# WEIGHT-VOLUME RELATIONSHIPS AND CONVERSION FACTORS FOR SOILS AND AGGREGATES OF WISCONSIN

By

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Civil Engineering-Master of Science

2024

# ABSTRACT

This research aimed to develop accurate earthwork expansion and conversion factors for various geomaterials, thereby enhancing the accuracy of earthwork calculations for Wisconsin's roadway construction. Survey results from 26 state Departments of Transportation (DOTs) were obtained to understand existing practices of earthwork calculations and show that only about 31% of the DOTs surveyed provide specific expansion factor equations for commonly used soils. Less than half of the DOTs consistently align their design expansion factors with post-construction data. For aggregates, the survey results were less conclusive, with only about 23% of DOTs providing conversion factors, and a notable lack of consistent data alignment between design factors and post-construction results. These findings reveal that practice for applying earthwork factors substantially relies on personnel experience and a wide variety of methodologies, thus highlighting the need for a more systematic approach. To address this, comprehensive field and laboratory testing was conducted on 29 aggregates and 14 natural soil types collected across Wisconsin. Test results were used to develop a suite of expansion and conversion factors for natural soils and aggregates in various states of compaction (bank, loose, compacted). Expansion factors for natural soils from the compacted to bank state show considerable variation, with factors for sands ranging from 1% to 15%, silts at 12%, and clays between (-5)% to 9%. Results for aggregates show a range of conversion and expansion factors between 1.50 to 1.98 and 27% to 60%, respectively. There are notable variations in factors across different material types, in particular with overconsolidated clays. An Excel-based decision-making tool was developed that utilizes the index properties of materials to accurately estimate expansion and conversion factors. The findings of this study are crucial for practitioners in the field of geotechnical engineering and provide a comprehensive framework for precise earthwork calculations. These insights offer a thorough understanding of the behavior of geomaterials under different conditions, which is essential for improving the accuracy and reliability of construction projects. The methodologies and tools developed through this research can be effectively applied in similar geotechnical contexts, offering significant benefits for roadway construction and related earthwork applications.

This work is dedicated to my dear grandmother Fatma Yesilkas, whose memory will always remain in my heart. To my mom, Selma Bulduk, and my dad, Zekeriye Bulduk, your endless support and love made all of this possible. I also dedicate this to my beloved wife, Feyza Betul Bulduk, my love and best friend, for always being there with understanding and patience. And to Dr. Ahmet Gokce, whose guidance and support have profoundly shaped my career.

# ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my committee chair, Dr. Bora Cetin, for his invaluable guidance, motivation, and patience throughout my graduate studies. His advice, assistance with my research, technical writing, presentations, and the opportunities provided while working under his supervision were pivotal to the success of this work. His unwavering support was crucial to its completion.

My sincere thanks also go to my committee members, Dr. Karim Chatti and Dr. Surya S. C. Congress, for their valuable time, suggestions, and support throughout this research project. Learning under their guidance was a remarkable opportunity.

I extend my gratitude to Dr. William J. Likos and Dr. Tuncer B. Edil for supervising this research as co-Principal Investigators. Our collaborative efforts, including regular meetings and their technical support, have been vital in bringing this project to completion. Their insights and expertise have significantly enhanced the quality and scope of our research. I also wish to express my appreciation to Dr. Hyunjun Oh, who was instrumental in the initial stages of our project, for his early contributions that helped pave the way for our subsequent achievements.

I would also like to thank Dr. Haluk Sinan Coban for his dedicated support and time in conducting the field tests essential for this research. My appreciation extends to team members Oguzhan Saltali, Dr. Ceren Aydin, Mohammad Wasif Naqvi, Celso Santos, and Md Fyaz Sadiq for their contributions and support in both field and laboratory testing.

I am grateful to the Wisconsin Highway Research Program (WHRP) for funding this research and wish to acknowledge the Project Oversight Committee (POC) for their guidance.

Last but certainly not least, my deepest love and appreciation go to my parents, wife, sisters, and brother for their unwavering support and encouragement throughout my journey.

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# CHAPTER 1:INTRODUCTION

## 1.1 Background

Accurate estimation of the state of compaction of soils and aggregates in earthwork design calculations is crucial for both the planning and financial aspects of roadway construction projects. Earthwork construction involves the excavation, hauling, and placement (cut-haul-fill) of geomaterials, which include natural soils such as gravel, sand, silt, and clay, virgin aggregates such as dense graded base (DGB) and backfill materials, large-sized rock materials such as breaker run, and recycled aggregates such as recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP). During the cut-haul-fill cycle, these geomaterials experience considerable volume changes, including generally positive volume change after excavation from the "bank" state to the "loose" state (referred to as expansion) and generally negative volume change (shrinkage) from the bank state to the compacted state after construction. Uncertainty in the weight-volume state of geomaterials during these transitions can lead to a mismatch between initial earthwork estimates and the actual volume of materials used or required in construction, often directly impacting project cost for materials priced on a cost-per-unit-volume basis. Inaccuracies in earthwork estimations are frequently attributed to improper use and/or uncertainty in shrinkage and expansion factors designed to account for volume changes as materials transition through different states during construction: the bank state, loose (stockpile/hauling) state, and compacted state, as shown in Figure 1.1.

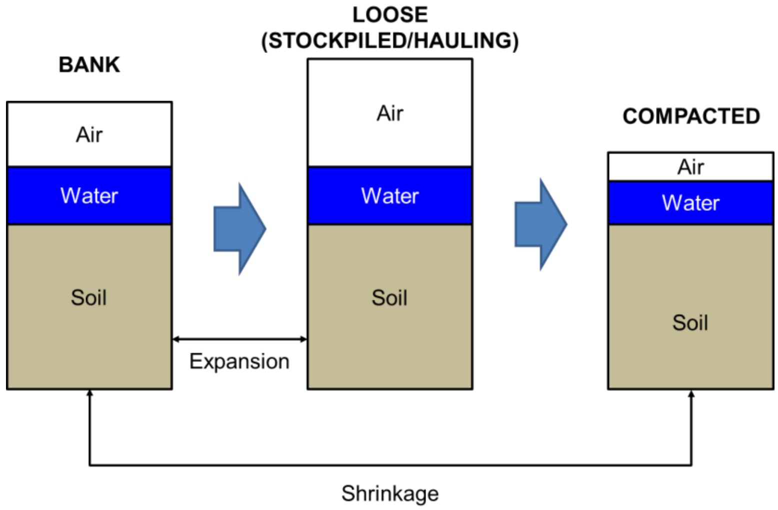


**Figure 1.1 Schematic diagram of geomaterial states**

## 1.2 Earthwork Calculation Methods

The terminology and procedures used in calculating expansion and shrinkage factors for geomaterials vary among different agencies and sources. A shrinkage factor is commonly employed to determine the volume change from the bank to the compacted state (Eq. 1) in earthwork calculations, while an expansion (or swell) factor is applied to determine volume change between the bank (e.g., deposit or borrow source) and loose states (Eq. 2). Equations 1 and 2 are not used by the Wisconsin Department of Transportation (WisDOT).

WisDOT employs the ‘expand the fill’ method to calculate the amount of natural soil required from its bank state by expanding anticipated fill (compacted) volume (Eq. 3). Table 1.1 presents typical soil expansion values employed by WisDOT based on generalized soil type.

**Table 1.1 Typical expansion values (WisDOT, 2017)**

| Soil Type | Typical Expansion Value (%) |
|---|---|
| Clean Sands | 10 – 15 |
| Silty Sands | 15 – 25 |
| Silts | 20 – 30 |
| Silty Clays and Clays | 25 – 35 |

Unlike natural soils, WisDOT does not employ expansion factors for aggregates. Instead, WisDOT uses weight-to-volume conversion factors, which are essentially compacted unit weights (tons/cubic yard) for aggregates. Statewide conversion factors for compacted granular materials are based on regional experience and are detailed in Table 1.2 (WisDOT, 2022a).

**Table 1.2 Compacted aggregate conversion factors (WisDOT, 2022a)**

| Material Name | Conversion Factor (tons/cubic yard) |
|---|---|
| Dense Graded Base ¾-inch | 1.75 – 2.1 |
| Dense Graded Base 11/4-Inch | 1.75 – 2.0 |
| Dense Graded Base 3-inch | 1.75 – 2.2 |
| Breaker Run | 1.60 – 1.9 |
| Select Crushed Material | 1.70 – 1.9 |
| Backfill Structure (Grade A or B) | 1.75 – 2.0 |
| Backfill Granular (Grade 1 or 2) | 1.50 – 1.7 |

In this thesis, WisDOT's methodology for both natural soils and aggregates was adopted. For natural soils, Equations 3 and 4 are utilized to calculate the expansion factors from the compacted to bank state and from the bank to loose state, respectively. For aggregates, in addition to applying WisDOT's statewide conversion factors, a methodology was developed to calculate expansion factors. This approach involved using the proposed Equation 5 to determine the volume change from the compacted to the loose (stockpile) state for aggregates.

$$\text{Shrinkage Factor (\%)} = \left(1 - \frac{\text{weight / bank(loose) volume}}{\text{weight / compacted volume}}\right) \text{x } 100 \tag{1}$$

$$\text{Expansion (Swell) Factor (\%)} = \left(\frac{\text{weight / bank volume}}{\text{weight / loose volume}} - 1\right) \text{x } 100 \tag{2}$$

$$\text{Expansion Factor (\%)} = \left(\frac{\text{weight / compacted volume}}{\text{weight / bank volume}} - 1\right) \text{x } 100 \tag{3}$$

$$\text{Expansion Factor (\%)} = \left(\frac{\text{weight / bank volume}}{\text{weight / loose volume}} - 1\right) \text{x } 100 \tag{4}$$

$$\text{Expansion Factor (\%)} = \left(\frac{\text{weight / compacted volume}}{\text{weight / loose volume}} - 1\right) \text{x } 100 \tag{5}$$

### 1.3 Research Objectives

The primary goal of this project was to establish a robust and data-driven framework for weight-volume relationships and conversion factors of a diverse range of geomaterials specific to Wisconsin. A key outcome of this endeavor was the development of a data-driven Excel-based tool designed to precisely estimate/predict earthwork conversion and expansion factors. The specific objectives of the research included:

1. Conducting a comprehensive review and assessment of the current practices among various state DOTs, through reports and an online survey or interview. This review focused on the prevailing methods related to expansion and conversion factors for soils and aggregates.

2. Collecting and sampling a diverse range of soils and aggregates, including recycled materials and large-sized aggregates, to ensure the study offered a wide representation of Wisconsin's soil and aggregate types.

3. Performing detailed laboratory tests on these materials to determine their index properties and compaction characteristics.

4. Conducting a comprehensive field investigation, including in-situ density and moisture measurements of geomaterials at their different material states (bank, loose, and compacted).

5. Developing an Excel-based, data-driven decision-making tool that utilizes laboratory index properties of soils and aggregates to accurately estimate the expansion and conversion factors of geomaterials between different states.

## 1.4 Research Approach

The approach of this study was structured to address the diverse characteristics of geomaterials in Wisconsin. Initially, the research focused on understanding existing practices of earthwork calculations through a review of state DOTs' methodologies and a survey to capture the current state of practice in estimating and applying expansion and conversion factors. Following this, a wide range of soils and aggregates were collected and analyzed, including recycled and large-sized aggregate materials. Laboratory tests were conducted to determine key properties and characteristics of these materials. Field tests were conducted to measure in-situ density and moisture conditions in different material states (e.g., bank, loose, compacted). The findings from these investigations were used to develop an excel-based tool designed to accurately estimate/predict conversion and expansion factors for various geomaterials based on their index properties, thereby enhancing the precision and accuracy of earthwork calculations.

## 1.5 Literature Review

A comprehensive literature review was conducted to gain a better understanding on determination of shrinkage, expansion, and conversion factors. The main objective of this literature review was to summarize the current knowledge of other departments of transportation (DOTs) about earthwork volumetric calculations. The review aimed to gather information from other studies about recommended in-situ or laboratory test methods and any parameters affecting these factors. All available documents provided by fifty different state DOTs were reviewed to summarize their approach to developing these factors. This literature review covers design manuals, geotechnical manuals and standard specifications of DOTs, research papers, and books, research reports to government agencies.

The literature review revealed that the majority of state DOTs consider shrinkage, expansion, or conversion factors in earthwork calculations. While most of these DOTs have developed shrinkage and expansion factors based on engineering judgment, some provide specific factors based on soil or bedrock type. However, for some state DOTs, no specific recommendations or exact factors for shrinkage or expansion were found.

While most of the state DOTs give recommended shrinkage or expansion factors based on soil or bedrock type, recommended factors provided by Indiana DOT rely on the amount of the earthwork whereas Tennessee DOT specifies shrinkage factors of earth depending on the depth of cut (InDOT, 2013; TDOT, 2021). Some state DOTs like North Carolina DOT and Massachusetts DOT, define shrinkage factor to estimate the loss of material during stockpiling or clearing and grubbing (MassDOT, 2006; NCDOT, 2021). Ohio DOT is unique in providing an equation for estimating shrinkage factor before compaction in the field (ODOT, 1998). California DOT, Washington State DOT, and New York State DOT use a table from the Alaska DOT Geotechnical Procedures Manual (1983) listing shrinkage and expansion factors (AKDOT, 1983). Shrinkage factors in technical documents of state DOTs range from 0% to 50% for different soil types, while expansion factors range from 0% to 72% for different rock types, as listed in Appendix C, Tables A.1 and A.2.

Several other studies, dating back to 1981, were reviewed to gain historical insights into the weight/volume changes of soil or rock during earthwork. Church (1981) was one of the first to provide precise shrinkage and expansion factors, compiling data from engineers, contractors, mining companies, machinery manufacturers, and handbook authors. The detailed factors from Church's study are presented in Table A.3 in Appendix C. Federal Highway Administration (2022) design manual contains a table of factors similar to those provided by Church, detailed in Table A.4 in Appendix C. Burch (1997) uniquely offers factors based on the final degree of compaction and discusses ground loss due to heavy equipment, as outlined in Table A.5 in Appendix C. Chopra (1999) conducted a comprehensive study to develop improved shrinkage and expansion factors in Florida, involving tracking soil volumetric changes through laboratory and field tests. This study’s findings significantly differed from the factors used by Florida DOT and suggested using weigh stations for accurate weight/volume conversions, as shown in Table A.6 in Appendix C.

In summary, the literature review shows that previous studies are mainly based on historical data and engineering judgment and limited number of studies conducted test in the laboratory and in the field to determine shrinkage and expansion (swell) factors. Moreover, only a limited number of DOTs exercised to create a database, highlighting a lack of comprehensive surveys in determining shrinkage and expansion factors across DOTs.

## 1.6 Organization of the Thesis

This thesis is organized into six chapters. Chapter 1, "Introduction," introduces the research objectives, summarizes the background and literature review, and outlines the research approach. Chapter 2, "Survey Results," presents a summary of the survey conducted with state DOTs to understand their practices in determining key geotechnical factors for earthwork construction. Chapter 3, "Research Methodology," details the processes of material collection and field and laboratory testing. Chapter 4, "Test Results and Analysis," provides a comprehensive summary of the field and laboratory test results and the subsequent analysis, focusing on estimating the expansion and conversion factors for different types of natural soils and aggregates. Chapter 5, "Summary and Conclusions," along with Chapter 6, "Recommendation and Implementation," offer a series of conclusions drawn from the research and recommendations for the implementation of the research findings.

# CHAPTER 2: SURVEY RESULTS

## 2.1 Introduction

This chapter outlines the survey results conducted with state Departments of Transportation (DOTs) to understand their practices in determining key geotechnical factors for earthwork construction. As part of this study, a questionnaire was prepared to collect information that was used to determine expansion/shrinkage values representing volume change between the natural and compacted state of natural soils and bedrocks, as well as conversion factors between the loose and compacted volume of processed construction materials (aggregates) in a truck or stockpile, or for fill during a roadway construction process. The objective of this questionnaire was to compile and synthesize the current state of Department of Transportation practices, identify expansion/shrinkage values and conversion factors based on soil/rock/geomaterial types, along with soil tests, equations, and historical databases utilized for such applications.

Responses from 26 state DOTs provide comprehensive information on the diverse methods and materials employed in earthwork construction across the United States. Figure 2.1 features a map of the United States with the states that responded to the survey highlighted, offering a visual representation of the geographical spread of the survey data. This chapter presents a detailed analysis of these survey responses, offering insights into the varied practices in geotechnical engineering and detailing how different regions approach earthwork construction.

## 2.2 Survey Method

The survey was conducted in 2022 and targeted the geotechnical or materials divisions of state Departments of Transportation (DOTs) specifically involved in earthwork and road construction. The goal was to gather valuable insights into the current practices of these divisions for determining expansion/shrinkage values and conversion factors.

The survey was structured into two main sections to comprehensively cover state DOT practices. The first section, comprising 8 questions, focuses on the expansion/shrinkage values of natural soils and bedrocks. The second section, containing 7 questions, investigates the conversion factors of aggregates, vital for the precise estimation and calculation of material quantities in road construction projects. This approach provides insights into the varied methodologies used by state DOTs for establishing accurate weight/volume relationships.

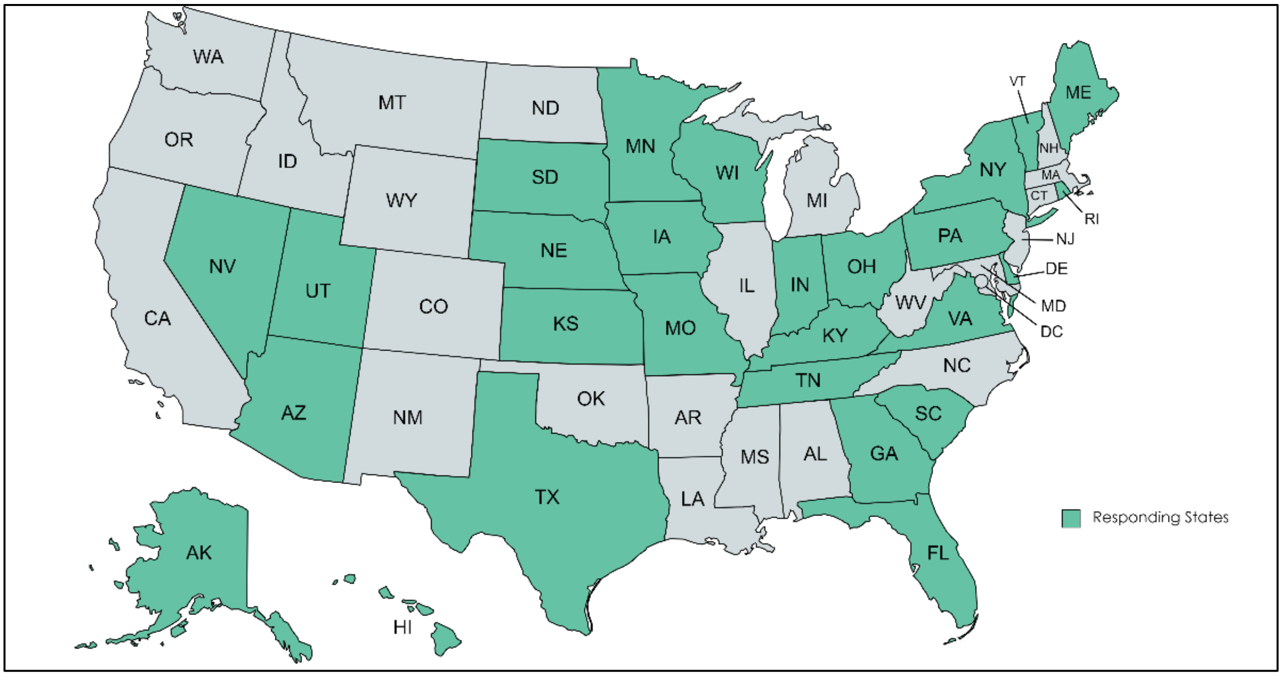


**Figure 2.1 Map of participating state DOTs**

## 2.3 Survey Results and Discussion

### 2.3.1 Part-1: Expansion/Shrinkage Factor Related Questions

The first question in the survey asked, "*What type of soils are predominantly used in your region for earthwork construction (e.g., such as excavation and compaction)?*" This question is for understanding the variety of soil types commonly employed in different states for earthwork projects. The options provided for responses included Gravel, Sand, Fine Sand, Silty/Clayey Sand, Silty/Clayey Gravel, Silty Soils, Clayey Soils, and Other. The distribution of responses to each option is represented in Figure 2.2.

Figure 2.2 shows that Sand and Silty/Clayey Sand are the most common soils used in earthwork construction, with 17 responses each. Clayey Soils follow closely with 16 responses. Silty Soils and Silty/Clayey Gravel have moderate preference, while Fine Sand and "Other" are less common. This data indicates regional preferences and geological variations in soil use during earthwork construction.

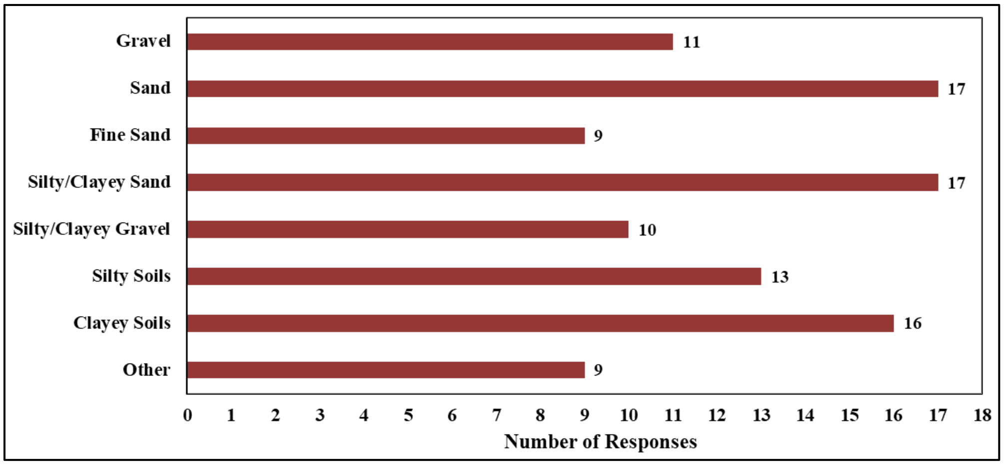


**Figure 2.2 Distribution of soil types used in earthwork construction**

The second question of the survey inquired, "*How are expansion/shrinkage values for various soil types and geomaterials determined? Do you have any equations, tables, or other references that you are using to estimate these factors?*" This question was critical for understanding the approaches state DOTs take in calculating these important values for geotechnical engineering. The results showed that 16 DOTs do not use specific equations or references, whereas 9 DOTs apply certain expansion/shrinkage factors or equations. Some respondents mentioned referencing their manuals for these factors, while others depend on engineering judgment.

The third question of the survey inquired about the methods and tests state Departments of Transportation (DOTs) employ to determine the degree of final compaction in the field. Respondents were presented with a range of options, including the Proctor test (both AASHTO T 99-Standard and AASHTO T 180-Modified), in-situ density tests, visual inspection, Light Weight Deflectometer (LWD) Test, Dynamic Cone Penetrometer (DCP) Test, and other methods not specified in the survey. The distribution of responses to each option is represented in Figure 2.3.

From the responses shown in Figure 2.3, it's clear that the Proctor tests, alongside in-situ density tests, is frequently used by 16 state DOTs as a standard method for assessing compaction. Figure 2.3 also shows that some DOTs employ LWD and DCP tests, with certain agencies incorporating additional in-situ density tests and Proctor testing in their protocol. One state notably relies solely on LWD for compaction quality checks, while another is considering its future use. These varied responses, as detailed in Figure 2.3, demonstrate a wide spectrum of methodologies adopted by state DOTs for compaction assessment in earthwork projects.

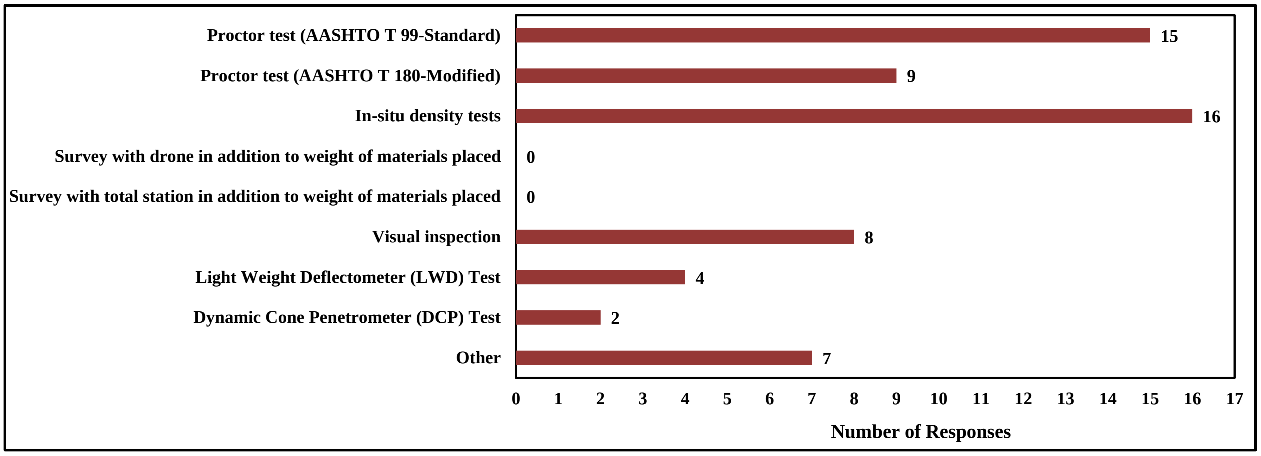


**Figure 2.3 Distribution of methods/tests used for determining final compaction by state DOTs**

The fourth question of the survey addressed what data state Departments of Transportation (DOTs) use to predict/determine expansion/shrinkage factors. Participants could mark all applicable types of data they utilize in this process. The options included soil type, maximum dry unit-weight (in the lab), optimum moisture content (in the lab), in-situ density, in-situ moisture content, fines content, gravel content, sand content, effective size diameters ($D_{10}$, $D_{30}$, and $D_{60}$), specific gravity, Atterberg limits, plasticity index, agency tables/guidance, experience/judgment, and other. The distribution of responses to each data type is represented in Figure 2.4.

The results indicated soil type as the most commonly used data, marked by 15 DOTs, and maximum dry unit-weight (in the lab) followed with 11 responses. In-situ density and moisture content data were also notably utilized by 11 DOTs. Experience/engineering judgment plays a significant role in this process, with 10 DOTs considering it as part of their process for predicting expansion/shrinkage factors. Other data such as fines content, specific gravity, plasticity index, and agency tables/guidance were less commonly chosen, reflecting varied practices and preferences in data utilization for estimating these factors.

The fifth question of the survey asked, "*Do you account for any additional factors when determining shrinkage or expansion factors?*" Respondents were able to mark all factors that apply, revealing the additional considerations taken into account by state DOTs beyond the standard data points. The range of factors included laboratory and in-situ tests, fill location, vegetation, water content, type of clay mineral in the soil, grading operations, source of material, degree of final compaction, compaction settlement, waste or spillage, depth of cuts/fills, state of soil, geological origin, weather conditions, and reliance on experience or judgment. The distribution of responses to each factor is represented in Figure 2.5.

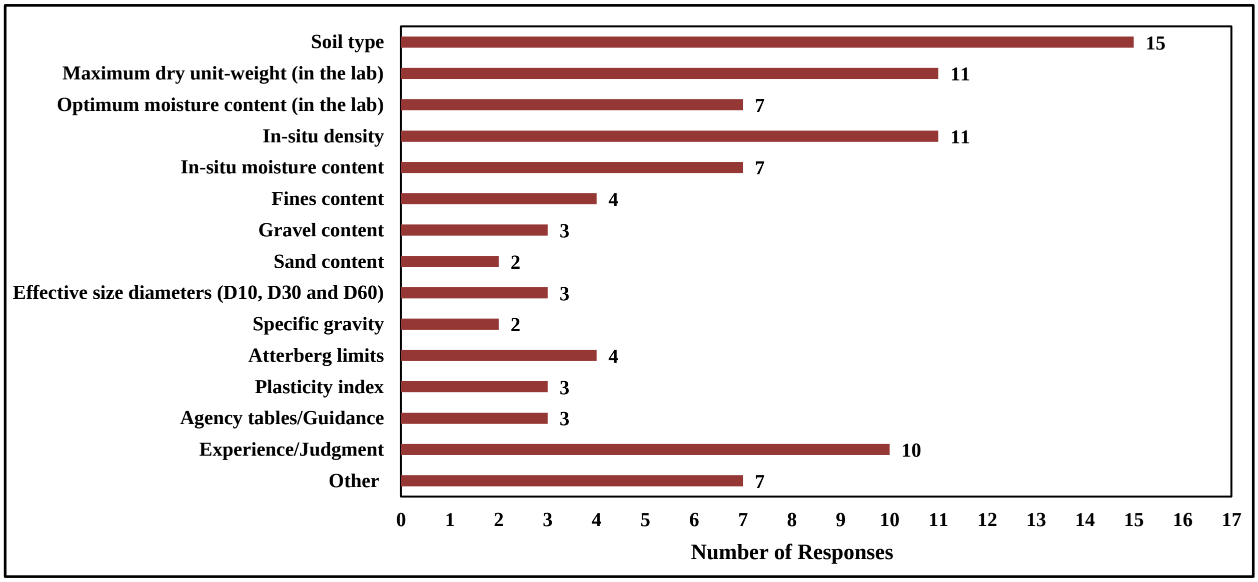


Figure 2.4 Data used by state DOTs to determine expansion/shrinkage factors

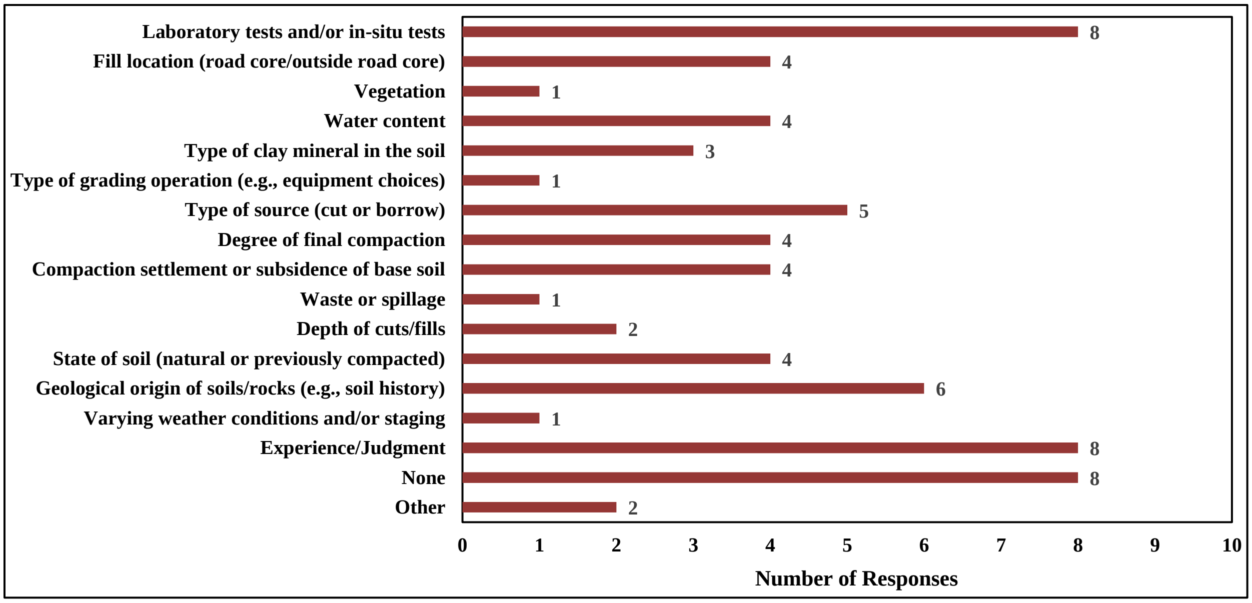


Figure 2.5 Additional factors used by state DOTs to determine expansion/shrinkage factors

The responses summarized in Figure 2.5 indicate that experience/engineering judgment and laboratory/in-situ tests are prominent considerations, with each being selected by 8 DOTs when determining shrinkage or expansion factors. The geological history of soils/rocks and the condition of the soil (natural or previously compacted) were also marked by 6 DOTs as important considerations. Notably, 8 DOTs indicated that they do not consider any additional factors.

The sixth question asked whether DOTs use multiple expansion/shrinkage factors or a single factor for an entire project. Nine DOTs reported using multiple factors depending on the type of material whereas 5 DOTs indicated that they apply a single factor. One DOT elaborated that typically, a single estimated factor is provided by the district materials division for an entire project; however, for larger projects with diverse soil types, they may apply more than one factor to properly estimate the volume change.

The seventh survey question asked, "*Do your design expansion/shrinkage factors generally match with those determined after construction is completed? If no, please explain how the differences are resolved.*" This query aimed to assess the accuracy of predicted volume changes compared to actual outcomes. From the survey results, eight state DOTs reported that their design expansion/shrinkage factors match the ones observed after construction, indicating accurate predictions in their projects. Ten DOTs selected the "no information" option, indicating a need for further evaluation in their processes. The remaining seven respondents did not answer the question.

The survey's eighth question asked, "*Is there anything else you would like to recommend and/or provide information regarding this expansion/shrinkage? If yes, please provide any other useful information on your expansion/shrinkage factors practices.*" This query was intended to elicit any additional insights or practices related to expansion and shrinkage factors that DOTs may employ. One DOT reported that they calculate excavation payments by the cubic yard and make payment adjustments when the actual excavated quantity exceeds the bid amount by more than 5%. Only the excess amount beyond this 5% threshold is eligible for additional payment. Another DOT mentioned that while they consider shrinkage and swell factors during the design phase, these factors do not affect payment adjustments after construction.

### 2.3.2 Part-2: Conversion Factor Related Questions

The first question of the second part of the survey inquired, "*What type of granular materials are being predominantly used in your region for earthwork construction?*" The objective of this question was to assess the range of aggregates that are frequently used for earthwork projects in various states. Respondents were provided with a range of material options, including base aggregates, breaker run, select crushed material, pit run, backfill materials, recycled aggregates, and others. Detailed definitions of these materials, as well as the distribution of replies for each aggregate type, are shown in Figure 2.6.

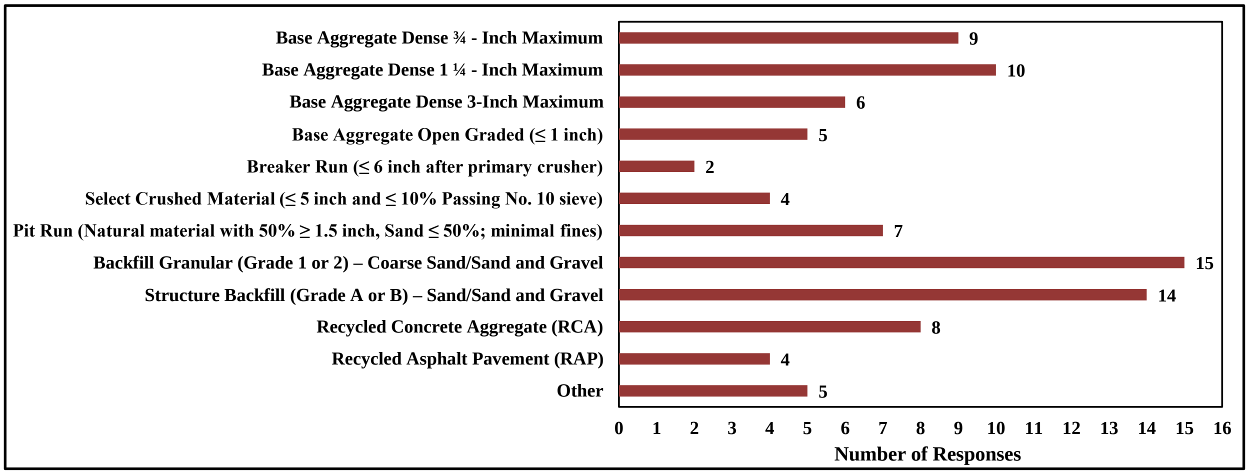


**Figure 2.6 Distribution of granular materials used in earthwork construction**

As depicted in Figure 2.6, the survey results show that Backfill Granular (Grade 1 or 2) – Coarse Sand/Sand and Gravel, and Structure Backfill (Grade A or B) – Sand/Sand and Gravel are the most frequently used materials in earthwork construction, noted by 15 and 14 states, respectively. Base Aggregate Dense ¾-inch Maximum and Base Aggregate Dense 1 ¼-inch Maximum were also commonly used, with 10 and 9 responses each, respectively. Slightly less prevalent, Pit Run was used by 7 state DOTs, and Base Aggregate Dense 3-inch Maximum was chosen by 6 DOTs. Recycled materials, such as Recycled Concrete Aggregate (RCA) and Recycled Asphalt Pavement (RAP), were used by 8 and 4 states, respectively. Breaker Run and Select Crushed Material were selected by 2 and 4 state DOTs, indicating these aggregates are less common in earthwork construction. Lastly, five respondents chose “Other”, suggesting the use of region-specific aggregates not listed in the survey, such as Limerock Base, with at least 97% passing a 3-1/2 inch sieve and well-graded down to dust, Subbase and Aggregate Base Materials, Dense – 2 inch Maximum, and Select Material Type 1 3-inch Maximum.

The second question of the survey asked state DOTs, “*How are these conversion factors for various materials determined? Do you have any equations, tables, or other references that you are using to estimate these factors?*” This question was aimed at understanding the methodologies employed in calculating the conversion factors for different construction materials. Only 6 state DOTs referenced specific conversion factors or their manuals for guidance. The rest of the respondents did not provide any conversion factor, suggesting a reliance on engineering judgment, past experience, and contractor's responsibility for these estimations. These findings suggest that this research is crucial for future studies, due to the apparent lack of consistent and widely available data on conversion factors for earthwork construction materials among many state DOTs. The need for comprehensive and standardized guidelines or estimation methods is evident to promote more consistent practices in the construction industry.

The third question of the survey asked state DOTs about the methods and tests used to determine the degree of final compaction for granular materials. The options provided included the Proctor test (both AASHTO T 99-Standard and AASHTO T 180-Modified), in-situ density tests, visual inspection, Light Weight Deflectometer (LWD) Test, Dynamic Cone Penetrometer (DCP) Test, sand cone test, nuclear gauge test, e-gauge test, and other methods not specified in the survey. The distribution of responses is depicted in Figure 2.7.

As shown in Figure 2.7, it's clear that Proctor tests, alongside in-situ density tests, is frequently used by 14 state DOTs as a standard method for assessing compaction. The results also show that some DOTs employ LWD and DCP tests in the field, with certain agencies incorporating additional in-situ density tests and Proctor testing in their protocol. One state notably relies solely on LWD for compaction checks. Visual inspection is also cited by 9 state DOTs, it is generally utilized in conjunction with other tests like Proctor or in-situ density tests. Moreover, 5 respondents indicated the use of "other" methods, which include specific equipment and number of passes, or criteria defined as creating a stable condition of the compacted material, with no rutting, displacement, or shear wave under equipment.

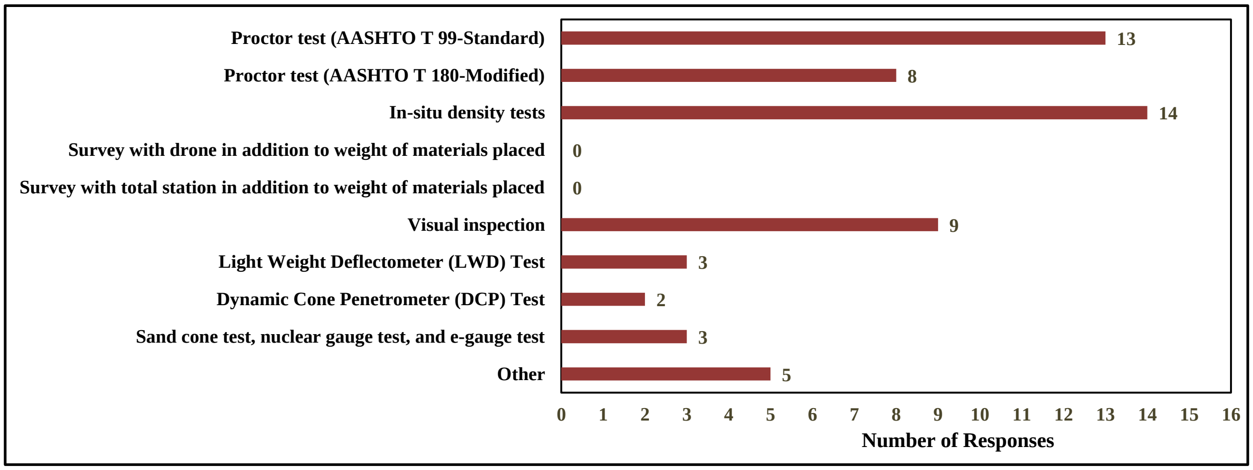


**Figure 2.7 Distribution of methods/tests used for determining final compaction for granular materials by state DOTs**

The fourth question of the survey addressed what data state DOTs use to predict/determine conversion factors. Participants could mark all applicable types of data they utilize in this process. The options included maximum dry unit-weight (in the lab), optimum moisture content (in the lab), in-situ density, in-situ moisture content, fines content, gravel content, sand content, effective size diameters ($D_{10}$, $D_{30}$, and $D_{60}$), specific gravity, agency tables/guidance, experience/judgment, and other. The distribution of responses is presented in Figure 2.8.

The results indicated that the maximum dry unit-weight (in the lab) is the most commonly used data, reported by 13 DOTs, while optimum moisture content (in the lab) and experience/judgment were also frequently selected, with 9 mentions each. In-situ density followed in second, utilized by 5 DOTs. Other data points such as in-situ moisture content, fines content, gravel content, and sand content were each noted by 3 DOTs. This variety suggests a broad range of approaches for determining conversion factors, taking into account diverse material characteristics. Specific gravity and agency tables/guidance were less commonly used, only marked by 2 and 3 DOTs, respectively. Furthermore, 8 respondents selected "other", indicating the adoption of additional data or methods not specified in the provided list, such as aggregate type. In examining the types of data used to predict or determine weight/volume conversion factors, it is noteworthy that the majority of state DOTs rely on standardized measurements. However, some DOTs who chose the "other" option provided additional insights. For instance, they specified that the measurement and payment for excavation and placement of materials were based on the volume of in-place compacted material. This perspective suggests that concerns of material volume change are primarily the contractor's responsibility, thereby influencing their decisions on material hauling and purchasing.

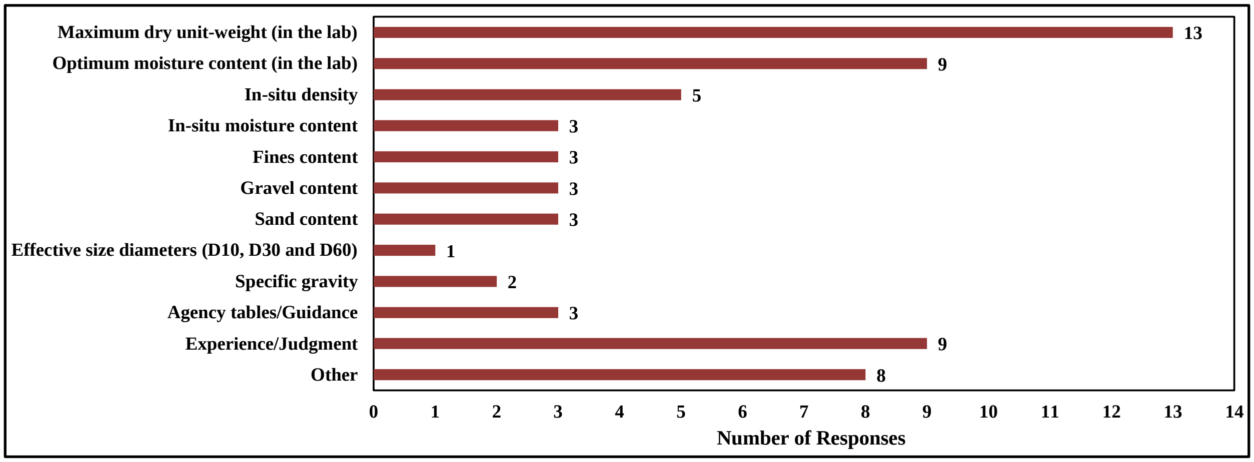


**Figure 2.8 Data used by state DOTs to determine conversion factors**

The fifth question of the survey sought to understand if state Departments of Transportation (DOTs) apply any modification factors while calculating weight/volume conversion factors. The possible factors included a range of considerations such as source material (natural vs. recycled), fill location, laboratory and/or in-situ tests, water content, type of bedrock, type of grading operation, degree of final compaction, compaction settlement or subsidence of base soil, waste or spillage, varying weather conditions and/or staging, experience/judgment, and others. The distribution of responses is illustrated in Figure 2.9.

A majority of respondents, 12 DOTs, indicated that they do not apply any modification factors in their calculations. This suggests a straightforward approach to weight/volume conversions, potentially reflecting confidence in the primary data. However, experience/judgment was noted by 5 DOTs as a modifying factor, pointing to the value of empirical knowledge in the field. Laboratory and/or in-situ tests, as well as type of bedrock, were each mentioned by 2 DOTs, revealing an approach that refines conversions with specific material properties and test results. Furthermore, water content and degree of final compaction were each considered by 1 DOT, and compaction settlement or subsidence of base soil was considered by 2 DOTs.

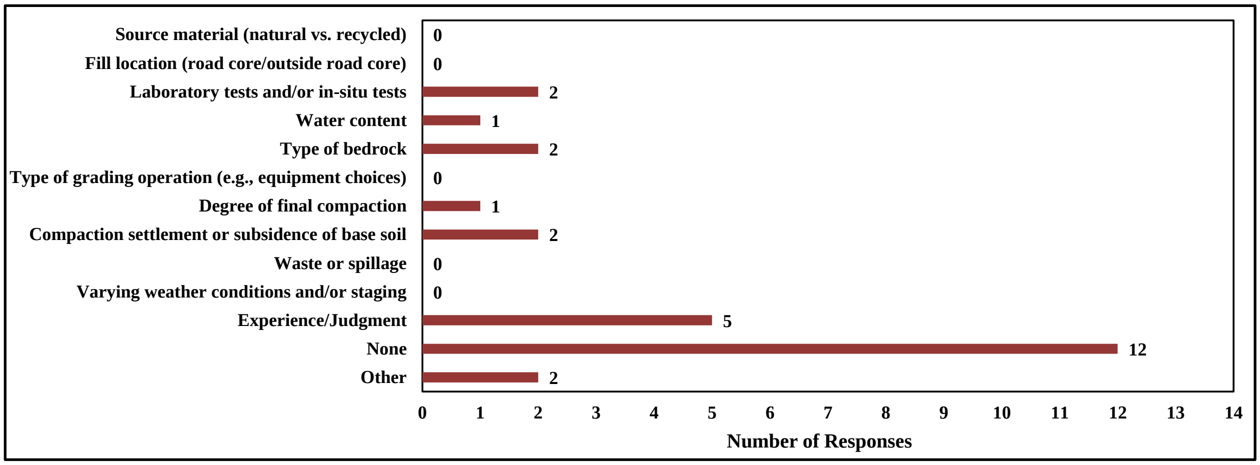


**Figure 2.9 Modification factors used by state DOTs to determine conversion factors**

The sixth survey question asked, "*Do your design weight/volume conversion factors match with those determined after construction is completed? If no, please explain situations in which they occur and how differences are resolved.*" This question was designed to measure the accuracy of anticipated volume changes versus actual post-construction results. According to the survey results, seven DOTs confirmed that their design weight/volume conversion factors match the ones observed after construction, indicating accurate estimations in their projects. 17 DOTs chose the "no information" option, suggesting areas for potential advancement in their assessment procedures. The remaining respondents did not answer the question.

The survey's seventh question asked, "*Is there anything else you would like to recommend and/or provide information regarding conversion factors? If yes, please provide any other useful information on your conversion factor practices.*" The intention of this question was to gather more in-depth knowledge about practices that DOTs employ beyond the standard procedures. In response, one DOT outlined their specific method. They detailed that project payments are determined based on the defined limits in the plans. Additionally, they noted that the mass of materials, as indicated by truck tickets, is converted to volume using loose bulk density. This step is used as a Quality Assurance (QA) check, ensuring the amount of material delivered aligns with the approved stockpile volume.

## 2.4 Summary

In 2022, a comprehensive survey was conducted by Michigan State University and the University of Wisconsin-Madison to understand the practices of state DOTs in determining expansion/shrinkage and weight/volume conversion values for earthwork construction volume calculations. The survey received responses from 26 state DOTs across the United States and was divided into two main sections. The first section focused on the expansion/shrinkage values of natural soils and bedrocks, while the second section investigated the conversion factors of aggregates. These factors are essential for the precise estimation and calculation of material quantities in road construction projects. The conclusions from the two sections are given below.

**Part-1**

- Among the various types of natural soils, Sand and Silty/Clayey Sand are the most common soils used in earthwork construction, followed by Clayey Soils.
- Only about 31% (8 out of 26) of state DOTs provided an equation or a number for expansion factor.
- Proctor compaction tests, alongside in-situ density tests, are frequently used by state DOTs as a standard method for assessing the degree of final compaction. A limited number of state DOTs use LWD and DCP tests, and they generally do not prefer using field measurements to determine the degree of final compaction.
- Soil type, maximum dry unit-weight (in the lab), in-situ density, and in-situ moisture content are the most commonly used data to determine expansion/shrinkage factors.
- Among the respondents, 44% of state DOTs (8 out of 18) confirmed that their design expansion factors align with the data observed after construction. Experience/judgment and laboratory/in-situ tests are primary considerations when determining shrinkage and expansion factors.
- DOTs generally do not use any modification factor when calculating the expansion/shrinkage factor.

**Part-2**

- Among aggregates, Backfill Granular (Grade 1 or 2) – Coarse Sand/Sand and Gravel, and Structure Backfill (Grade A or B) – Sand/Sand and Gravel are the materials most frequently used in earthwork construction. These materials are followed by Base Aggregate Dense ¾-inch Maximum and Base Aggregate Dense 1 ¼-inch Maximum, which are also commonly used in the construction process.

- Only about 23% (6 out of 26) provided a conversion factor or referenced their manuals for aggregates.
- The maximum dry unit-weight (in the lab), optimum moisture content (in the lab), and experience/judgment are frequently used data to determine conversion factors.
- Among the respondents 29% (7 out of 24) indicated that their design conversion factors correspond with the measurements taken after construction. The remaining 71% did not provide specific information regarding the match between their design and post-construction data. DOTs generally don’t use any modification factor such as type of bedrock, fill location, and staging while calculating conversion factor.

The survey results provide a comprehensive perspective on the diverse methods and materials employed in earthwork construction across the United States. The information gathered is critical in understanding and improving the estimations in earthwork construction. In conclusion, the survey results provide a wealth of information that can be used to improve earthwork construction practices. By analyzing these results, both agencies and construction industry can gain insights into the current state of practices, identify areas for improvement, and adopt best practices from other regions.

# CHAPTER 3: RESEARCH METHODOLOGY

This chapter outlines the research methodology employed to determine the geotechnical properties of various soil and aggregate materials. The process began with the selection of material types and project locations, followed by a sample collection phase. Field tests and laboratory tests were conducted to assess the in-situ conditions and properties of the materials, respectively. The methodology provided a thorough understanding of the materials' properties, which is fundamental for the development of weight-volume relationships and conversion factors, ultimately contributing to the improvement of earthwork calculations for roadway construction projects in Wisconsin.

## 3.1 Project Site Selection and Material Collection

The project site selection and material collection process played a crucial role in ensuring a comprehensive investigation of the geotechnical properties of various soil and aggregates in Wisconsin. In coordination with the Project Oversight Committee (POC), "Bedrock Geology of Wisconsin" and "Soil Regions of Wisconsin" maps were utilized to determine project locations that encompassed a wide range of materials from different regions of Wisconsin. The POC initially provided a list of construction projects scheduled for that year, along with the relevant project documents. These documents were carefully reviewed to verify if the projects included the predetermined material types specified in their proposal and to determine the project locations.

Subsequently, these project locations were plotted on the "Bedrock Geology of Wisconsin" and "Soil Regions of Wisconsin" maps, with the goal of selecting sites that encompassed the majority of soil and bedrock types in the state. Once the preliminary selection was developed, the findings were presented to the POC for review and approval.

Upon receiving the POC's approval, coordination was initiated with the project managers of the approved locations to schedule site visits for sampling and testing. These arrangements were made in accordance with the contractors' schedule to ensure a smooth and efficient process. The maps displaying the project locations and corresponding geological information are presented in Figure 3.1 for aggregates and Figure 3.2 for natural soils.

Figure 3.1 (a) shows the bedrock geology map and Figure 3.1 (b) displays the pinpoints and regions for aggregate sampling and testing. Similarly, Figure 3.2 presents the soil regions map on the left and the Wisconsin map with pinpoints and regions for natural soil sampling and testing on the right.

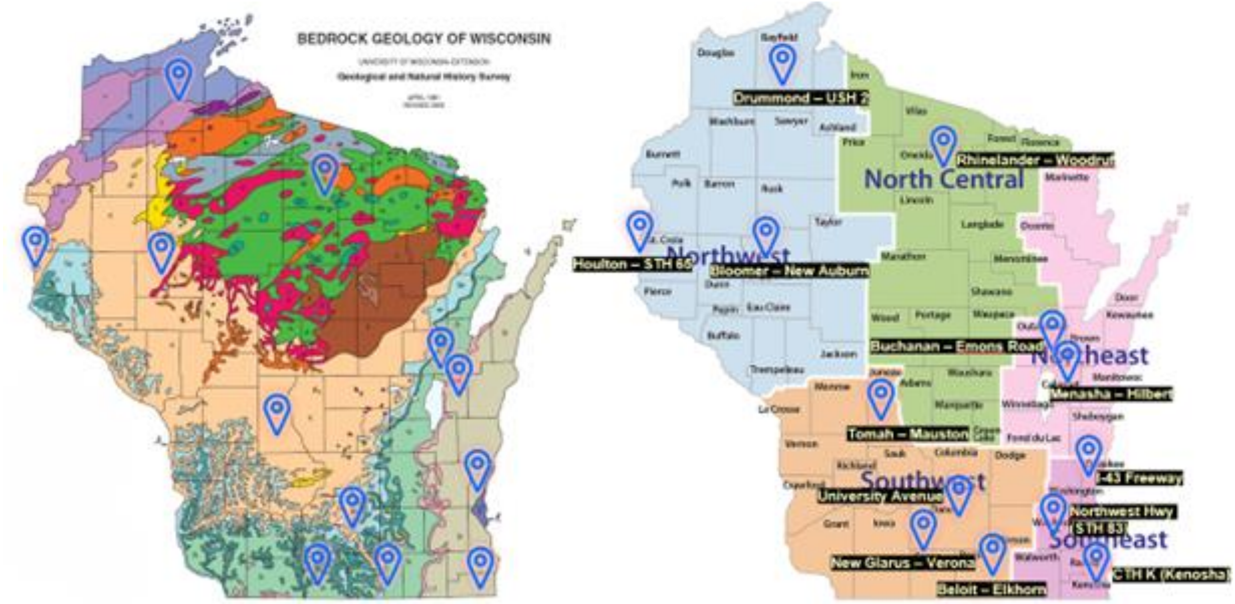


**Figure 3.1 (a) Bedrock geology of Wisconsin (Wisconsin Geological and Natural History Survey, 2005), (b) sampling and testing locations**

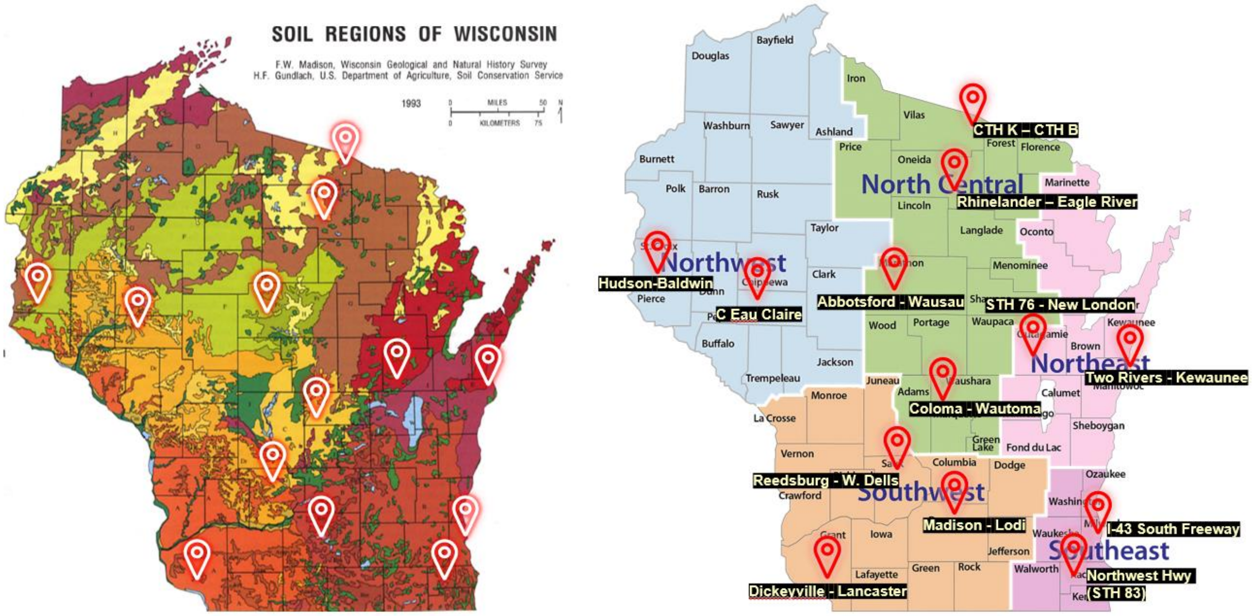


**Figure 3.2 (a) Soil regions of Wisconsin (Madison & Gundlach, 1993), (b) sampling and testing locations**

Over the course of the project, a total of 41 site visits were conducted for aggregate and natural soil sampling across 25 different projects. This extensive fieldwork allowed for the collection of 29 different types of aggregates and 14 different types of natural soil samples.

By selecting project locations based on the geology maps (Figure 3.1 and Figure 3.2) and coordinating with the POC, a diverse range of soil and aggregate types was gathered. The pinpoints on the maps in Figure 3.1 and Figure 3.2 illustrate the wide geographical coverage of the project locations, ensuring a comprehensive representation of the materials existed across the state.

During the sampling process, the guidelines of (ASTM D75/D75M - 19, 2019) were followed to ensure the collection of representative samples. Figure 3.3 illustrates typical aggregate sampling at a quarry located in northern Wisconsin, demonstrating the approach taken in complying with the ASTM D75 guidelines.

(a) (b)

**Figure 3.3 Typical aggregate sampling: (a) sampling pad preparation by loader, (b) sampling from the pad**

### 3.2 Materials

In coordination with the POC, the aim was to cover a wide range of materials commonly used in Wisconsin as subgrade and aggregates as defined in sections 209, 210, and 301 of the Wisconsin Department of Transportation Standard Specifications (WisDOT, 2022c). The goal was to include natural soils (e.g., gravel, sand, silt and clay), virgin aggregates such as Dense Graded Base (3-inch, 1 ¼-inch, and ¾-inch sizes), and recycled aggregates such as recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP). Additional materials include large-sized rock materials such as breaker run, and granular/structure backfill materials.

A total of 43 materials, encompassing a diverse range of material types, were collected, including 14 natural soil samples, 13 dense graded base materials with different sizes, 4 large-sized rock samples, 4 backfill granular/structure samples, 1 subbase sample, 6 recycled asphalt pavement (RAP) samples, and 2 recycled concrete aggregate (RCA) samples for dense graded base material. These materials represent a comprehensive range of soil and aggregate types found across Wisconsin, ensuring a thorough investigation of their geotechnical properties. The complete list of collected materials is presented in Table 3.1 and Table 3.2, providing an overview of the diverse range of materials included in the study.

**Table 3.1 List of collected natural soils**

| No | Material Type | Project Name | Region | County |
|---|---|---|---|---|
| **1** | Natural Soil | Hudson – Baldwin | NW | St. Croix |
| **2** | Natural Soil | Eau Claire – S Hastings Way | NW | Eau Claire |
| **3** | Natural Soil | STH 76 – New London | NE | Outagamie |
| **4** | Natural Soil | Two Rivers – Kewaunee | NE | Manitowoc |
| **5** | Natural Soil | Rhinelander – Eagle River | NC | Oneida |
| **6** | Natural Soil | Coloma – Wautoma | NC | Waushara |
| **7** | Natural Soil | Abbotsford – Wausau | NC | Marathon |
| **8** | Natural Soil | CTH K – CTH B | NC | Vilas |
| **9** | Natural Soil | Madison – Lodi | SW | Dane |
| **10** | Natural Soil | Madison – Lodi | SW | Dane |
| **11** | Natural Soil | Dickeyville – Lancaster | SW | Grant |
| **12** | Natural Soil | Reedsburg – Wisconsin Dells | SW | Sauk |
| **13** | Natural Soil | I 43 N-S Freeway | SE | Milwaukee |
| **14** | Natural Soil | Northwest Highway (STH 83) | SE | Racine |

**Table 3.2 List of collected aggregates**

| No | Material Type | Project Name | Region | County |
|---|---|---|---|---|
| **1** | Backfill Structure Type A | Tomah – Mauston | SW | Juneau |
| **2** | Backfill Structure Type A | I 43 N-S Freeway | SE | Ozaukee |
| **3** | Backfill Granular Grade 2 | Bloomer – New Auburn | NW | Chippewa |
| **4** | Dense Graded Base 3-inch | City of Madison Uni. Avenue | SW | Dane |

**Table 3.2 (cont'd)**

| | | | | |
|---|---|---|---|---|
| **5** | Dense Graded Base 3-inch | T Buchanan Emons Road | NE | Outagamie |
| **6** | Dense Graded Base 1 ¼-inch | New Glarus – Verona | SW | Dane |
| **7** | Dense Graded Base 1 ¼-inch | City of Madison Uni. Avenue | SW | Dane |
| **8** | Dense Graded Base 1 ¼-inch | I 43 N-S Freeway | SE | Ozaukee |
| **9** | Dense Graded Base 1 ¼-inch | CTH K (Kenosha) | SE | Kenosha |
| **10** | Dense Graded Base 1 ¼-inch | Menasha – Hilbert | NE | Calumet |
| **11** | Dense Graded Base 1 ¼-inch | Bloomer – New Auburn | NW | Chippewa |
| **12** | Dense Graded Base 1 ¼-inch | T Buchanan Emons Road | NE | Outagamie |
| **13** | Dense Graded Base 1 ¼-inch | Houlton – STH 65 | NW | St. Croix |
| **14** | Dense Graded Base ¾-inch | New Glarus – Verona | SW | Dane |
| **15** | Dense Graded Base ¾-inch | Tomah – Mauston | SW | Juneau |
| **16** | Dense Graded Base ¾-inch | Rhinelander – Woodruff | NC | Oneida |
| **17** | Select Crushed Material | New Glarus – Verona | SW | Dane |
| **18** | Breaker Run | I 43 N-S Freeway | SE | Ozaukee |
| **19** | Select Crushed Material | Beloit – Elkhorn | SW | Rock |
| **20** | Breaker Run | CTH K (Kenosha) | SE | Kenosha |
| **21** | Recycled Asphalt Base (RAP) | Beloit – Elkhorn | SW | Rock |
| **22** | Recycled Asphalt Base (RAP) | Bloomer – New Auburn | NW | Chippewa |
| **23** | Recycled Asphalt Base (RAP) | CTH K (Kenosha) | SE | Kenosha |
| **24** | Recycled Asphalt Base (RAP) | Houlton – STH 65 | NW | St. Croix |
| **25** | Recycled Asphalt Base (RAP) | Tomah – Mauston | SW | Juneau |
| **26** | Crushed Concrete (RCA) | Tomah – Mauston | SW | Juneau |
| **27** | Crushed Concrete (RCA) | Northwest Highway (STH 83) | SE | Racine |
| **28** | Reclaimed Pavement Material | Drummond – USH 2 | NW | Bayfield |
| **29** | Subbase | Houlton – STH 65 | NW | St. Croix |

## 3.3 Field Testing

### 3.3.1 In-Place Density Test by Nuclear Density Gauge (AASHTO T 310)

The Nuclear Density Gauge (NDG), shown in Figure 3.4, was used to measure the in-place dry unit weight and moisture content of the soil, in accordance with the (AASHTO T 310-13, 2017) "Standard Method of Test for Density of Soil and Soil-Aggregate In-Place by Nuclear Methods." Soil samples were also collected from the exact locations where the NDG measurements were taken to verify the NDG data. These samples were sealed carefully before being transported to the laboratory for further moisture content determination in accordance with AASHTO T 265 “Laboratory Determination of Moisture Content of Soils.”

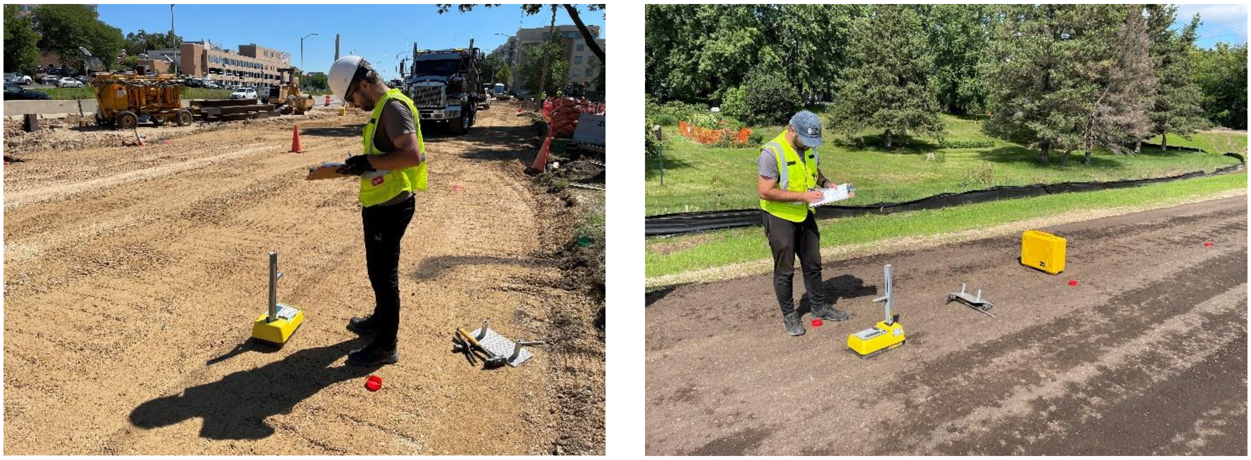

(a) (b)

**Figure 3.4 In-place density and moisture content test by nuclear density gauge (NDG) at (a) Dane County and (b) St. Croix County**

### 3.3.2 In-Place Density Test by the Sand-Cone Method (AASHTO T 191)

The Sand-Cone Method, depicted in Figure 3.5, was also employed to measure the in-place dry unit weight and moisture content of the soil, as per (AASHTO T 191-14, 2018) “Density of Soil In-Place by the Sand-Cone Method.” This method was conducted alongside the Nuclear Density Gauge to cross-verify the density and moisture data obtained. The Sand-Cone method’s measurements at different points within the construction sites provided an additional layer of data, aiding in a more comprehensive understanding of the compaction condition of the soil and base aggregates across the various locations.

(a) (b)

**Figure 3.5 In-place density and moisture content test by sand cone method at (a) Calumet County and (b) Ozaukee County**

### 3.3.3 Light Weight Deflectometer (LWD) Test

The Light Weight Deflectometer (LWD) test, illustrated in Figure 3.6, was conducted following the guidelines of (ASTM E2583 - 07, 2020) "Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD)." This test was carried out to measure the in-situ stiffness and elastic modulus of the soil and base aggregates at the various construction sites. The LWD test is quick and provides immediate results on-site regarding the stiffness of the tested material, making it a valuable tool for understanding the compaction quality and bearing capacity of the soil and base aggregates. By employing the LWD test, the aim was to gather data that could reflect the variations in material stiffness across different sites and under varying compaction conditions. This data is fundamental in analyzing the suitability of the materials in supporting the structural loads, which in turn, contributes to the overall performance and longevity of the pavement structures. Through the LWD test, a more thorough understanding of the material characteristics in their in-place condition was achieved, which is critical for accurate analysis and reliable project outcomes.

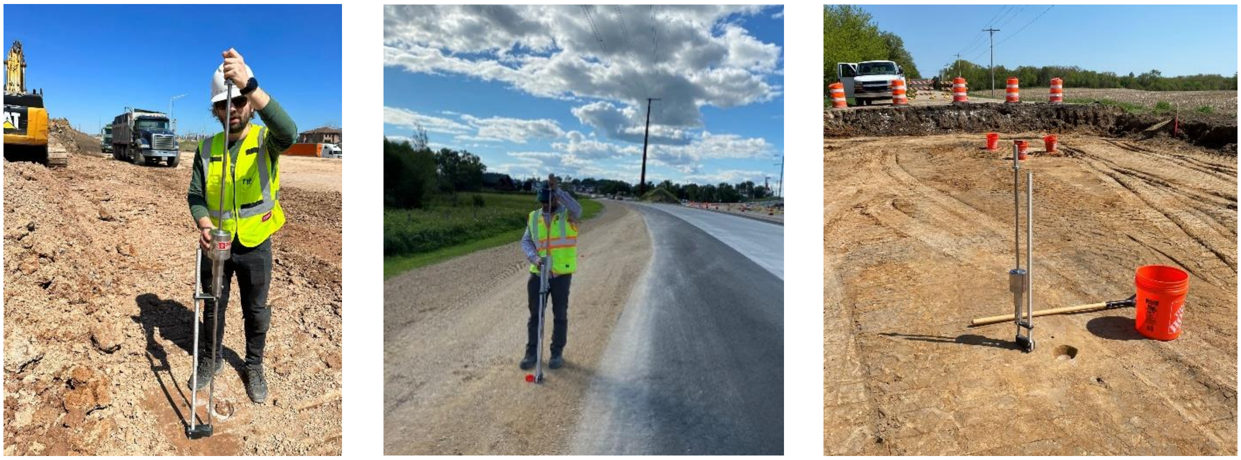
(a) (b)

**Figure 3.6 Light-weight deflectometer (LWD) test at (a) St. Croix County and (b) Dane County**

### 3.3.4 Dynamic Cone Penetrometer (DCP) Test

The Dynamic Cone Penetrometer (DCP) Test, illustrated in Figure 3.7, was conducted following (ASTM D6951/D6951M - 18, 2018) “Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications.” This test was utilized to evaluate the in-situ strength of soil and base aggregates across various sites by measuring the penetration rate of an 8-kg (17.6-lb) hammer through the soil or aggregates. The penetration rate can be related to in situ strength, providing an estimated California Bearing Ratio (CBR), which is a vital parameter for geotechnical analysis. Additionally, although the DCP does not measure density directly, by relating the density to penetration rate on the same material, the DCP may be used to assess the density of a fairly uniform material, helping to identify under compacted or “soft” spots.

The DCP apparatus drives a cone into the pavement structure or subgrade, recording the number of blows needed to reach a certain depth, allowing for a quick assessment of material resistance. Like the LWD test, the DCP test delivers immediate on-site results, facilitating a rapid evaluation of material conditions across various site points.



(a) (b) (c)

**Figure 3.7 Dynamic cone penetrometer (DCP) test performed at (a) Milwaukee County, (b) Juneau County and (c) Racine County**

### 3.3.5 Unit Box Test (Adopted by ASTM C29)

The Unit Box Test, illustrated in Figure 3.8, was utilized, following the approach of (Chopra, 1999) to assess the dry density of soil and aggregate materials in their loose state in stockpile or hauling process. (ASTM C29/C29M - 17a, 2017) “Standard Test Method for Bulk Density (“Unit Weight”) and Voids in Aggregate” specifies the capacity of measures according to the nominal maximum size of aggregates as outlined in Table 3.3. In addition to Chopra’s methodology, different sizes of boxes were used based on the aggregate size. The 1 ft$^3$ and ½ ft$^3$ boxes were used for 1 ¼-inch, and smaller sized aggregates, whereas a 1 ft$^3$ box was used for 3” aggregates and a 4.3 ft$^3$ box was used for breaker run and select crushed materials. Figure 3.9 displays the three different box sizes used in this study. The 1 ft$^3$ and ½ ft$^3$ boxes were filled with smaller sized aggregates in the field and then weighed. However, due to the impracticality of handling a filled 4.3 ft$^3$ box in the field as a result of its considerable weight and size, it was only used in the laboratory to test breaker run and select crushed materials. Approximately 800 lb samples of breaker run and select crushed materials were collected in the field. These samples were stored in sealed buckets to maintain the actual moisture for unit box testing in the laboratory. These sealed buckets were weighed in the field and then re-weighed in the lab to verify that there was no moisture loss in the samples. The laboratory unit box testing for breaker run and select crushed materials then was performed before the alternative laboratory compaction test explained in Section 3.4.6.

Following the weighing process, samples from each box were collected and sealed properly to preserve their moisture content. These sealed samples were then transported to the laboratory for further moisture content determination, in accordance with (AASHTO T 265-15, 2018) “Laboratory Determination of Moisture Content of Soils.” The obtained moisture content data, along with the wet density data from weighing, were used to calculate the dry density. This information is crucial for accurate project planning and cost assessment, ensuring the correct amount of material is ordered and delivered, considering the volume change during transportation.

**Figure 3.8 Unit box test: (a) filling, (b) leveling**

**Figure 3.9 Unit box types**

**Table 3.3 Capacity of measures as specified in ASTM C29**

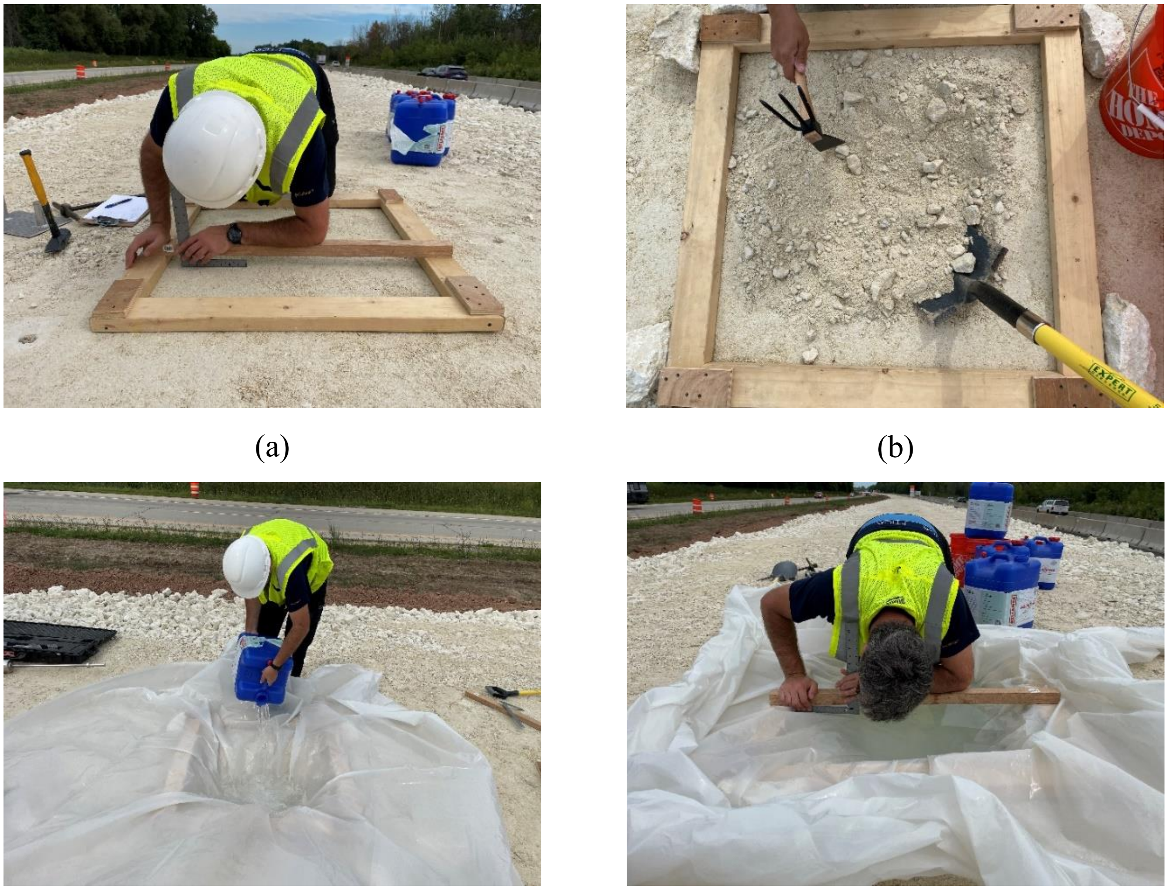
| Nominal Maximum Size of Aggregate | | Capacity of Measure | |
|---|---|---|---|
| mm | in. | $m^3$ [L] | $ft^3$ |
| 12.5 | ½ | 0.0028 [2.8] | $^1/_{10}$ |
| 25.0 | 1 | 0.0093 [9.3] | $^1/_3$ |
| 37.5 | 1 ½ | 0.014 [14] | ½ |
| 75 | 3 | 0.028 [28] | 1 |
| 100 | 4 | 0.070 [70] | 2 ½ |
| 125 | 5 | 0.100 [100] | 3 ½ |

### 3.3.6 In-Place Density Test by the Water Replacement Method (ASTM D5030)

The Water Replacement Method, illustrated in Figure 3.10, was employed as per the guidelines of (ASTM D5030/D5030M - 21, 2021), to ascertain the in-place density of materials with larger aggregate sizes, where the Nuclear Density Gauge or Sand-Cone Method could not be applied. A 30" x 30" square frame was built in the lab, adhering to the specifications outlined in Table 3.4 adapted from ASTM D5030 Table A1.1, to ensure a 30" x 30" opening for the excavation, targeting a minimum required volume of 2 $ft^3$ with a minimum depth of 12 inches for materials having a maximum particle size of 5 inches. As depicted in Figure 3.11, three essential pieces of equipment utilized in this method are shown. The 30" x 30" frame serves as a template to maintain the opening dimensions during the excavation. A 6 mil thick liner is laid within the excavated area, extending beyond the outside of the frame to line the excavation and retain the test water effectively. The water container is used to fill the excavation for volume determination. In addition, a scale was also used to accurately measure the weight of the excavated material and the water filled into the hole. This setup ensures a precise measurement of the in-place density of the materials being tested.

**Table 3.4 Test apparatus and minimum excavation volume and depth (ASTM D5030/D5030M - 21, 2021)**

| Maximum Particle Size, in. | Minimum Required Volume, $ft^3$ | Suggested Apparatus and Template Opening | Required Minimum Depth, in. |
|---|---|---|---|
| 3 | 1.0 | 24-in. square frame | 18 |
| 5 | 2 | 30-in. square frame | 12 |
| 8 | 8 | 4-ft diameter ring | 24 |
| 12 | 27 | 6-ft diameter ring | 24 |
| 18 | 90 | 9-ft diameter ring | 36 |



(a)

(b)

(c)

(d)

**Figure 3.10 Water replacement test: (a) measuring the depth of surface before the test, (b) excavation, (c) filling the hole with water on the placed liner, (d) measuring the water level**

(a)

(b)

(c)

**Figure 3.11 (a) 30” x 30” frame, (b) water Container, and (c) 6 mil thick liner**

## 3.4 Laboratory Testing

### 3.4.1 Sieve/Hydrometer Analysis (AASHTO T 27, T 11, T88)

Sieve analysis was conducted on coarse and fine-grained aggregates, as well as natural soils, in accordance with AASHTO standards as mentioned in the (WisDOT, 2022) . (AASHTO T 11-05, 2018) “Standard Method of Test for Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing” was used for separating fine particles through wet sieving, crucial for accurate determinations of material finer than 75 µm. This was followed by (AASHTO T 11-05, 2018) “Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates” to assess the particle size distribution of the remaining material. Lastly, (AASHTO T 88-13, 2017) “Standard Method of Test for Particle Size Analysis of Soils” was utilized for determining the size distribution of the particles finer than 75-µm.

### 3.4.2 Specific Gravity ($G_s$) and Absorption (AASHTO T 84, T 85, T 100)

Specific gravity tests for both coarse and fine aggregates, as well as for natural soils, were conducted following AASHTO guidelines. These tests complied with (AASHTO T 84-13, 2017) “Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate”, (AASHTO T 85-14, 2018) “Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate”, and (AASHTO T 100-15, 2018) “Standard Method of Test for Specific Gravity of Soils”. Various aggregates including base, subbase, backfill, select crushed material and breaker run were tested in accordance with AASHTO T 84-13 and T 85-14. Natural soils, on the other hand, were tested following the protocols of AASHTO T 100-13. In addition to specific gravity, the absorption capacity of the aggregates was also determined, adhering to the procedures outlined in AASHTO T 84-13 and T 85-14.

### 3.4.3 Standard Proctor Test (AASHTO T 99)

In compliance with the (WisDOT, 2022a) requirements, the Standard Proctor compaction test, as outlined in (AASHTO T 99-18, 2018), Method C, was performed. This test, essential for determining the optimum moisture content (OMC) and maximum dry unit weight (MDU) for materials with less than 30% retained on a 19 mm (¾-inch) sieve, utilized a Mechanical Soil Compactor, as shown in Figure 3.12. The Mechanical Soil Compactor used in the tests is equipped with a programmable digital controller, which includes pre-programmed settings for various test procedures, including AASHTO T 99-18 Method C. This feature ensures the automatic adjustment of parameters like drop height and blow count, in line with the specified standards. The test sample was prepared based on controlled gradation, as demonstrated in Figure 3.13, ensuring that the particle size distribution matched specific gradations for each material identified through prior sieve analysis.

**Figure 3.12 Mechanical soil compactor**

**Figure 3.13 Gradation controlled sample preparation**

### 3.4.4 Atterberg Limit Tests (AASHTO T 89, T 90)

The Atterberg limit tests, conducted according to (AASHTO T 89-13, 2017) "Determining the Liquid Limit of Soils" and (AASHTO T 90-16, 2018) "Determining the Plastic Limit and Plasticity Index of Soils", were used to determine the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of fine-grained soils.

### 3.4.5 Moisture Content (AASHTO T 265)

The moisture content of soil samples was determined following AASHTO T 265, "Laboratory Determination of Moisture Content of Soils." This standard test method requires measuring the water content of the samples by comparing their mass before and after oven-drying. Soil or aggregate samples collected from the field were carefully sealed and transported to the laboratory to prevent any moisture loss. Ensuring the samples remained intact and well-preserved was essential for accurate moisture determination.

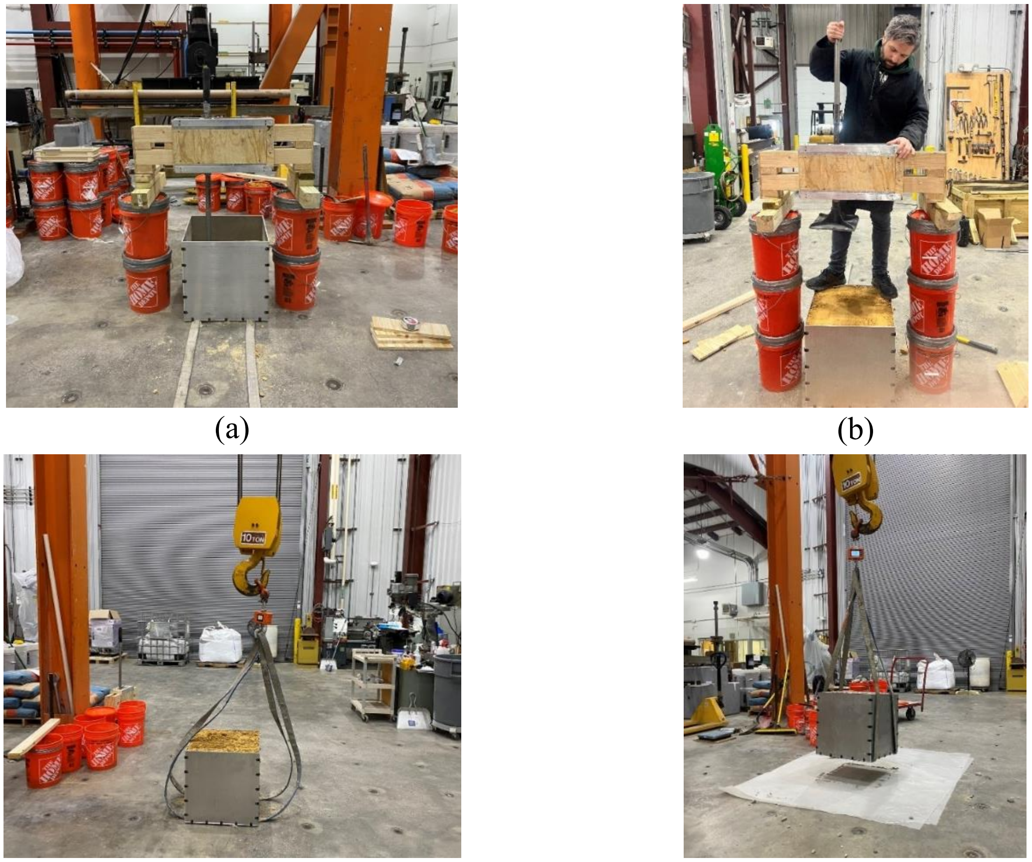
### 3.4.6 Alternative Laboratory Compaction Test for Oversized Aggregates

The standard Proctor test is not applicable for materials retaining more than 30% on a ¾-inch sieve. Given this limitation, an alternative lab compaction method was developed, designed to deliver the same compaction energy as the standard Proctor test, specifically 12,400 ft-lbf/ft³. The objective was to evaluate the compaction behavior of oversized aggregates such as 3" Dense Graded Base, Select Crushed Material with a 5-inch nominal maximum size, and Breaker Run with a 6-inch nominal maximum size as shown in Figure 3.14. To be consistent with ASTM standards, we considered the minimum required volume of the material based on ASTM 5030, as outlined in Section 3.3.6. According to this table, a minimum volume of 2 ft³ is required for materials with a 5-inch maximum particle size, and 8 ft³ for an 8-inch size. Furthermore, ASTM C29 also specifies the capacity of measures for such aggregates. As detailed in Section 3.3.5, a 3.5 ft³ box is suggested for materials with a 5-inch nominal maximum size of aggregate. Therefore, to be on the safe side, a 4.3 ft³ box was chosen for this alternative method, as shown in Figure 3.9 and Figure 3.15 (a).

**Figure 3.14 Breaker Run and Select Crushed Materials**

The compaction test started with the placement of the 4.3 ft³ box on a stable surface and an adjustable apparatus for guiding the 13.05 lb hammer in a vertical drop is positioned above the box, as illustrated in Figure 3.15 (b). The aggregate material, at its as-received moisture content from the quarry, was then prepared for testing. Using a shovel, the aggregate is placed into the 4.3 ft³ box in three lifts. Each lift fills approximately one-third of the box's height. For each lift, the 13.05 lb hammer was dropped from a height of 24 inches above the aggregate surface. A total of

680 drops were required per lift to achieve the standard Proctor test's compaction energy of 12,400 ft-lbf/ft$^3$. To ensure uniform compaction, the hammer moved in a structured pattern across the 19" x 19" mold, conceptually divided into four quadrants. The hammering followed a systematic path, slightly overlapping between quadrants to maintain uniformity. After completing the third lift, the surface of the compacted aggregate was leveled, and the weight of the compacted material in the box was measured by utilizing a crane, as demonstrated in Figures 3.15 (c) and (d).



(a) (b)

(c) (d)

**Figure 3.15 Alternative laboratory compaction test for oversized aggregates: (a) Setup with 4.3 ft$^3$ box and 13.05 lb. hammer, (b) compaction process with guided hammer drops, (c) & (d) weight measurement of compacted material using crane**

In addition to the primary tests, a calibration test was conducted using ¾-inch base aggregate, which had a known compacted unit weight from the standard Proctor test. This was conducted to verify the reliability of our alternative compaction method for large-sized aggregates. The aggregates were not preconditioned to a specific moisture level; instead, the existing moisture content was used. After compaction, the unit weight of the aggregate was compared with the unit weights from the established standard Proctor curve for the corresponding moisture content. The comparison revealed a close alignment between the unit weight from the calibration test and the expected unit weight for the same moisture content on the Proctor curve. This result confirms the effectiveness of the alternative compaction method in providing reliable unit weight measurements for oversized aggregates.

# CHAPTER 4: TEST RESULTS AND ANALYSIS

## 4.1 Laboratory Test Results

### 4.1.1 Materials

43 different geomaterials, as listed in Table 3.2 were utilized for laboratory testing to determine the properties of soils and aggregates in Wisconsin. These geomaterials include natural soils (e.g., gravel, sand, silt, and clay), dense-graded bases (3-inch, 1 ¼-inch, and ¾-inch sizes), and recycled aggregates such as recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP). Additional materials include large-sized rock materials, such as breaker run, and various granular/structure backfills. Table 4.1 presents the gradation limits for these materials, as specified by WisDOT (2022c).

**Table 4.1 WisDOT gradation limits (WisDOT, 2022c)**

| Sieve | 3-inch Base | 1 ¼-inch Base | ¾-inch Base | Select Crushed Material | Breaker Run | Backfill Granular Grade 2 | Backfill Structure Type A |
|---|---|---|---|---|---|---|---|
| 6-inch | - | - | - | - | 100 | 100* | - |
| 5-inch | - | - | - | 90 - 100 | - | - | - |
| 3-inch | 90 - 100 | - | - | - | - | 85 - 100* | 100* |
| 1 ½-inch | 60 - 85 | - | - | 20 - 50 | - | - | - |
| 1 ¼-inch | - | 95 - 100 | - | - | - | - | - |
| 1 inch | - | - | 100 | - | - | - | - |
| ¾-inch | 40 - 65 | 70 - 93 | 95 - 100 | - | - | - | - |
| 3/8 inch | - | 42 - 80 | 50 - 90 | - | - | - | - |
| No. 4 | 15 - 40 | 25 - 63 | 35 - 70 | - | - | 25 - 100* | 25 - 100* |
| No. 10 | 10 - 30 | 16 - 48 | 15 - 55 | 0 - 10 | - | - | - |
| No. 40 | 5 - 20 | 8 - 28 | 10 - 35 | - | - | - | 0 - 75** |
| No. 100 | - | - | - | - | - | 0 - 30** | 0 - 15** |
| No. 200 | 2 - 12 | 2 - 12 | 5 - 15 | - | - | 0 - 15** | 0 - 8** |

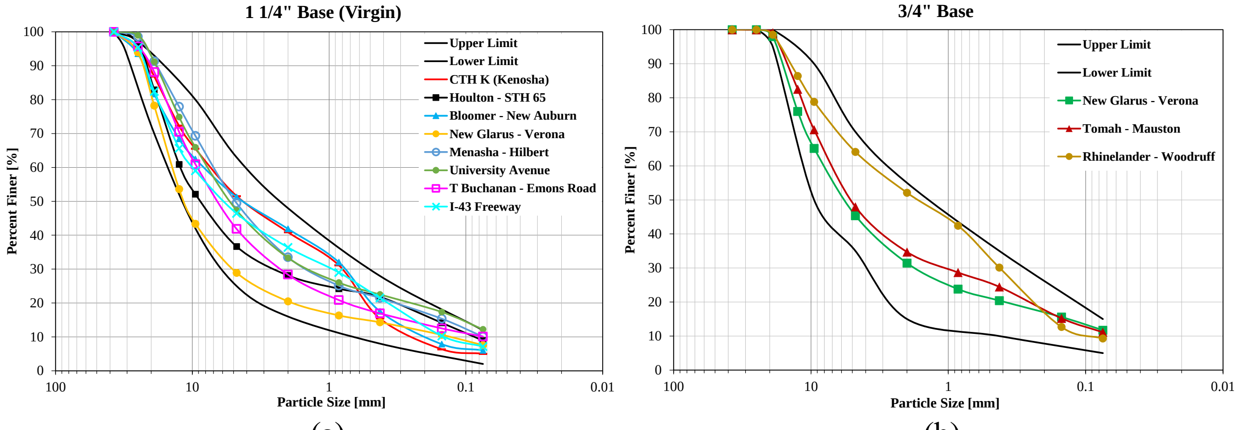
*For the entire sample

**For the portion of the sample passing the No. 4 sieve

### 4.1.2 Material Classification

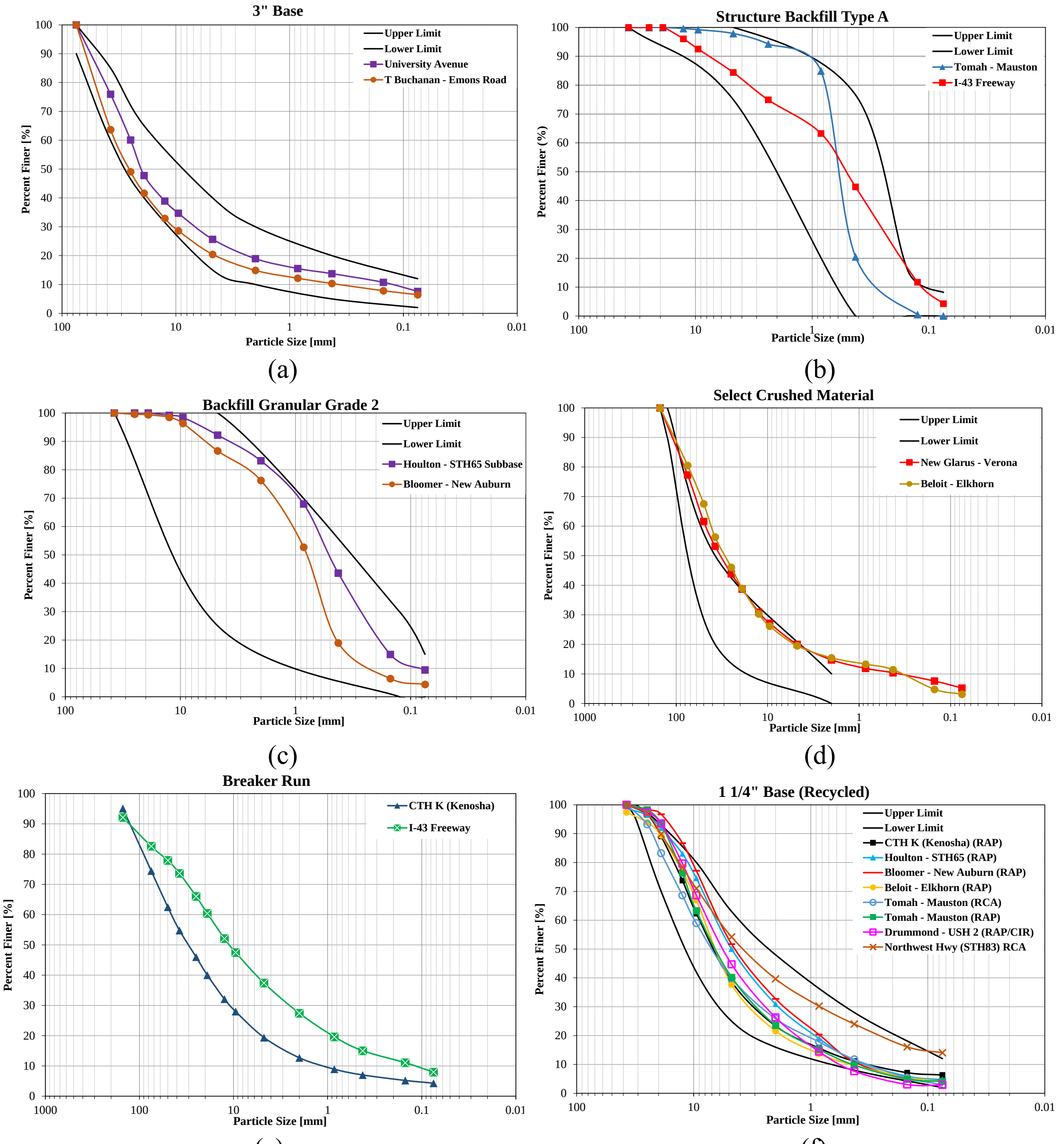
A series of index tests were performed to determine the characteristics of the materials, as specified in Section 3.4. The particle size distributions of the materials were determined in accordance with AASHTO T 11-05, T 27-14, and T 88-13. Figure 4.1 (a) illustrates the particle size distributions of 1 ¼-inch base materials. All eight materials tested fell within the limits specified in Table 4.1. The upper and lower bounds of these limits are also depicted in Figure 4.1 (a). Figure 4.1 (b) presents the gradations of three ¾-inch base materials. Two of these materials exhibited similar gradation curves, while one demonstrated a finer gradation. Nonetheless, all three conform to the WisDOT gradation requirements for ¾-inch base material. This trend of compliance with WisDOT specification limits extends to all tested materials, including 3-inch base materials, structure backfill, and backfill granular as shown in Figure 4.2 (a), (b), and (c) respectively. The gradation of each material category aligns closely with the established requirements. The particle size distributions of select crushed materials and breaker run materials are shown in Figure 4.2 (d) and (e) respectively. The select crushed material was slightly finer than the specified limits, indicating a minor deviation. For breaker run materials, the absence of established upper or lower bounds allows for a wider range of particle sizes.

In addition, the project included recycled 1 ¼-inch base materials such as recycled asphalt pavement (RAP), reclaimed pavement material (RPM), and recycled concrete aggregate (RCA). According to WisDOT specifications, reclaimed asphalt fully passing a 1 ¼-inch sieve is acceptable for 1 ¼-inch base, typically assessed visually. Our results, shown in Figure 4.2 (f), revealed that five RAP, one RPM, and two RCA materials primarily fell within the gradation limits for 1 ¼-inch virgin aggregates. One RAP material had a slightly finer gradation for some sieve sizes. Additionally, one RCA material had a fine content passing sieve No. 200 of 14%, slightly above the target of 12%. These findings indicated a high degree of compliance with the existing standards, validating the effectiveness of the sampling methods employed. The sampling procedures, conducted meticulously in accordance with ASTM D75, ensured that representative samples were collected for accurate assessment and analysis.



(a) (b)

**Figure 4.1 Particle size distribution of materials: (a) 1 ¼-inch base, (b) ¾-inch base**



(a) (b)

(c) (d)

(e) (f)

**Figure 4.2 Particle size distribution of materials: (a) 3-inch base, (b) structural backfill type a, (c) backfill granular grade 2, (d) select crushed material, (e) breaker run, (f) 1 ¼-inch base (recycled)**

Finally, Figure 4.3 shows the particle size distributions of 14 different natural soils. These soils, collected from various locations across the state, include sand, silt, and clay. The wide range in gradation observed underscores the diversity in natural soil compositions and highlights the comprehensive nature of the research conducted. Specifically, the materials passing the No. 4 sieve range from 72% to 100%, while those passing the No. 200 sieve vary between 1% and 98%. This part of the study greatly improves our understanding of soil properties in Wisconsin, offering important information for upcoming engineering work in the state.

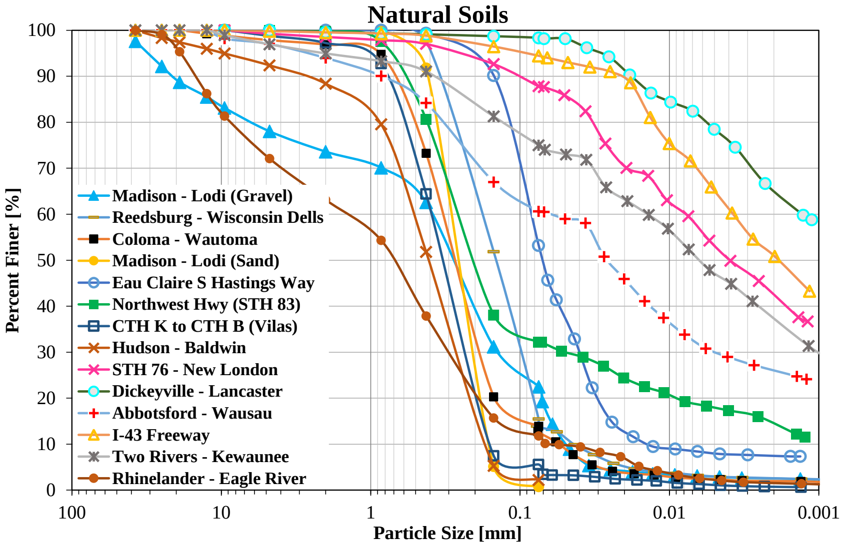


**Figure 4.3 Particle size distribution of natural soils**

Material classifications were established using the AASHTO Soil Classification System (AASHTO M 145) and the Unified Soil Classification System (USCS) (ASTM D2487-17, 2017), detailed in Table 4.2 and Table 4.3. For backfill materials, the USCS classification identified them as SP (poorly graded sand), while subbase materials were categorized as SW-SM (well-graded sand with silt), aligning with A-1-b under the AASHTO system. Additionally, most base materials, including 3-inch, 1 ¼-inch (both virgin and recycled), and ¾-inch sizes, were classified as A-1-a per AASHTO, except for one ¾-inch base material, which was classified as A-1-b. In terms of USCS classification, virgin base aggregates predominantly fell into the GP-GM (poorly graded gravel with silt and sand) category, whereas recycled base aggregates were mostly categorized as GW (well-graded gravel with sand). Variations in base materials also included classifications such as SP-SM (poorly graded sand with silt and gravel), SW (well-graded sand with gravel), GW-GM (well-graded gravel with silt and sand), and GM (silty gravel with sand). Breaker run materials were classified as either GP-GM or GW, and select crushed materials as GP-GM or GP according to the USCS. All these materials were designated as A-1-b in the AASHTO system.

In addition to the aggregates, natural soils were also classified according to both USCS and the AASHTO soil classification system. Natural soils ranged from ML (sandy silt) to SP (poorly graded sand), including variants like CL (lean clay), CH (fat clay), SM (silty sand), SC-SM (silty, clayey sand), SW-SM (well-graded sand with silt and gravel), and SP-SM (poorly graded sand with silt). Correspondingly, these soils were classified into various categories according to the AASHTO soil classification system including A-3, A-4, A-6, A-1b, A-2-4, and A-7-6. This comprehensive classification, covering a broad range of soil types, reflects the diversity of natural soils that were collected.

**Table 4.2 Index properties of aggregates**

| No. | Material | Gravel (%) | Sand (%) | Fine (%) | $C_u$ | $C_c$ | $D_{60}$ | $D_{30}$ | $D_{10}$ | AASHTO | USCS | LL | PI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Backfill Str. Type A | 2 | 98 | 0 | 2.4 | 1.2 | 0.7 | 0.5 | 0.3 | A-1-b | SP | NA | NP |
| **2** | Backfill Str. Type A | 16 | 80 | 4 | 5.8 | 0.9 | 0.8 | 0.3 | 0.1 | A-1-b | SP | NA | NP |
| **3** | Backfill Gr. Grade 2 | 13 | 82 | 4 | 5.3 | 1.2 | 1.2 | 0.6 | 0.2 | A-1-b | SP | NA | NP |
| **4** | Base 3-inch | 74 | 18 | 8 | 188.7 | 15.0 | 25.0 | 7.0 | 0.1 | A-1-a | GP-GM | NA | NP |
| **5** | Base 3-inch | 80 | 14 | 6 | 88.2 | 8.2 | 34.4 | 10.5 | 0.4 | A-1-a | GP-GM | NA | NP |
| **6** | Base 1 ¼-inch | 71 | 21 | 8 | 104.9 | 13.6 | 14.2 | 5.1 | 0.1 | A-1-a | GP-GM | NA | NP |
| **7** | Base 1 ¼-inch | 53 | 35 | 12 | 130.3 | 4.4 | 8.0 | 1.5 | 0.1 | A-1-a | GM | NA | NP |
| **8** | Base 1 ¼-inch | 54 | 39 | 7 | 69.4 | 0.7 | 9.9 | 1.0 | 0.1 | A-1-a | GP-GM | NA | NP |
| **9** | Base 1 ¼-inch | 48 | 47 | 5 | 29.3 | 0.3 | 7.6 | 0.8 | 0.3 | A-1-a | SP-SM | NA | NP |
| **10** | Base 1 ¼-inch | 51 | 39 | 10 | 97.6 | 4.3 | 7.3 | 1.5 | 0.1 | A-1-a | GP-GM | NA | NP |
| **11** | Base 1 ¼-inch | 49 | 45 | 6 | 40.2 | 0.4 | 8.4 | 0.8 | 0.2 | A-1-a | SP-SM | NA | NP |
| **12** | Base 1 ¼-inch | 58 | 32 | 10 | 124.9 | 7.9 | 9.3 | 2.3 | 0.1 | A-1-a | GP-GM | NA | NP |
| **13** | Base 1 ¼-inch | 63 | 28 | 9 | 134.9 | 6.1 | 12.2 | 2.6 | 0.1 | A-1-a | GP-GM | NA | NP |
| **14** | Base ¾-inch | 55 | 34 | 12 | 129.3 | 6.0 | 8.3 | 1.8 | 0.1 | A-1-a | GP-GM | NA | NP |
| **15** | Base ¾-inch | 52 | 37 | 11 | 108.0 | 2.5 | 7.3 | 1.1 | 0.1 | A-1-a | GW-GM | NA | NP |
| **16** | Base ¾-inch | 36 | 55 | 9 | 42.2 | 0.5 | 3.8 | 0.4 | 0.1 | A-1-b | SP-SM | NA | NP |
| **17** | Select Crushed Mat. | 80 | 15 | 5 | 123.1 | 7.5 | 47.7 | 11.8 | 0.4 | A-1-a | GP-GM | NA | NP |
| **18** | Breaker Run | 63 | 29 | 8 | 150.6 | 3.2 | 18.7 | 2.7 | 0.1 | A-1-a | GP-GM | NA | NP |
| **19** | Select Crushed Mat | 80 | 16 | 3 | 113.6 | 9.9 | 41.6 | 12.3 | 0.4 | A-1-a | GP | NA | NP |
| **20** | Breaker Run | 81 | 15 | 4 | 39.1 | 2.2 | 46.0 | 11.0 | 1.2 | A-1-a | GW | NA | NP |
| **21** | RAP 1 ¼-inch | 62 | 34 | 4 | 18.0 | 3.0 | 8.4 | 3.4 | 0.5 | A-1-a | GW | NA | NP |
| **22** | RAP 1 ¼-inch | 48 | 47 | 4 | 16.4 | 1.3 | 6.3 | 1.7 | 0.4 | A-1-a | SW | NA | NP |
| **23** | RAP 1 ¼-inch | 61 | 32 | 6 | 26.1 | 3.3 | 9.0 | 3.2 | 0.3 | A-1-a | GP-GM | NA | NP |
| **24** | RAP 1 ¼-inch | 50 | 45 | 5 | 18.8 | 1.5 | 6.7 | 1.9 | 0.4 | A-1-a | GW | NA | NP |
| **25** | RAP 1 ¼-inch | 60 | 36 | 4 | 19.8 | 2.4 | 8.8 | 3.1 | 0.4 | A-1-a | GW | NA | NP |
| **26** | RCA 1 ¼-inch | 60 | 37 | 3 | 28.1 | 2.3 | 9.8 | 2.8 | 0.4 | A-1-a | GW | NA | NP |
| **27** | RCA 1 ¼-inch | 46 | 40 | 14 | 119.9 | 2.0 | 6.4 | 0.8 | 0.1 | A-1-a | SM | NA | NP |
| **28** | RPM | 55 | 42 | 3 | 13.6 | 1.5 | 7.8 | 2.6 | 0.6 | A-1-a | GW | NA | NP |
| **29** | Subbase | 8 | 83 | 9 | 8.6 | 1.5 | 0.7 | 0.3 | 0.1 | A-1-b | SW-SM | NA | NP |

Fines = silt and clay; $C_u$ = uniformity coefficient; $C_c$ = coefficient of curvature; LL = liquid limit; PI = plasticity index; USCS = Unified Soil Classification System; AASHTO = American Association of State Highway and Transportation Officials; NP = non-plastic; NA = not available

**Table 4.3 Index properties of natural soils**

| No. | Material | Gravel (%) | Sand (%) | Fine (%) | $C_u$ | $C_c$ | $D_{60}$ | $D_{30}$ | $D_{10}$ | AASHTO | USCS | LL | PI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Natural Soil | 8 | 90 | 2 | 3.1 | 0.9 | 0.6 | 0.3 | 0.2 | A-3 | SP | NA | NP |
| **2** | Natural Soil | 0 | 47 | 53 | 6.3 | 1.3 | 0.1 | 0.0 | 0.0 | A-4 | ML | 19 | 0 |
| **3** | Natural Soil | 1 | 11 | 88 | 24.2 | 0.4 | 0.0 | 0.0 | 0.0 | A-6 | CL | 37 | 17 |
| **4** | Natural Soil | 3 | 22 | 75 | 53.9 | 0.3 | 0.0 | 0.0 | 0.0 | A-6 | CL | 34 | 17 |
| **5** | Natural Soil | 28 | 60 | 12 | 26.4 | 1.1 | 1.6 | 0.3 | 0.1 | A-1-b | SW-SM | NA | NP |
| **6** | Natural Soil | 2 | 84 | 14 | 6.5 | 2.0 | 0.4 | 0.2 | 0.1 | A-2-4 | SM | NA | NP |
| **7** | Natural Soil | 3 | 36 | 61 | 94.1 | 1.1 | 0.0 | 0.0 | 0.0 | A-6 | CL | 36 | 16 |
| **8** | Natural Soil | 1 | 93 | 6 | 2.5 | 1.0 | 0.4 | 0.3 | 0.2 | A-3 | SP-SM | NA | NP |
| **9** | Natural Soil | 0 | 99 | 1 | 2.0 | 1.0 | 0.3 | 0.2 | 0.2 | A-3 | SP | NP | NP |
| **10** | Natural Soil | 22 | 56 | 23 | 12.1 | 1.5 | 0.4 | 0.1 | 0.0 | A-2-4 | SM | 11 | NP |
| **11** | Natural Soil | 0 | 2 | 98 | 6.9 | 1.3 | 0.0 | 0.0 | 0.0 | A-7-6 | CH | 80 | 48 |
| **12** | Natural Soil | 0 | 84 | 16 | 4.1 | 1.1 | 0.2 | 0.1 | 0.0 | A-2-4 | SM | NA | NP |
| **13** | Natural Soil | 0 | 5 | 94 | 14.1 | 0.6 | 0.0 | 0.0 | 0.0 | A-6 | CL | 38 | 18 |
| **14** | Natural Soil | 0 | 68 | 32 | 272.0 | 8.0 | 0.3 | 0.1 | 0.0 | A-2-4 | SC-SM | 25 | 7 |

Fines = silt and clay; $C_u$ = uniformity coefficient; $C_c$ = coefficient of curvature; LL = liquid limit; PI = plasticity index; USCS = Unified Soil Classification System; AASHTO = American Association of State Highway and Transportation Officials; NP = non-plastic; NA = not available

### 4.1.3 Specific Gravity ($G_s$) and Absorption

Specific gravity ($G_s$) and absorption of the materials were determined in accordance with AASHTO T 84-13 for fine aggregate, T 85-14 for coarse aggregate, and T 100-13 for natural soils. The $G_s$ and absorption capacity of the aggregates were ascertained by calculating the weighted average of the coarse (> No. 4 sieve) and fine (< No. 4 sieve) fractions. Table 4.4 and Table 4.5 shows 3 distinct Gs values: oven dry (OD), saturated surface dry (SSD), and apparent $G_s$, along with the absorption of the aggregates. It is important to note that for the natural soils, only the $G_s$ value is reported, as AASHTO T 100-13 does not have the measurement of absorption.

The tested materials exhibited a wide range of specific gravity ($G_s$) and absorption values. For backfill and subbase materials, $G_s$ values were observed between 2.64 and 2.74, with absorption percentages ranging from 0.48% to 1.17%. In contrast, base materials, including sizes of 3-inch, 1 ¼-inch (virgin), and ¾-inch, had $G_s$ ranging from 2.46 to 2.70 and absorption between 1.28% and 4.20%. Notably, the 1 ¼-inch base material from the City of Madison University Avenue project (No. 7), which had the highest fines content, also exhibited the highest absorption rate at 4.2%. This correlation underscores the impact of fines content on absorption characteristics.

For breaker run and select crushed materials, $G_s$ values varied between 2.55 and 2.67, while absorption values ranged from 1.24% to 3.02%. The recycled materials, including RAP, RCA, and RPM, demonstrated similar $G_s$ values, ranging from 2.27 to 2.43. However, their absorption values varied more significantly, from 1.61% to 5.79%. The lower $G_s$ in recycled materials compared to virgin aggregates can be attributed to their differing compositions. Particularly, RCA materials exhibited higher absorption rates than virgin aggregates, RAP, and RPM, likely due to their residual mortar content and more porous structure.

**Table 4.4 Specific gravity ($G_s$) and absorption of aggregates**

| No. | Material | Oven-Dry (OD) $G_s$ | Saturated - Surface-Dry (SSD) $G_s$ | Apparent $G_s$ | Absorption (%) |
|---|---|---|---|---|---|
| **1** | Backfill Str. Type A | 2.64 | 2.65 | 2.67 | 0.48 |
| **2** | Backfill Str. Type A | 2.74 | 2.76 | 2.79 | 0.54 |
| **3** | Backfill Gr. Grade 2 | 2.64 | 2.67 | 2.72 | 1.09 |
| **4** | Base 3-inch | 2.57 | 2.63 | 2.75 | 2.67 |
| **5** | Base 3-inch | 2.68 | 2.71 | 2.78 | 1.38 |
| **6** | Base 1 ¼-inch | 2.57 | 2.64 | 2.77 | 2.83 |
| **7** | Base 1 ¼-inch | 2.46 | 2.57 | 2.75 | 4.20 |
| **8** | Base 1 ¼-inch | 2.70 | 2.73 | 2.79 | 1.28 |
| **9** | Base 1 ¼-inch | 2.63 | 2.68 | 2.76 | 1.85 |
| **10** | Base 1 ¼-inch | 2.64 | 2.70 | 2.80 | 2.06 |
| **11** | Base 1 ¼-inch | 2.64 | 2.69 | 2.78 | 1.92 |
| **12** | Base 1 ¼-inch | 2.63 | 2.69 | 2.80 | 2.38 |
| **13** | Base 1 ¼-inch | 2.56 | 2.64 | 2.77 | 3.00 |
| **14** | Base ¾-inch | 2.56 | 2.63 | 2.77 | 3.00 |
| **15** | Base ¾-inch | 2.50 | 2.58 | 2.72 | 3.18 |
| **16** | Base ¾-inch | 2.60 | 2.66 | 2.75 | 2.04 |
| **17** | Select Crushed Mat. | 2.55 | 2.62 | 2.76 | 3.02 |
| **18** | Breaker Run | 2.57 | 2.63 | 2.73 | 2.22 |
| **19** | Select Crushed Mat | 2.56 | 2.64 | 2.78 | 3.12 |
| **20** | Breaker Run | 2.67 | 2.71 | 2.77 | 1.24 |
| **21** | RAP 1 ¼-inch | 2.38 | 2.43 | 2.50 | 2.11 |
| **22** | RAP 1 ¼-inch | 2.34 | 2.38 | 2.44 | 1.74 |
| **23** | RAP 1 ¼-inch | 2.32 | 2.38 | 2.48 | 2.79 |
| **24** | RAP 1 ¼-inch | 2.32 | 2.37 | 2.43 | 1.92 |
| **25** | RAP 1 ¼-inch | 2.27 | 2.32 | 2.39 | 2.26 |
| **26** | RCA 1 ¼-inch | 2.28 | 2.40 | 2.59 | 5.25 |
| **27** | RCA 1 ¼-inch | 2.32 | 2.45 | 2.68 | 5.79 |
| **28** | RPM | 2.43 | 2.47 | 2.53 | 1.61 |
| **29** | Subbase | 2.64 | 2.67 | 2.72 | 1.17 |

$G_s$ = specific gravity; NA = not available

In addition to aggregates, the apparent $G_s$ values for natural soils were determined to range from 2.63 to 2.76, indicating a narrower variability in comparison to aggregates.

**Table 4.5 Specific gravity ($G_s$) and absorption of natural soils**

| No. | Material | Oven-Dry (OD) $G_s$ | Saturated - Surface-Dry (SSD) $G_s$ | Apparent $G_s$ | Absorption (%) |
|---|---|---|---|---|---|
| **1** | Natural Soil | NA | NA | 2.67 | NA |
| **2** | Natural Soil | NA | NA | 2.65 | NA |
| **3** | Natural Soil | NA | NA | 2.75 | NA |
| **4** | Natural Soil | NA | NA | 2.73 | NA |
| **5** | Natural Soil | NA | NA | 2.71 | NA |
| **6** | Natural Soil | NA | NA | 2.65 | NA |
| **7** | Natural Soil | NA | NA | 2.69 | NA |
| **8** | Natural Soil | NA | NA | 2.65 | NA |
| **9** | Natural Soil | NA | NA | 2.67 | NA |
| **10** | Natural Soil | NA | NA | 2.68 | NA |
| **11** | Natural Soil | NA | NA | 2.74 | NA |
| **12** | Natural Soil | NA | NA | 2.63 | NA |
| **13** | Natural Soil | NA | NA | 2.76 | NA |
| **14** | Natural Soil | NA | NA | 2.68 | NA |

$G_s$ = specific gravity; NA = not available

### 4.1.4 Compaction Test

The maximum dry unit weight (MDU) and optimum moisture content (OMC) values for aggregates and natural soils were determined in accordance with AASHTO T 99-18. Corrections were applied to materials containing oversized particles, specifically those retaining on a ¾-inch sieve, as per AASHTO T 99-18. Table 4.6 and Table 4.7 display both the actual and corrected compaction test results. For all analyses presented in this thesis, only the corrected values are reported.

As previously discussed in Section 3.4.6, the standard Proctor test has its limitations, particularly for materials retaining more than 30% on a ¾-inch sieve. Consequently, an alternative laboratory compaction test was applied for materials such as 3-inch base, select crushed material, and breaker run. These oversized aggregates were compacted at their as-received moisture content using compaction energy equivalent to the standard Proctor test. Table 4.7 also includes the compacted unit weights and corresponding moisture contents for these materials, offering a detailed perspective on their compaction characteristics under the adapted testing method.

The subbase material had a MDU of 123 pcf and an OMC of 0.4%. For backfill materials, MDUs ranged from 111 pcf to 127 pcf, all with a consistent OMC of 0.4%. These results suggested that these materials could attain maximum density at relatively low moisture contents. Typically, poorly graded sands (SP) lack distinct peaks in their compaction moisture-density curves, with MDUs and OMCs often occurring near zero (Arcement & Wright, 2001), aligning closely with our findings. The 1 ¼-inch and ¾-inch virgin base materials had a range of MDU from 133 pcf to 147 pcf, with (OMCs) ranging from 5.6% to 8.5%. RAP and RPM materials had MDUs between 122 pcf and 125 pcf, with OMCs ranging from 6.9% to 8.6%. RCA materials had MDUs of 119 pcf and 128 pcf with higher OMCs of 9.8% and 11.0% respectively, indicating a greater need for moisture for optimal compaction, likely due to their more porous nature compared to virgin aggregates. Moreover, an increase in fines content in one RCA material led to higher MDU and OMC values. It is also noteworthy that recycled materials generally showed lower MDUs, correlating with their lower specific gravities. For oversized aggregates like 3-inch base, select crushed, and breaker run, MDUs ranged from 131 pcf to 138 pcf, with as-received moisture contents between 1.9% and 5.6%. The alternative compaction method revealed comparable MDUs for these materials, despite varying moisture contents.

The natural soils demonstrated a wide range of MDUs, varying from 91 pcf to 137 pcf, and OMCs from 0.3% to 27.5%. As anticipated, silty sand with gravel (SM) exhibited the highest MDU at 137 pcf at an OMC of 6.5%, while fat clay (CH) showed the lowest MDU at 91 pcf and the highest OMC at 27.5%. This extensive range highlights the diverse soil types that were collected, reflecting the varied geotechnical properties of soils across different sites.

**Table 4.6 Uncorrected (actual) and corrected Proctor compaction test results for natural soils**

| No. | Material | AASHTO | USCS | Proctor Compaction Test Results | | Corrected Proctor Compaction Test Results | |
|---|---|---|---|---|---|---|---|
| | | | | MDU (pcf) | OMC (%) | MDU (pcf) | OMC (%) |
| **1** | Natural Soil | A-3 | SP | 113 | 0.4 | NA | NA |
| **2** | Natural Soil | A-4 | ML | 118 | 11.9 | NA | NA |
| **3** | Natural Soil | A-6 | CL | 112 | 17.1 | NA | NA |
| **4** | Natural Soil | A-6 | CL | 115 | 14.9 | NA | NA |
| **5** | Natural Soil | A-1-b | SW-SM | 136 | 0.7 | NA | NA |
| **6** | Natural Soil | A-2-4 | SM | 120 | 8.4 | NA | NA |

### Table 4.6 (cont'd)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **7** | Natural Soil | A-6 | CL | 117 | 13.7 | NA | NA |
| **8** | Natural Soil | A-3 | SP-SM | 110 | 0.4 | NA | NA |
| **9** | Natural Soil | A-3 | SP | 110 | 0.3 | NA | NA |
| **10** | Natural Soil | A-2-4 | SM | 137 | 6.5 | NA | NA |
| **11** | Natural Soil | A-7-6 | CH | 91 | 27.5 | NA | NA |
| **12** | Natural Soil | A-2-4 | SM | 113 | 8.0 | NA | NA |
| **13** | Natural Soil | A-6 | CL | 111 | 17.5 | NA | NA |
| **14** | Natural Soil | A-2-4 | SC-SM | 119 | 12.8 | NA | NA |

MDU = maximum dry unit weight; OMC = optimum moisture content; NA = not available

### Table 4.7 Uncorrected (actual) and corrected Proctor compaction test results for aggregates

| **No.** | **Material** | **AASHTO** | **USCS** | **Proctor Compaction Test Results** | | **Corrected Proctor Compaction Test Results** | |
|---|---|---|---|---|---|---|---|
| | | | | **MDU (pcf)** | **OMC (%)** | **MDU (pcf)** | **OMC (%)** |
| **1** | Backfill Str. Type A | A-1-b | SP | 111 | 0.4 | 111 | 0.4 |
| **2** | Backfill Str. Type A | A-1-b | SP | 127 | 0.4 | 127 | 0.4 |
| **3** | Backfill Gr. Grade 2 | A-1-b | SP | 120 | 0.3 | 120 | 0.3 |
| **4** | Base 3-inch | A-1-a | GP-GM | 132* | 4.8** | NA | NA |
| **5** | Base 3-inch | A-1-a | GP-GM | 139* | 4.8** | NA | NA |
| **6** | Base 1 ¼-inch | A-1-a | GP-GM | 137 | 8.5 | 141 | 7.3 |
| **7** | Base 1 ¼-inch | A-1-a | GM | 131 | 8.6 | 132 | 8.1 |
| **8** | Base 1 ¼-inch | A-1-a | GP-GM | 143 | 7.4 | 147 | 6.3 |
| **9** | Base 1 ¼-inch | A-1-a | SP-SM | 136 | 7.4 | 139 | 6.6 |
| **10** | Base 1 ¼-inch | A-1-a | GP-GM | 137 | 8.1 | 139 | 7.5 |
| **11** | Base 1 ¼-inch | A-1-a | SP-SM | 136 | 6.6 | 141 | 5.6 |
| **12** | Base 1 ¼-inch | A-1-a | GP-GM | 143 | 7.3 | 145 | 6.6 |
| **13** | Base 1 ¼-inch | A-1-a | GP-GM | 135 | 8.0 | 139 | 7.2 |
| **14** | Base ¾-inch | A-1-a | GP-GM | 136 | 8.6 | 137 | 8.5 |
| **15** | Base ¾-inch | A-1-a | GW-GM | 133 | 8.1 | 133 | 8.1 |
| **16** | Base ¾-inch | A-1-b | SP-SM | 138 | 6.9 | 138 | 6.8 |
| **17** | Select Crushed Mat. | A-1-a | GP-GM | 131* | 4.6** | NA | NA |
| **18** | Breaker Run | A-1-a | GP-GM | 135* | 3.3** | NA | NA |
| **19** | Select Crushed Mat | A-1-a | GP | 134* | 5.6** | NA | NA |
| **20** | Breaker Run | A-1-a | GW | 138* | 1.9** | NA | NA |
| **21** | RAP 1 ¼-inch | A-1-a | GW | 123 | 8.6 | 125 | 7.9 |
| **22** | RAP 1 ¼-inch | A-1-a | SW | 122 | 7.5 | 123 | 7.4 |
| **23** | RAP 1 ¼-inch | A-1-a | GP-GM | 125 | 7.5 | 126 | 6.9 |
| **24** | RAP 1 ¼-inch | A-1-a | GW | 123 | 8.5 | 124 | 8.0 |
| **25** | RAP 1 ¼-inch | A-1-a | GW | 122 | 8.3 | 123 | 7.9 |
| **26** | RCA 1 ¼-inch | A-1-a | GW | 119 | 11.0 | 122 | 9.9 |
| **27** | RCA 1 ¼-inch | A-1-a | SM | 128 | 10.4 | 129 | 9.8 |

Table 4.7 (cont'd)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **28** | RPM | A-1-a | GW | 120 | 8.3 | 122 | 7.9 |
| **29** | Subbase | A-1-b | SW-SM | 123 | 0.4 | NA | NA |

* Established by Alternative Laboratory Compaction Test for Oversized Aggregates
** As received moisture content

## 4.2 Field Test Results

### 4.2.1 In-situ Density and Moisture Content

In-situ dry unit weights and moisture contents of aggregates and natural soils across various sites were determined following AASHTO and ASTM standards. These tests encompassed a range of methods, including in-place density measurement via nuclear density gauge (NDG), sand cone (SC), water replacement (WR), and unit box test (UB). The specifics of these methods were detailed in Section 3.3. The unit box test was employed to establish the loose state unit weight of the materials. Compacted and bank state unit weights for most materials were measured using NDG and SC, except for larger aggregates like 3-inch base, select crushed material, and breaker run, where NDG or SC methods were not applicable due to the size of the aggregates. SC test was performed alongside the NDG to cross-verify the density and moisture data. Soil samples were collected from the precise locations of NDG measurements for further verification. In instances of moisture content discrepancies, the dry unit weight was recalculated based on the oven-dry moisture content. Therefore, the compacted and bank state dry unit weights presented in Table 4.8 and Table 4.9 are the corrected values, adjusted according to the oven-dry moisture content data.

**Table 4.8 In-situ dry unit weight and moisture contents of aggregates**

| No. | Material | Compacted State | | Loose State | | Bank State | |
|---|---|---|---|---|---|---|---|
| | | Dry Unit Weight (pcf) | Moisture Content (%) | Dry Unit Weight (pcf) | Moisture Content (%) | Dry Unit Weight (pcf) | Moisture Content (%) |
| **1** | Backfill Str. Type A | 106 | 3.0 | 83 | 2.9 | NA | NA |
| **2** | Backfill Str. Type A | 116 | 3.3 | 86 | 3.8 | NA | NA |
| **3** | Backfill Gr. Grade 2 | 119 | 3.5 | 87 | 7.0 | NA | NA |
| **4** | Base 3-inch | 137* | 4.8 | 99 | 4.8 | NA | NA |
| **5** | Base 3-inch | 150* | 2.4 | 96 | 5.6 | NA | NA |
| **6** | Base 1 ¼-inch | 135 | 2.1 | 95 | 5.0 | NA | NA |
| **7** | Base 1 ¼-inch | 135 | 6.8 | 90 | 6.7 | NA | NA |
| **8** | Base 1 ¼-inch | 138 | 1.9 | 104 | 3.1 | NA | NA |
| **9** | Base 1 ¼-inch | 138 | 2.2 | 104 | 4.6 | NA | NA |
| **10** | Base 1 ¼-inch | 141 | 3.0 | 98 | 4.6 | NA | NA |

### Table 4.8 (cont'd)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **11** | Base 1 ¼-inch | 136 | 3.7 | 97 | 5.6 | NA | NA |
| **12** | Base 1 ¼-inch | 148 | 2.5 | 95 | 4.5 | NA | NA |
| **13** | Base 1 ¼-inch | 129 | 3.9 | 95 | 5.4 | NA | NA |
| **14** | Base ¾-inch | 124 | 2.1 | 101 | 2.5 | NA | NA |
| **15** | Base ¾-inch | 127 | 4.8 | 92 | 5.3 | NA | NA |
| **16** | Base ¾-inch | 131 | 5.1 | 94 | 6.3 | NA | NA |
| **17** | Select Crushed Mat. | 144* | 3.1 | 103 | 4.6 | NA | NA |
| **18** | Breaker Run | 140* | 2.2 | 106 | 3.3 | NA | NA |
| **19** | Select Crushed Mat | 139* | 6.0 | 104 | 5.6 | NA | NA |
| **20** | Breaker Run | 154* | 2.2 | 107 | 1.9 | NA | NA |
| **21** | RAP 1 ¼-inch | 120 | 4.5 | 91 | 4.1 | NA | NA |
| **22** | RAP 1 ¼-inch | 127 | 4.8 | 84 | 6.0 | NA | NA |
| **23** | RAP 1 ¼-inch | 133 | 4.2 | 86 | 4.1 | NA | NA |
| **24** | RAP 1 ¼-inch | 121 | 6.4 | 92 | 3.4 | NA | NA |
| **25** | RAP 1 ¼-inch | 127 | 2.1 | 89 | 3.9 | NA | NA |
| **26** | RCA 1 ¼-inch | 119 | 5.8 | 89 | 6.6 | NA | NA |
| **27** | RCA 1 ¼-inch | 123 | 7.0 | 81 | 8.8 | NA | NA |
| **28** | RPM | 121 | 3.3 | 86 | 3.2 | NA | NA |
| **29** | Subbase | 115 | 5.7 | 81 | 5.4 | NA | NA |

NA = not available, *Established by Water Replacement Method (ASTM D5030)

### Table 4.9 In-situ dry unit weight and moisture contents of natural soils

| **No.** | **Material** | **Compacted State** | | **Loose State** | | **Bank State** | |
|---|---|---|---|---|---|---|---|
| | | **Dry Unit Weight (pcf)** | **Moisture Content (%)** | **Dry Unit Weight (pcf)** | **Moisture Content (%)** | **Dry Unit Weight (pcf)** | **Moisture Content (%)** |
| **1** | Natural Soil | 116 | 4.7 | 99 | 0.4 | 103 | 5.2 |
| **2** | Natural Soil | NA | NA | 83 | 0.4 | 105 | 19.1 |
| **3** | Natural Soil | NA | NA | 77 | 0.3 | 106 | 17.2 |
| **4** | Natural Soil | NA | NA | 80 | 0.5 | 112 | 18.9 |
| **5** | Natural Soil | 133 | 4.5 | 106 | 0.5 | 123 | 7.1 |
| **6** | Natural Soil | 116 | 10.7 | 97 | 0.2 | 105 | 4.6 |
| **7** | Natural Soil | 120 | 14.2 | 79 | 0.3 | NA | NA |
| **8** | Natural Soil | 104 | 7.1 | 96 | 0.4 | 95 | 10.5 |
| **9** | Natural Soil | 117 | 4.5 | 93 | 0.3 | 100 | 5.6 |
| **10** | Natural Soil | 137 | 3.4 | 100 | 0.5 | 124 | 5.2 |
| **11** | Natural Soil | 86 | 33.7 | 66 | 0.5 | 83 | 34.0 |
| **12** | Natural Soil | NA | NA | 89 | 0.3 | 112 | 5.3 |
| **13** | Natural Soil | NA | NA | 74 | 0.5 | 117 | 16.3 |
| **14** | Natural Soil | 116 | 10.9 | 86 | 0.4 | 107 | 16.1 |

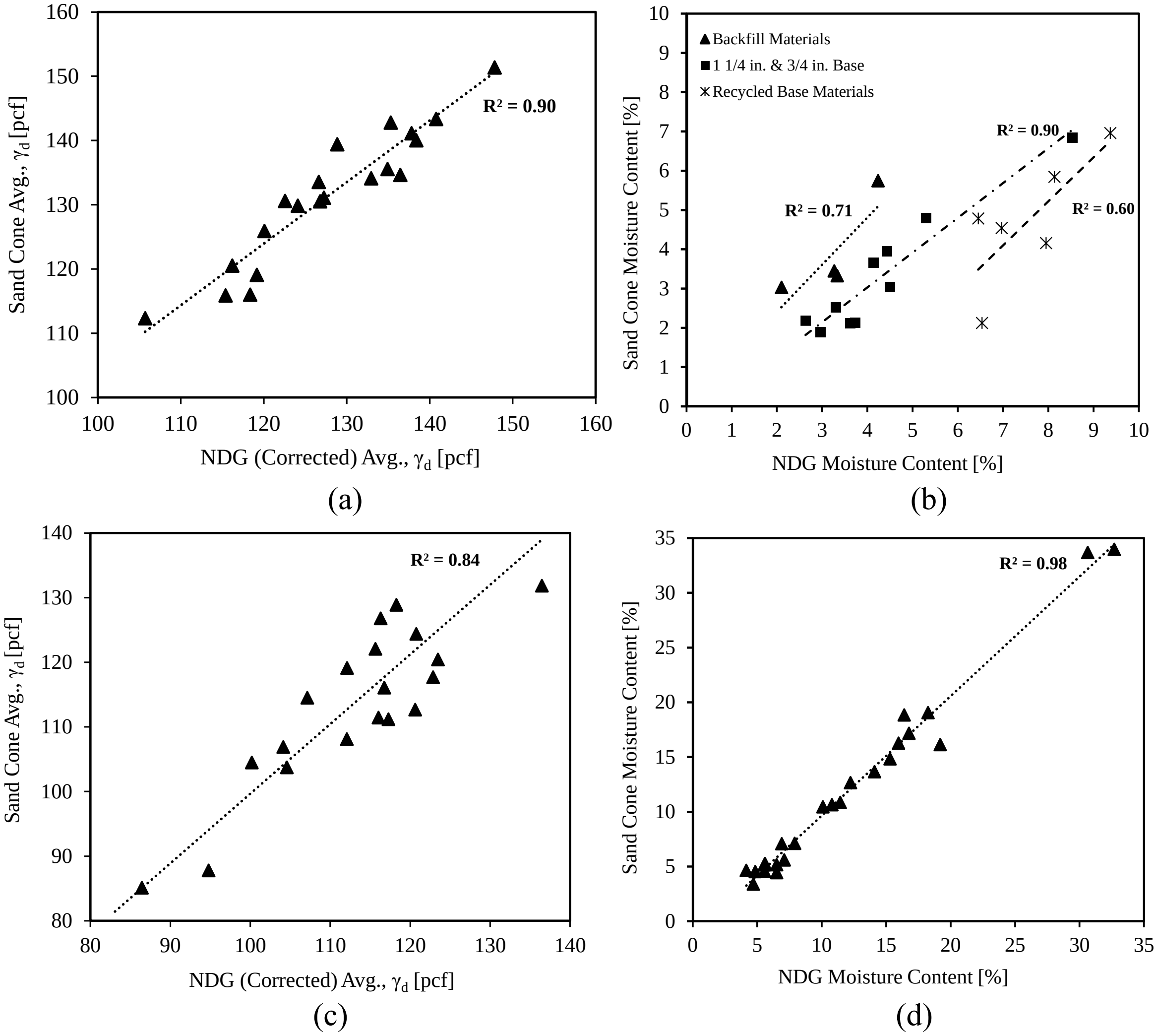
NA = not available

The subbase and backfill materials presented a range of compacted state dry unit weights from 106 pcf to 123 pcf, with moisture contents ranging from 3.0% to 5.7%. In the loose state, these materials demonstrated dry unit weights between 83 pcf and 87 pcf, with moisture contents from 2.9% to 7.0%. For the 1 ¼-inch base materials, the compacted state dry unit weights ranged from 135 pcf to 148 pcf, with moisture contents between 1.9% and 6.8%. Their loose state dry unit weights varied from 90 pcf to 104 pcf, with moisture contents ranging from 3.1% to 6.7%. Similarly, the ¾-inch base materials displayed compacted state dry unit weights ranging from 124 pcf to 131 pcf, with moisture contents between 2.1% and 5.1%, and loose state dry unit weights between 95 pcf and 104 pcf, with moisture contents from 2.5% to 6.3%. For oversized aggregates like 3-inch base, select crushed, and breaker run, the compacted dry unit weights, as measured by the water replacement method, ranged from 137 pcf to 154 pcf, with moisture contents between 2.2% and 6.0%. Conversely, the loose dry unit weights, established by the unit box test, varied between 96 pcf and 106.7 pcf, with moisture contents ranging from 1.9% to 5.6%. On the other hand, recycled base materials yielded a narrow range of compacted state dry unit weights, varying between 119 pcf and 133 pcf, accompanied by moisture contents ranging from 2.1% to 6.4%. In their loose state, these materials exhibited unit weights from 81 pcf to 92 pcf, with moisture contents spanning from 3.2% to 6.6%. The natural soils displayed a broad spectrum of dry unit weights and moisture contents, reflecting the diverse soil types that were gathered and the varied geotechnical properties of soils from different locations. As shown in the Proctor compaction results in the prior section, silty sand with gravel (SM) had the highest compacted unit weight at 137 pcf, with a moisture content of 3.4%. Conversely, fat clay (CH) had the lowest compacted unit weight at 86 pcf and the highest moisture content at 33.7%. A similar trend was observed in the loose state dry unit weights. However, the bank state dry unit weights slightly diverged from this trend. Sands and sands with gravels adhered to the expected pattern of lower dry unit weights compared to their compacted states, yet the bank state dry unit weights for some clay materials approached or exceeded their MDUs. Bank state dry unit weights for clays, higher than 100 pcf and reaching up to 117 pcf, align with the bank state measurements performed by (Edil & Mickelson, 1995) for overconsolidated clays in eastern Wisconsin. This paper discusses overconsolidated glacial tills, noting that clay tills in eastern Wisconsin exhibit varying degrees of overconsolidation depending on their vertical location. This finding is significant for expansion factor calculations for clayey materials.

In addition, the compacted state dry unit weights measured in the field were compared with MDU weights obtained from standard Proctor tests conducted in the laboratory, providing a gauge for relative compaction. This comparison revealed that a majority of the materials achieved a relative compaction exceeding 95%, while the remaining materials displayed compaction levels above 90%. These findings underscore the effectiveness of the compaction processes utilized in construction projects throughout the state, indicating a high standard of quality in material compaction.

Figure 4.4 shows a comparison of dry unit weight and moisture content measurements as determined by Nuclear Density Gauge (NDG) and Sand Cone (SC) tests. In Figure 4.4 (a), a strong correlation is observed between the NDG and SC tests for the dry unit weight of aggregates, with a coefficient of determination ($R^2$) of 0.90, indicating a high level of agreement between the two test methods. Figure 4.4 (b) compares moisture content measurements from NDG and SC tests for aggregates, considering three distinct material types: backfill materials, 1 ¼-inch & ¾-inch base materials, and recycled base materials. Backfill materials showed a good correlation with an $R^2$ of 0.71, while the 1 ¼-inch & ¾-inch base materials had a very strong correlation with an $R^2$ of 0.90. However, the recycled base materials, marked by crosses, demonstrate a moderate correlation with an $R^2$ of 0.60, indicating a more significant variation between the NDG and SC measurement methods for moisture content. These findings suggested that while NDG and SC tests were generally well-aligned in measuring the dry unit weight of materials, some discrepancies were observed in moisture content measurements, particularly with recycled base materials. This variation could be attributed to the NDG method's reliance on hydrogen detection for assessing moisture, which may be influenced by the presence of hydrogen-rich compounds such as gypsum, coal, lime, fly ash, organic substances, mica clays, and phosphates, as noted by (Troxler, 2009). The presence of these compounds in forms other than water can lead to imprecise moisture readings. Figure 4.4 (c) illustrates the correlation between the NDG and SC tests for dry unit weights of natural soils, with an $R^2$ of 0.84. This indicates a high level of agreement between the two test methods for testing natural soils. In Figure 4.4 (d), the moisture content measurements for natural soils are compared, revealing an even stronger correlation with an $R^2$ of 0.98. The near-perfect alignment of the data points along the trend line highlights the precise agreement between the NDG and SC tests in determining the moisture content of natural soils.

These results confirm that the NDG and SC tests are well-matched in measuring both the dry unit weight and moisture content of natural soils, providing confidence in the use of these methods for geotechnical evaluation. The high $R^2$ values across both parameters suggest that the NDG method is a reliable tool for assessing the moisture and density characteristics of natural soils in the field.



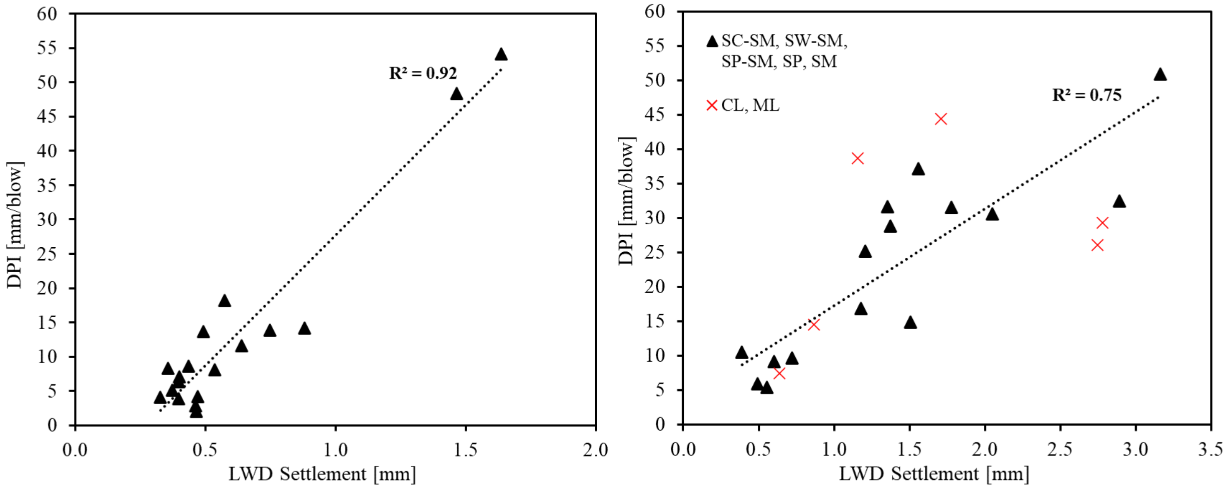
(a) (b)

(c) (d)

**Figure 4.4 Dry unit weight and moisture content comparison between NDG and SC tests: (a) dry unit weights for aggregates, (b) moisture contents for aggregates, (c) dry unit weights for natural soils, and (d) moisture contents for natural soils**

### 4.2.2 LWD and DCP Tests Results

LWD and DCP tests were performed in the field to assess the mechanical properties of natural soils and aggregates at various construction sites. Figure 4.5 shows a comparative analysis between these two testing methods. Figure 4.5 (a) illustrates the relationship between LWD settlement values (in mm) and DCP penetration index (DPI) values (in mm/blow) for aggregates. A strong correlation was observed, with an $R^2$ of 0.92, indicating a high level of agreement between these two tests in assessing aggregates. On the other hand, Figure 4.5 (b) shows the correlation for natural soils, including sandy soils, silt, and clays. Sandy soils exhibited a strong relationship between these two tests with an $R^2$ of 0.75, while silts and clays showed a lower $R^2$, yet still presented a noticeable trend.



(a) (b)

**Figure 4.5 LWD and DCP tests comparison: (a) aggregates, (b) natural soils**

### 4.3 Development of Expansion and Conversion Factors

The main goal of this project, as stated in the research objectives, is the development of expansion and conversion factors for geomaterials. Utilizing the methodologies outlined in Section 1.2, "Earthwork Calculation Methods," Equations 3 and 4 were applied to determine expansion factors for natural soils, and Equation 5 was applied for aggregates. Laboratory and field test results, detailed in Sections 4.1 and 4.2, respectively, were fundamental in developing these volumetric factors. These tests played a crucial role in determining the unit weights of different geomaterials in their compacted (fill), bank (natural), and loose (stockpile) states. The maximum dry unit weight, determined by laboratory Proctor tests, was used for the compacted unit weight. Field unit weight measurements through nuclear gauge and sand cone tests were utilized to calculate the bank unit weight of natural soils. The loose unit weight was assessed using the unit box test method, as outlined in Section 3.3.5. Table 4.10 presents the developed expansion factor ranges for natural soils, categorized based on the United States Soil Classification System (USCS).

**Table 4.10 Expansion factors for natural soils**

| **Soil Type** | **Expansion Factor (Bank to Loose)** (%) | **Expansion Factor (Compacted to Bank)** (%) | **Soil Classification (USCS)** |
|---|---|---|---|
| Sands with Gravel | 16 – 23 | 11 | SW-SM, SM |
| Clean Sands | 4 – 8 | 9 – 10 | SP |
| Silty Sands | 2 – 27 | 1 – 15 | SM, SP-SM, SC-SM |
| Silts | 27 | 12 | ML |
| Clays | 26 – 58 | (-5) – 9 | CL, CH |

For soils classified as sands with gravel (SW-SM, SM), the expansion factor ranged from 16% to 23% when transitioning from the bank to the loose state, and was 11% from compacted to bank state. Clean Sands (SP) exhibited expansion factors between 4% and 8%, and 9% to 10%, respectively, for the same transitions. Silty Sands (SM, SP-SM, SC-SM) showed a wider range, from 2% to 27% for bank to loose state, and 1% to 15% for compacted to bank state. Silts (ML) had expansion factors of 27% and 12% for these respective volume changes. Clays (CL, CH) exhibited the most significant variability, with expansion factors ranging from 26% to 58% for bank to loose state and (-5)% to 9% for compacted to bank state. The bank state unit weight of the clay materials was similar to or higher than the MDU for the lean clays (CL), as outlined in Section 4.2.1. Bank state dry unit weights for clays align with measurements performed by (Edil & Mickelson, 1995) for overconsolidated clays in eastern Wisconsin. This finding is crucial for the research because the typical expansion factors for clay materials in WisDOT guidelines range between 25-35%. These results indicate the need for region-specific expansion factors for particular materials. In summary, these results highlight the significant variability in expansion behavior across different soil types, underscoring the importance of soil classification in determining appropriate expansion factors.

On the other hand, Table 4.11 outlines the conversion and expansion factors for various types of aggregates, providing detailed insight into their behavior when transitioning from a compacted to a loose state.

**Table 4.11 Conversion and proposed expansion factors for aggregates**

| Material Name | Number of Samples Tested | Conversion Factor (tons/cubic yard) | Expansion Factor (Compacted to Loose) (%) |
|---|---|---|---|
| Dense Graded Base ¾-inch | 3 | 1.80 – 1.86 | 36 – 47 |
| Dense Graded Base 1 ¼-inch | 8 | 1.79 – 1.98 | 34 – 52 |
| Dense Graded Base 3-inch | 2 | 1.78 – 1.87 | 34 – 45 |
| Breaker Run | 2 | 1.82 – 1.87 | 27 – 30 |
| Select Crushed Material | 2 | 1.77 – 1.81 | 27 – 29 |
| Backfill Structure (Grade A or B) | 2 | 1.50 – 1.72 | 35 – 48 |
| Backfill Granular (Grade 1 or 2) | 2 | 1.62 – 1.66 | 38 – 52 |
| RAP Base 1 ¼-inch | 6 | 1.64 – 1.71 | 35 – 46 |
| RCA Base 1 ¼-inch | 2 | 1.65 – 1.75 | 37 – 60 |

RAP: Recycled asphalt pavement, RCA: Recycled concrete aggregate

For Dense Graded Base aggregates, the conversion factors ranged as follows: 1.80 to 1.86 for ¾-inch, 1.79 to 1.98 for 1 ¼-inch, and 1.78 to 1.87 for 3-inch, with corresponding expansion factors between 34% to 47%, 34% to 52%, and 34% to 45%, respectively. Breaker Run and Select Crushed Material showed conversion factors ranging from 1.82 to 1.87 and 1.77 to 1.81, with expansion factors of 27% to 30% and 27% to 29%, respectively. Backfill Structure (Grade A or B) had conversion factors between 1.50 to 1.72 and expansion factors from 35% to 48%, while Backfill Granular (Grade 1 or 2) ranged from 1.62 to 1.66 in conversion factors with expansion factors of 38% to 52%. All the aggregates were within the range of the WisDOT guidelines for conversion factors as shown in Table 1.2, except for the Backfill Structure (Grade A) materials, based on 2 samples tested, demonstrated lower conversion factors of 1.50 and 1.72, falling below the guideline's lower limit of 1.75. In addition to the current list of aggregates provided by WisDOT for conversion factors, 1 ¼-inch RAP and RCA base materials were also included in Table 4.11 to enhance the database by incorporating recycled materials. These RAP and RCA materials exhibited conversion factors of 1.64 to 1.71 and 1.65 to 1.75, and their expansion factors range from 35% to 46% and 37% to 60%, respectively.

### 4.4 Estimation of Expansion and Conversion Factors

The forward stepwise regression technique was employed to predict key parameters of materials tested in this project which includes MDU, loose dry unit weight for natural soils and aggregates, and bank dry unit weight for natural soils. The choice of multivariate regression modeling was driven by the need for straightforward and transparent analysis, which is especially crucial in civil engineering for clear model interpretation and data-driven decision-making. In this process, forward stepwise analysis was vital in identifying the most significant variables, ensuring that the models remained focused and practical. By selecting only statistically significant variables (p-value less than 0.05), the models effectively utilized important index properties that significantly impact predictions. This approach not only enhanced the precision of the models but also ensured their relevance for each specific condition. The predictive model was customized using various sets of index properties for each scenario, in order to ensure accuracy, by utilizing the index characteristics of the geomaterials. A comprehensive evaluation process was followed, where each independent variable's significance was assessed, including only those with a p-value less than 0.05. This methodology was fundamental in developing reliable and accurate expansion and conversion factors. Notably, large-sized aggregates such as 3-inch base, select crushed material, and breaker run were excluded from the prediction models. Their substantially larger nominal maximum size and unique gradation parameters led to inconsistencies in the model. Furthermore, these materials exhibited similar dry unit weights and compacted dry unit weights, regardless of their index properties, which posed challenges in creating an accurate model. The limited sample size, with only two samples for each of these materials, further constrained the dataset, making it inadequate for a reliable regression model. Consequently, for these specific materials, this study provides a range for the expansion and conversion factors, as shown in Table 4.7, based on direct test results rather than specific predictions derived from a model based on index properties. This approach ensures a more accurate representation and understanding of these unique materials in the context of expansion factor calculations.

Table 4.12 summarizes the regression equations used to predict the maximum, loose, and bank dry unit weights of natural soils and aggregates. This table also includes the coefficient of determination ($R^2$), the adjusted coefficient of determination, and the standard error for each regression model.

**Table 4.12 Equations for predicting maximum dry unit weight (MDU), loose dry unit weight (LDU), and bank dry unit weight (BDU) of natural soils and aggregates**

| Model Description | Equation | $R^2$ | Adj. $R^2$ | Std. Error |
|---|---|---|---|---|
| Aggregate MDU | $53.2052 \times \text{OD } G_s - 0.3473 \times \text{Gravel}(\%) - 0.8312 \times \text{Sand}(\%) - 0.5881 \times C_c + 54.1093$ | 0.97 | 0.95 | 2.05 |
| Aggregate LDU | $28.1019 \times \text{OD } G_s + 0.3998 \times \text{Gravel}(\%) - 2.2722 \times D_{30} - 1.2952 \times \text{MC}(\%) + 11.4956$ | 0.92 | 0.89 | 2.09 |
| Natural Soil MDU | $-0.9022 \times \text{Sand}(\%) - 0.8794 \times \text{Fine}(\%) - 0.6154 \times \text{PI} - 76.9710 \times D_{10} + 209.9725$ | 0.97 | 0.94 | 2.82 |
| Natural Soil LDU | $-0.4651 \times \text{Sand}(\%) - 0.5691 \times \text{Fine}(\%) - 0.2477 \times \text{PI} - 26.6985 \times D_{30} + 135.0309$ | 0.99 | 0.99 | 1.31 |
| Natural Soil BDU | $-0.8602 \times \text{Sand}(\%) - 1.3170 \times \text{Silt}(\%) - 1.6813 \times \text{PI} - 87.9950 \times D_{30} + 207.9188$ | 0.95 | 0.90 | 3.76 |

OD $G_s$ = oven-dry specific gravity, $C_u$ = uniformity coefficient, $C_c$ = coefficient of curvature, $D_{30}$ = The diameter at which 30% of the soil particles are finer (mm), $D_{10}$ = The diameter at which 10% of the soil particles are finer (mm), MC = actual moisture content of stockpile, PI = plasticity index

An Excel-based tool, designed with a user-friendly interface, was developed to facilitate the practical application of these findings, specifically for predicting expansion and conversion factors utilizing the regression equations derived from the analysis. This tool allows users to input basic index properties such as specific gravity ($G_s$), gravel and sand contents, $D_{60}$, $D_{30}$, $D_{10}$ and actual moisture content of stockpile for aggregates. For natural soils, inputs include sand, fine and silt contents, plasticity index, $D_{30}$, and $D_{10}$. The tool then provides predictions of expansion and conversion factors for aggregates and expansion factors for natural soils based on the given index properties. Detailed instructions for using the tool, along with examples, are provided in Appendix B of this document.

# CHAPTER 5: SUMMARY AND CONCLUSIONS

This study presents a detailed investigation into the development of expansion and conversion factors for various geomaterials, including natural soils and aggregates. The goal of the project was to accurately determine the volumetric characteristics of a wide range of Wisconsin geomaterials in different states (bank, loose, and compacted) during the cut-haul-fill cycle in roadway construction. Initially, a thorough review of current earthwork calculation methods was completed, followed by an extensive survey of 26 state DOTs to understand their practices in determining expansion and conversion factors. Subsequently, a methodical approach was adopted for project site selection, material collection, and comprehensive field and laboratory testing. These steps were crucial in evaluating the properties of a variety of materials, encompassing natural soils and different aggregates from different regions of Wisconsin. Following this, expansion and conversion factors were developed. In addition, the research led to the creation of prediction models for these factors. Lastly, an Excel-based, data-driven decision-making tool was developed to facilitate the estimation/prediction of expansion and conversion factors using the simple index properties of the materials.

The outcomes of this study provide insight into the behavior of natural soils and aggregates under different compaction conditions, enhancing the precision of earthwork calculations. Key conclusions from this research are summarized as follows:

- A survey of 26 state DOTs revealed that sand and silty/clayey sand are the most commonly used soils in earthwork construction, followed by clayey soils. Only about 31% (8 out of 26) of state DOTs employ specific equations or numbers for expansion factors. The predominant data used to determine expansion/shrinkage factors include soil type, lab-determined MDU, in-situ density, and in-situ moisture content. Notably, 44% of DOT respondents (8 out of 18) reported that their design expansion factors match post-construction observations. Experience, engineering judgment, and lab/in-situ tests are key in determining these factors, with most DOTs not employing any modification factor in their calculations.
- The survey indicated that Backfill Granular (Grade 1 or 2) and Structure Backfill (Grade A or B), primarily consisting of coarse sand/sand and gravel, are the most frequently used materials in earthwork construction, followed by Base Aggregate Dense in ¾-inch and 1

¼-inch sizes. Only about 23% (6 out of 26) of state DOTs employ specific conversion factors or referenced their manuals for these aggregates. The parameters commonly used to determine conversion factors include lab-determined MDU, OMC, and experience/engineering judgment. Approximately 29% (7 out of 24) of DOT respondents confirmed that their design conversion factors align with post-construction measurements, while the majority (71%) did not specify the correlation between design and actual data. It was also noted that DOTs generally do not apply any modification factor while calculating conversion factors for aggregates.

- An extensive project site selection process was conducted to ensure a broad representation of geomaterials throughout Wisconsin. Using “Bedrock Geology of Wisconsin” and “Soil Regions of Wisconsin” maps, diverse project locations were identified in collaboration with the POC. This careful selection process ensured a representative sampling of various soil and aggregate types from multiple regions, contributing to a thorough statewide geotechnical analysis.
- Throughout the study, 29 different types of aggregates were collected, including 3-inch, 1 ¼-inch, and ¾-inch bases, backfill materials, large-sized aggregates such as breaker run and select crushed material, and recycled base materials such as RAP and RCA. Additionally, 14 different types of natural soils were gathered, including sands with gravel, silty and clean sands, silts, and clay.
- Comprehensive field and laboratory testing methodologies were employed to accurately determine the index properties of natural soils and aggregates in Wisconsin, thereby enhancing the understanding of their volumetric characteristics. In addition to standard field and laboratory tests, alternative methods were conducted for specific scenarios. These included the “Unit Box Test” for determining loose density, the “In-Place Density by the Water Replacement Method,” and the “Alternative Laboratory Compaction Test for Oversized Aggregates,” essential for density measurements of oversized aggregates in both field and laboratory, where conventional methods were not applicable.
- A strong correlation was observed in the comparison between nuclear density gauge (NDG) and sand cone (SC) test methods for aggregates and natural soils in dry unit weight measurements. However, discrepancies were noted in the moisture content measurements, especially for recycled base materials. These variations were attributed to the NDG

method's sensitivity to hydrogen-rich compounds, leading to imprecise moisture readings. This underscored the necessity of taking additional moisture samples alongside NDG tests to correct the results, ensuring more accurate moisture content assessment in geotechnical evaluations.

- In-place density tests on various aggregates revealed a wide range of compacted dry unit weights. Subbase and backfill materials exhibited compacted dry unit weights ranging from 106 pcf to 123 pcf. For 1 ¼-inch and ¾-inch base materials, the results varied from 124 pcf to 148 pcf. Large-sized aggregates, including 3-inch base, select crushed, and breaker run, showed compacted dry unit weights between 137 pcf and 154 pcf. Recycled base materials displayed a narrower range, with compacted dry unit weights spanning from 119 pcf to 133 pcf.
- Unit box tests assessing the loose state densities of various aggregates revealed a range of dry unit weights. Subbase and backfill materials displayed loose state dry unit weights from 83 pcf to 87 pcf. The 1 ¼-inch and ¾-inch base materials demonstrated loose dry unit weights ranging from 90 pcf to 104 pcf and 95 pcf to 104 pcf, respectively. Large-sized aggregates showed loose dry unit weights from 96 pcf to 107 pcf, while recycled base materials presented loose dry unit weights between 81 pcf and 92 pcf.
- This project reported a wide spectrum of dry unit weights and moisture contents in natural soils, highlighting the varied geotechnical properties across different locations. Silty sand with gravel (SM) showed the highest compacted unit weight at 137 pcf, while high-plasticity (fat) clay (CH) had the lowest at 86.4 pcf and the highest moisture content at 33.7%. In loose states, a similar trend was observed.
- Bank state dry unit weight measurements for natural soils ranged between 83 pcf and 124 pcf. As expected, most materials demonstrated lower unit weights compared to their MDUs. However, some overconsolidated clays presented a notable exception, deviating significantly from expected patterns by showing densities similar to or even exceeding their MDUs. These observations are in strong alignment with the results presented by (Edil & Mickelson, 1995), emphasizing the necessity of region-specific expansion factors for precise earthwork calculations in areas with unique soil characteristics.
- Compacted state dry unit weights in the field were compared with MDUs determined in the lab using standard Proctor tests, which are a measure of relative compaction. The

findings showed that the majority of materials achieved a relative compaction of over 95%. The rest exhibited compaction levels above 90%. These results highlight the quality of compaction in construction projects across the state.

- Sieve analysis results for aggregates closely conformed to WisDOT gradation requirements. The particle size distributions for all tested materials fell within the specified limits, with some minor deviations. Furthermore, recycled base materials such as RAP, RPM, and RCA predominantly met the gradation limits for 1 ¼-inch virgin aggregates, even though their only requirement was to pass through a 1 ¼-inch sieve. These results highlight the effectiveness of the sampling methods and the high quality of aggregates used in construction projects throughout the state.
- The tested materials displayed a range of oven-dry specific gravity ($G_s$) and absorption characteristics. Backfill and subbase materials had $G_s$ values between 2.64 and 2.74 with absorption values from 0.5% to 1.2%. Base materials, including 3-inch, 1 ¼-inch, and ¾-inch sizes, showed $G_s$ values from 2.46 to 2.70 and higher absorption values between 1.3% and 4.2%, with a notable correlation between higher fine content and increased absorption. Breaker run and select crushed materials varied in $G_s$ from 2.55 to 2.67, and absorption from 1.2% to 3.0%. Recycled materials had $G_s$ values from 2.27 to 2.43 with a wider absorption range of 1.6% to 5.8%, reflecting their different compositions, especially the higher absorption rates in RCA due to residual mortar content and porosity. Natural soils, in contrast, exhibited a narrower range of apparent $G_s$ values from 2.63 to 2.76.
- Standard Proctor test results showed a diverse range of maximum dry unit weights (MDUs) and optimum moisture contents (OMCs) across various materials. Subbase and backfill materials had MDUs ranging from 111 pcf to 127 pcf with consistently low OMCs around 0.4%, suggesting maximum density achievement at low moisture levels. Virgin base materials, including 1 ¼-inch and ¾-inch sizes, exhibited MDUs from 133 pcf to 147 pcf and OMCs from 5.6% to 8.5%. Recycled materials like RAP, RPM, and RCA had lower MDUs, ranging from 122 pcf to 128 pcf, and higher OMCs up to 11.0%, with RCA requiring more moisture for optimal compaction. Large-sized aggregates showed compacted dry unit weights between 131 pcf and 138 pcf with their as-received moisture contents. Natural soils demonstrated the widest range, with MDUs from 91 pcf to 137 pcf

and OMCs from 0.3% to 27.5%, reflecting the diversity of soil types and their distinct geotechnical properties.

- Methods for calculating weight-to-volume conversion factors for aggregates, as well as expansion factors for natural soils and aggregates across different geomaterial states—compacted (fill), bank (natural), and loose (stockpile)—were clearly explained using equations and by comparing them with current practices.
- Expansion factors for soils varied significantly according to their classification. Sands with gravel (SW-SM, SM) exhibited expansion factors of 16%-23% from bank to loose state and 11% from compacted to bank state. Clean Sands (SP) ranged from 4%-8% to 9%-10% for the same transitions. Silty Sands (SM, SP-SM, SC-SM) showed a broader range of 2%-27% for bank to loose and 1%-15% for compacted to bank. Silts (ML) had factors of 27% and 12%, while Clays (CL, CH) varied most significantly, with 26%-58% for bank to loose state and (-5)%-9% for compacted to bank state. Notably, the bank state unit weight of some clays was similar to or exceeded their maximum dry unit weights, aligning with previous findings for overconsolidated clays in eastern Wisconsin. These results underscore the need for region-specific expansion factors, especially for clays where variability is considerable, highlighting the critical role of soil classification in determining expansion factors.
- Conversion and proposed expansion factors for dense graded base aggregates varied, with ¾-inch, 1 ¼-inch, and 3-inch bases showing conversion factors of 1.80-1.86, 1.79-1.98, and 1.78-1.87, respectively, and corresponding expansion factors of 34%-47%, 34%-52%, and 34%-45%. Breaker Run and Select Crushed Material had conversion factors of 1.82-1.87 and 1.77-1.81, with expansion factors of 27%-30% and 27%-29%. Backfill Structure (Grade A or B) and Backfill Granular (Grade 1 or 2) displayed conversion factors of 1.50-1.72 and 1.62-1.66, and expansion factors of 35%-48% and 38%-52%. These aggregates were generally within WisDOT guidelines, with the addition of 1 ¼-inch RAP and RCA materials in the database, exhibiting conversion factors of 1.64-1.71 and 1.65-1.75, and expansion factors of 35%-46% and 37%-60%.
- The estimation of expansion and conversion factors was refined using a forward stepwise regression technique, focusing on key parameters like MDU and dry unit weights for both loose and bank states in soils and aggregates. This regression model, chosen for its

straightforwardness and transparency, was vital for clear interpretation and data-driven decision-making in civil engineering. Index properties of the geomaterials were utilized by selecting only statistically significant variables (p-value $< 0.05$), enhancing precision and applicability. Large-sized aggregates like 3-inch base, select crushed material, and breaker run were excluded due to inconsistencies in modeling caused by their unique characteristics and limited sample sizes. For these materials, a range of expansion and conversion factors was provided based on direct test results. Additionally, an Excel-based tool was developed for practical estimation of expansion factors using the materials' index properties, ensuring accurate and reliable calculations for diverse geotechnical conditions.

# CHAPTER 6: RECOMMENDATION AND IMPLEMENTATION

This chapter presents insights from the project on the behavior of natural soils and aggregates under various conditions, thereby enhancing the precision of earthwork calculations in roadway construction. It outlines practical recommendations based on these insights, along with strategies for their real-world implementation to ensure a positive impact on earthwork construction calculations.

The research emphasizes the need for region-specific expansion factors, especially for consolidated clays, to accurately reflect their unique expansion rates. Future studies should examine the densification effects of heavy machinery during clearing and grubbing operations. Moreover, expanding the database to encompass a wider range of soil types and aggregates is essential for refining predictive models. For field applications, particularly with large-sized aggregates, it's important to extensively utilize the study's developed methods. This includes employing the developed *In-Place Density Measurement by Water Replacement Method* in the field and the *Alternative Compaction Method* for large-sized aggregates in the laboratory. The potential for using *3D Lidar Scanning on dump trucks* to enhance loose density measurement accuracy is highlighted, although this requires meticulous coordination with contractors and quarries to minimize operational disruptions. In addition, future research should consider employing unit weight measurements at various excavation depths, which could lead to the development of a modification factor for improved accuracy in expansion factors. Furthermore, it is recommended that the proposed expansion factors be adopted for aggregates.

Implementing these recommendations involves several practical steps. It is important to acknowledge, however, that this analysis has been completed with the available samples collected for this study, which for some materials involved relatively few samples. As such, further refinement and development of a more comprehensive database, either statewide or on a regional level, will greatly improve the accuracy and applicability of expansion and conversion factors. The Excel-based tool created in this study offers significant advantages for Wisconsin construction projects, including a user-friendly interface for easy data entry, thereby streamlining the calculation of expansion and conversion factors. This not only saves time and effort for construction professionals but also ensures precise, reliable estimations of expansion and conversion factors, leading to more efficient and cost-effective earthwork operations. It is recommended that the application of this tool across diverse Wisconsin construction projects should be validated with project construction data. Furthermore, projects should consider using multiple factors specifically determining specific material types and conditions for more accurate earthwork calculations. These strategies are designed to translate the study’s findings into effective, practical solutions, improving the accuracy of earthwork construction estimations.

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## APPENDIX A – Survey Questions

**Project Title:** Weight-Volume Relationships and Conversion Factors for Soils and Aggregates of Wisconsin

**Note:** This questionnaire will be conducted across the US, and the results of this questionnaire will be shared with the participants.

**Project Description:** Michigan State University and the University of Wisconsin-Madison are preparing a questionnaire on Weight-Volume Relationships and Conversion Factors for Soils and Aggregates for Wisconsin DOT. In this questionnaire, expansion/shrinkage values represent volume change between natural and compacted state of natural soils and bedrocks, whereas conversion factors represent comparison of weight to loose or compacted volume of processed materials in a truck or stockpile or fill. Geomaterials considered herein include natural soils (e.g., gravel, sand, silt, and clay), natural aggregates, and recycled aggregates (e.g., recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP)), and large-sized rock materials such as breaker run (quarried rock or concrete material processed through a primary crusher with particles smaller than 6-inch). Design earthwork estimates may not match actual construction quantities if shrinkage or expansion factors are not representative of the earthwork materials, which can impact project schedule and costs. Therefore, using representative shrinkage and expansion factors are important for accurate earthwork estimates.

Different state DOTs use different methods for calculation of earthwork quantities. While some DOTs prefer using “shrink the cut” method, other DOTs use “expand the fill” method for natural soils and bedrocks. Therefore, shrinkage and expansion terms vary depending on earthwork calculation method or approach. For example, Wisconsin DOT prefers using “expand the fill” method for soils and expansion factors for bedrocks for earthwork computations where the excavated bedrock volume is expanded. WisDOT provides statewide weight to volume conversion factor ranges for unbound granular aggregate materials. Expansion values and conversion factors that Wisconsin DOT is currently using are shown in Table 1, Table 2, and Table 3 below, respectively.

**Table A.1 Typical Soil Expansion Values (WisDOT, 2017)**

| Soil Type | Typical Expansion Value % |
|---|---|
| Clean Sands | 10-15 |
| Silty Sands | 15-25 |
| Silts | 20-30 |
| Silty Clays and Clays | 25-35 |

### Table A.2 Typical Bedrock Expansion Values (WisDOT, 2017)

| Soil Type | Typical Expansion Value % |
|---|---|
| Sandstone | 0-5 |
| Shale | 0-5 |
| Limestone | 5-10 |
| Igneous Rock | 10-15 |
| Metamorphic Rock | 10-15 |

### Table A.3 Compacted Aggregate Conversion Factors (WisDOT, 2022)

| Soil Type | Conversion Factor (Tons/Cubic Yard) |
|---|---|
| Base Aggregate Dense ¾ - Inch | 1.75 – 2.1 |
| Base Aggregate Dense 1 ¼ - Inch | 1.75 – 2.0 |
| Base Aggregate Dense 3-Inch | 1.75 – 2.2 |
| Base Aggregate Open Graded | 1.6 – 1.9 |
| Breaker Run | 1.7 – 1.8 |
| Select Crushed Material | 1.7 – 1.9 |
| Pit Run | 1.6 – 1.8 |
| Backfill Granular (Grade 1 or 2) | 1.5 – 1.7 |
| Backfill Structure (Grade A or B) | 1.75 – 2.0 |

The objective of this questionnaire is to compile and synthesize the current state of Department of Transportation practices, identify shrinkage/expansion values and conversion factors based on soil/rock/geomaterial types, also determine soil tests, equations, and historical databases used. Expansion/shrinkage related questions are in Section 1 of this questionnaire, and conversion factors related questions are in Section 2 of this questionnaire.

**Note:** If you use the word version of the questionnaire, could you please email the questionnaire to Mehdi Bulduk with the following email: cetinbor@msu.edu.

**Questions:**

**Part-1: Expansion/Shrinkage Factors**

1. Please provide your contact information so that we may follow-up?

☐ Name:____________

☐ Email:____________

☐ Phone:____________

2. What type of soils are predominantly used in your region for earthwork construction (e.g., such as excavation and compaction)? Mark all that apply.

- ☐ Gravel
- ☐ Sand
- ☐ Fine Sand
- ☐ Silty/Clayey Sand
- ☐ Silty/Clayey Gravel
- ☐ Silty Soils
- ☐ Clayey Soils
- ☐ Other (specify):

3. How are expansion/shrinkage values for various soil types and geomaterials determined? Do you have any equations, tables, or other references that you are using to estimate these factors? If yes, please send them to cetinbor@msu.edu. If no, please proceed to Question 4.

4. What type of methods/tests do you use to determine the degree of final compaction in the field? Mark all that apply.

- ☐ Proctor test (AASHTO T 99-Standard)
- ☐ Proctor test (AASHTO T 180-Modified)
- ☐ In-situ density tests
- ☐ Survey with drone in addition to weight of materials placed
- ☐ Survey with total station in addition to weight of materials placed
- ☐ Visual inspection
- ☐ Light Weight Deflectometer (LWD) Test
- ☐ Dynamic Cone Penetrometer (DCP) Test
- ☐ Other (specify):

5. What data do you use to predict/determine shrinkage/expansion factors? Mark all that apply.

- ☐ Soil type
- ☐ Maximum dry unit-weight (in the lab)
- ☐ Optimum moisture content (in the lab)
- ☐ In-situ density
- ☐ In-situ moisture content
- ☐ Fines content
- ☐ Gravel content
- ☐ Sand content
- ☐ Effective size diameters ($D_{10}$, $D_{30}$ and $D_{60}$)
- ☐ Specific gravity
- ☐ Atterberg limits
- ☐ Plasticity index
- ☐ Agency tables/Guidance

☐ Experience/Judgment
☐ Other (Specify):

6. Do you account for any additional factors when determining shrinkage or expansion factors? Mark all that apply.

☐ Laboratory tests and/or in-situ tests
☐ Fill location (road core/outside road core)
☐ Vegetation
☐ Water content
☐ Type of clay mineral in the soil
☐ Type of grading operation (e.g., equipment choices)
☐ Type of source (cut or borrow)
☐ Degree of final compaction
☐ Compaction settlement or subsidence of base soil
☐ Waste or spillage
☐ Depth of cuts/fills
☐ State of soil (natural or previously compacted)
☐ Geological origin of soils/rocks (e.g., soil history)
☐ Varying weather conditions and/or staging
☐ Experience/Judgment
☐ None
☐ Other (specify):

7. Do you use multiple shrinkage/expansion factors or a single factor for an entire project? If you use a single factor, please provide specific information about how these single factors are determined? If no, please proceed to Question 8.

8. Do your design expansion/shrinkage factors generally match with those determined after construction is completed? If no, please explain how the differences are resolved.

9. Is there anything else you would like to recommend and/or provide information regarding this expansion/shrinkage? If yes, please provide any other useful information on your expansion/shrinkage factors practices.

## Part-2: Aggregate Weight/Volume Conversion Factors

1. What type of granular materials are being predominantly used in your region for earthwork construction? Mark all that apply.

☐ Base Aggregate Dense ¾ - Inch Maximum
☐ Base Aggregate Dense 1 ¼ - Inch Maximum
☐ Base Aggregate Dense 3-Inch Maximum

☐ Base Aggregate Open Graded (≤ 1 inch)
☐ Breaker Run (≤ 6 inch after primary crusher)
☐ Select Crushed Material (≤ 5 inch and ≤ 10% Passing No. 10 sieve)
☐ Pit Run (Natural material with 50% ≥ 1.5 inch, Sand ≤ 50%; minimal fines)
☐ Backfill Granular (Grade 1 or 2) – Coarse Sand/Sand and Gravel
☐ Structure Backfill (Grade A or B) – Sand/Sand and Gravel
☐ Recycled Concrete Aggregate (RCA)
☐ Recycled Asphalt Pavement (RAP)
☐ Other (specify):

2. How are these conversion factors for various materials determined? Do you have any equations, tables, or other references that you are using to estimate these factors? If yes, please include below. If no, please proceed to Question 3.

3. What type of methods/tests do you use to determine the degree of final compaction in the field for granular materials? Mark all that apply.

☐ Proctor test (AASHTO T 99-Standard)
☐ Proctor test (AASHTO T 180-Modified)
☐ In-situ density tests
☐ Survey with drone in addition to weight of materials placed
☐ Survey with total station in addition to weight of materials placed
☐ Visual inspection
☐ Light Weight Deflectometer (LWD) Test
☐ Dynamic Cone Penetrometer (DCP) Test
☐ Other (specify):

4. What data do you use to predict/determine weight/volume conversion factors? Mark all that apply.

☐ Maximum dry unit-weight (in the lab)
☐ Optimum moisture content (in the lab)
☐ In-situ density
☐ In-situ moisture content
☐ Fines content
☐ Gravel content
☐ Sand content
☐ Effective size diameters ($D_{10}$, $D_{30}$ and $D_{60}$)
☐ Specific gravity
☐ Agency tables/Guidance

- ☐ Experience/Judgment
- ☐ Other (specify):

5. Do you apply any modification factors while calculating weight/volume conversion factors? Mark all that apply.

- ☐ Source material (natural vs. recycled)
- ☐ Fill location (road core/outside road core)
- ☐ Laboratory tests and/or in-situ tests
- ☐ Water content
- ☐ Type of bedrock
- ☐ Type of grading operation (e.g., equipment choices)
- ☐ Degree of final compaction
- ☐ Compaction settlement or subsidence of base soil
- ☐ Waste or spillage
- ☐ Varying weather conditions and/or staging
- ☐ Experience/Judgment
- ☐ None
- ☐ Other (specify):

6. Do your design weight/volume conversion factors match with those determined after construction is completed? If no, please explain situations in which they occur and how differences are resolved.

7. Is there anything else you would like to recommend and/or provide information regarding conversion factors? If yes, please provide any other useful information on your conversion factor practices.

# APPENDIX B – Expansion and Conversion Factors Prediction Tool Instructions

## Expansion and Conversion Factors Prediction Tool Instructions

**Purpose:**

This tool is designed to predict expansion and conversion factors for natural soils and aggregates by utilizing specific index properties.

**Input Section:**

1) Select the type of the material by checking the corresponding checkbox.

2) Input index properties:

- For natural soils: Sand (%), Fine (%), Silt (%), $D_{30}$, $D_{10}$, PI
- For aggregates: OD Gs, Gravel (%), Sand (%), $D_{60}$, $D_{30}$, $D_{10}$, and MC (%)

*Gravel (%) : Gravel content, in (percent),*

*Sand (%) : Sand content, in (percent),*

*Fine (%) : Fine content, in (percent),*

*Silt (%) : Silt content, in (percent),*

*OD* $G_s$ *: oven-dry specific gravity,*

$D_{60}$ *: The diameter at which 60% of the soil particles are finer, in (mm),*

$D_{30}$ *: The diameter at which 30% of the soil particles are finer, in (mm),*

$D_{10}$ *: The diameter at which 10% of the soil particles are finer (mm),*

*MC : Actual moisture content of stockpile, in (percent),*

*PI : plasticity index, in (percent),if non-plastic, enter "0".*

**Instructions:**

1) Under the "INPUT" section, choose the material type by checking the appropriate box.

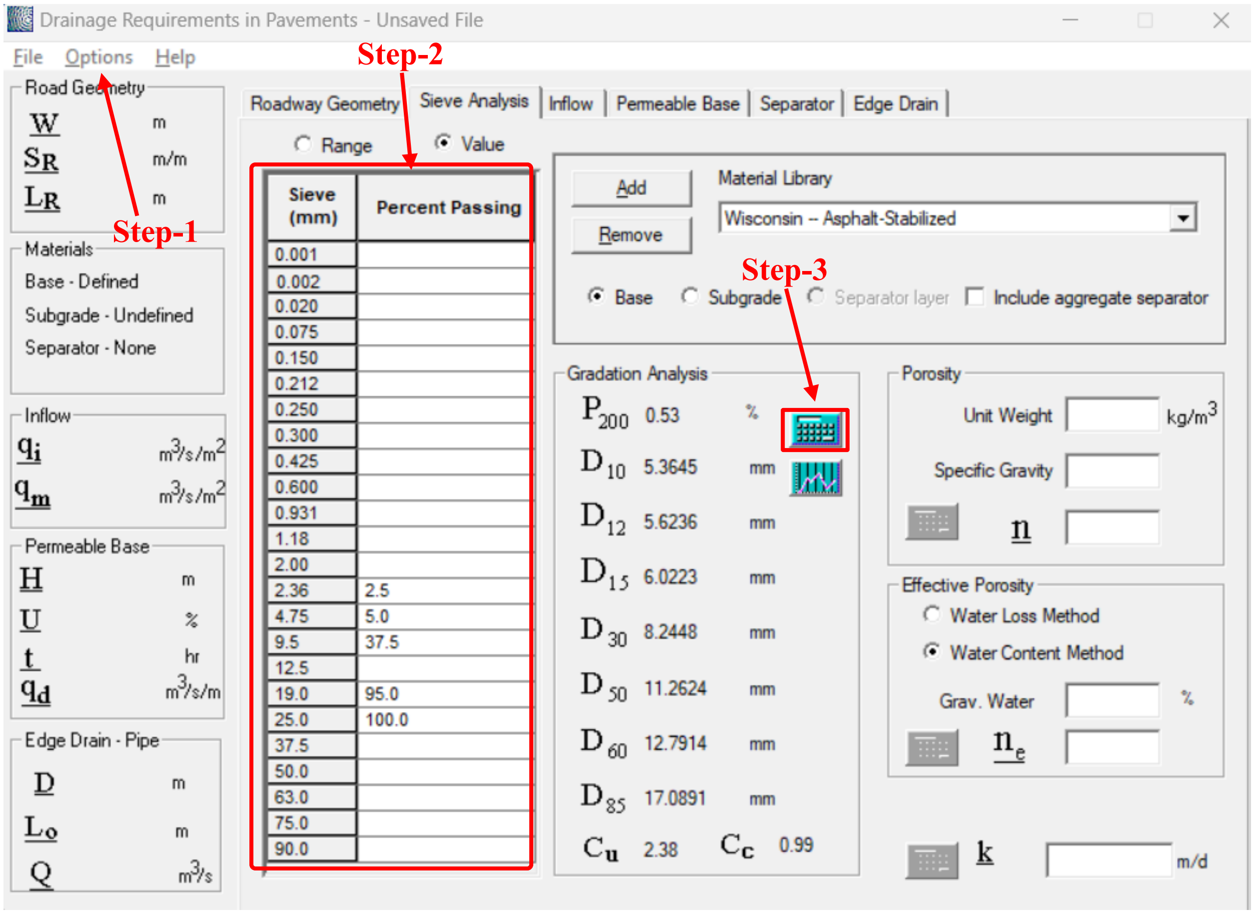
2) Fill in the index properties for the selected material type.

3) To ensure accurate determination of $D_{10}$, $D_{30}$, and $D_{60}$, crucial for analysis, the DRIP software, developed by the Federal Highway Administration, is recommended. This application, aimed at subsurface drainage analysis, features a sieve analysis calculation suitable for this purpose. Download DRIP from the provided link:

https://me-design.com/medesign/DRIP.html?AspxAutoDetectCookieSupport=1

4) After installation, navigate to the "Sieve Analysis" section to input gradation data, facilitating precise calculation of $D_{10}$, $D_{30}$, and $D_{60}$. Before entering the data, ensure to change the units to metric via the option menu for consistency in analysis. After inputting the data, click the

“Calculate” button, marked with a calculator logo, to compute the values. See the example provided below for a visual guide.



Base - Defined
Subgrade - Undefined
Separator - None

○ Range ● Value

| Sieve (mm) | Percent Passing |
|---|---|
| 0.001 | |
| 0.002 | |
| 0.020 | |
| 0.075 | |
| 0.150 | |
| 0.212 | |
| 0.250 | |
| 0.300 | |
| 0.425 | |
| 0.600 | |
| 0.931 | |
| 1.18 | |
| 2.00 | |
| 2.36 | 2.5 |
| 4.75 | 5.0 |
| 9.5 | 37.5 |
| 12.5 | |
| 19.0 | 95.0 |
| 25.0 | 100.0 |
| 37.5 | |
| 50.0 | |
| 63.0 | |
| 75.0 | |
| 90.0 | |

Material Library: Wisconsin -- Asphalt-Stabilized

● Base ○ Subgrade ○ Separator layer ☐ Include aggregate separator

Gradation Analysis

$P_{200}$ 0.53 %
$D_{10}$ 5.3645 mm
$D_{12}$ 5.6236 mm
$D_{15}$ 6.0223 mm
$D_{30}$ 8.2448 mm
$D_{50}$ 11.2624 mm
$D_{60}$ 12.7914 mm
$D_{85}$ 17.0891 mm
$C_u$ 2.38 $C_c$ 0.99

Effective Porosity: ○ Water Loss Method ● Water Content Method

Figure A.1 Example from DRIP software

5) Once all inputs are entered, click the "CALCULATE" button under the respective material section.

6) The "OUTPUT" section will display the estimated expansion factors for natural soils for "compacted to bank" and "bank to loose" states, and for aggregates, the conversion factor in (tons/cubic yards) and expansion factor for "compacted to loose" state.

**Output Section:**

The tool outputs expansion factors (in percent) and conversion factors (in tons/cubic yard), based on the entered index properties.

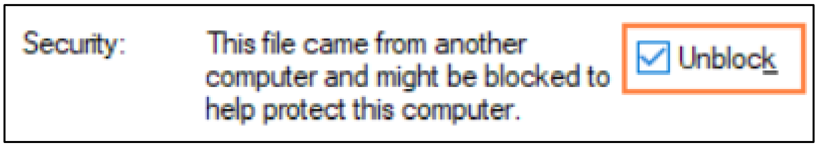
**Notes:**

1) Fill in all required fields to enable calculation.

2) If calculations do not appear, ensure that Excel macros are enabled.

3) If a Security Warning about macros appears, follow these steps:

- Close the workbook.
- Right-click the file and select *Properties* from the menu.
- In the *Properties* dialog box, check "*Unblock*" and then click "OK".

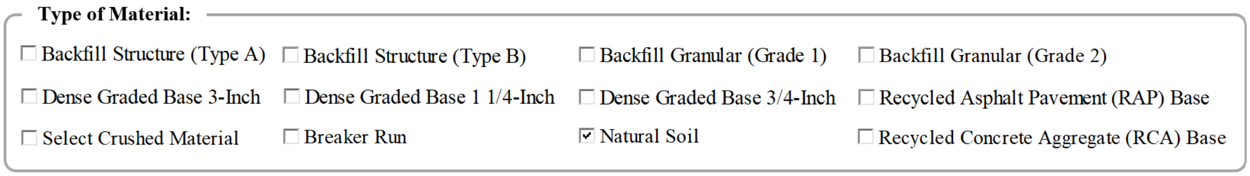


Security: This file came from another computer and might be blocked to help protect this computer.

☑ Unblock

**Figure A.2 Properties dialog box**

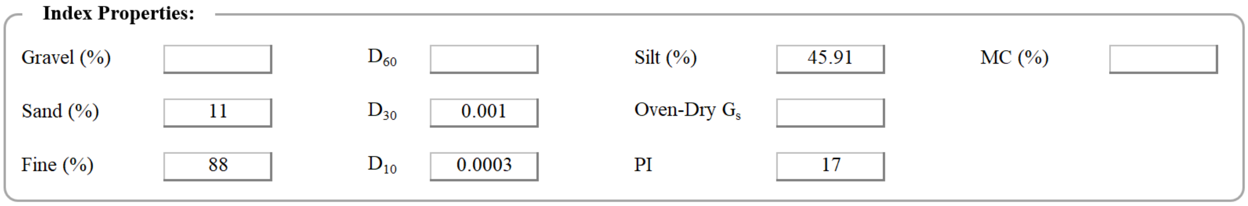
## Example for Natural Soils



**Type of Material:**

☐ Backfill Structure (Type A)
☐ Dense Graded Base 3-Inch
☐ Select Crushed Material
☐ Backfill Structure (Type B)
☐ Dense Graded Base 1 1/4-Inch
☐ Breaker Run
☐ Backfill Granular (Grade 1)
☐ Dense Graded Base 3/4-Inch
☑ Natural Soil
☐ Backfill Granular (Grade 2)
☐ Recycled Asphalt Pavement (RAP) Base
☐ Recycled Concrete Aggregate (RCA) Base

**Figure A.3 Step – 1: Selection of material type**



**Index Properties:**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Gravel (%) | | $D_{60}$ | | Silt (%) | 45.91 | MC (%) | |
| Sand (%) | 11 | $D_{30}$ | 0.001 | Oven-Dry $G_s$ | | | |
| Fine (%) | 88 | $D_{10}$ | 0.0003 | PI | 17 | | |

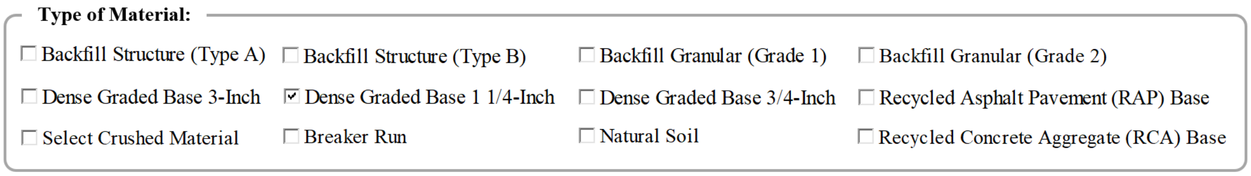
**Figure A.4 Step – 2: Input index properties**

**Natural Soil**

| | *Compacted to Bank* | *Bank to Loose* |
|---|---|---|
| Expansion Factor (%) | 3 | 45 |

**Figure A.5 Step – 3: Output**

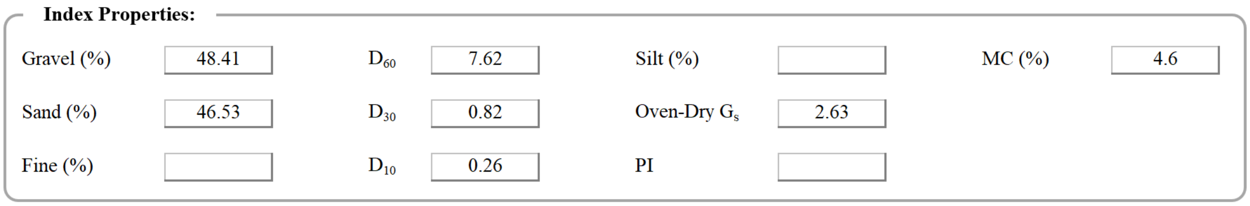
## Example for Aggregates



**Type of Material:**

☐ Backfill Structure (Type A)
☐ Dense Graded Base 3-Inch
☐ Select Crushed Material
☐ Backfill Structure (Type B)
☑ Dense Graded Base 1 1/4-Inch
☐ Breaker Run
☐ Backfill Granular (Grade 1)
☐ Dense Graded Base 3/4-Inch
☐ Natural Soil
☐ Backfill Granular (Grade 2)
☐ Recycled Asphalt Pavement (RAP) Base
☐ Recycled Concrete Aggregate (RCA) Base

**Figure A.6 Step – 1: Selection of material type**



**Index Properties:**

Gravel (%) 48.41

Sand (%) 46.53

Fine (%)

$D_{60}$ 7.62

$D_{30}$ 0.82

$D_{10}$ 0.26

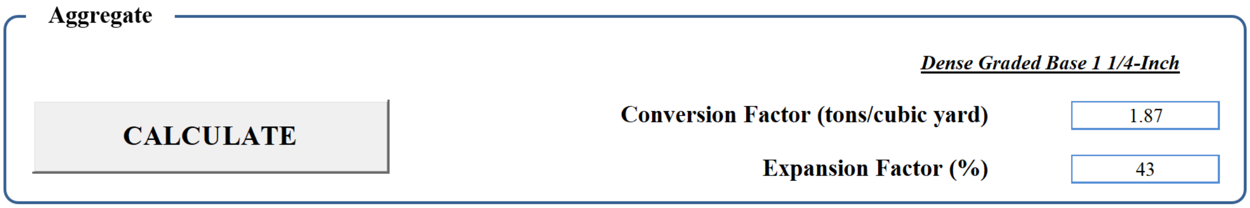
Silt (%)

Oven-Dry $G_s$ 2.63

PI

MC (%) 4.6

Figure A.7 Step – 2: Input index properties



**Aggregate**

***Dense Graded Base 1 1/4-Inch***

Conversion Factor (tons/cubic yard) 1.87

Expansion Factor (%) 43

Figure A.8 Step – 3: Output

## Optional/Additional Instructions for Expansion of the Database

### Purpose:

This guide provides step-by-step instructions for users to add new material index properties to the database and to update the predictive equations based on multivariate regression analysis. The aim is to refine the tool's capability to predict Maximum Dry Unit Weight (MDU), Loose Dry Unit Weight (LDU), and, for natural soils, Bank Dry Unit Weight (BDU), ensuring high accuracy and relevance.

### Step 1: Adding New Material Index Properties

1) Navigate to the “Index Properties Database” Tab:

- This tab is divided into sections for aggregates, large-sized aggregates, and natural soils. Choose the appropriate section for the new data.

2) Enter New Data:

- Input the index properties for the new material. Ensure all relevant fields are filled to maintain data integrity and accuracy.

### Step 2: Utilizing Excel's Multivariate Regression Tool

1) Prepare Data for Analysis:

- Ensure the new data added is correctly formatted and ready for regression analysis.

2) Split the Data for Training and Testing:

- Divide your dataset into two parts: 70% for training the model and 30% for testing its accuracy. This split helps in validating the predictive power of your model on unseen data.

3) Perform Trial and Error with Multivariate Regression:

- Use Excel’s regression tool to analyze the relationship between index properties (independent variables) and MDU, LDU (for aggregates, large-sized aggregates, and natural soils), and BDU (for natural soils) as dependent variables.
- Aim for a model where the p-value is lower than 0.05, indicating statistically significant variables, and the $R^2$ value is high, signifying a good fit.

### Step 3: Updating Equations in the “Data” Tab

1) Navigate the “Data” Tab:

- This tab contains sections for LDU, MDU and BDU (for natural soils), with columns for variables and coefficients.

2) Input New Regression Equations:

- For each material type (aggregates, large-sized aggregates, natural soils), update the intercept and coefficients based on your regression analysis.
- Follow the simple regression equation format: Intercept + (Variable1 * Coefficient1) + (Variable2 * Coefficient2) + ..

### Step 4: Ensuring Accuracy of Conversion and Expansion Factors

- After revising the regression equations, the tool will automatically update the expansion and conversion factors based on the input parameters in the 'Calculation' tab.

Note: Users do not need to manually revise the conversion factor and expansion factor formulas as these are dynamically linked to the regression equations.

### Step 5: Using the Updated Tool

1) Navigate to the “Calculation” sheet:

- This is the main tab where users input material types and index properties to obtain predictions.

2) Input data and calculate:

- Select the type of material and input the required index properties. The tool, utilizing Visual Basic code, will reference the updated expansion factor from the “Data” tab specific to the material type.

# APPENDIX C – Shrinkage and Expansion (swell) Factors from Literature Review

**Table A.4 Summary of shrinkage and swell factors (InDOT, 2013; TDOT, 2021; NCDOT, 2021; MassDOT, 2006)**

| References | Material or Condition | Shrinkage Factor (%) | Expansion (Swell) Factor (%) |
|---|---|---|---|
| InDOT (2013) | Divided-roadway: 0<cys<1000/100 lft | 25 | - |
| | Divided-roadway: 1000<cys<2000/100 lft | 20 | - |
| | Divided-roadway: ≥2000 cys/100 lft | 15 | - |
| | Two-lane-roadway: 0<cys<500/100 lft | 25 | - |
| | Two-lane-roadway: 500<cys<1000/100 lft | 20 | - |
| | Two-lane-roadway: ≥1000 cys/100 lft | 15 | - |
| | Shoulder-widening project | 30 – 35 | - |
| | Rock fill | - | 30 – 35 |
| TDOT (2021) | Light Cut and Fills (1-2 ft) – Earth | 30 – 50 | - |
| | Light Cut and Fills (2-4 ft) – Earth | 25 – 30 | - |
| | Light Cut and Fills (4-6 ft) – Earth | 15 – 20 | - |
| | Heavy Cut and Fills – Earth | 10 | - |
| | Heavy Cut and Light Fills – Cuts 12 ft, Fills 1-2 ft | 15 – 20 | - |
| | Heavy Cut and Light Fills – Cuts 12 ft, Fills 2-4 ft | 10 – 15 | - |
| | Shale and Slate | 5 – 10 | - |
| | Sandstone | - | 0 – 15 |
| | Limestone – Heavy cuts and fills | - | 15 – 20 |
| | Limestone – Light fills | - | 20 |
| NCDOT (2021) | Mountains | 15 – 20 | - |
| | Eastern coastal plain | 25 – 30 | - |
| MassDOT (2006) | Estimate of earth excavation available for embankment: earth excavation quantity measured and/or computed | 5 | - |
| | Estimate of embankment required: embankment quantity measured and/or computed | - | 15 |
| | Estimate of rock excavation available for embankment: rock excavating quantity measured and/or computed | - | 37.5 |
| | Estimate of muck excavation: muck excavating quantity measured and/or computed | 0 | 0 |
| | Estimate of gravel borrow required: borrow quantity measured and/or computed | - | 25 |
| | Estimate of loam required: loam quantity measured and/or computed | - | 25 |
| | Estimate of topsoil required: topsoil quantity measured and/or computed | - | 25 |

cys = cubic yards, lft = linear foot

**Table A.5 Summary of shrinkage and swell factors (AKDOT, 1983)**

| References | Material | In situ wet unit weight (pcf) | Percent Swell | Loose Condition wet unit weight (pcf) | Percent Shrink (-) or Swell (+) | Compacted wet unit weight (pcf) |
|---|---|---|---|---|---|---|
| AKDOT (1983) | Sand | 114 | 5 | 109 | -11 | 129 |
| | Sandy Gravel | 131 | 5 | 124 | -7 | 141 |
| | Silt | 107 | 35 | 79 | -17 | 129 |
| | Loess | 91 | 35 | 67 | -25 | 120 |
| | Rock/Earth Mixtures | | | | | |
| | 75% R/25% E | 153 | 25 | 122 | +12 | 136 |
| | 50% R/50% E | 139 | 29 | 108 | -5 | 146 |
| | 25% R/75% E | 125 | 26 | 99 | -8 | 136 |
| | Granite | 168 | 72 | 98 | +28 | 131 |
| | Limestone | 162 | 63 | 100 | +31 | 124 |
| | Sandstone | 151 | 61 | 94 | +29 | 117 |
| | Shale-Siliceous | 165 | 40 | 118 | +25 | 132 |
| | Siltstone | 139 | 45 | 96 | +9 | 127 |

**Table A.6 Summary of shrinkage and swell factors (Chopra, 1999)**

| | Shrinkage Factor (%) | Bulkage (swell) Factor (%) |
|---|---|---|
| Current Factors | 30 – 35 | 25 |
| Recommended Factors | 15 – 20 | 25 |

## Table A.7 Summary of shrinkage and swell factors (Church, 1981)

| **Material** | **In-situ** | | | **Loose Condition** | | **Fill Condition** | |
|---|---|---|---|---|---|---|---|
| | **Specific Gravity** | | **Bulk Density (kg/m$^3$)** | **Swell (%)** | **Bulk Density (kg/m$^3$)** | **Swell or Shrink (%)** | **Bulk Density (kg/m$^3$)** |
| Adobe, S | (1.91) | | 1917 | 35 | 1413 | -10 | 2119 |
| Andesite, I | 2.94 | | 2938 | 67 | 1763 | 33 | 2214 |
| Basalt, I | 2.94 | | 2938 | 64 | 1792 | 36 | 2160 |
| Dolomite, S | 2.88 | | 2891 | 67 | 1727 | 43 | 2018 |
| Gabbro, I | 3.10 | | 3098 | 67 | 1858 | 33 | 2339 |
| Granite, I | 2.69 | | 2695 | 72 | 1567 | 33 | 2024 |
| Gypsum, S | 2.43 | | 2422 | 72 | 1413 | - | - |
| Limestone, S | 2.61 | | 2600 | 63 | 1597 | 36 | 1911 |
| Asphalt | 1.93 | | 1923 | 50 | 1151 | 0 | 1923 |
| Quartz, I | 2.59 | | 2588 | 67 | 1549 | 33 | 1947 |
| Quartzite, M | 2.68 | | 2683 | 67 | 1608 | 33 | 2018 |
| Sandstone, S | 2.42 | | 2416 | 61 | 1496 | 34 | 1798 |
| Schist, M | 2.59 | | 2689 | 67 | 1608 | 33 | 2024 |
| Shale, S | 2.64 | | 2641 | 50 | 1763 | 33 | 1988 |
| Silt, S | (1.93) | | 1923 | 36 | 1413 | -17 | 2309 |
| Siltstone, S | 2.42 | | 2416 | 61 | 1496 | -11 | 2707 |
| Topsoil, S | (1.44) | | 1442 | 56 | 962 | -26 | 1947 |
| Clay, S: | Dry | (1.91) | 1911 | 35 | 1413 | -10 | 2119 |
| | Damp | (1.99) | 1988 | 40 | 1425 | -10 | 2208 |
| Earth, loam, S: | Dry | (1.84) | 1798 | 35 | 1330 | -12 | 2089 |
| | Damp | (2.00) | 2000 | 40 | 1425 | -4 | 2089 |
| | Wet, | (1.75) | 1745 | 0 | 1745 | -20 | 2089 |
| Gravel, S: | Dry | (1.79) | 1792 | 15 | 1549 | -7 | 1923 |
| | Wet | (2.09) | 2095 | 5 | 1988 | -3 | 2160 |

I = igneous rock, S = sedimentary rock, M = metamorphic rock, ( ) = Apparent specific gravity as material is not solid, (-) = shrinkage

Notes: Bulk densities provided by Church (1981) are subject to an average ±10 percent variation. Swell and shrinkage factors are subject to an average ±33 percent variation for both rock and earth materials.

### Table A.8 Summary of shrinkage and swell factors (FHWA, 2022)

| Material | | In-situ | Loose | | Embankment | |
|---|---|---|---|---|---|---|
| | | **Mass Density (kg/m$^3$)** | **Mass Density (kg/m$^3$)** | **Swell (%)** | **Mass Density (kg/m$^3$)** | **Swell (%)** |
| Andesite | | 2930 | 1760 | 67 | 2050 | 43 |
| Basalt | | 2935 | 1790 | 64 | 2160 | 36 |
| Dolomite | | 2890 | 1725 | 67 | 2015 | 43 |
| Gabbro | | 3095 | 1855 | 67 | 2165 | 43 |
| Granite | | 2695 | 1565 | 72 | 1880 | 43 |
| Gypsum | | 2420 | 1410 | 72 | - | - |
| Limestone | | 2600 | 1595 | 63 | 1910 | 36 |
| Asphalt | | 1920 | 1150 | 50 | 1920 | 0 |
| Quartz | | 2585 | 1550 | 67 | 1780 | 43 |
| Quartzite | | 2680 | 1610 | 67 | 1875 | 43 |
| Sandstone | | 2415 | 1495 | 61 | 1795 | 34 |
| Schist | | 2685 | 1610 | 67 | 1880 | 43 |
| Shale | | 2640 | 1470 | 79 | 1775 | 49 |
| Silt | | 1920 | 1410 | 36 | 2310 | -17 |
| Siltstone | | 2415 | 1495 | 61 | 2705 | -11 |
| Topsoil | | 1440 | 960 | 56 | 1945 | -26 |
| Clay | Dry | 1910 | 1275 | 50 | 2120 | -10 |
| | Damp | 1985 | 1180 | 67 | 2205 | -10 |
| Sand | Dry | 1710 | 1535 | 11 | 1920 | -11 |
| | Wet | 1915 | 1835 | 5 | 2050 | -11 |
| Earth, loam | Dry | 1795 | 1230 | 50 | 2090 | -12 |
| | Damp | 2000 | 1400 | 43 | 2090 | -4 |
| | Wet, mud | 1745 | 1745 | 0 | 2090 | -20 |
| Gravel (Dry) | Uniformly Graded | 1770 | 1600 | 10 | 1870 | -5 |
| | Avg. Gradation | 1945 | 1620 | 20 | 2120 | -8 |
| | Well Graded | 2180 | 1645 | 33 | 2450 | -11 |
| Gravel (Wet) | Uniformly Graded | 1965 | 1870 | 5 | 1870 | -5 |
| | Avg. Gradation | 2160 | 1950 | 10 | 2120 | -2 |
| | Well Graded | 2425 | 2090 | 16 | 2450 | -1 |

(-) = shrinkage

**Table A.9 Summary of shrinkage and swell factors (Burch, 1997)**

| Soil type & moisture level | Swell factor | Shrink factor | Compaction requirements |
|---|---|---|---|
| Dry sand | 1.13 | 1.00 | BCY |
| Dry sand | 1.32 | 0.83 | 95% S.P. |
| Dry sand | 1.39 | 0.77 | 100% S.P. |
| Dry sand | 1.38 | 0.78 | 95% M.P. |
| Dry sand | 1.45 | 0.72 | 100% M.P. |
| Damp sand | 1.13 | 1.00 | BCY |
| Damp sand | 1.16 | 0.98 | 95% S.P. |
| Damp sand | 1.22 | 0.93 | 100% S.P. |
| Damp sand | 1.21 | 0.94 | 95% M.P. |
| Damp sand | 1.27 | 0.84 | 100% M.P. |
| Damp gravel | 1.14 | 1.00 | BCY |
| Damp gravel | 1.23 | 0.93 | 95% S.P. |
| Damp gravel | 1.29 | 0.87 | 100% S.P. |
| Damp gravel | 1.32 | 0.84 | 95% M.P. |
| Damp gravel | 1.39 | 0.78 | 100% M.P. |
| Dry clay | 1.31 | 1.00 | BCY |
| Dry clay | 1.18 | NA | 85% S.P. |
| Dry clay | 1.25 | NA | 90% S.P. |
| Dry clay | 1.39 | 0.94 | 100% S.P. |
| Dry clay | 1.39 | 0.94 | 90% M.P. |
| Dry clay | 1.54 | 0.82 | 100% M.P. |
| Dry dirt | 1.32 | 1.00 | BCY |
| Dry dirt | 1.31 | 1.00 | 85% S.P. |
| Dry dirt | 1.39 | 0.95 | 90% S.P. |
| Dry dirt | 1.54 | 0.83 | 100% S.P. |
| Dry dirt | 1.45 | 0.90 | 90% M.P. |
| Dry dirt | 1.61 | 0.78 | 100% M.P. |
| Damp dirt | 1.28 | 1.00 | BCY |
| Damp dirt | 1.17 | NA | 85% S.P. |
| Damp dirt | 1.23 | NA | 90% S.P. |
| Damp dirt | 1.37 | 0.93 | 100% S.P. |
| Damp dirt | 1.29 | 1.00 | 90% M.P. |
| Damp dirt | 1.43 | 0.89 | 100% M.P. |

BCY = bank cubic yards, S.P. = standard Proctor, M.P. = Modified Proctor, NA = areas where the bank material has a greater density than required for the compacted material