32	1.54	na	2.17	3.38
CTH SS	7/11/01	36+115 - 36+130 S	na	1.26	1.61	na	2.12	2.93
CTH SS	7/11/01	35+840 - 35+860 S	na	.58	.78	na	1.16	1.60
CTH SS	7/11/01	35+840 - 35+860 N	na	1.53	1.51	na	2.63	3.03
CTH SS	7/11/01	36+815 - 36+825 S	na	1.18	1.27	na	1.70	1.90
USH 41	8/31/01	16+160 - 16+180	na	1.51	0.56	na	2.40	1.42
USH 41	8/31/01	16+300 - 16+400	na	1.74	1.79	na	4.42	4.30
USH 41	8/31/01	4+250 - 4+280	na	0.03	0.14	na	0.53	0.73
USH 41	8/31/01	18+070 - 18+190	na	1.97	2.30	na	3.80	3.42
USH 41	9/27/01	16+500 - 16+514	1.82	1.34	1.23	2.46	3.14	2.02
USH 41	9/27/01	4+150 - 4+088	1.38	1.30	1.32	2.38	2.65	3.24
STH 57	9/28/01	713+50 - 713+80 E	3.02	1.89	0.86	4.01	2.54	1.50
STH 57	9/28/01	693+50 - 693+90 W	2.34	1.52	0.52	2.88	1.78	1.13
STH 57	9/28/01	693+50 - 693+90 E	2.26	2.31	1.86	2.87	2.92	2.52

Table 3.2: Errors Associated With Various Deflection Acceptance Thresholds

Deflection Acceptance Threshold (inch)	Probability of Error, %	
	Type 1 [(1)]	Type 2 [(2)]
1.00	21.1	17.2
1.25	13.0	29.5
1.50	7.7	42.8
1.75	4.8	56.5
2.00	3.1	67.6

(1) Type 1 error probability indicates percentage of time passing grade would be rejected
(2) Type 2 error probability indicates percentage of time failing grade would be accepted

Table 4.1 - Unconfined Compression Test Results

Test Specimen	Moisture Content During Compaction %	Compacted Dry Density pcf	Test Results Immediately After Compaction		Test Results After 48 Hour Soaking		
			Unconfined Compressive Strength qu, psi	CBR	Moisture Content %	Unconfined Compressive Strength qu, psi	CBR
STH 33 Silt							
1	10.4	115.4	38.03	8	14.9	15.91	4
2	12.3	118.4	46.08	10	14.3	36.49	8
3	15.4	114.7	15.07	3	16.0	14.77	3
STH 57 Red Clay							
1	13.2	114.3	42.79	10	16.3	18.44	4
2	14.2	115.9	54.21	12	15.1	36.49	8
3	17.2	111.8	19.49	4	17.5	17.64	4

Figure 3.1
RWD vs CBR Comparison

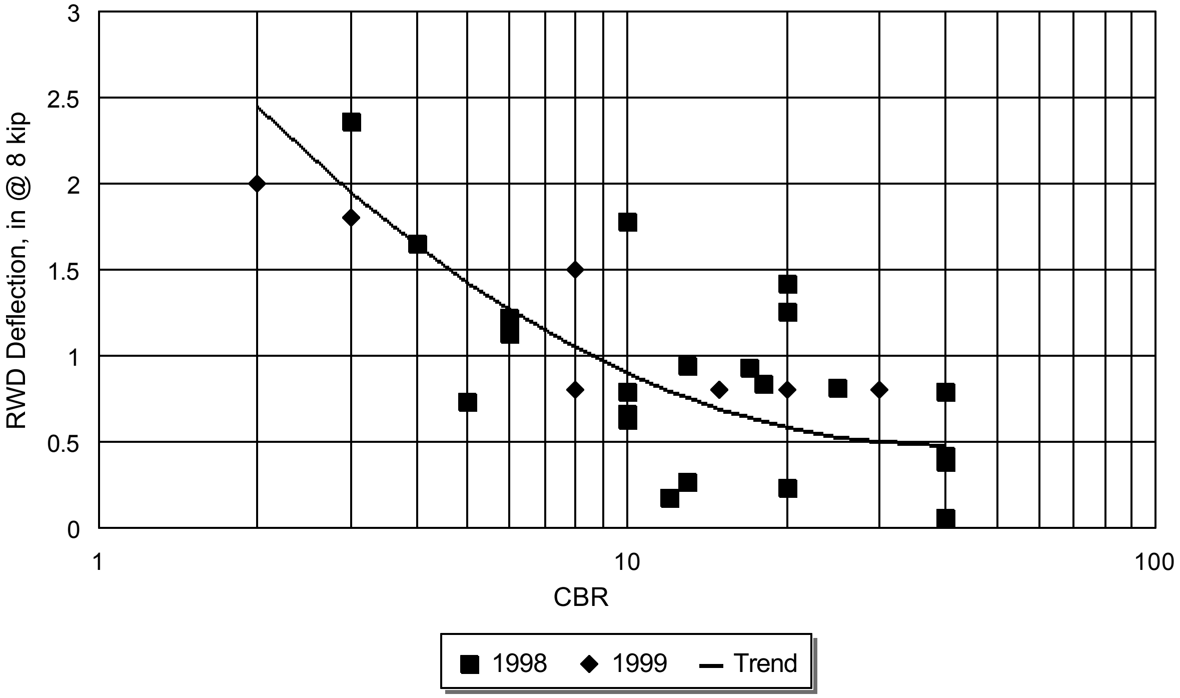


Figure 3.2
Rut Depth vs CBR Comparison

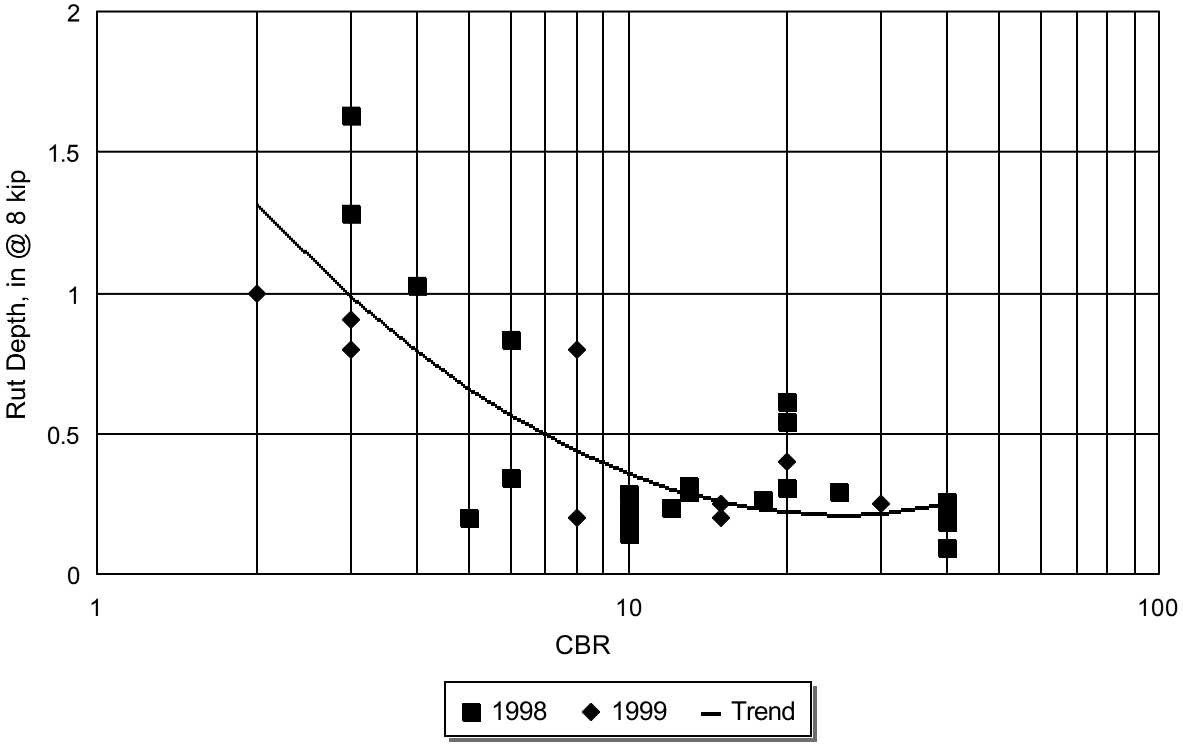


Figure 3.3 Deflection vs CBR

All Year 2000 Data

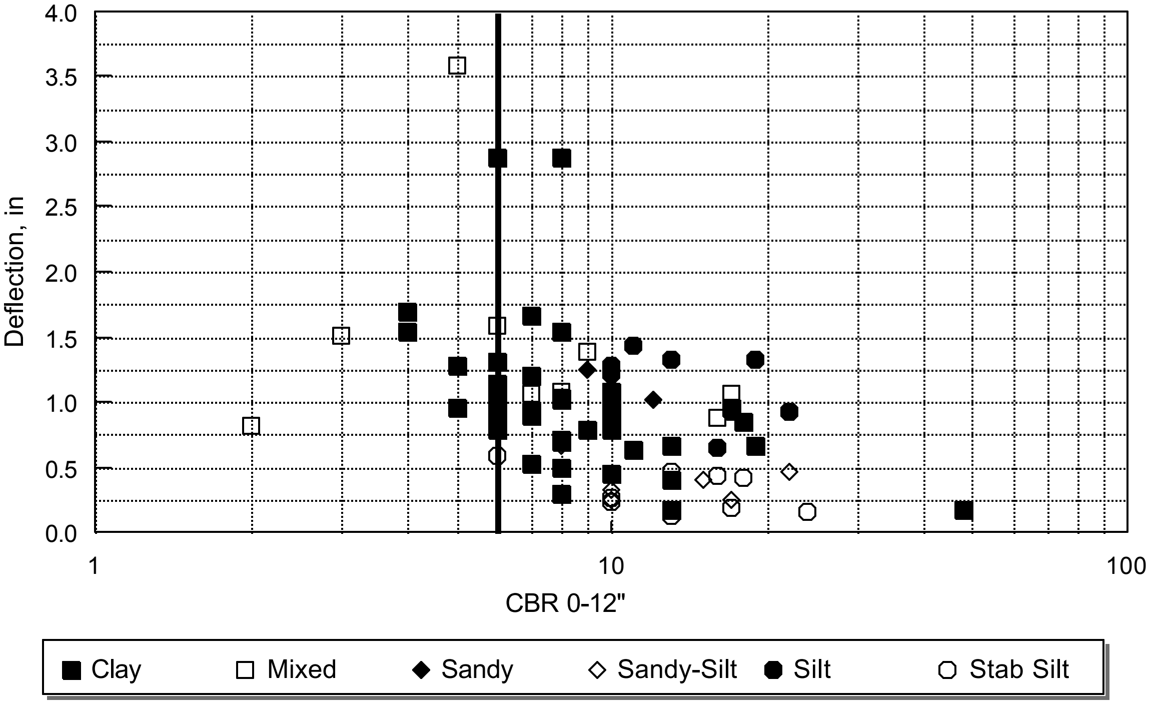


Figure 3.4 Deflection vs CBR

All Year 2000 Data

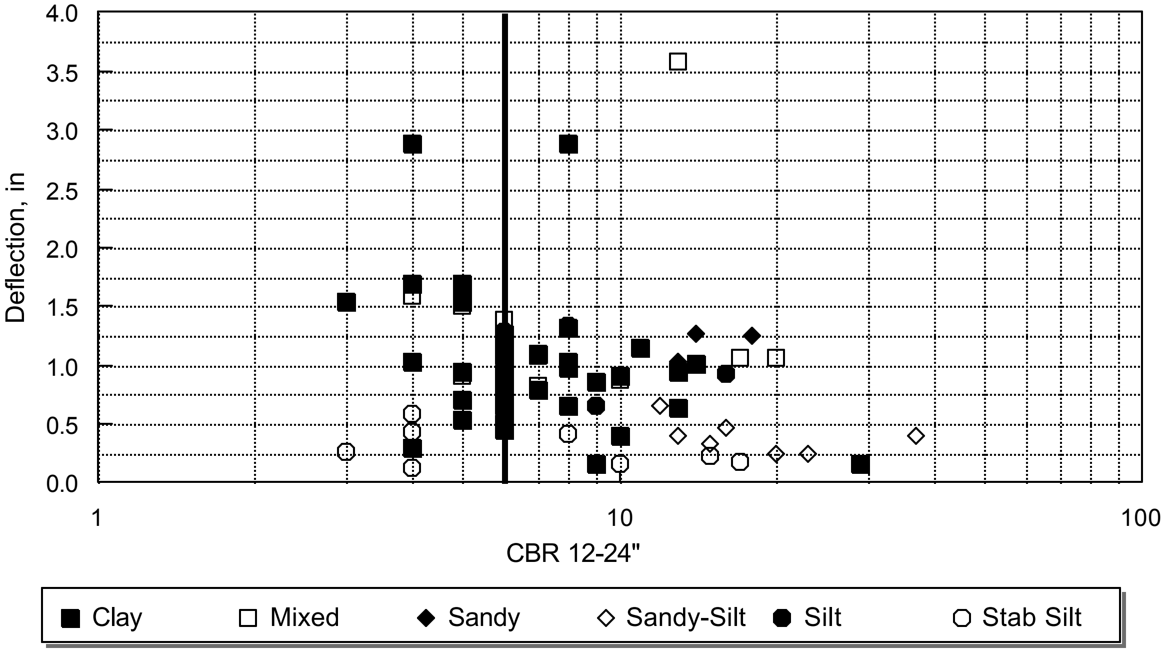


Figure 3.5 Deflection vs CBR
All Year 2000 Data

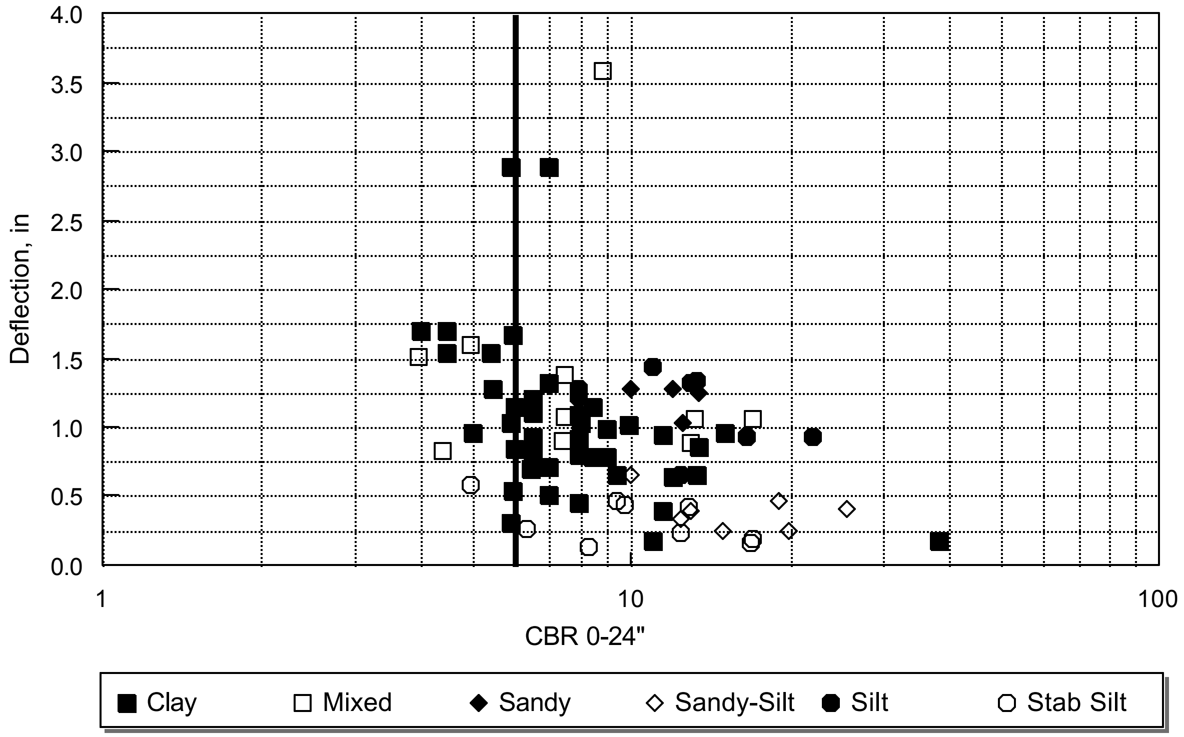


Figure 3.6 Deflection vs CBR
All Data With CBR<7 from 12-24"

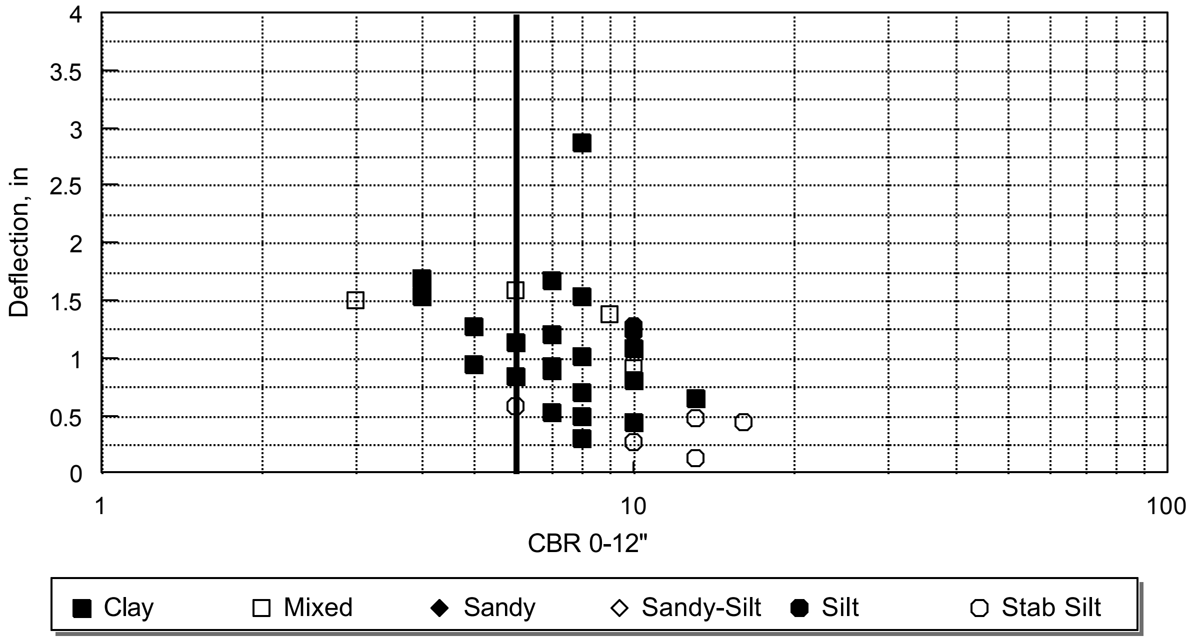


Figure 3.7

RDW-CBR Comparison Plot

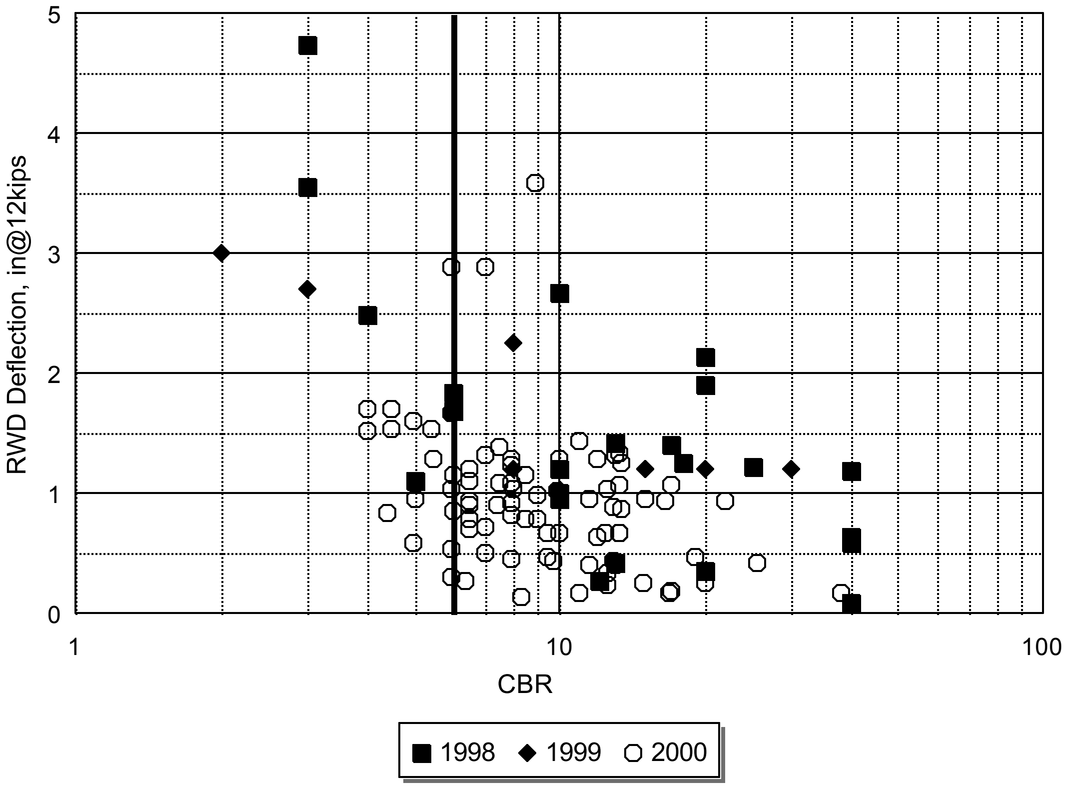


Figure 3.8
All D2 Test Data

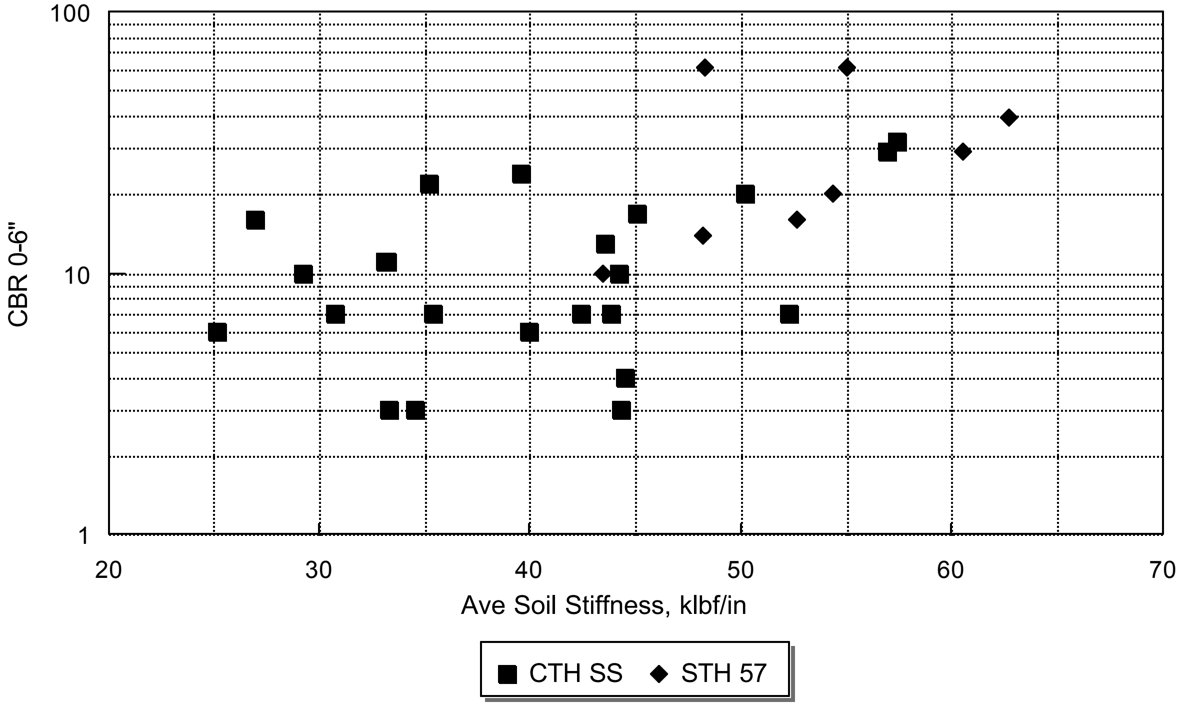


Figure 3.9
All D2 Test Data

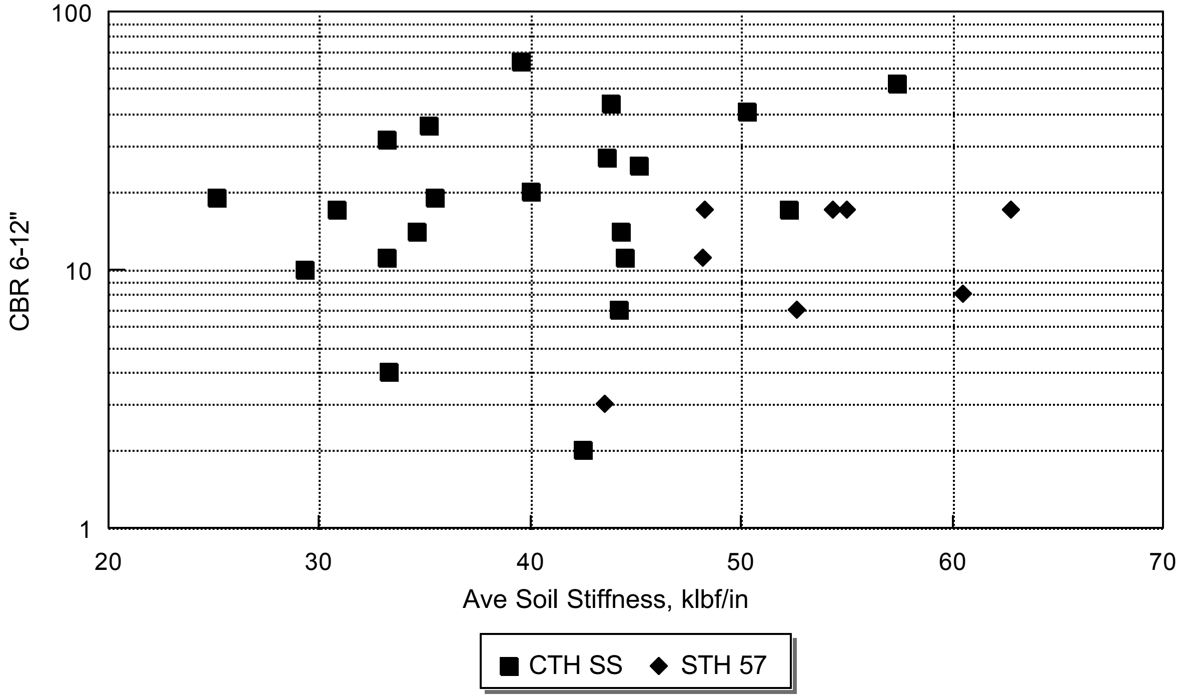


Figure 3.10
All D2 Test Data

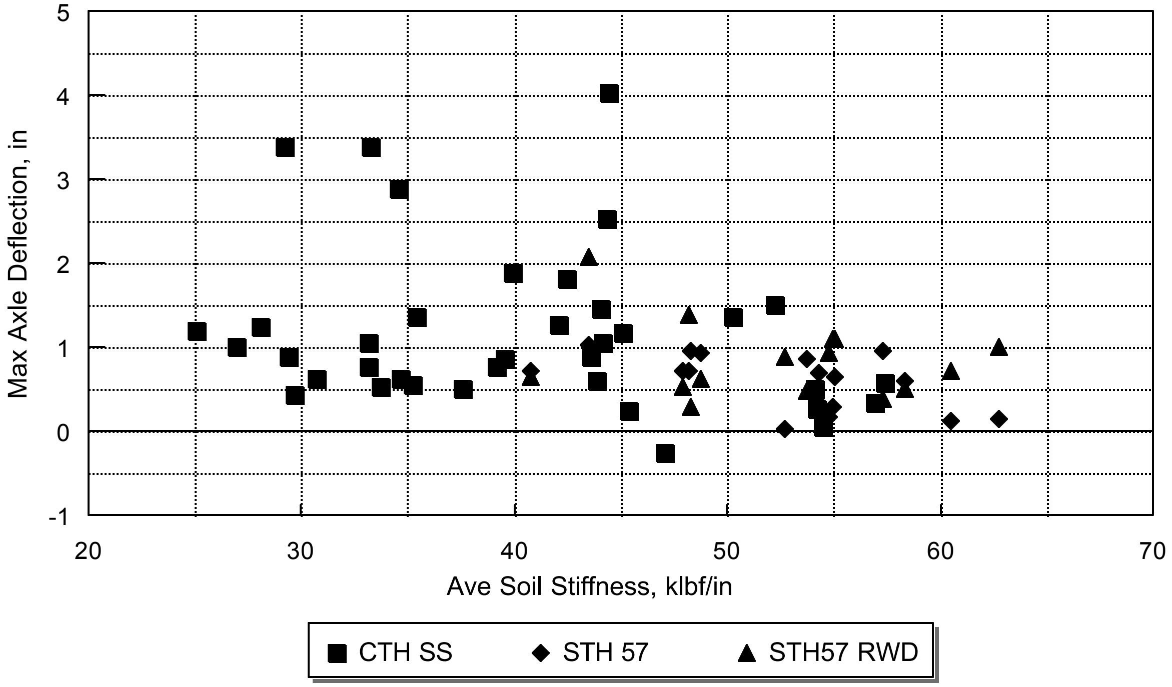


Figure 3.11
All D2 Test Data

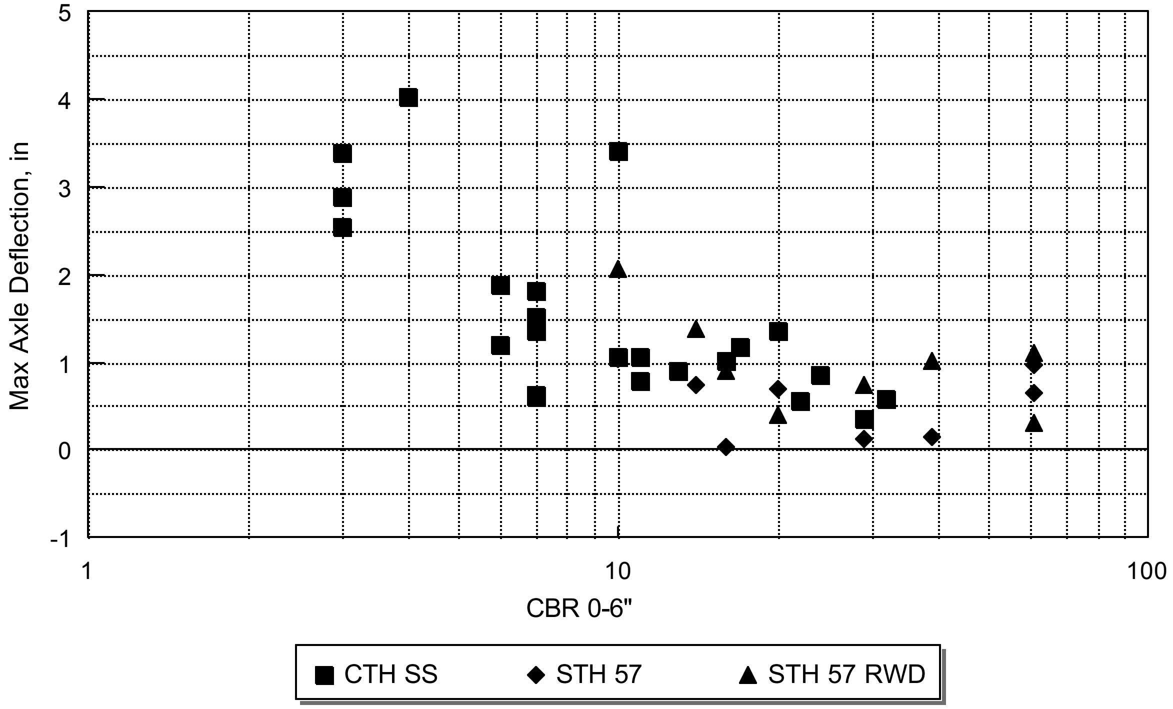


Figure 3.12
All D2 Test Data

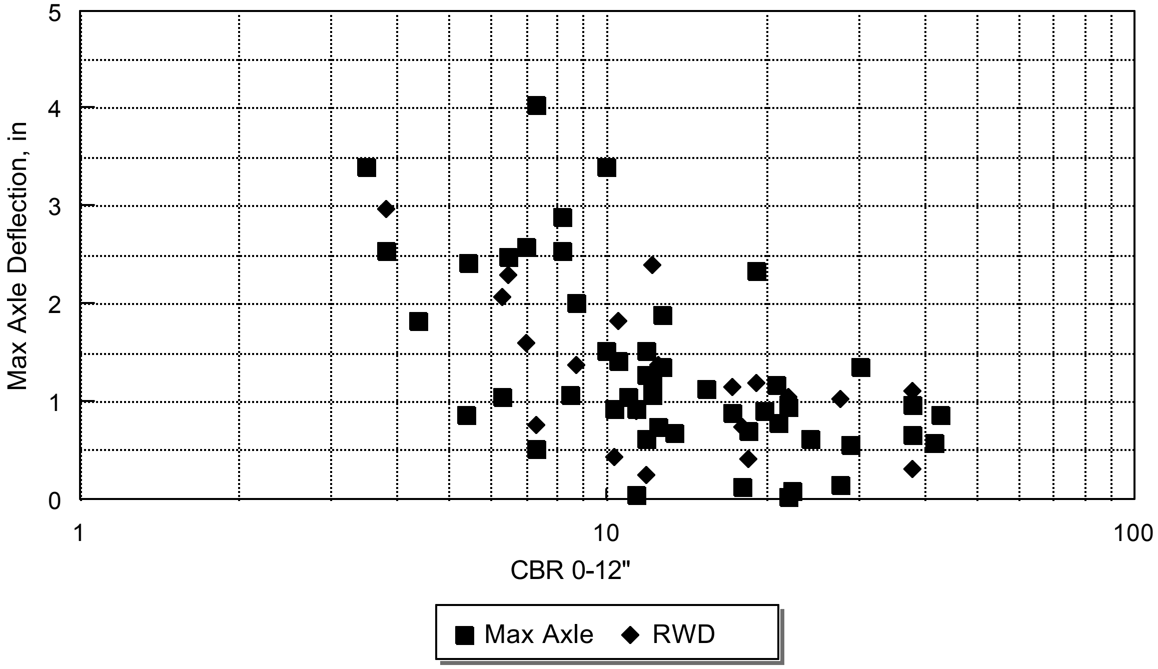


Figure 3.13
CBR-Deflection Comparison

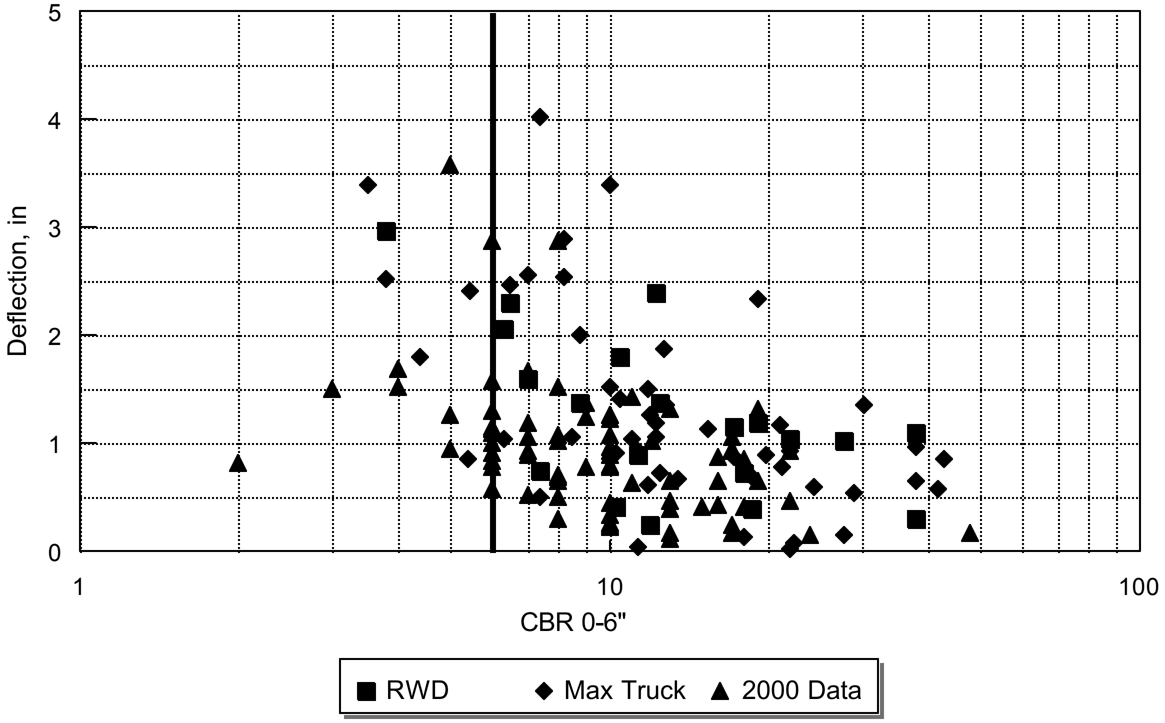


Figure 3.14

STH 57-Ozaukee Co-All RWD Test Results

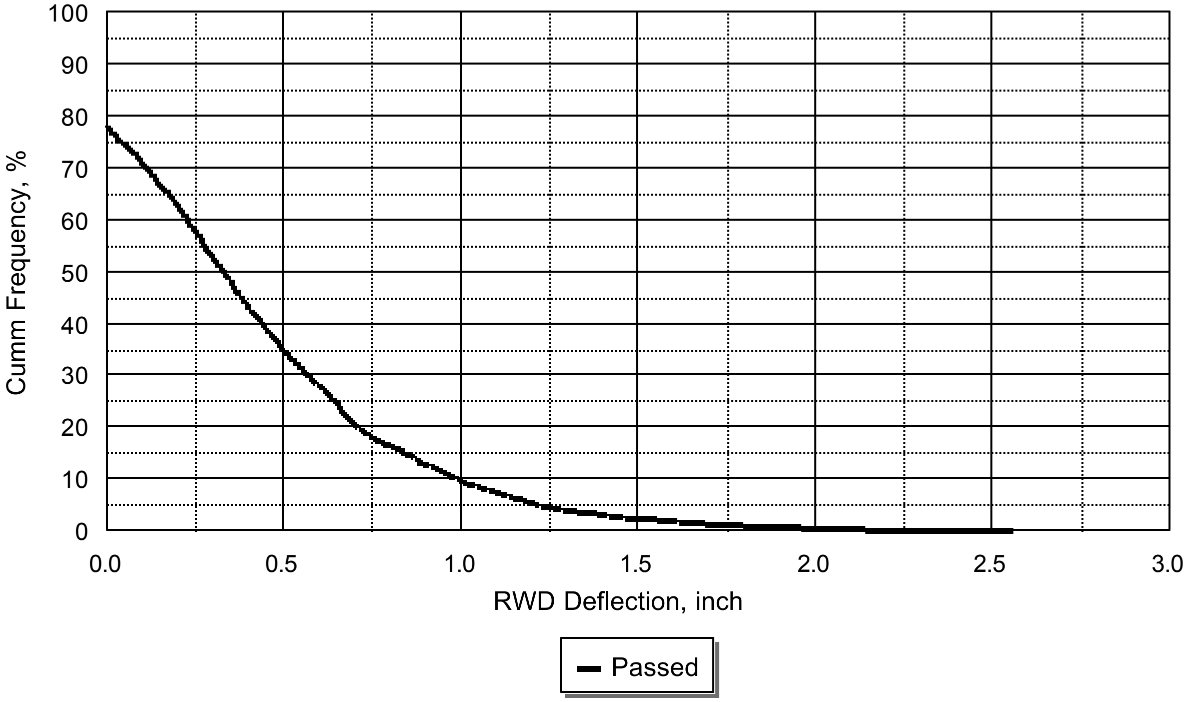


Figure 3.15

STH 57-Sheboygan Co- All RWD Test Results

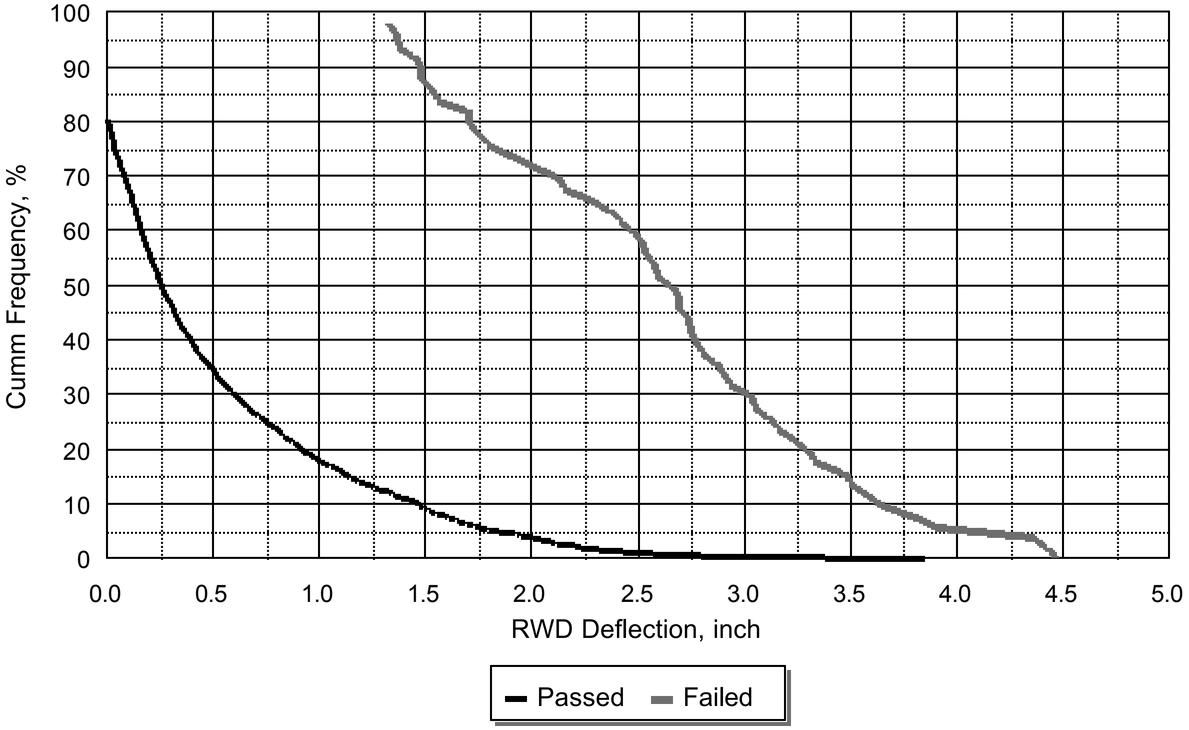


Figure 3.16
USH 41-Oconto Co-All RWD Test Results

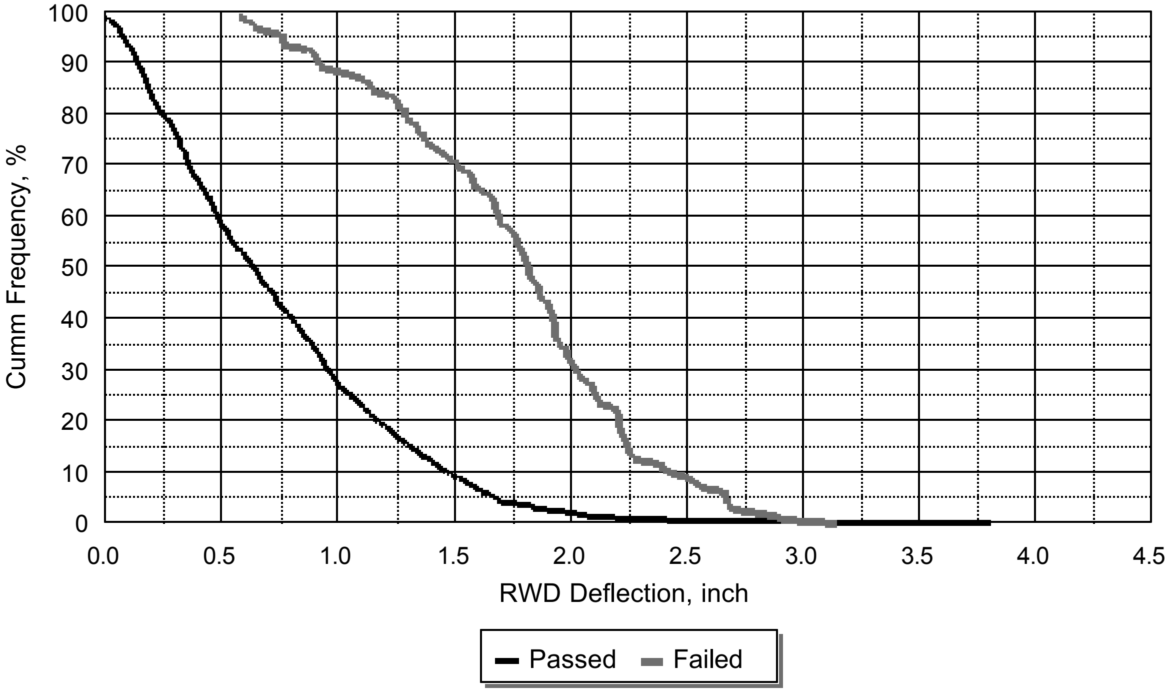


Figure 3.17
All 2001 RWD Data

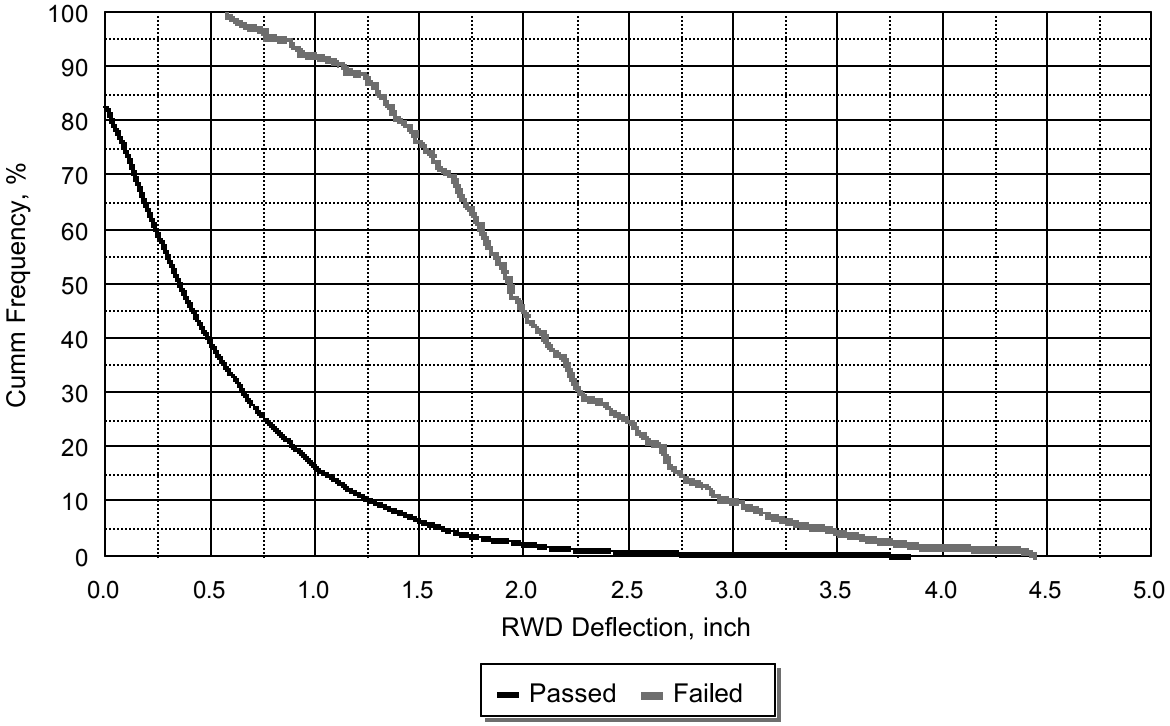


Figure 3.18

CTH SS-Waukesha Co-All Truck Test Results

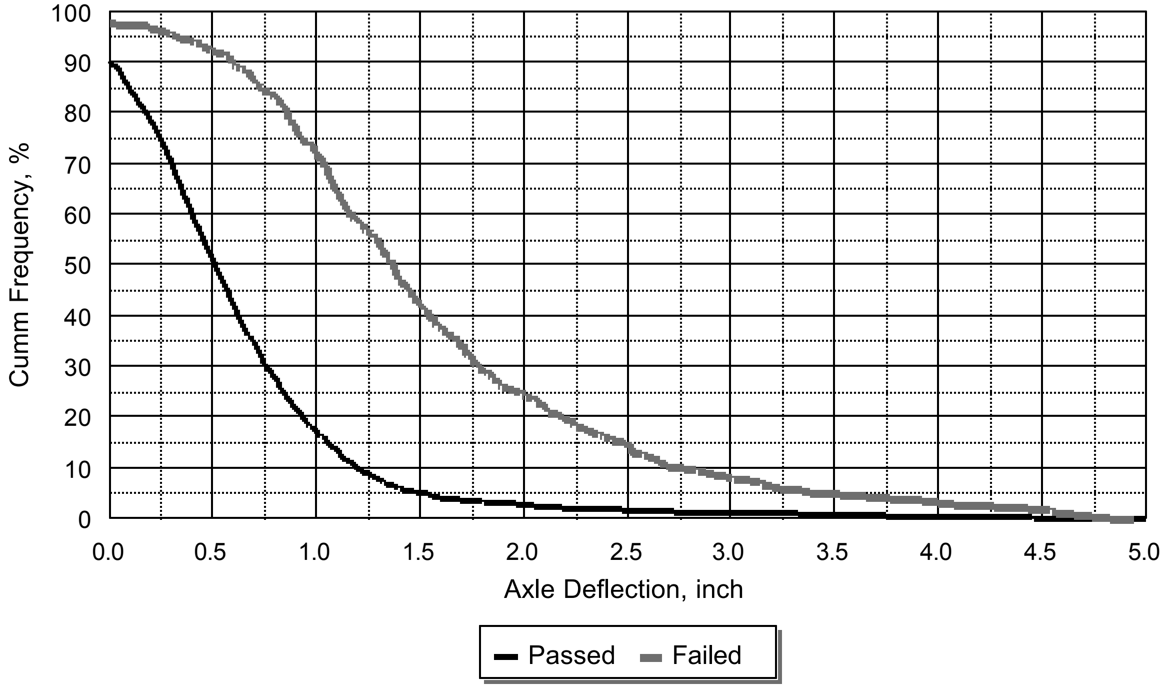


Figure 3.19

STH 57-Ozaukee Co-All Truck Test Results

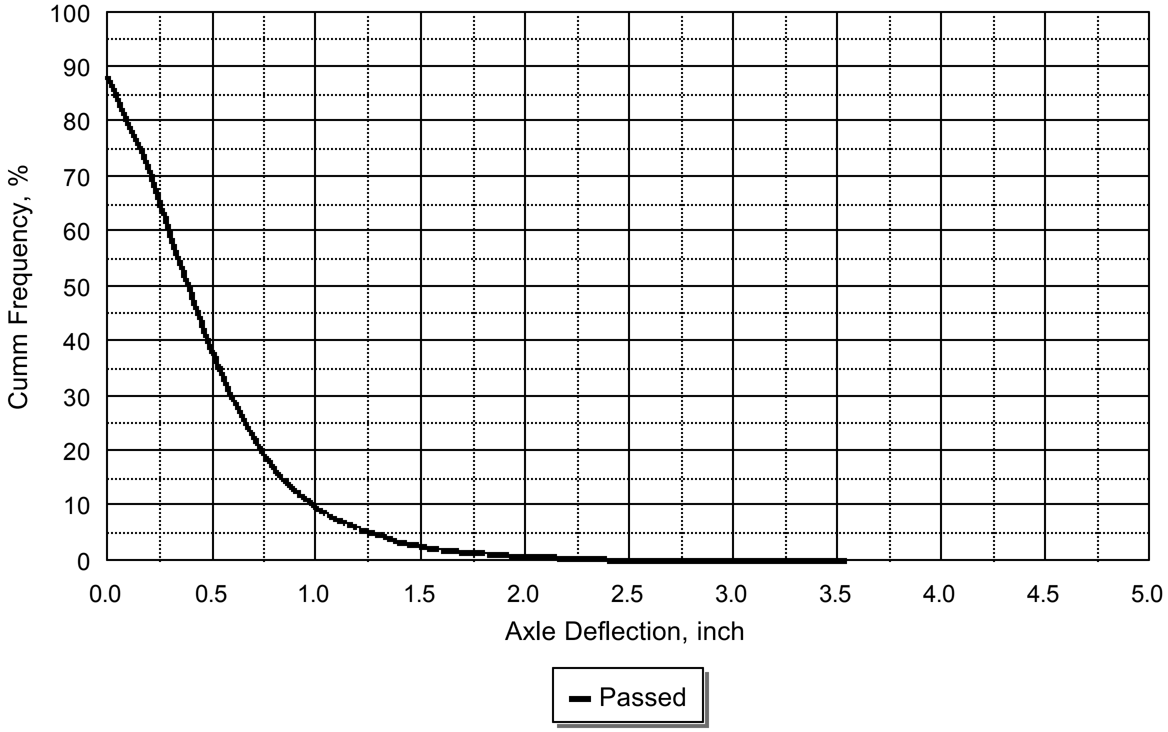


Figure 3.20

STH 57-Sheboygan Co-All Truck Test Results

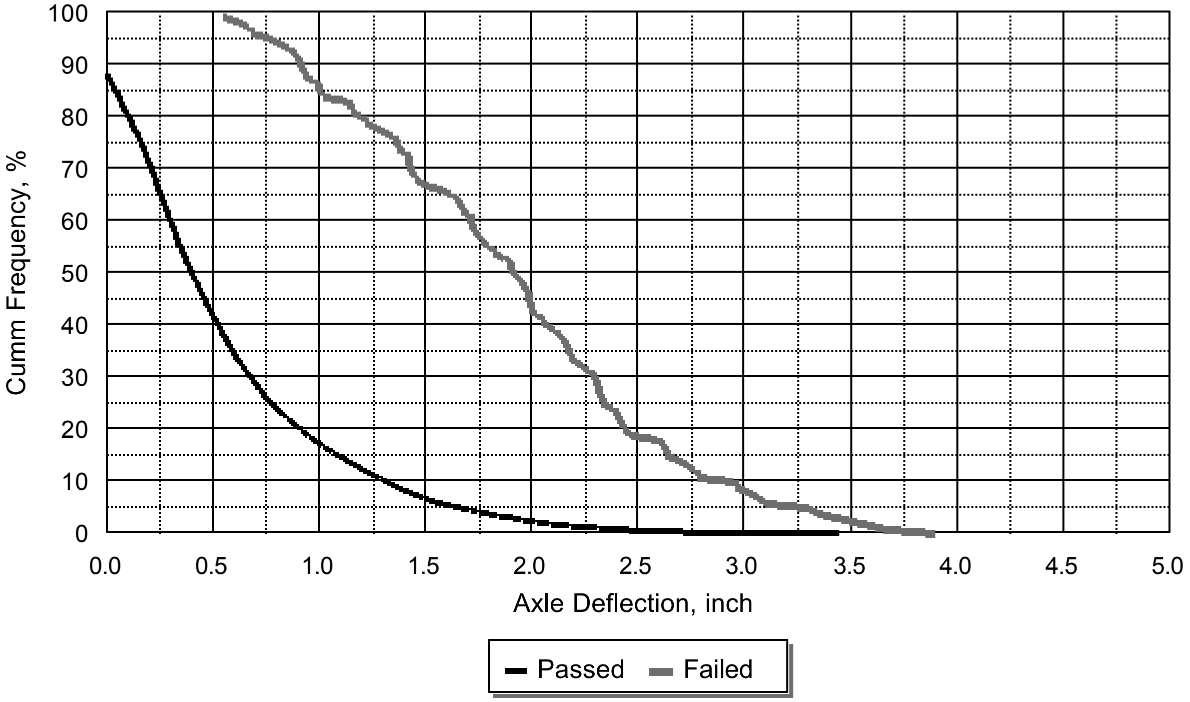


Figure 3.21

USH 41-Oconto Co-All Truck Test Results

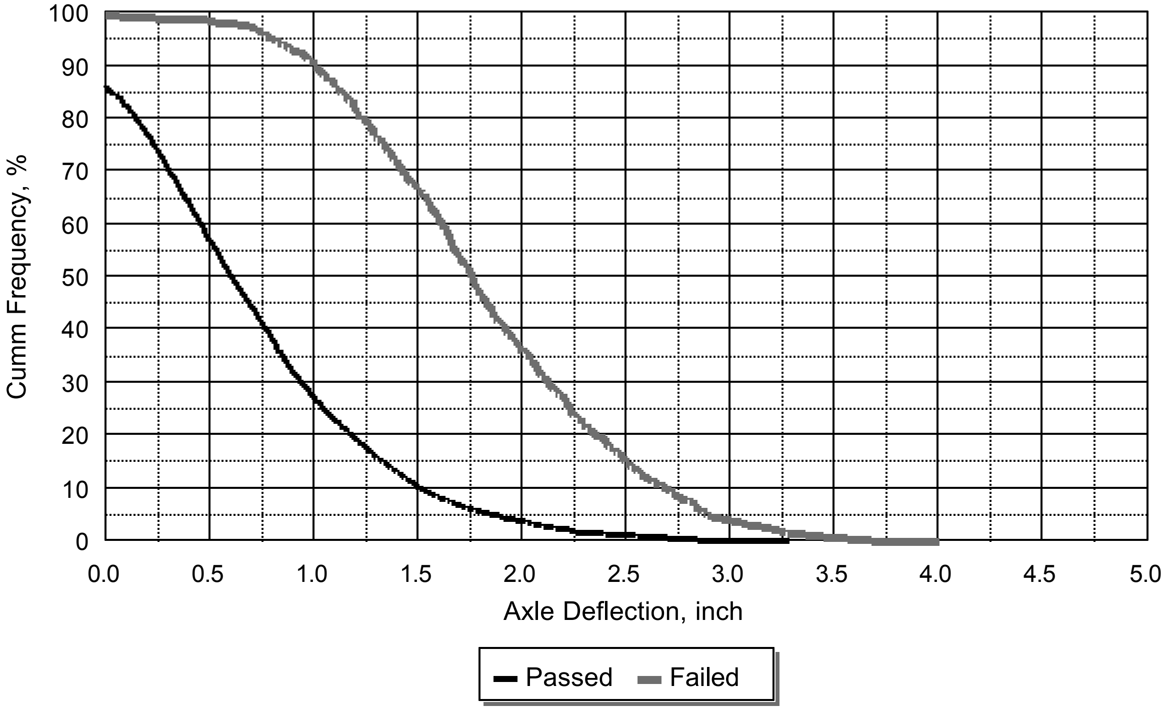


Figure 3.22

All 2001 Projects-All Truck Test Results

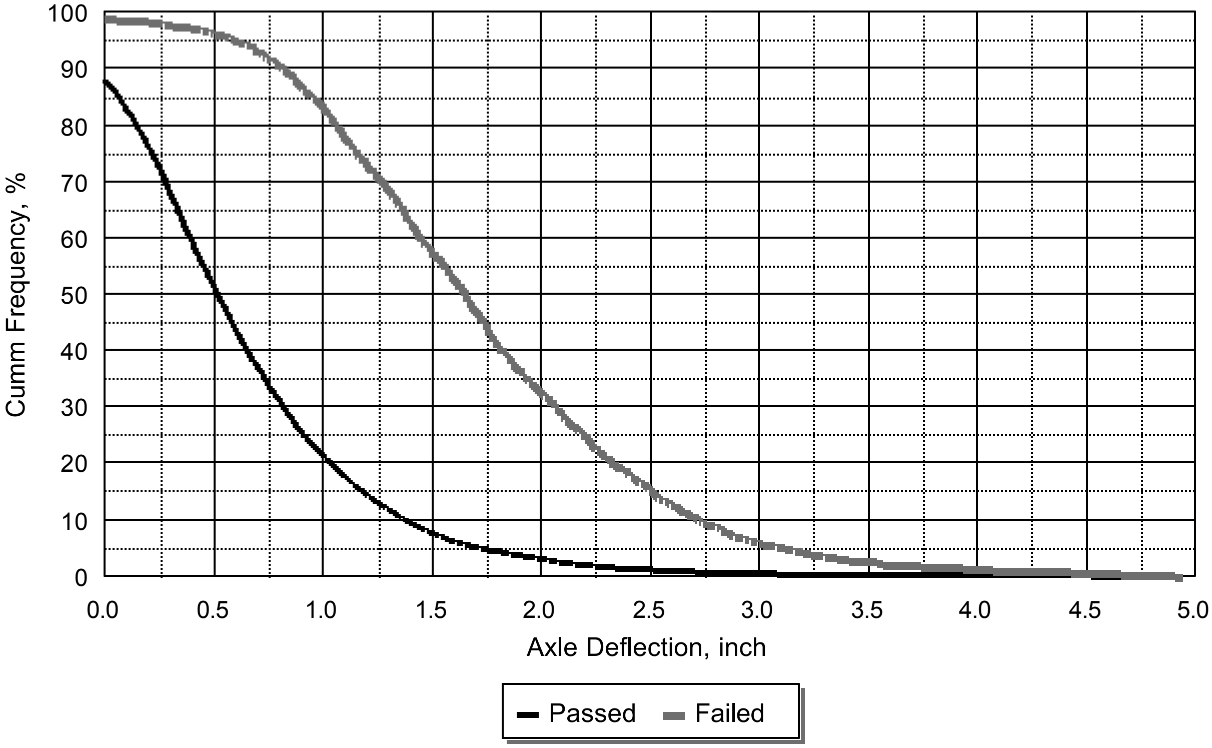


Figure 4.1 Proctor-CBR Results
STH 164 - Silty Soil

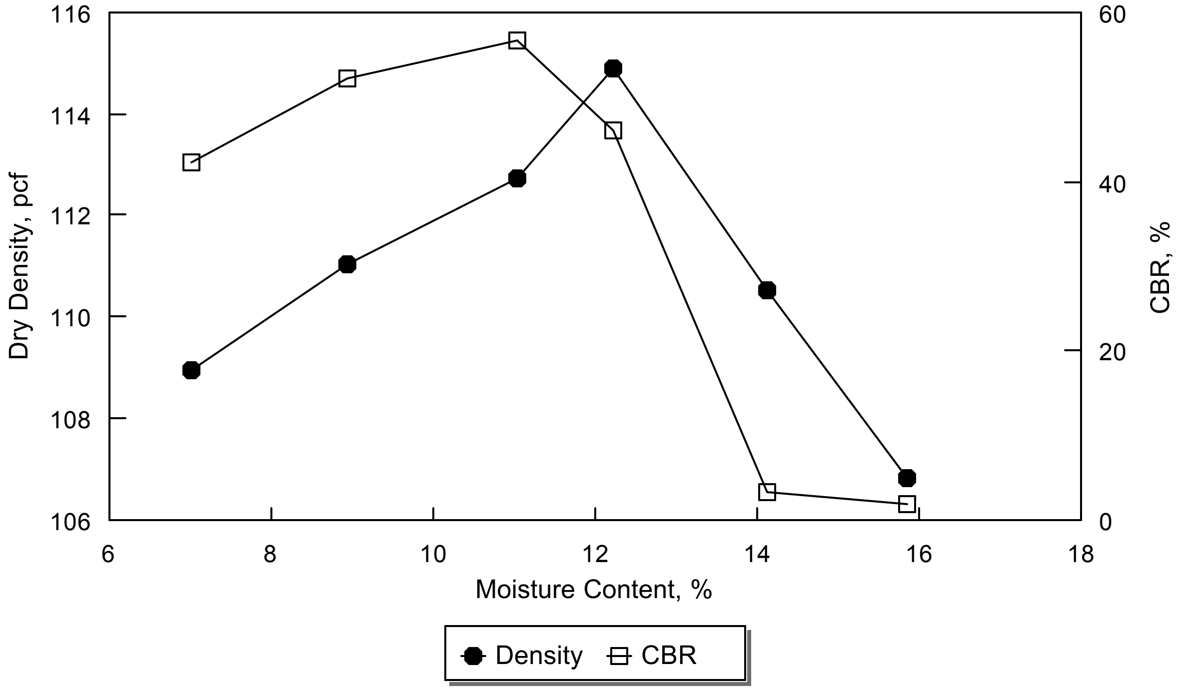
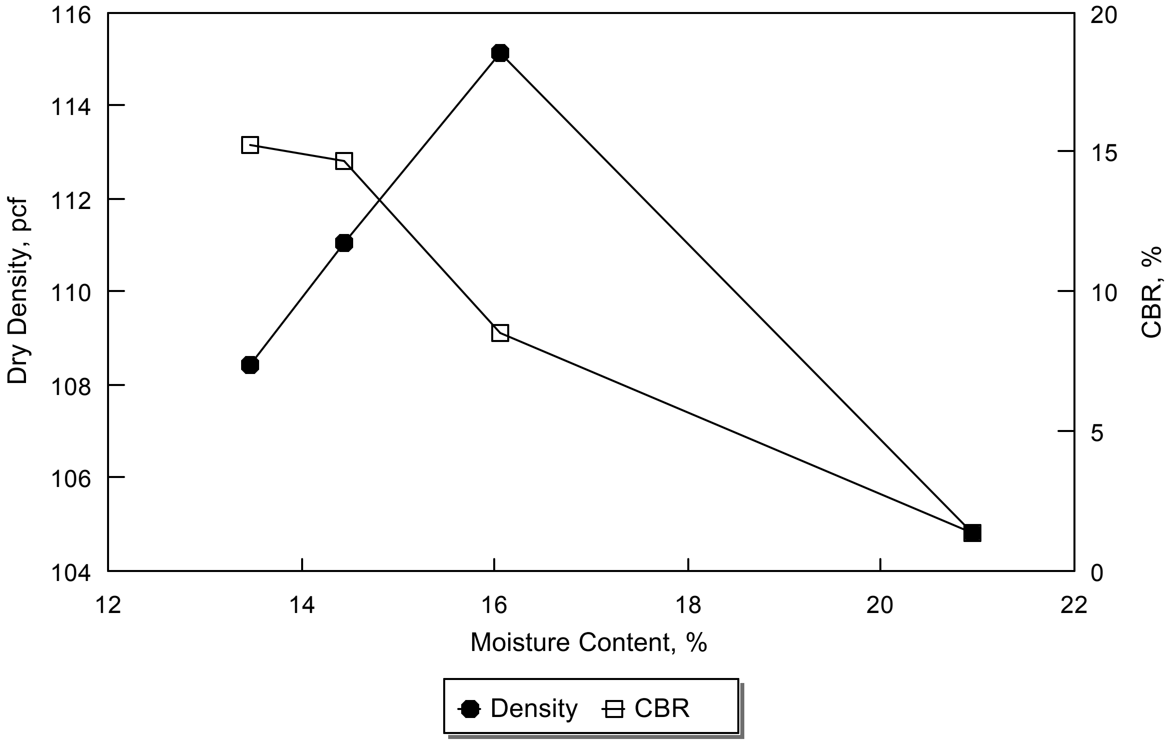


Figure 4.2 Proctor-CBR Results
STH 57 - Red Clay



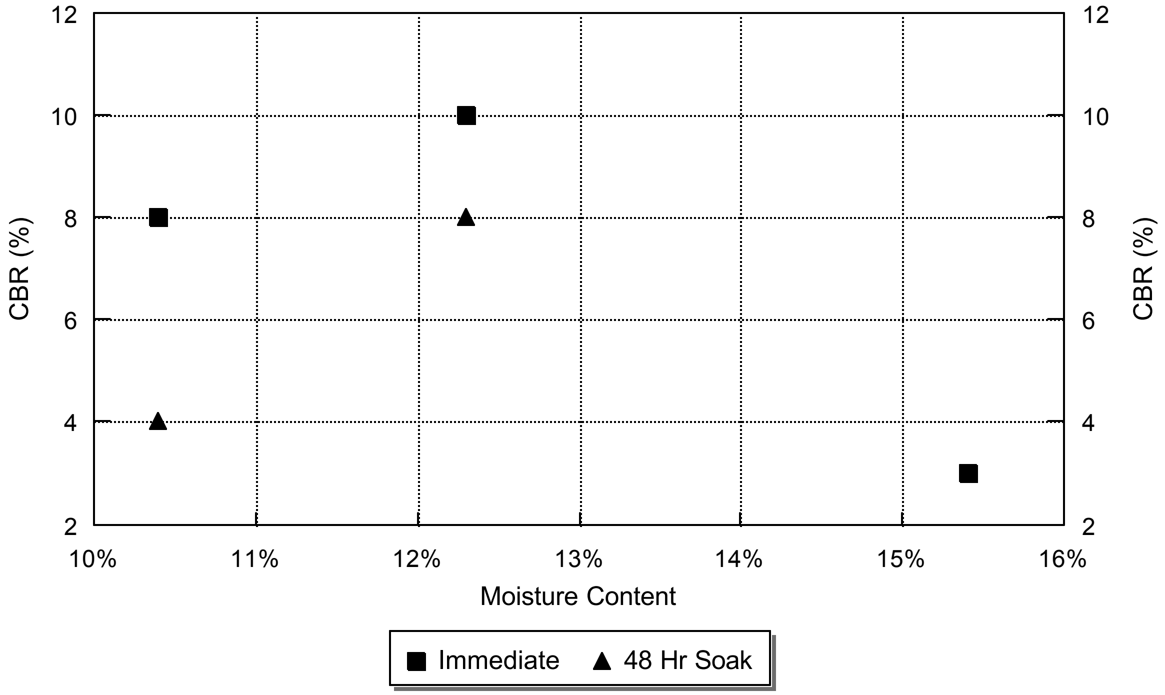


Fig 4.3 Harvard/CBR Results

STH 33 Silt

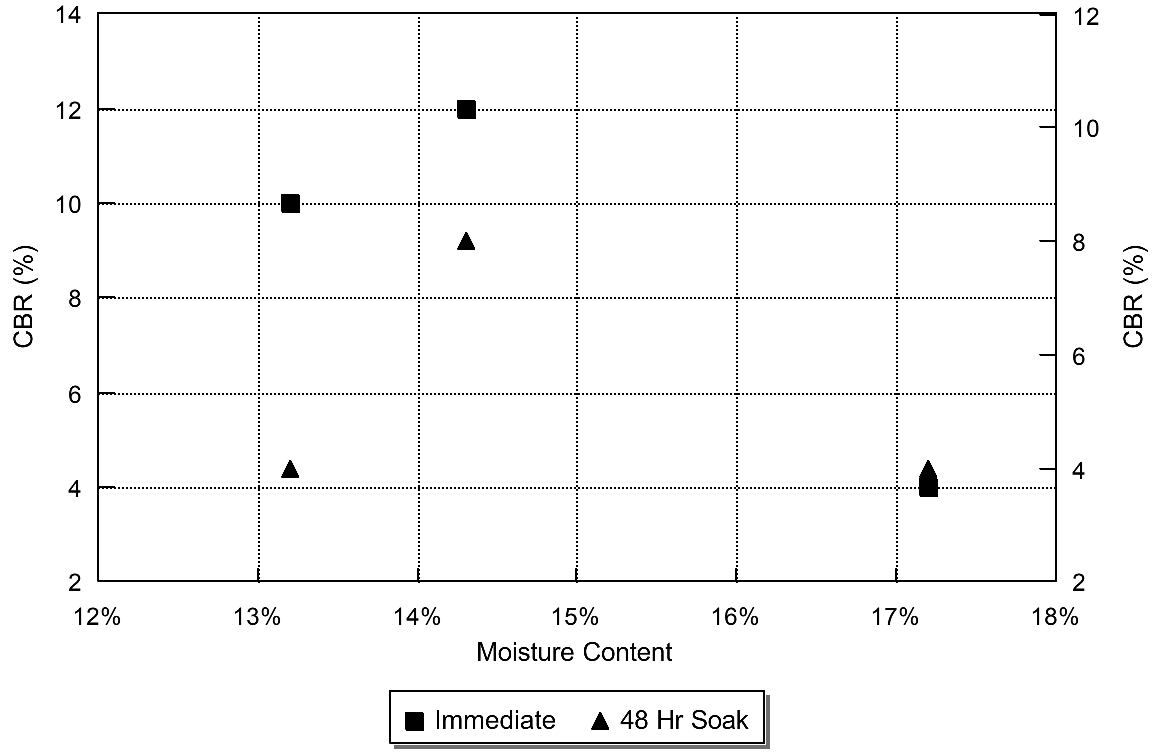


Fig 4.4 Harvard/CBR Results

STH 57 Red Clay

Fig 4.5 Harvard/CBR Results
STH 33 Silt - 13% Moisture