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# Use of Soil-Steel Slag-Class-C Fly Ash Mixtures in Subgrade Applications

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**16. Abstract**

In Indiana, the steelmaking industries and power plants generate large quantities of steel slag, blast furnace slag and fly ash every year. The excess of these underutilized industrial by-products are stockpiled and eventually landfilled at disposal sites. Use of steel slag, fly ash and blast furnace slag in road applications, such as in subgrade stabilization projects, can be a cost-effective alternative to lime stabilization in some cases. In addition, use of large quantities of these underutilized industrial by-products in these types of applications helps to reduce the need for new disposal sites and to conserve natural resources.

The main objectives of this research were to evaluate the feasibility of using soil-steel slag-Class-C fly ash and soil-steel slag-blast furnace slag mixtures in subgrade applications and to implement the selected mixture as a subgrade material in a road construction project of INDOT. In order to achieve these goals, in situ clayey soils, collected from a prospective implementation site, were characterized through a series of laboratory tests which included specific gravity, grain size distribution, Atterberg limits, compaction and unconfined compressive strength. Two types of steel slag mixtures were evaluated for use in subgrade stabilization applications: i) steel slag-Class-C fly ash mixtures and ii) steel slag-blast furnace slag mixtures. The mechanical properties of soil-5% steel slag-5% Class-C fly ash, soil-7% steel slag-3% Class-C fly ash, soil-8% steel slag-2% Class-C fly ash, and soil-7% steel slag-3% blast furnace slag mixtures were determined through compaction and unconfined compression tests. CBR swelling tests were also performed to assess the swelling potential of the mixtures.

The optimum moisture content and maximum dry unit weight of the in situ clayey soil samples were 13% and 18.56 kN/m3 (118.2 pcf), respectively. Based on the results of the long-term CBR swelling tests, the maximum swelling strain of the compacted soil samples was approximately 0.41 %. The average unconfined compressive strength of the in situ soil samples was 282.9 kPa (41 psi). Unconfined compressive strength tests performed on various mixtures at different times indicated the occurrence of stronger cementitious reactions in the soil-steel slag-Class-C fly ash mixtures than in the soil-steel slag-blast furnace slag mixtures. The two-day and seven-day unconfined compressive strength of the compacted soil-7% steel slag-3% Class-C fly ash mixture were 820 kPa (119 psi) and 886 kPa (128 psi), respectively. The maximum 1-D swelling strain of the soil-7% steel slag-3% Class-C fly ash mixture was 0.13 %. The soil-7% steel slag-3% Class-C fly ash mixture was selected as the most suitable and cost-effective subgrade material for the implementation project.

The implementation project for the soil-steel slag-Class-C fly ash mixture was located at the intersection of 109th Avenue and I-65, near Crown Point, Indiana. The pre-mixed 7% steel slag-3% Class-C fly ash mixture was used to stabilize the in situ subgrade soils of some sections of the I-65 ramps located in the SW and NW quadrants of the intersection of 109th Avenue and I-65. Field compaction quality control was done by performing DCPTs and nuclear gauge tests. Cracks or signs of distress were not observed on the subgrade before base course and concrete placement. The soil-steel slag-Class-C fly ash stabilized subgrade performed satisfactorily.

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# EXECUTIVE SUMMARY

## USE OF SOIL-STEEL SLAG-FLY ASH MIXTURES IN SUBGRADE APPLICATIONS

### Introduction

In Indiana, large quantities of recyclable materials—such as steel slag, blast furnace slag and fly ash—are generated each year as by-products of various industries. Instead of disposing these by-products into landfills, we can recycle them into beneficial civil engineering applications by replacing traditional construction materials with these industrial by-products. Replacing traditional materials with these industrial by-products may be a cost-effective alternative that can help save natural resources and reduce the costs associated with landfilling.

In this research study, the suitability of using mixtures of steel slag and Class-C fly ash and mixtures of steel and blast furnace slags to replace lime in subgrade stabilization applications was evaluated. Initially, mixtures of steel slag and Class-C fly ash were explored as a replacement for lime. *In situ* soil collected from a proposed implementation project was mixed with 10% (by weight of soil) of steel slag and Class-C fly ash mixtures. The following mixtures of steel slag and Class-C fly ash were considered in this study: 5% steel slag-5% Class-C fly ash, 7% steel slag-3% Class-C fly ash and 8% steel slag-2% Class-C fly ash by weight of soil. Since the Class-C fly ash used in this study is expensive, a 7% steel slag-3% blast furnace slag mixture by weigh of soil was also investigated for use as an alternative mixture that could also be used for soil stabilization.

In order to determine the properties of the soils prior to stabilization, initial tests were performed on the clayey soil collected from the proposed implementation site. The clayey subgrade soil was characterized through a series of tests that included specific gravity, Atterberg limits, grain size analysis, compaction, swelling and unconfined compression tests.

The mechanical properties of the mixtures of soil, steel slag and Class-C fly ash and soil, steel slag and blast furnace slag were determined through compaction and unconfined compression tests. In order to assess the swelling potential of the *in situ* soil and mixtures, CBR swelling tests were also performed.

### Findings

The present report includes the following findings:

1. The soil collected from the implementation site was classified as lean clay (CL) according to the USCS classification and as A-6, with a group index of 7, according to the AASHTO classification system. In general, materials in this group show high volume change behavior when the moisture content changes and therefore, they are not considered suitable as subgrade materials. The general rating of A-6 soils according to AASHTO is fair to poor as subgrade material.
2. The optimum moisture content and maximum dry unit weight of the clayey soil were 13% and 18.56 kN/m$^3$ (118.2 pcf), respectively.
3. The unconfined compressive strength of the soil samples compacted to 95 to 101% relative compaction ranged between 214 and 329 kPa. The average unconfined compressive strength of the samples was 282.9 kPa (41 psi). Since INDOT typically requires a minimum unconfined compressive strength of about 552 kPa (80 psi) for subgrade soils, the clayey soil at the implementation site required stabilization to support the loads from the pavement without causing excessive settlements.
4. Long-term CBR swelling tests were performed on the compacted soil samples. After approximately 13 days of soaking, the compacted soil samples reached a maximum swelling strain of approximately 0.41% and then started shrinking. Eventually, the soil samples reached equilibrium at a swelling strain of approximately 0.24% after 35 days of soaking.
5. No significant change was observed in the Plasticity Index (PI) of the soil-7% steel slag-3% Class-C fly ash and soil-7% steel slag-3% blast furnace slag mixtures when compared to that of the *in situ* clayey soil.
6. The optimum moisture content and maximum dry unit weight of the soil-7% steel slag-3% Class-C fly ash mixture were 15% and 18.04 kN/m$^3$ (114.8 pcf), respectively. The optimum moisture content and maximum dry unit weight of the soil-7% steel slag-3% blast furnace slag mixture were 16% and 16.94 kN/m$^3$ (107.7 pcf), respectively.
7. The compaction curves for both the soil-steel slag-Class-C fly ash and soil-steel slag-blast furnace slag mixtures indicated higher water content and lower maximum dry unit weight than those obtained from the compaction curve of the *in situ* clayey soil. This trend is similar to that observed in lime treated soils.
8. The two-day unconfined compressive strength of the soil-7% steel slag-3% Class-C fly ash and soil-7%steel slag-3% blast furnace slag mixtures were 820 kPa (119 psi) and 602 kPa (87 psi), respectively.
9. Based on the unconfined compressive strength test results, the strength gain rate of the compacted soil-7% steel slag-3% Class-C fly ash mixture was higher than that of the compacted soil-7% steel slag-3% blast furnace slag mixture. These results indicate the occurrence of stronger cementitious reactions in the mixture of *in situ* soil, steel slag and Class-C fly ash.
10. The maximum swelling strains of the compacted soil-7% steel slag-3% Class-C fly ash and soil-7% steel slag-3% blast furnace slag mixtures were 0.13% and 0.052% based on the results of the long-term CBR swelling tests. These results showed that both the steel slag-Class-C fly ash and steel slag-blast furnace slag mixtures were effective in reducing the swelling potential of the *in situ* clayey soil.
11. The mixture of soil-7% steel slag-3% Class-C fly ash was selected as the most suitable and cost-effective subgrade material for the implementation project.

### Implementation

The mixture of *in situ* soil, steel slag, and Class-C fly ash selected based on the laboratory test results was implemented as a subgrade material in an INDOT project.

The implementation project for the mixture of soil, steel slag and Class-C fly ash selected was carried out at the intersection of 109th Avenue and I-65, near Crown Point, Indiana. The 7% steel slag-3% Class-C fly ash mixture was used to stabilize the *in situ* subgrade soils of some sections of the I-65 ramps located in the SW and NW quadrants of the intersection of 109th Avenue and I-65.

The main construction steps followed for the stabilization of the *in situ* soils with the pre-mixed 7% steel slag-3% Class-C fly ash mixture were: (1) spreading; (2) mixing and water spraying; and (3) compaction. Field compaction quality control was done by performing Dynamic Cone Penetration Tests (DCPT) and nuclear gauge tests.

$N_{DCPT}$ values recorded for 0 to 6 inch and 6 to 16 inch penetration at various stations in the SW ramp were in the ranges of 11–24 and 12–32 96 hours after subgrade compaction, respectively. The $N_{DCPT}$ values recorded for 0 to 6 inch and 6 to 16 inch penetration at various stations in the NW ramp were in the ranges of 5–15 and 6–15 approximately 1 hour after subgrade compaction, respectively. The ranges of values recorded in the NW ramp were lower than those recorded in the SW ramp. This was attributed to the fact that the testing in the NW ramp was done only 1 hour after compaction of the subgrade, and a period of 1 hour is not sufficient to allow for the cementitious reactions to take place.

$N_{DCPT}$ values recorded at all stations in the NW and SW ramps fall in the range specified by criteria developed by U.S. DOTs and hence, the compaction of the subgrade was deemed satisfactory.

INDOT performed nuclear gauge tests at five stations in the stabilized SW subgrade. Based on the maximum dry unit weight values recorded by the nuclear gauge, the relative compaction values for the subgrade at these five stations ranged between 102.6 and 106.7%. INDOT requires a minimum relative compaction of 100% for field compaction of subgrades soil and hence, the stabilized subgrade met INDOT compaction criterion.

The stabilized subgrade was monitored and checked for possible cracks or signs of distress. Cracks or signs of distress were not observed on the surface of the subgrade before the placement of the base course and the concrete. The soil-7% steel slag-3% Class-C fly ash subgrade performed satisfactorily.

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# 1. INTRODUCTION

## 1.1 Background

In Indiana, large quantities of recyclable materials—such as steel slag, blast furnace slag and fly ash—are generated each year as by-products of various industries. These industrial by-products can be recycled into beneficial civil engineering applications. There are several advantages of using recyclable materials in geotechnical applications. Replacing of traditional materials with industrial by-products, can be a cost-effective alternative that can help to save natural resources. In addition, space requirements and costs associated with landfilling are reduced.

According to the American Coal Ash Association (ACAA), the U.S. produced 130 million tons of coal combustion products (CCBP's) in 2010 (*1*). Of this total production, only 43% was used beneficially, while nearly 75 MT (million metric tons) were disposed of in landfills. Large quantities of fly ash are still being disposed of in landfills or stored for future use. Similarly, the iron and steelmaking industries in the U.S. generate 9–14 MT of blast furnace slag and 10–15 MT of steel slag every year. Typically, the amount of blast furnace slag generated each year from the iron making processes in the U.S. is completely utilized in beneficial applications. However, this is not the case for steel slag. In 2009, the steel slag generation after metal recovery was estimated to be 6–9 MT in the U.S. and 120–180 MT in the world (*2,3*). The steel slag produced in the U.S. is used as aggregate for road and pavement construction (~50 to 70%) and in other miscellaneous applications (~10 to 15%). The remaining steel slag that is not reutilized (~15 to 40%) is stockpiled in steel plants and is eventually sent to slag disposal sites.

In Indiana, several steel plants and power plants are in continuous production, generating blast furnace slag, steel slag and fly ash as by-products on a daily basis. Use of steel slag and fly ash in geotechnical applications, such as subgrade stabilization, will help with the recycling of large quantities of these under-utilized industrial by-products. Beneficial use of fly ash and steel slag in road stabilization projects will not only create a cost-effective alternative to lime stabilization, but also reduce the need for new disposal sites. With successful implementation of these recyclable materials in geotechnical applications, the Indiana Department of Transportation (INDOT) has the opportunity to promote similar sustainable applications in the future.

## 1.2 Research Objective

In the course of this research, we evaluated the suitability of using soil-steel slag-Class-C fly ash mixtures and soil-steel slag-blast-furnace slag mixtures for subgrade applications through laboratory testing, designed suitable steel slag-soil mixtures for subgrade applications, and provided technical support during subgrade construction for a demonstration project with the selected mixture.

## 1.3 Research Approach

Clayey soil samples were collected at the location of an INDOT implementation project at the intersection of 109th Avenue and I-65, near Crown Point, Indiana. The clayey soil was characterized through a series of laboratory tests which included, specific gravity, grain size analysis, compaction and unconfined compression tests. In order to improve the *in situ* clayey soil, two types of mixtures were investigated: (i) steel slag-Class-C fly ash mixtures and (ii) steel slag-blast-furnace slag mixtures. In order to design suitable mixtures for subgrade applications, the following soil-steel slag-Class-C fly ash mixtures were evaluated:

- Soil-5% steel slag (by weight of soil)-5% Class-C fly ash (by weight of soil)
- Soil-8% steel slag (by weight of soil)-2% Class-C fly ash (by weight of soil)
- Soil-7% steel slag (by weight of soil)-3% Class-C fly ash (by weight of soil)

In order to assess the feasibility of using steel slag-blast-furnace slag mixtures to stabilize clayey soils, the following mixture was also evaluated:

- Soil-7% steel slag (by weight of soil)-3% blast-furnace slag (by weight of soil)

The laboratory tests performed on the mixtures included unconfined compression, compaction and long-term swelling tests. Based on the results of the laboratory tests, the most suitable and cost-effective mixture was selected to stabilize the subgrade soil of some sections of the I-65 ramps located in the SW and NW quadrants of the intersection of 109th Avenue and I-65. Dynamic cone penetration tests (DCPT) and nuclear gauge tests were used to perform compaction quality control of the stabilized subgrade.

## 1.4 Scope and Organization

In this research, an experimental program was undertaken to evaluate the feasibility of utilizing soil-steel slag-Class-C fly ash and soil-steel slag-blast furnace slag mixtures as subgrade materials. The report is organized in five chapters, which are outlined below:

Chapter 1 provides a brief introduction, background information, research objectives and scope.

Chapter 2 provides the experimental program and the details of the laboratory tests performed in this study.

Chapter 3 provides the experimental results of tests performed on soils and soil-steel slag-Class-C fly ash and soil-steel slag-blast-furnace slag mixtures.

Chapter 4 presents the implementation of a soil-steel slag-Class-C fly ash mixture as a subgrade material.

Chapter 5 presents the summary and conclusions.

# 2. TESTING MATERIALS AND EXPERIMENTAL PROGRAM

## 2.1 Overview

In order to design suitable mixtures that could be used as an alternative for lime, a series of laboratory tests were performed on soil and soil-steel slag-Class-C fly ash and soil-steel slag-blast-furnace slag mixtures. Table 2.1 provides a summary of the laboratory tests performed on soil, soil-steel slag-Class-C fly ash mixtures and soil-steel slag-blast-furnace slag mixtures.

## 2.2 Testing Materials and Representative Sampling

The following testing materials were used in this research:

(a) Clayey soil
(b) Steel Slag (i.e.; electric-arc-furnace steel slag fines)
(c) Blast furnace slag (i.e.; blast furnace slag fines)
(d) Class-C Fly ash

The implementation project was located in Crown Point, Indiana (see Figure 2.1). Clayey soil samples were obtained from the southwest (SW) and northwest (NW) quadrants of the intersection between I-65 and 109th Avenue (see Figure 2.2).

Edward C. Levy Co., which is a slag-processer company with many locations in the U.S., supplied the samples of steel slag and blast furnace slag used in this research. Northern Indiana Public Service Company (NIPSCO) supplied the Class-C fly ash.

The water content of the clayey soil samples at their natural state was very high since they were collected after a snow fall. Initially, the soil samples were air-dried for a minimum of 24 hours. The drying process was facilitated by using a ventilator. Clayey soils tend to form clusters when dried. The large dried clusters of soil were first crushed with a plastic hammer before proceeding with the testing.

TABLE 2.1
**Summary of experimental program**

| Engineering Properties | Experiments |
|---|---|
| **Experimental Program** | |
| Index | Atterberg Limits<br>Grain Size Distribution<br>Specific Gravity Test |
| Mechanical | Proctor Compaction Test<br>Unconfined Compression Test |
| Swelling | CBR Swelling Test |
| **Tests performed on soil-steel slag-Class-C fly ash and soil-steel slag-blast-furnace slag mixtures** | |
| Index | Atterberg Limits |
| Mechanical | Unconfined Compression Test<br>Compaction |
| Swelling | CBR Swelling Test |

**Figure 2.1** Project location, Crown Point, Indiana.

Blast furnace slag, steel slag and Class-C fly ash samples were stored in air-tight buckets. Whenever a smaller portion of these samples was required for testing, a sample splitter was used to obtain representative samples, as shown in Figure 2.3, per ASTM C702-98 (*3a*).

## 2.3 Laboratory Tests

The index properties of the soil samples were determined through grain size distribution and Atterberg limits tests. The mechanical properties of the *in situ* soil, and soil-steel slag-Class-C fly ash mixtures, and soil-steel slag-blast furnace slag mixtures were determined through compaction and unconfined compression tests. In order to assess the swelling potential of the *in situ* soil and soil-steel slag mixtures, CBR swelling tests were also performed. The details of the laboratory tests are provided in the following section.

### *2.3.1 Grain Size Distribution*

The grain size distributions of the soil samples were determined in accordance with ASTM D422-63 (*4*), which is the standard method for particle-size analysis

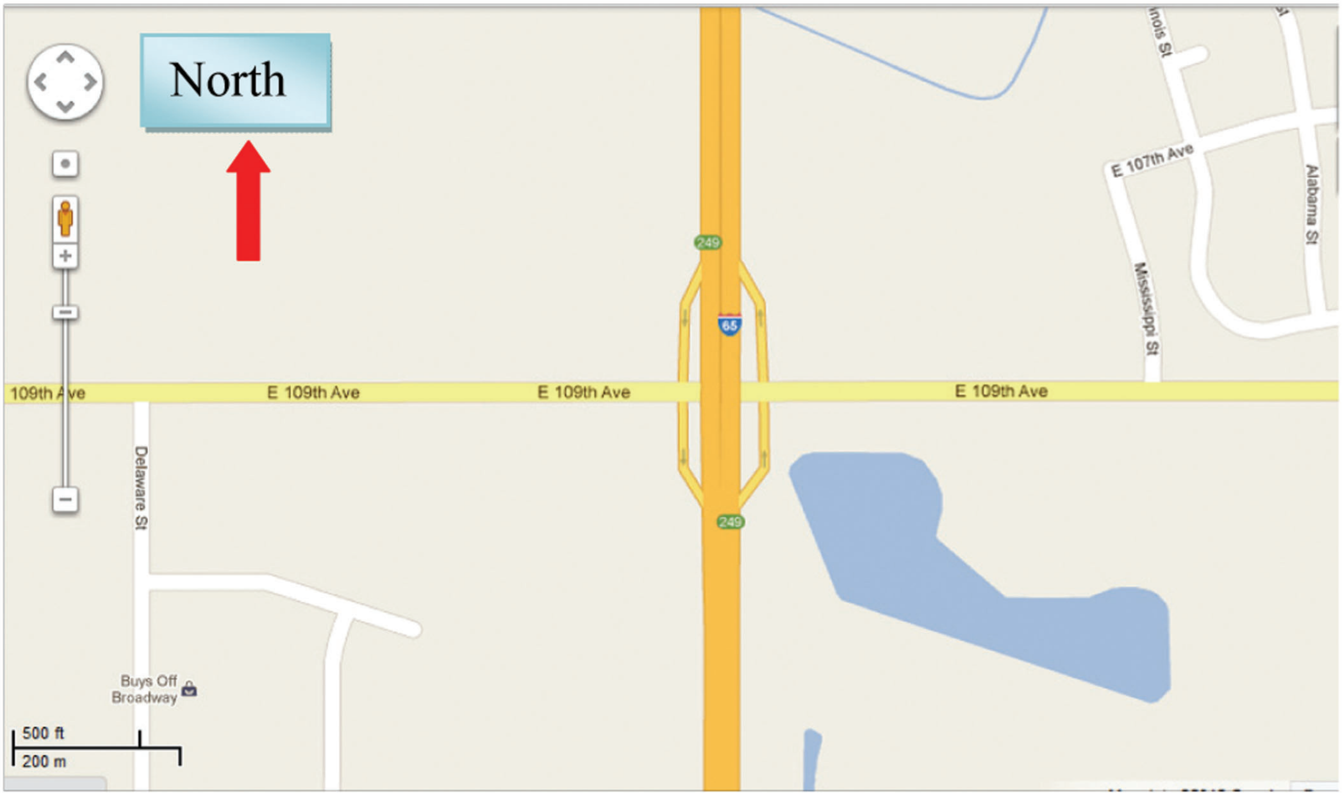


**Figure 2.2** Intersection of I-65 and 109th Avenue, Crown Point, Indiana.

of soils. The standard sieve set (Nos. 4, 10, 20, 40, 60, 100, 140 and 200) was used to obtain the grain size distribution curves of the samples. Since the soil was clayey in nature, a combined sieving procedure (both wet and dry sieving) was performed. Soil samples were sieved through the No. 40 (0.425 mm) sieve. Hydrometer analysis was performed on particle sizes smaller than 0.425 mm.

**Figure 2.3** Soil splitter used to obtain representative samples.

### *2.3.2 Atterberg Limits and Soil Classification*

Atterberg limits tests were performed on the *in situ* soil, soil-steel slag-Class-C fly ash mixtures and soil-steel slag-blast furnace slag mixtures. The samples were sieved through the No. 40 (0.425 mm) sieve, and the fraction passing the No. 40 sieve was used for the tests in accordance with ASTM D4318 (*5*). The *in situ* soil was classified using the Unified Soil Classification System (USCS), following ASTM D2487-06 (*6*), and the AASHTO Classification System, which is the standard used for soils and aggregate mixtures for highway construction, following AASHTO M145 (*7*).

### *2.3.3 Specific Gravity*

The specific gravity values of the soil samples were obtained using the water pycnometer method in accordance with ASTM D854-06 (*8*). The mass of the pycnometer, filled only with de-aired water up to a known volume, was recorded at different temperatures in order to calibrate the pycnometer in accordance with ASTM D854-06 (*8*). The initial mass of the oven-dried samples was recorded. The soil samples were then placed in the empty pycnometer that had been previously calibrated. After adding de-aired water to about two-thirds of the volume of the pycnometer, the de-airing process was initiated. De-airing is an essential step in the water pycnometer method as entrapped air can cause erroneous volume measurements. De-airing was performed by both the heating and air vacuuming techniques. Figure 2.4 shows the de-airing process.

### *2.3.4 Compaction*

The moisture-density relationships of the *in situ* soil, soil-steel slag-Class-C fly ash mixtures, and soil-steel slag-blast furnace slag mixtures were determined by performing Standard Proctor compaction tests, as described in ASTM D698-00a (*9*). Air-dried soil samples were used for the compaction tests. To obtain mixtures for the compaction tests with the desired% of each component by weight, the dry weight of the components of the mixtures – soil, steel slag, Class-C fly ash and blast-furnace slag – was first determined and measured. The dry mixtures were then mixed thoroughly to achieve uniformity. Samples were then moistened by the water-spraying technique until the desired water content was achieved. Special attention was paid to ensure thorough mixing of the samples with water prior to compaction. The *in situ* soil, soil-steel slag-Class-C fly ash mixtures and soil-steel slag-blast furnace slag mixtures were compacted in a 10 cm (4-in) diameter mold in three layers with 25 blows per layer using a Standard Proctor rammer (Method A of ASTM D698) (*9*). The Standard Proctor rammer of 5.50lbf (24.5N) was dropped from a height of 305 mm (12.0 in).

Compaction was performed by distributing the rammer blows evenly on the surface of each layer. Each compacted layer was scratched carefully before placing the next layer. After recording the mass of the compacted soil, the samples were recovered using a hydraulic jack and dried in the oven for water content determination. Before placing the samples in the oven, the intact samples were broken into pieces to facilitate drying. The main steps of the compaction procedure for the samples are water spraying, compaction in the 10 cm (4–in) diameter mold, trimming, mass measurement, sample recovery with the hydraulic jack, and oven drying (see Figure 2.5 (a), (b), (c), (d), (e), and (f)).

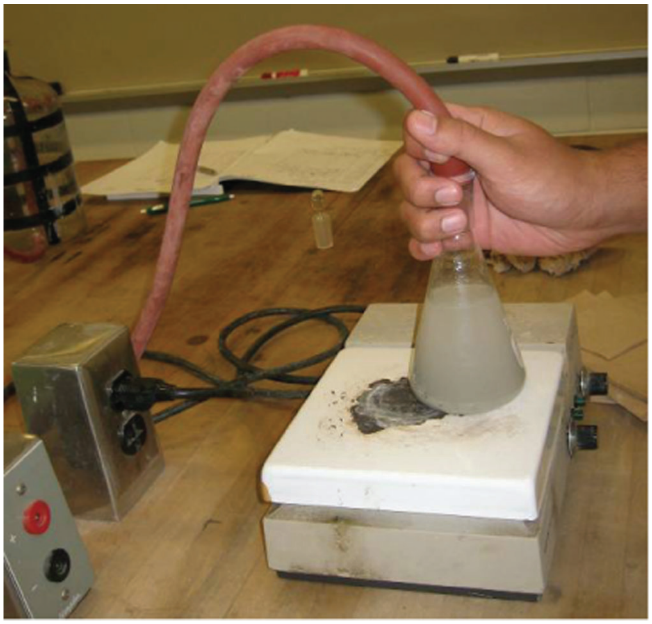


**Figure 2.4** De-airing of the slurry during the specific gravity test.

### *2.3.5 Unconfined Compression Tests*

In order to determine the feasibility of using soil-steel slag-Class-C fly ash and soil-steel slag-blast-furnace-slag mixtures as subgrade material, it is important to assess the strength-gain characteristics of these mixtures. For this purpose, unconfined compression (UC) tests were performed in accordance with ASTM D2166 (*10*) to determine the strength of the *in situ* clayey soil prior to stabilization. Unconfined compression (UC) tests were then performed on soil-steel slag-Class-C fly ash mixtures and soil-steel slag-blast-furnace-slag mixtures in accordance with ASTM D5102-04 (*11*), which is the standard test method for unconfined compressive strength of compacted soil-lime mixtures.

For each test, the required dry mass of each testing material (soil, steel slag, Class-C fly ash and blast-furnace slag) was determined and measured to obtain

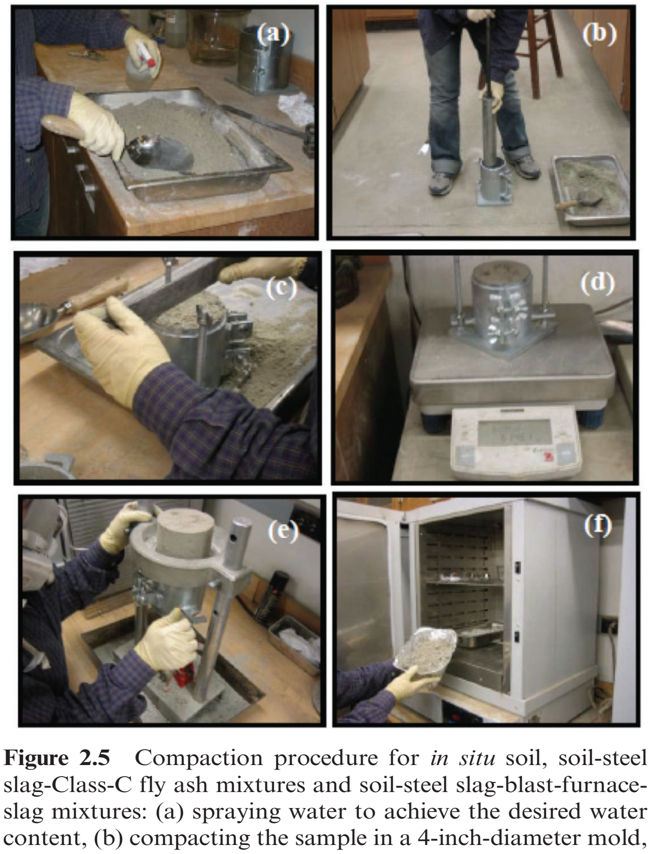


**Figure 2.5** Compaction procedure for *in situ* soil, soil-steel slag-Class-C fly ash mixtures and soil-steel slag-blast-furnace-slag mixtures: (a) spraying water to achieve the desired water content, (b) compacting the sample in a 4-inch-diameter mold, (c) trimming the compacted sample, (d) measuring the compacted mass, (e) recovering the sample with a hydraulic jack, and (f) oven drying for water content measurement.

mixtures with the desired percentages of each component. The dry mixture of the testing materials was then mixed thoroughly to ensure uniformity. Next, the mixture was sprayed with water and mixed continuously until the optimum water content was achieved. The unconfined compression test samples were prepared using the Harvard miniature compaction apparatus to achieve a sample height-to-diameter ratio in the range of 2 to 2.5. The apparatus consists of a cylindrical mold and a collar, a sample extractor and a compaction tamper with a 20lb spring. The cylindrical mold was 33 mm (1–5/16 in) in diameter and 71 mm (2.8 in) in height. The number of blows required to reach the maximum dry density of the sample was calibrated for the volume of the mold. The wet soil-steel slag mixtures were compacted to 97–100% relative compaction in three layers by applying 25 blows per layer with the cylindrical tamper. After completion of compaction, the collar was dismounted and the surface of each sample was trimmed. After extrusion, measurements were taken to determine the diameter, height and mass of each sample. After recording the measurements, the samples were securely wrapped with a transparent stretch plastic and placed back in the moist room facility (80% humidity at 20 °C) and maintained there for the targeted curing time periods. UC tests were performed on the compacted soil-steel slag-Class-C fly ash mixtures and soil-steel slag-blast furnace slag mixtures that were cured for 1, 2, 4, 7, 14, and 28 days. As per ASTMD 5102-04 (*11*), unconfined compression tests are typically performed at a deformation rate of 0.5%–2%/min. Slower rates are usually adopted when testing brittle specimens, while faster rates are typically applied to non-brittle specimens. Measurements of the axial load and strain were done with a shear beam load cell 1000 lbs and an LVDT with a displacement measurement range of 10 cm (2 in) mounted on the top platen. The axial load and axial displacement were recorded using a computerized data acquisition system. The unconfined compression tests on the mixtures were performed at a strain rate of 1.5–2%/min.

### *2.3.6 Swelling Tests*

Swelling tests were performed on the *in situ* soil, soil-steel slag-Class-C fly ash mixtures, and soil-steel slag-blast furnace slag mixtures in accordance with ASTM D1883-07 (*12*) to assess their long-term expansion characteristics. Prior to compaction, a standard cylindrical spacer disc of 15.2 cm (6 in) in diameter and 6.1 cm (2.4 in) in height was placed at the bottom of the CBR molds, which were 15.2 cm (6 in) in diameter and 17.8 cm (7 in) in height. The *in situ* soil and the mixtures were compacted at their optimum moisture content in three layers with an energy equivalent to the Standard Proctor energy (56 blows/layer using the Standard Proctor rammer). The compacted samples were trimmed, and a filter paper was placed on the trimmed surface of each sample. Next, the compacted samples were flipped onto perforated base plates, and the spacer disks were removed from the top. A filter paper was then placed on the top of each sample (see Figure 2.6). The height of each sample was approximately equal to 11.6 cm (4.6 in). The compacted dry unit weight of each sample was determined from the mass measurements. Collars were then mounted on the molds. Annular surcharge weights having a total mass of approximately 4.54 kg were placed on the perforated swelling plates connected to adjustable stems. The perforated swelling plates (together with the annular surcharge weights on the top) were then placed on the top of the samples. The one-dimensional vertical swelling of the samples was measured by dial gauges with a range of 25.4 mm (1 in) with a least count equal to 0.001 mm. The dial gauges were mounted using tripods and placed on the collar of the CBR molds. Extension rods were used to lengthen the core of the dial gauges to touch the adjustable stem of the perforated plates placed on top of the samples. Figure 2.7 shows the components of the CBR mold setup with the dial gauge.

In order to allow the samples to have access to water from the perforated base plates, stainless steel (304 SS) meshes with sizes of 25 cm by 71 cm (10 in × 28 in) were placed at the bottom of the soaking containers. Following the sample preparation, the CBR molds were placed in the soaking containers. Immediately after soaking completely the CBR molds in water, the initial zero readings were recorded from the dial gauges. Using a stop watch, readings were taken from the dial gauges at 1 min, 2 min, 4 min, 10 min, 15 min, 20 min, 30 min, 1 hr, 2 hrs, 4 hrs, 8 hrs, and 24 hrs after the zero reading. After the first day of soaking, readings were taken at every 24 hrs. The one-dimensional swelling of the samples was monitored for more than 3 months. Figure 2.8 (a) and (b) show one of the plastic soaking containers (28 cm × 43 cm × 37 cm) before

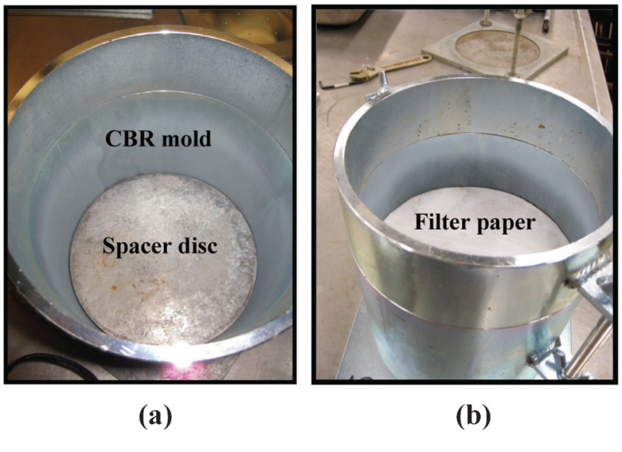


**Figure 2.6** Sample preparation in the CBR mold: (a) spacer disc placed at the bottom of the CBR mold prior to compaction and (b) spacer disc removed and filter paper placed on the top of the sample after compaction.

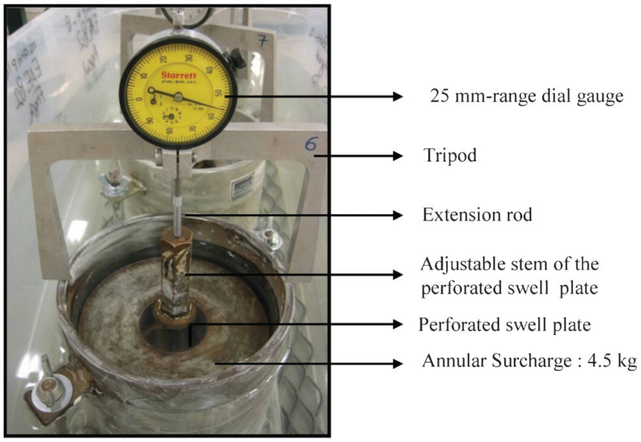


**Figure 2.7** Components of the CBR swelling test setup.


(a) (b)

**Figure 2.8** (a) Plastic soaking containers with a steel mesh placed at the bottom and (b) long-term swelling test setup.

placement of the samples and the test setup for long-term swelling monitoring, respectively.

## 3. DESIGN OF MIXTURES FOR SUBGRADE STABILIZATION

### 3.1 Overview

This Chapter presents the results of the laboratory tests performed on the *in situ* soil, soil-steel slag-Class-C fly ash mixtures and soil-steel slag-blast furnace slag mixtures. A series of tests were performed on the *in situ* clayey soil to determine its properties prior to stabilization. The laboratory tests performed on the *in situ* clayey soil included specific gravity, grain size distribution, Atterberg limits, compaction and unconfined compressive strength. Two types of steel slag mixtures were evaluated as a possible replacement for lime in subgrade stabilization applications: i) steel slag-Class-C fly ash mixtures and ii) steel slag-blast furnace slag mixtures. The mechanical properties of the soil-steel slag-Class-C fly ash and soil-steel slag-blast furnace slag mixtures were determined through compaction and unconfined compression tests. In order to assess the swelling potential of the mixtures, CBR swelling tests were also performed. Test results are presented in the following main sections of this Chapter:

- *In situ* soil
- Soil-steel slag-fly ash mixtures
- Soil-steel slag-blast furnace slag mixture

### 3.2 *In Situ* Soil

Atterberg Limits, grain size distribution, specific gravity, swelling and unconfined compression tests were performed on the *in situ* soil. The results of these tests are summarized in the next sections.

#### *3.2.1 Grain Size Distribution*

The gradation of the clayey soil samples were determined by sieve and hydrometer analyses. Due to the clayey nature of the *in situ* soil, a combination of dry and wet sieving was required. In addition, hydrometer analysis was performed to assess the gradation of particles passing the sieve No. 40. Three soil samples were tested to characterize the gradation of the *in situ* soil. Figure 3.1 shows the gradation curves obtained for the *in situ* clayey soil samples.

As shown in Figure 3.1, the tested soil samples exhibited similar gradations. The percentages of sand-size, silt-size and clay-size particles in the soil samples were in the ranges of 22–31%, 43–56%, and 22–26% by weight, respectively.

#### *3.2.2 Atterberg Limits and Soil Classification*

Atterberg limits tests were performed on representative soil samples passing the No. 40 sieve in accordance with ASTM D4318 (*5*). Figure 3.2 shows a plot of the recorded moisture content (%) versus blow count (N)

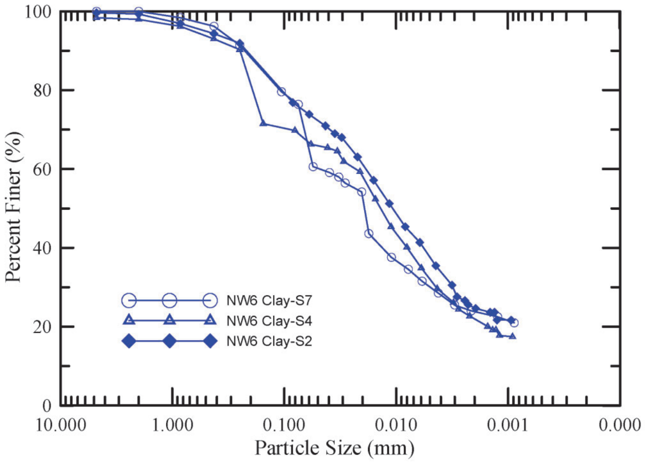


**Figure 3.1** Grain size distributions of soil samples.

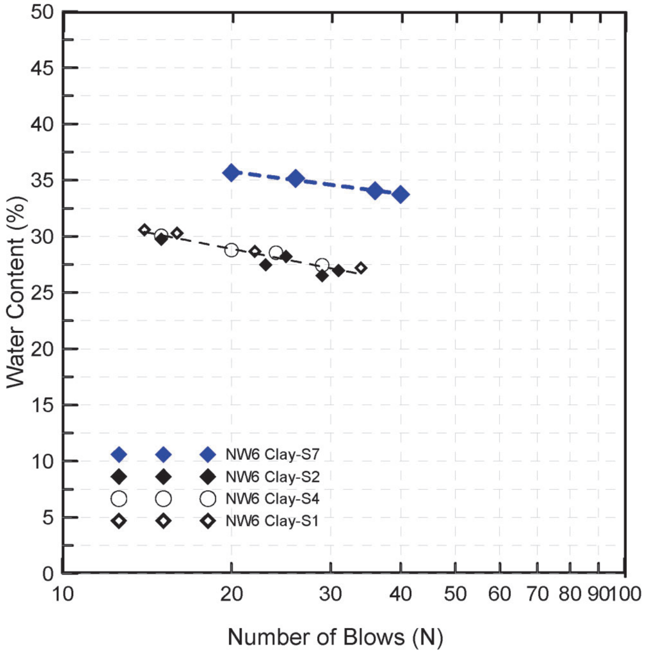


**Figure 3.2** Moisture content versus blow count (N) for soil samples.

from the liquid limit tests performed on the *in situ* clayey soil samples. Results of the Atterberg limits tests are summarized in Table 3.1.

As shown in Table 3.1, all samples tested for Atterberg limits tests exhibited almost identical plasticity index (PI). Based on the representative grain size distribution curves and the results of the Atterberg limits tests, the soil samples were classified as lean clay (CL) according to the USCS classification system. As per the AASHTO Classification System (AASHTO M145) (*7*), the soil samples were classified as A-6 with group index of 7. In general, materials in this group show high volume change with changes in water content and, therefore, they are not suitable as subgrade materials. The general rating of A-6 soils is fair to poor for use as a subgrade material according to AASHTO.

### 3.2.3 Specific Gravity

The specific gravity of the soil samples was determined to be 2.71 according to the water-pycnometer method. Typically, the specific gravity of clays and silty clays is in the range between 2.67 and 2.9. The specific gravity of the CL clay tested in this study falls within the range reported in the literature.

TABLE 3.1
**Atterberg limits test results for soil samples**

| Sample ID | LL | PL | PI |
|---|---|---|---|
| NW6 Clay S-1 | 30 | 17 | 13 |
| NW6 Clay S-2 | 28 | 16 | 12 |
| NW6 Clay S-4 | 28 | 16 | 12 |
| NW6 Clay S-7 | 35 | 22 | 13 |

### 3.2.4 Moisture-Density Relationship

Standard Proctor compaction tests were performed on soil samples collected from the field. Figure 3.3 shows the moisture-density relationship obtained for the *in situ* clayey soil.

The optimum moisture content of the *in situ* soil was in the range of 13–15%. The maximum dry unit weight was 18.5 kN/m$^3$ (118.2 pcf). Table 3.2 summarizes the results of the compaction tests performed on the soil samples.

### 3.2.5 Unconfined Compressive Strength

In order to assess the strength properties of the *in situ* soil before stabilization, a total of 8 unconfined compression tests were performed immediately after sample preparation (samples were tested without allowing any curing time). The results of these tests are summarized in Table 3.3.

As shown in Table 3.3, the unconfined compressive strength of the samples compacted to 95 to 101% relative compaction ranged between 214 and 329 kPa. The average unconfined compressive strength of the samples was 282.9 kPa (41 psi). Typically, INDOT requires a minimum unconfined compressive strength of 552 kPa (80 psi) for subgrade soils.

The experimental test results showed that the *in situ* clayey soil at the implementation site required improvement to support the loads from the pavement without causing excessive settlements. Traditionally, clayey subgrade soils are stabilized with lime. In this project, several steel slag mixtures were explored as possible

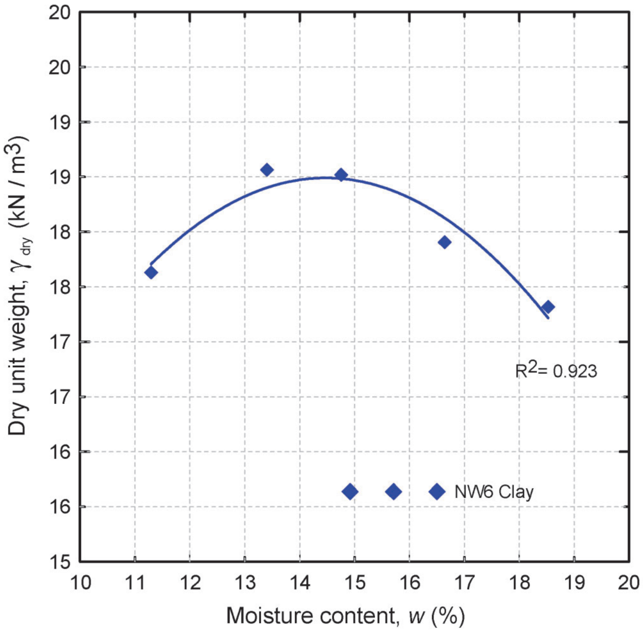


**Figure 3.3** Moisture-density relationship of *in situ* soil.

TABLE 3.2
**$\gamma_{d,max}$ and $w_{opt}$ of clayey soil samples**

| Sample ID | $w_{opt}$ (%) | $\gamma_{d,max}$(kN/m$^3$) | $\gamma_{d,max}$(pcf) |
|---|---|---|---|
| NW6 Clay | 13 | 18.56 | 118.2 |

stabilizing agents and as a cost-effective alternative to lime. Experiments were performed on various soil-steel slag-Class-C fly ash mixtures and soil-steel-slag-blast furnace mixtures. The results of the tests performed on these mixtures are provided in the next sections.

### *3.2.6 Long-Term Swelling Behavior of Soil*

Long-term swelling tests were performed on the *in situ* clayey soil to assess its volume change behavior in the presence of water. Soil samples were compacted at a moisture content of approximately 13% to 100% relative compaction in CBR molds. The compacted samples were soaked in water and a surcharge weight equivalent to approximately 2.5 kPa was placed on their top. The one-dimensional swelling of the *in situ* soil samples was monitored for a period of about 2 months at room temperature. Figure 3.4 shows the time versus volumetric strain curves obtained from the long-term swelling tests performed on the *in situ* clayey soil.

As shown in Figure 3.4, the soil sample reached a maximum 1D swelling strain of approximately 0.41% after approximately 13 days of soaking and started shrinking after that. Eventually, the soil sample reached equilibrium at approximately 0.24% 1D swelling strain after 35 days of soaking.

## 3.3 Soil-Steel Slag-Class-C Fly Ash Mixtures

The following soil-steel slag-Class-C fly ash mixtures were considered in this study:

- Soil-5% steel slag (by weight of soil)-5% Class-C fly ash (by weight of soil)
- Soil-7% steel slag (by weight of soil)-3% Class-C fly ash (by weight of soil)
- Soil-8% steel slag (by weight of soil)-2% Class-C fly ash (by weight of soil)

TABLE 3.3
**Unconfined compressive strength of soil immediately after sample preparation**

| UC Samples | Relative Compaction | Unconfined Compressive Strength ($q_u$) | |
|---|---|---|---|
| Sample (ID) | (%) | (psi) | (kPa) |
| SW2Soil15 | 100 | 31.1 | 214.4 |
| NW6Soil17 | 101 | 41.1 | 283.4 |
| NW6Soil18 | 100 | 44.6 | 307.5 |
| NW6Soil49 | 98 | 37.8 | 260.6 |
| NW6Soil50 | 98 | 45.0 | 310.3 |
| NW6Soil57 | 95 | 47.8 | 329.6 |
| NW6Soil58 | 95 | 39.8 | 274.4 |

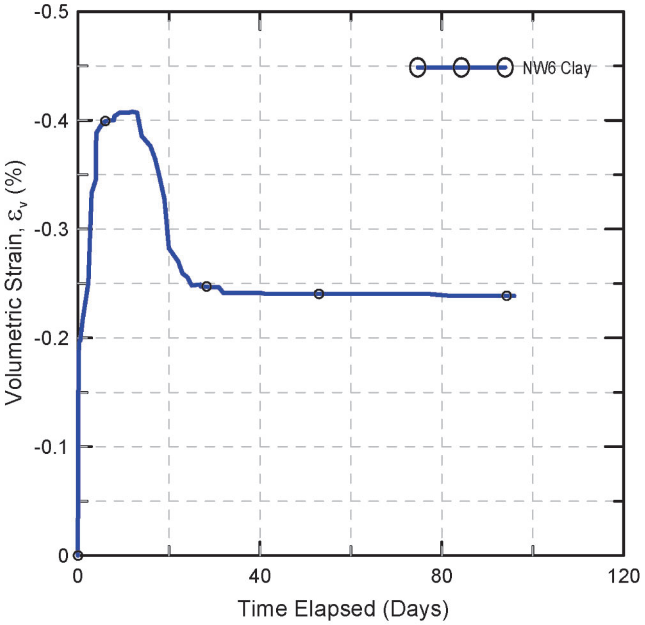


**Figure 3.4** Time versus volumetric strain curve for soil.

The tests performed on the soil-steel slag-Class-C fly ash mixtures included Atterberg limits, compaction, swelling and unconfined compression tests. The results of these tests are summarized in this section.

### *3.3.1 Atterberg Limits*

Atterberg limit tests were performed for the soil-7% steel slag-3% Class-C fly ash mixture. Figure 3.5 shows a plot of the moisture content (%) versus blow count (N) obtained from the liquid limit tests for both the *in*

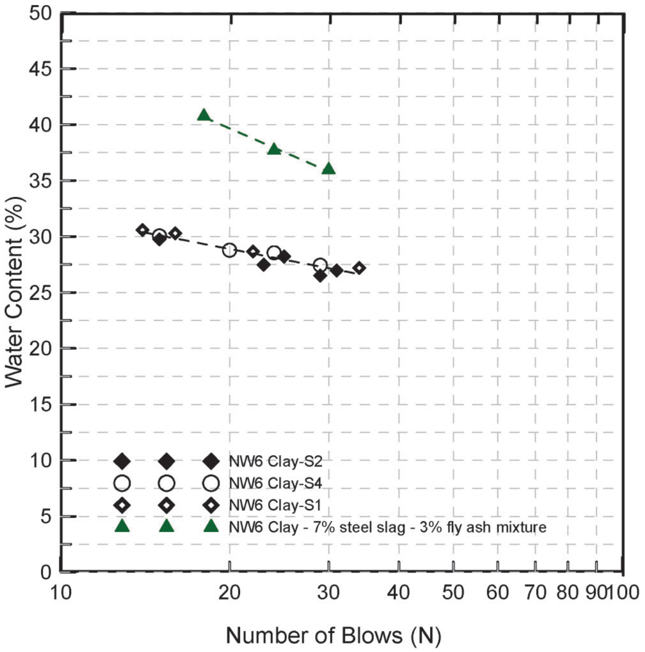


**Figure 3.5** Moisture content versus blow count (N) for soil and soil-7% steel slag-3% Class-C fly ash mixture.

*situ* clayey soil and the soil-7% steel slag-3% Class-C fly ash mixture. As shown in Figure 3.5 and Table 3.4, the soil-7% steel slag-3% Class-C fly ash mixture exhibited higher LL and PL values than the *in situ* clayey soil. A substantial difference in PI was not observed for the mixture with respect to the *in situ* clayey soil. The Atterberg limits (i.e.; LL, PL and PI) of the soil-steel slag-Class-C fly ash mixture and the *in situ* clayey soil are summarized in Table 3.4.

### *3.3.2 Moisture-Density Relationship*

In order to determine the effects of steel slag and Class-C fly ash addition on the moisture-density curve of the *in situ* soil, Standard Proctor compaction tests were performed on the soil-7% steel slag-3% Class-C fly ash mixture. Figure 3.6 shows the moisture-density relationship of the *in situ* clayey soil and the soil-7% steel slag-3% Class-C fly ash mixture.

As shown in Figure 3.6, addition of the steel slag-Class-C fly ash mixture to the clayey soil resulted in changes in the moisture-density relationship. The compaction curve for the soil-steel slag-Class-C fly ash exhibited higher moisture content and lower maximum dry unit weight than the *in situ* clayey soil. This trend is similar to that observed in lime-treated soils. Several researchers reported the same trend (i.e., an increase of optimum moisture content and a decrease in dry unit weight) in lime-stabilized soils (*13–16*). Table 3.5 summarizes the results of the compaction tests performed on the *in situ* soil and soil-7% steel slag-3% Class-C fly ash mixture.

### *3.3.3 Strength Gain of Soil-Steel Slag-Class-C Fly Ash Mixtures*

In order to increase the unconfined compressive strength of the *in situ* clayey soil, varying amounts of steel slag and Class-C fly ash were added to soil samples. Soil-5% steel slag-5% Class-C fly ash and soil-8% steel slag-2% Class-C fly ash mixtures were compacted and cured for 1, 2, 4 and 28 days after sample preparation. Soil-7% steel slag-3% Class-C fly ash samples were compacted and cured for 1, 2, 4, 7, 14 and 28 days after sample preparation. Table 3.6 and Table 3.7 summarize the unconfined compression strength data of the soil-steel slag-Class-C fly ash mixtures tested at various curing time periods in SI and U.S. customary units, respectively.

The unconfined compressive strength of soil-steel slag-Class-C fly ash mixtures increases with curing time, which indicates the occurrence of cementitious reactions.

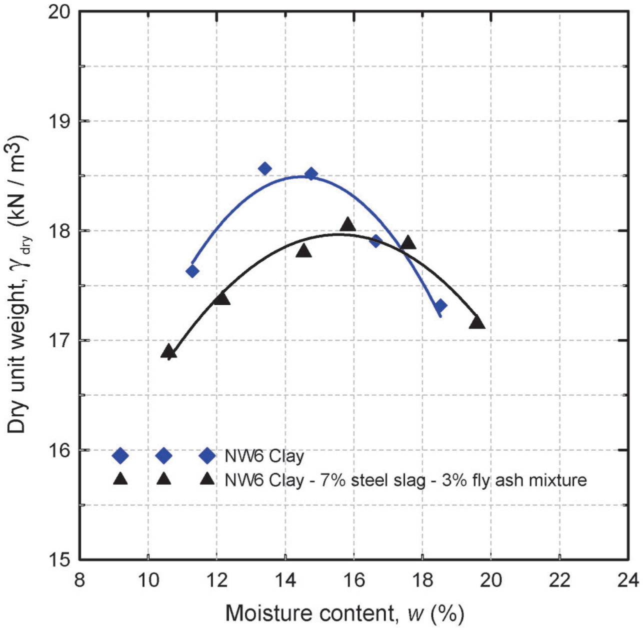


**Figure 3.6** Moisture-density relationships of *in situ* soil and soil-steel slag-Class-C fly ash mixture.

Figure 3.7 and Figure 3.8 show the curing time versus unconfined compressive strength of the soil-7% steel slag-3% Class-C fly ash mixture in SI and in U.S. customary units, respectively. The unconfined compressive strength of the soil-7% steel slag-3% Class-C fly ash mixture increases with curing time as the cementitious reactions take place. In order to represent the strength gain behavior of the mixture with curing time mathematically, power functions were fitted to the data points. Table 3.8 provides the empirical equations (regression functions) that can be used to predict the unconfined compressive strength of soil-7% steel slag-3% Class-C fly ash mixtures tested in this study as a function of curing time.

### *3.3.4 Long-Term Swelling Behavior of Soil-Steel Slag-Class-C Fly Ash Mixtures*

Two long-term swelling tests were performed on soil-7% steel slag-3% Class-C fly ash samples to assess the volume change behavior of the mixture in the presence of water. In addition, a long-term swelling test was also performed on the soil-10% steel slag mixture. The soil-steel slag-Class-C fly ash mixtures were compacted at a moisture content of approximately 16% to 100% relative compaction in CBR molds. One-dimensional swelling of the soil-steel slag-Class-C fly ash samples

TABLE 3.4
**Atterberg limits test results for *in situ* soil and soil-7% steel slag-3% Class-C fly ash mixture**

| Sample ID | LL | PL | PI |
|---|---|---|---|
| NW6 Clay S-1/S-2/S-4 | 28–30 | 16–17 | 12–13 |
| NW6 Clay-7% Steel Slag-3% Class-C Fly Ash Mixture | 35 | 22 | 13 |

TABLE 3.5

**$\gamma_{d,max}$ and $w_{opt}$ of *in situ* soil and soil-7% steel slag-3% Class-C fly ash mixture**

| Sample ID | $w_{opt}$ (%) | $\gamma_{d,max}$(kN/m$^3$) | $\gamma_{d,max}$(pcf) |
|---|---|---|---|
| NW6 | 13 | 18.56 | 118.2 |
| NW6-7% steel slag-3% Class-C fly ash mixture | 15 | 18.04 | 114.8 |

TABLE 3.6

**Summary of unconfined compressive strength of soil-steel slag-Class-C fly ash mixtures (in kPa)**

| Unconfined Compression Strength of Soil-Steel Slag-Class-C Fly ash Mixtures | | | | | | |
|---|---|---|---|---|---|---|
| **Curing time:** | **1 day** | **2 day** | **4 day** | **7 day** | **14 day** | **28 day** |
| Soil-5% steel slag-5% Class-C fly ash | 665 | 835 | 920 | —[a] | —[a] | 1089 |
| Soil-7% steel slag-3% Class-C fly ash | 766 | 820 | 843 | 886 | 939 | 1044 |
| Soil-8% steel slag-2% Class-C fly ash | 642 | 844 | 938 | —[a] | —[a] | 979 |

Notes:
[a]= data not available.

was monitored for a period of about 2 months at room temperature. Figure 3.9 shows the time versus volumetric strain curves obtained from the long-term swelling tests performed on soil-10% steel slag and soil-7% steel slag-3% Class-C fly ash mixtures together with that of the *in situ* clayey soil.

As shown in Figure 3.9, the two compacted soil-7% steel slag-3% Class-C fly ash samples reached maximum swelling strains of 0.12% and 0.13% after approximately 9 days of soaking. For both of the compacted soil-steel slag-Class-C fly ash samples, swelling stabilized after approximately 9 days of soaking. The compacted soil-10% steel slag mixture reached equilibrium at a maximum swelling strain of 0.04% after approximately 10 days of soaking. In comparison to the long-term swelling behavior of the *in situ* clayey soil, the swelling of both the soil-10% steel slag and soil-7% steel slag-3% Class-C fly ash mixtures stabilized sooner and at smaller maximum swelling strains. Figure 3.9 clearly indicates that blending of the *in situ* soil with steel slag or with a mixture of steel slag and Class C fly ash reduces the swelling of the *in situ* clayey soil.

## 3.4 Soil-Steel Slag-Blast Furnace Slag Mixtures

The tests performed on the soil-steel slag-Class-C fly ash mixtures suggested that these are promising materials for subgrade applications. The Class-C fly ash used in this study is an expensive material because of its self-cementing properties. Blast furnace slag is more cost-competitive than Class-C fly ash. Therefore, use of blast furnace slag as a replacement for some of the Class-C fly ash in the mixtures was explored. In order to select a suitable mixture for testing, preliminary strength tests were performed on various mixtures with varying proportions of steel slag and blast furnace slag in the mixtures. In particular, two mixtures—soil-7% steel slag-3% blast furnace slag and soil-10% steel slag-5% blast furnace slag—showed favorable results. However, considering that the increase in percentage of stabilizing agent results in an increase in the overall cost, the following mixture was determined to be more suitable for further testing:

- Soil-7% steel slag (by weight of soil)-3% blast furnace slag (by weight of soil)

The tests performed on the soil-7% steel slag-3% blast furnace slag mixture included Atterberg limits, compaction, swelling and unconfined compression. Tests were performed to determine the basic geotechnical properties of the soil-7% steel slag-3% blast furnace slag mixture. Long-term swelling tests were performed to determine the strength-gain and swelling characteristics of the mixture. The results of the laboratory tests

TABLE 3.7

**Summary of unconfined compressive strength data of the soil-steel slag-Class-C fly ash mixtures (in psi)**

| Unconfined Compression Strength of Soil-Steel Slag-Fly ash Mixtures | | | | | | |
|---|---|---|---|---|---|---|
| **Curing time:** | **1 day** | **2 day** | **4 day** | **7 day** | **14 day** | **28 day** |
| Soil-5% steel slag-5% Class-C fly ash | 96 | 121 | 133 | —[a] | —[a] | 158 |
| Soil-7% steel slag-3% Class-C fly ash | 111 | 119 | 122 | 128 | 136 | 151 |
| Soil-8% steel slag-2% Class-C fly ash | 93 | 132 | 136 | —[a] | —[a] | 142 |

Notes:
[a]= data not available.

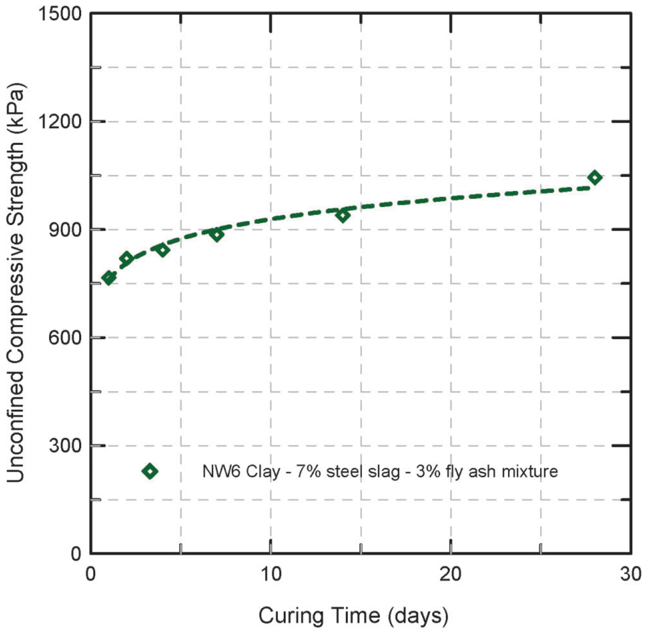


**Figure 3.7** Curing time versus unconfined compressive strength (in kPa) of compacted soil-7% steel slag-3% Class-C fly ash mixture.

performed on soil-steel slag-blast furnace slag mixture are summarized next.

*3.4.1 Atterberg Limits*

Atterberg limits tests were performed on the soil-7% steel slag-3% blast furnace slag mixture. Figure 3.10 shows a plot of the moisture content (%) versus blow count (N) obtained from the liquid limit tests performed on the *in situ* clayey soil samples and the soil-7% steel slag-3% blast furnace slag mixture.

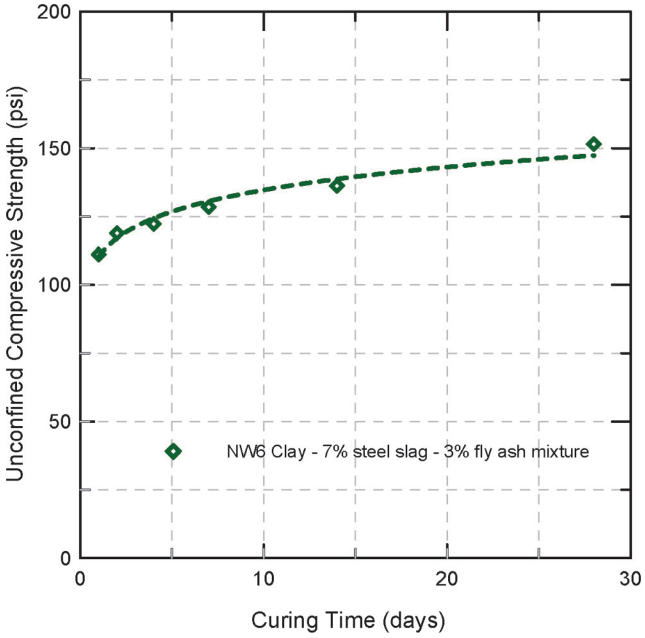


**Figure 3.8** Curing time versus unconfined compressive strength (in psi) of compacted soil-7% steel slag-3% Class-C fly ash mixture.

As shown in Figure 3.10, the soil-7% steel slag-3% blast furnace slag mixture has higher LL and PL values than the *in situ* clayey soil. The PI of soil-7% steel slag-3% blast furnace slag mixture was only slightly higher than that of the *in situ* clayey soil. The Atterberg limits (i.e.; LL, PL and PI) of the soil-steel slag-blast furnace slag mixture and the clayey soil are summarized in Table 3.9.

*3.4.2 Moisture-Density Relationship*

In order to determine the effects of steel slag and blast furnace slag addition on the moisture-density relationship of the *in situ* clayey soil, standard Proctor compaction tests were performed on the soil-7% steel slag-3% blast furnace slag mixture. Figure 3.11 shows the moisture-density relationship of the *in situ* clayey soil and soil-7% steel slag-3% blast furnace slag mixture.

As shown in Figure 3.10, addition of the steel slag-blast furnace slag mixture to the *in situ* clayey soil resulted in changes in the moisture-density relationship. Compared to the moisture-density relationship obtained for the *in situ* clayey soil, the soil-steel slag-blast furnace slag mixture exhibited a lower maximum dry unit weight and a higher optimum moisture content. This trend is similar to that observed for lime treated soils and also for the soil-steel slag-Class-C fly ash mixture tested in this study. Table 3.10 summarizes the results of the compaction tests performed on the soil and soil-7% steel slag-3% blast furnace slag mixture.

*3.4.3 Strength Gain Behavior of the Soil-Steel Slag-Blast Furnace Slag Mixtures*

Unconfined compression tests were performed on soil-7% steel slag-3% blast furnace slag samples to assess the strength gain behavior of the mixture with respect to time. The soil-7% steel slag-3% blast furnace slag samples were compacted and then cured for 1, 2, 4, 7, 14 and 28 days after sample preparation. Table 3.11 and Table 3.12 summarize the unconfined compressive strength data of the soil-7% steel slag-3% blast furnace slag mixture tested at various curing time periods in SI and U.S. customary units, respectively.

The unconfined compression test results showed that the unconfined compression strength of the soil-steel slag-blast furnace slag mixture increased slightly with curing time. Figure 3.12 and Figure 3.13 show the curing time versus unconfined compressive strength of the soil-7% steel slag-3% blast furnace slag mixture in SI and in U.S. customary units, respectively. The rate of increase in unconfined compressive strength with respect to time was not as high as that observed for the soil-steel slag-Class-C fly ash mixture. In order to represent the strength gain behavior of the mixture with

TABLE 3.8
**Unconfined compressive strength gain behavior of the soil-7% steel slag-3% Class-C fly ash mixture**

| Mixtures | (kPa) | (psi) | $R^2$ |
|---|---|---|---|
| Soil-7% Steel Slag-3% Fly Ash | $q_u = 760.06\ t^{0.087}$ | $q_u = 110.24\ t^{0.087}$ | 0.9675 |

$q_u$ =unconfined compressive strength; $t$=time (in days)

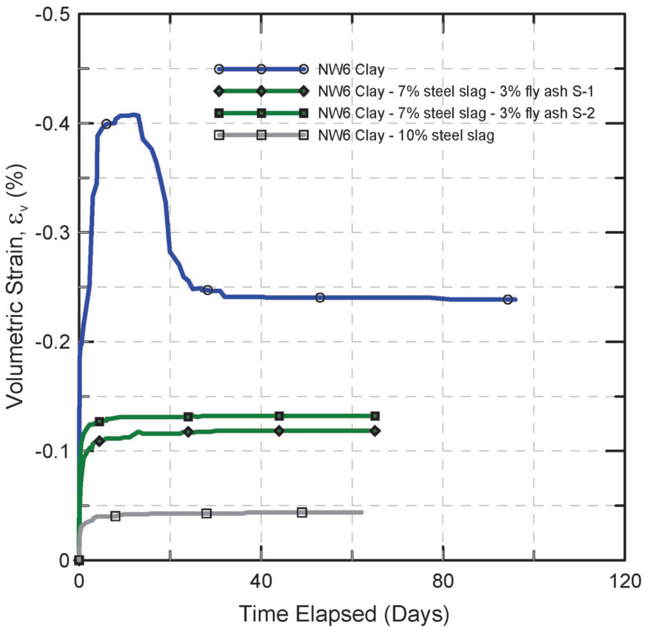


**Figure 3.9** Time versus volumetric strain curve for soil, soil-steel slag and soil-steel slag-Class-C fly ash mixtures.

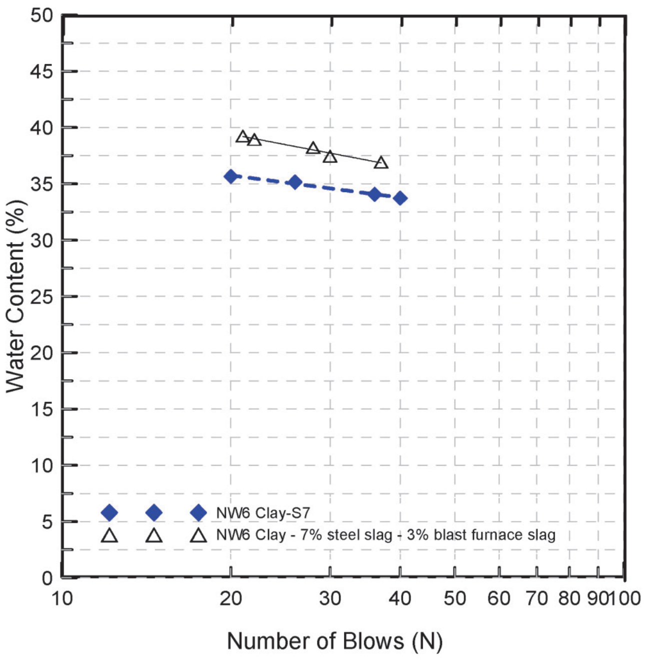


**Figure 3.10** Moisture content versus blow count (N) for soil and soil-7% steel slag-3% blast furnace slag mixture.

TABLE 3.9
**Atterberg limits test results for soil and soil-7% steel slag-3% blast furnace slag mixture**

| Sample ID | LL | PL | PI |
|---|---|---|---|
| NW6 Clay S-7 | 35 | 22 | 13 |
| NW6 Clay-7% Steel Slag-3% blast furnace slag mixture | 39 | 25 | 14 |

curing time mathematically, power functions were fitted to the data points. Table 3.13 provides the empirical equations (regression functions) that can be used to predict the unconfined compressive strength of the soil-7% steel slag-3% blast furnace slag mixture tested in this study with curing time.

### *3.4.4 Long-Term Swelling Behavior of the Soil-Steel Slag-Blast Furnace Slag Mixture*

Two long-term swelling tests were performed on the soil-7% steel slag-3% blast furnace slag mixture. The soil-steel slag-blast furnace slag samples were compacted at a moisture content of approximately 16.7% to 100% relative compaction in CBR molds. The one-dimensional swelling of the soil-steel slag-blast furnace

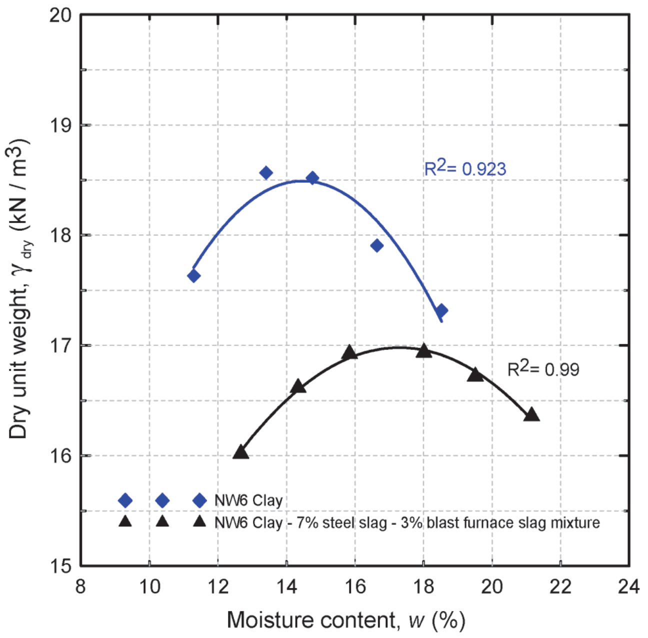


**Figure 3.11** Moisture-density relationship of *in situ* clayey soil and soil-steel slag-blast furnace slag mixture.

TABLE 3.10

**$\gamma_{d,max}$ and $w_{opt}$ of *in situ* soil and soil-7% steel slag-3% blast furnace slag mixture**

| Sample ID | $w_{opt}$ (%) | $\gamma_{d,max}$(kN/m$^3$) | $\gamma_{d,max}$ (pcf) |
|---|---|---|---|
| NW6 | 13 | 18.56 | 118.2 |
| NW6-7% steel slag-3% blast furnace slag mixture | 16 | 16.94 | 107.7 |

TABLE 3.11

**Summary of the unconfined compressive strength data of soil-steel slag-fly ash mixture (in kPa)**

| Unconfined Compression Strength of Soil-Steel Slag-Blast Furnace Slag Mixture | | | | | | |
|---|---|---|---|---|---|---|
| **Curing time:** | **1 day** | **2 day** | **4 day** | **7 day** | **14 day** | **28 day** |
| Soil-7% steel slag-3% blast furnace slag mixture | 574 | 602 | 634 | 643 | 658 | 662 |

TABLE 3.12

**Summary of unconfined compressive strength of soil-steel slag-fly ash mixture (in psi)**

| Unconfined Compression Strength of Soil-Steel Slag-Blast Furnace Slag Mixture | | | | | | |
|---|---|---|---|---|---|---|
| **Curing time:** | **1 day** | **2 day** | **4 day** | **7 day** | **14 day** | **28 day** |
| Soil-7% steel slag-3% blast furnace slag mixture | 83 | 87 | 92 | 93 | 95 | 96 |

slag mixture was monitored for more than three months at room temperature. Figure 3.14 shows the time versus volumetric strain curves obtained from the long-term swelling tests performed on the soil-7% steel slag-3% blast furnace mixtures together with that from the test performed on the *in situ* clayey soil.

As shown in Figure 3.14, one of the compacted soil-7% steel slag-3% blast furnace slag mixture reached a maximum swelling strain of 0.052% after approximately 6 days of soaking. The swelling strains measured for the second sample were negligible (i.e.; less than 0.01%) throughout the test period. The swelling of the soil-7% steel slag-3% blast furnace slag sample stabilized sooner and at much smaller maximum swelling strains than the *in situ* clayey soil. Figure 3.14 clearly

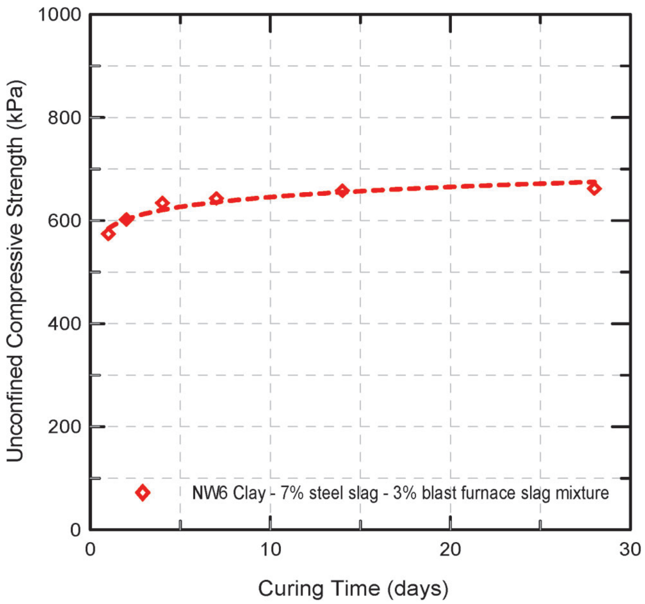


**Figure 3.12** Curing time versus unconfined compressive strength (in kPa) of the compacted soil-7% steel slag-3% blast furnace slag mixture.

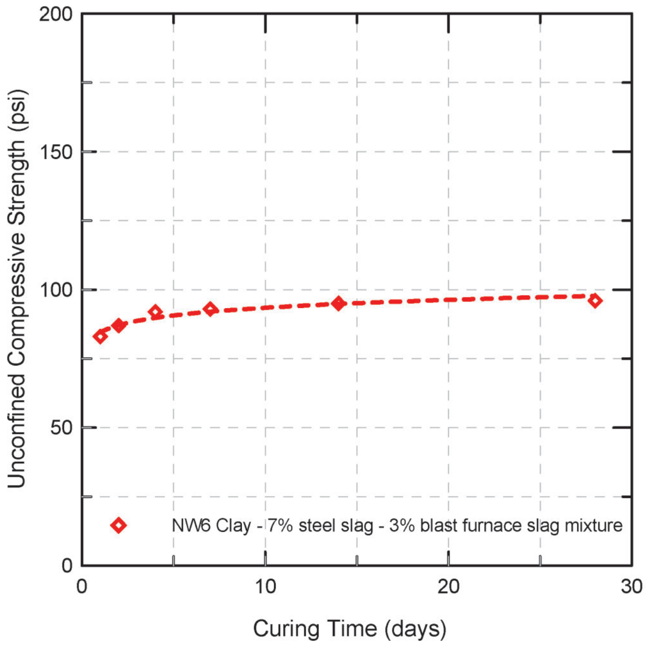


**Figure 3.13** Curing time versus unconfined compressive strength (in psi) of the compacted soil-7% steel slag-3% blast furnace slag mixture.

TABLE 3.13
**Unconfined compressive strength gain behavior of the soil-7% steel slag-3% blast furnace slag mixture**

| Mixtures | (kPa) | (psi) | $R^2$ |
|---|---|---|---|
| Soil-7% steel slag-3% blast furnace slag mixture | $q_u = 584.38\ t^{0.0431}$ | $q_u = 84.758\ t^{0.0431}$ | 0.9151 |

$q_u$ = unconfined compressive strength; $t$ = time (in days).

indicates that blending of soil with steel slag-blast furnace slag mixture helps in reducing significantly the swelling of the clayey soil tested in this study.

## 3.5 Design of Suitable Mixtures for Subgrade Stabilization

Based on the evaluation of the results of the laboratory tests performed on the *in situ* soil, soil-steel slag-Class-C fly ash and soil-steel slag-blast furnace slag mixtures, the most suitable mixture was selected for use as a subgrade material in an INDOT implementation project. The cost and availability of each mixture tested in this study in the vicinity of the proposed implementation site was also considered in this decision.

Figure 3.15 shows the curing time versus unconfined compressive strength curves of the compacted soil-7% steel slag-3% Class-C fly ash mixture and the soil-7% steel slag-3% blast furnace slag mixture for comparison purposes.

As shown in Figure 3.15, the unconfined compressive strength gain rate of the soil-7% steel slag-3% Class-C fly ash mixture is higher than that of the soil-7% steel slag-3% blast furnace slag mixture. The average unconfined compressive strength of the compacted soil-7% steel slag-3% Class-C fly ash and soil-7% steel slag-3% blast furnace slag mixture samples cured for 1 day were 766 kPa (111 psi) and 574 kPa (83 psi), respectively. These results indicate the occurrence of stronger cementitious reactions in the soil-steel slag-Class-C fly ash mixture. The maximum swelling strains of the soil-7% steel slag-3% Class-C fly ash and soil-7% steel slag-3% blast furnace slag mixtures were 0.13% and 0.052%, respectively, based on the long-term swelling tests. These results indicate that the soil-7% steel slag-3% blast furnace slag was somewhat more effective in stabilizing the *in situ* clayey soil. Nonetheless, the long-term swelling tests results showed that both mixtures were effective in reducing the swelling of the *in situ* clayey soil to negligible levels.

Based on the laboratory tests performed on various mixtures, soil-steel slag-Class-C fly ash mixtures were found to be suitable for subgrade applications. Since Class-C fly ash is more expensive than steel slag, minimizing the percentage of Class-C fly ash in the mixture was desirable in order to offer a cost-effective alternative to lime. The soil-7% steel slag-3% Class-C fly ash mixture was selected as the most suitable subgrade material for the implementation project.

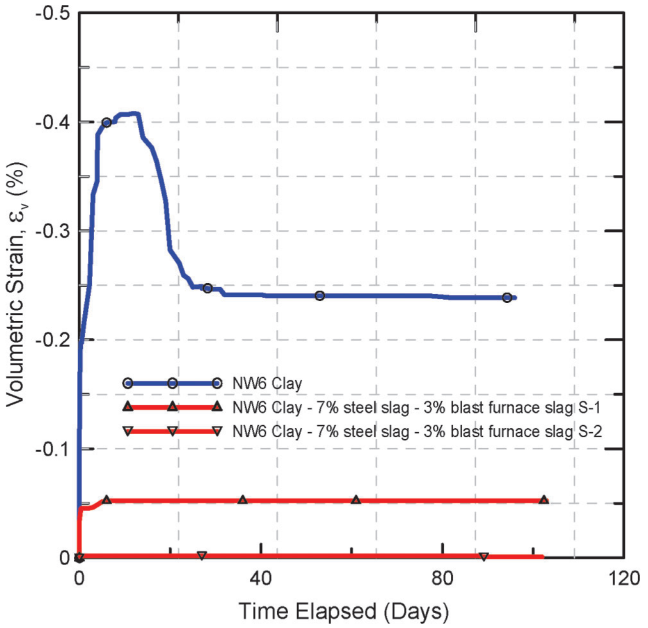


**Figure 3.14** Time versus volumetric strain curve for the *in situ* soil and soil-steel slag-blast furnace slag mixture.

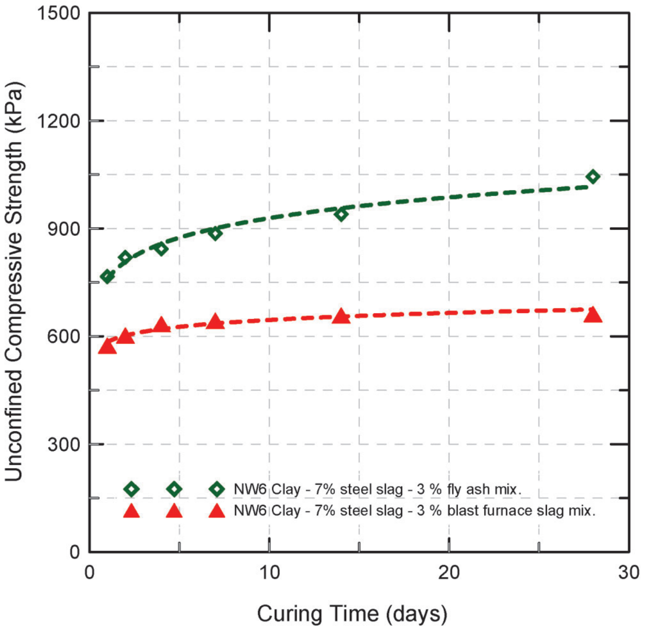


**Figure 3.15** Curing time versus unconfined compressive strength of the compacted soil-7% steel slag-3% Class-C fly ash slag and soil-7% steel slag-3% blast furnace slag mixtures.

# 4. FIELD IMPLEMENTATION OF SOIL-STEEL SLAG FLY ASH MIXTURE AS A SUBGRADE MATERIAL

## 4.1 Overview

The soil-steel slag-Class-C fly ash mixture selected based on the laboratory test results performed in this research was implemented as a subgrade material in an INDOT project. The implementation project for the soil-steel slag-Class-C fly ash mixture was carried out at the intersection of 109th Avenue and I-65, near Crown Point, Indiana. The steel slag-Class-C fly ash mixture was used to stabilize the *in situ* subgrade soil of some sections of the I-65 ramps at the intersection of 109th Avenue and I-65. This chapter explains the details of the implementation project and the construction sequence as well as the field quality control tests performed on the stabilized subgrade soils.

## 4.2 Implementation Project

Based on the results of the laboratory tests performed on various mixtures, the 7% steel slag-3% Class-C fly ash mixture was selected as the most suitable and cost-effective mixture to stabilize the *in situ* soils at the proposed implementation site. The implementation project for the soil-steel slag-fly ash mixture was carried out at the intersection of 109th Avenue and I-65. As explained in Chapter 2, the soil samples used in the laboratory tests were collected from the SW and NW quadrants of the intersection of 109th Avenue and I-65. The steel slag-Class-C fly ash mixture was used to stabilize the *in situ* subgrade soils of some sections of the ramps in NW and SW of the 109th Avenue and I-65 intersection. The following sections provide details of the construction sequence and general guidelines for subgrade stabilization.

## 4.3 Construction Guidelines for Subgrade Stabilization

Based on the results of the laboratory test performed on the compacted soil-7% steel slag-3% Class-C fly ash mixture, the following guidelines were proposed for the subgrade stabilization field work:

- The subgrade stabilization should be performed by in-place mixing of the *in situ* soils with the pre-mixed 7% steel slag-3% Class-C fly ash mixture;
- The quantity of steel slag-Class-C fly ash mixture should be maintained at a minimum of 10% (by weight) of dry mass of soil in all the sections treated with the 7% steel slag-3% Class-C fly ash mixture;
- The effect of mellowing on the properties of the soil-7% steel slag-3% Class-C fly ash mixture was not considered, and hence, the values of the unconfined compressive strength provided in this report are for samples compacted right after mixing. Therefore, compaction of the mixture in the field should begin without delay and be completed within 3 to 4 hours after mixing;
- The soil-7% steel slag-3% Class-C fly ash mixture shall be compacted within a moisture content range of 14 to 18%. A moisture content of 1 to 3% above the optimum moisture content is preferable to ensure that the free lime present in the Class-C fly ash and steel slag has sufficient water for completion of the cementitious reactions;
- If the dry steel slag-Class-C fly ash mixture is mixed with the *in situ* clayey soil without water spraying or aeration, the moisture content of the *in situ* clayey soil should be within 16–19% before the start of the stabilization work in order for the soil-steel slag-Class-C fly ash mixture to achieve an optimum moisture content in the range of 14–18%;
- A minimum relative compaction of 100% should be targeted for the stabilized subgrade soils (i.e.; soil-7% steel slag-3% Class-C fly ash mixture). The maximum dry unit weight and moisture content of the compacted soil-7% steel slag-3% Class-C fly ash mixture should be in the ranges of 17.9–18.1 kN/m$^3$ and 14–18%, respectively, to achieve 100% relative compaction;
- Construction traffic or equipment shall not traffic on the treated soil within 72 hours after compaction.

## 4.4 Subgrade Stabilization Construction Sequence

As explained in the previous chapters, the subgrade soils in some sections of the NW and SW ramps at the intersection of 109th Avenue and I-65 were stabilized with a 7% steel slag-3% Class-C fly ash mixture. Figure 4.1 shows a picture of the soil in the SW ramp before stabilization. The following steps, which are described in detail in the next section, were followed during the stabilization work:

1. Spreading
2. Mixing and Water Spraying
3. Compaction

### *4.4.1 Spreading*

The pre-mixed 7% steel slag-3% Class-C fly ash mixture was transported to the site using a self-unloading bulk tanker truck, which is also known as a spreader truck. Figure 4.2 shows the spreader truck used in this demonstration project. The pre-mixed 7% steel slag-3% Class-C fly ash mixture was spread uniformly on the subgrade soil using the spreader truck. Figure 4.3 shows the spreading of the steel slag-Class-C fly ash mixture on the *in situ* soil. Figure 4.4 is a photograph of a section of the ramp after the initial spreading operation.

### *4.4.2 Mixing and Water Spraying*

Thorough mixing of the stabilizing agent with the *in situ* soil is an essential step of the soil stabilization procedure. A rotary mixer truck plus an attached water truck were used for mixing of the 7% steel slag-3% Class-C fly ash mixture with the *in situ* soil. The top 16 inch of the *in situ* soils were mixed thoroughly with the 7% steel slag-3% Class-C fly ash mixture using the procedure known as disking. Figure 4.5 shows the

**Figure 4.1** *In situ* subgrade soil of the SW ramp before soil stabilization.

truck used for the mixing procedure together with the water truck. In order to achieve the optimum moisture content, water was also sprayed when deemed necessary. Figure 4.6 shows the *in situ* mixing of the steel slag-Class-C fly ash mixture and the subgrade soil.

**Figure 4.2** Spreader truck.

**Figure 4.3** Spreading of the steel slag-Class-C fly ash mixture on the subgrade soil.

### *4.4.3 Compaction*

After completion of thorough mixing, the soil-steel slag-Class-C fly ash mixture was compacted using a sheepsfoot roller. The compaction effort was evenly applied using the sheepsfoot roller, while the final smoothening of the compacted surface was done using a smooth-drum roller. The compaction of the subgrade soil using a sheepsfoot roller is shown in Figure 4.7.

**Figure 4.4** View of the ramp section after the spreading of the steel slag-Class-C fly ash mixture.

**Figure 4.5** Truck used for mixing operations together with the water truck.

Figure 4.8 (a) and (b) show the finishing compaction operations with the smooth-drum roller and the finished subgrade after final compaction, respectively.

## 4.5 Field Quality Control of Subgrade

The overall strength, stability and performance of a pavement rely on the quality of the subgrade. Proper compaction of the subgrade is essential for satisfactory pavement performance. INDOT requires a minimum stabilized subgrade thickness of 1 ft. The maximum dry unit weight corresponding to a relative compaction of 100% is also required. The effectiveness and quality of compaction of the stabilized subgrade in the field was determined through field compaction quality control tests. The field density and water content of the stabilized subgrade was determined with nuclear gauge tests. In addition, dynamic cone penetration tests were performed on the stabilized subgrade. The next sections provide a brief description on these two field quality control tests.

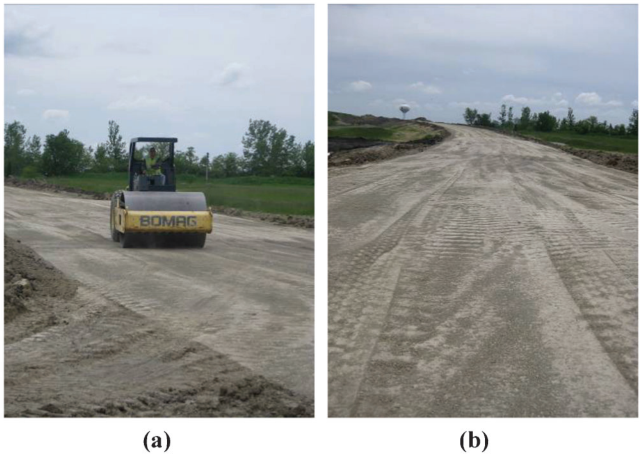
**Figure 4.6** Mixing of steel slag-fly ash mixture with the *in situ* subgrade soil.

**Figure 4.7** Compaction of the subgrade with sheepsfoot roller.

### *4.5.1 Nuclear Gauge Tests*

Nuclear gauge tests are widely used for quality control of subgrade. The main advantage of the nuclear gauge test is that it is easier to perform than other traditional test methods. Once, the specific gravity of the soil is known, the dry unit weight and water content of the soil can easily be determined. However, nuclear gauge measurements may be affected by the chemical composition of the soil tested. In addition, a radioactive material is used that can be potentially dangerous to the health of field personnel.

The principle of the nuclear gauge relies on emitting gamma radiation and detecting the reflected rays to determine the wet unit weight of the soil. The higher the wet unit weight of soil is, the lower the number of protons the receiver detects. Using a similar principle, the nuclear gauge is also equipped to measure water content. For water content measurement, the nuclear gauge emits high-speed neutrons. These high-speed



(a) (b)

**Figure 4.8** Finishing compaction operations: (a) compaction of the ramp with smooth-drum roller and (b) view of the finished subgrade of the SW ramp.

neutrons are retarded by the hydrogen atoms present in the soil-water system and hence, the number of slow-speed neutrons detected by the gauge indicates the hydrogen atoms present in the medium and hence, the water content of the soil (*17,18*).

The nuclear gauge has two different modes to measure wet unit weight of the soil. These modes are direct transmission and backscatter modes. The INDOT Manual (*19*) recommends the use of the direct transmission mode for field quality control of soils (*18*). Figure 4.9 shows a sketch of the nuclear gauge test equipment together with the locations of the source, the detector and the photon paths of the backscatter mode for density measurement, and the direct transmission mode for density measurement and moisture detection.

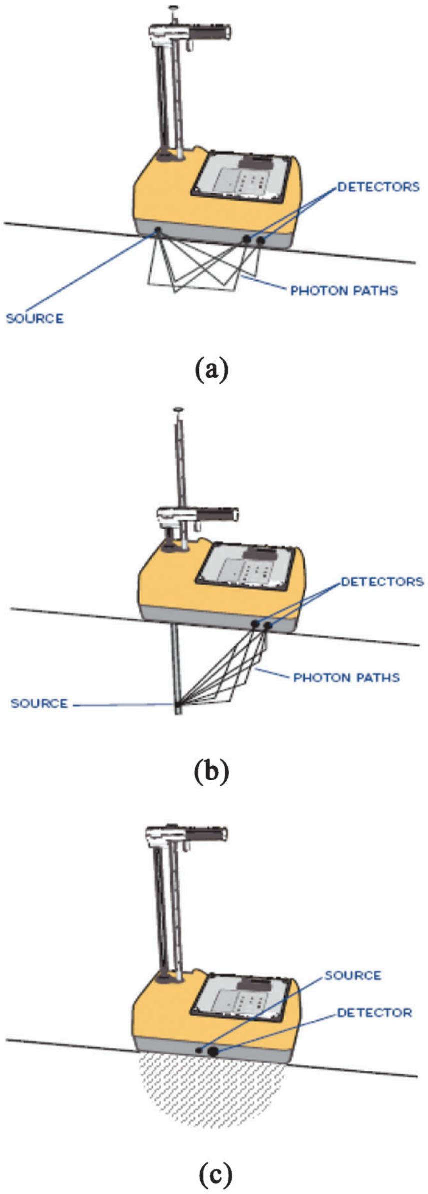


**Figure 4.9** Nuclear gauge measurements: (a) backscatter mode for density measurement, (b) direct transmission mode for density measurement, and (c) moisture detection (*18,20*).

Figure 4.10 shows nuclear gauge density measurements being taken on the subgrade soil stabilized with the steel slag-Class-C fly ash mixture.

### *4.5.2 Dynamic Cone Penetration Tests (DCPTs)*

Dynamic Cone Penetration Tests (DCPT) are performed to determine the penetration resistance of *in situ* materials at shallow depths, and hence are used as a compaction quality control tool for subgrade soils. The dynamic cone penetrometer is an easy-to-use, portable device that consists of: (1) an upper shaft that is directly connected to an 8 kg (17.6 lb) drop hammer, (2) a lower shaft with an anvil at the top and a cone at the bottom, and (3) a replaceable cone tip with an apex angle of 60 degrees and a diameter of 20 mm. A graphic representation of the DCP is presented in Figure 4.11.

The DCPT procedure involves the following two main steps:

1. The hammer is dropped from a standard fall height. The energy transferred to the cone by the impact of the hammer drop on top of the anvil causes penetration of the cone into the soil;
2. The number of blows ($N_{DCP}$) for the specified cone penetration (e.g., 0 to 6 in and 6 to 16 in) is recorded.

In the last decade, Illinois, Iowa, Minnesota and North Carolina DOTs developed criteria for subgrade compaction using a Dynamic Cone Penetration Index (DCPI), which is expressed as the penetration per blow (mm/blow). DCPI values can be converted to $N_{DCP}$ values corresponding to a 0 to 150 mm (0 to 6 in) penetration depth if desired. Kim et al. (*18*) summarized the criteria developed by these DOTs in the U.S. for $N_{DCP}$ values corresponding to a 0 to 150 mm (0 to 6 in)

**Figure 4.10** Nuclear gauge measurements on subgrade soils stabilized with 7% steel slag-3% Class-C fly ash mixture.

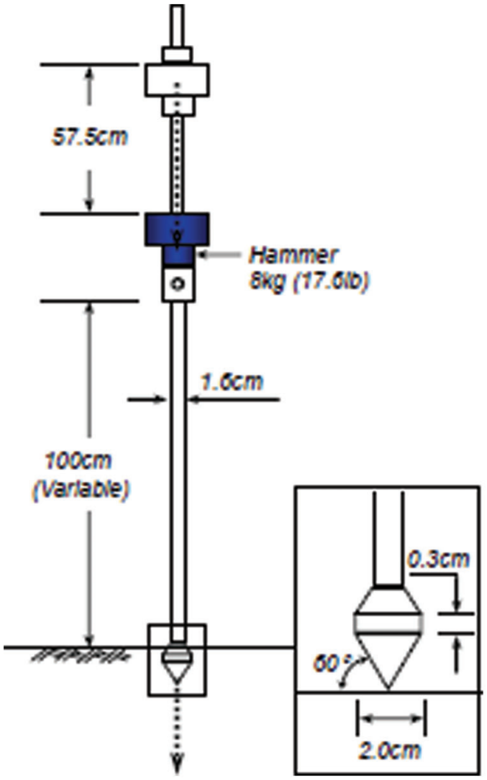


**Figure 4.11** Schematic of the dynamic cone penetrometer (*18,21*).

penetration depth (see Table 4.1) The proposed $N_{DCP}$ values were developed based on either the requirement that the compacted dry unit weight of the *in situ* soil exceeds 95% relative compaction or that the subgrade soil has a minimum California Bearing Ratio (CBR) value of 8. The criteria proposed by some of the DOTs are independent of the type of material, whereas other DOTs proposed values for sandy and clayey materials separately. As shown in Table 4.1, according to the criteria developed by the U.S. DOTs, the $N_{DCP}$ values corresponding to a 0 to 150 mm (0 to 6 in) penetration depth fall in the range of 3.8 to 6 for clayey subgrade soil.

Dynamic cone penetration tests were performed on the subgrade soils stabilized with the steel slag-Class-C fly ash mixture designed in this research (see Figure 4.12). The $N_{DCP}$ values were recorded for 0 to 150 mm (0 to 6 in) and 150 to 407 mm (6 to 16 in) penetration depths.

## 4.6 Field Quality Control Test Results

The steel slag-Class-C fly ash mixture was used to stabilize the *in situ* subgrade soils of some sections of the NW and SW I-65 ramps at the intersection of 109th Avenue and I-65, in Crown Point, Indiana. The length of the subgrade sections stabilized with the steel slag-Class-C fly ash mixture was approximately 150 ft and 100 ft in the NW and SW ramps, respectively. Field quality control of the compacted subgrade soils was done by performing DCP and nuclear gauge tests.

DCPT tests were performed on the stabilized sections in the SW and NW ramps 3 hours and 1 hour after compaction of the stabilized subgrade, respectively. In the SW ramp sections, two additional sets of DCPTs were performed 96 hours after completing compaction of the subgrade to evaluate the strength-gain associated with the cementitious reactions. The DCPT test results for the SW and NW ramp subgrades are presented in Table 4.2 and Table 4.3, respectively.

As shown in Table 4.2, the $N_{DCPT}$ values recorded for 0 to 6 inch and 6 to 16 inch penetration at various stations in the SW ramp 3 hours after subgrade compaction were in the ranges of 8 to 18 and 16 to 24, respectively, while at about 96 hours after subgrade compaction, $N_{DCPT}$ values corresponding to 0 to 6 inch and 6 to 16 inch penetration were in the ranges of 11 to 24 and 12 to 32, respectively. The increase in the $N_{DCPT}$ values with respect to time indicates the occurrence of cementitious reactions. The $N_{DCPT}$ values recorded for 0 to 6 inch and 6 to 16 inch penetration at various stations in the NW ramp were in the ranges of 5–15 and 6–15 approximately 1 hour after subgrade compaction, respectively. The ranges of values recorded in the NW ramp were lower than those recorded in the SW ramp because there was not enough time for the cementitious reactions to occur since the testing in the NW ramp was conducted only 1 hour after the subgrade compaction. As previously discussed, based on the criteria developed by several U.S. DOTs, the $N_{DCPT}$ values corresponding to a penetration depth of 0 to 150 mm (0 to 6 in) should

TABLE 4.1
**$N_{DCP}$ criteria for a 0 to 150 mm penetration depth (0 to 6 in) (*18*)**

| Materials | Illinois DOT (ILDOT) | Iowa DOT | Minnesota DOT (MnDOT) | North Carolina DOT |
|---|---|---|---|---|
| Sandy Soil | 6.1(a) | 3.4–4.4(b) | 12.5(c) | 4.0(d) |
| Clayey/Silty Soil | 3.8–4.4(b) | 6.0(c) | | |

(a) DCP blow counts associated with a CBR of 8 (*22*).

(b) Iowa DOT classified the soil either “suitable soil” or “unsuitable soil” in each group of soil. The values show the ranges of it (*23*).

(c) The criteria of frictional soil apply for “granular” base layer; MnDOT recorded $N_{DCP}$ values only for blow counts that are higher than two (*24*).

(d) DCP blow counts associated with a CBR of 8 (*25*).

**Figure 4.12** Dynamic cone penetration testing of the subgrade soils stabilized with 7% steel slag-3% Class-C fly ash mixture.

fall in the range of 3.8 to 6 for clayey subgrade soil. All $N_{DCPT}$ values recorded at stations in the NW and SW ramps fall in the range specified by U.S. DOT's, and hence, the compaction of the subgrade was deemed satisfactory.

Kim et al. (*18*) proposed criteria for the required $N_{DCPT}$ values for 0 to 6 inch penetration and 6 to 12 inch penetration as a function of the plasticity index (PI) and the percent passing the #40 sieve for silty clays. In our case, for a plasticity index of 12 and approximately 100% passing the #40 sieve, the required values for $N_{DCPT}$ are 8 and 12 for 0 to 6 inch penetration and 6 to 12 inch penetration, respectively. At all stations in the SW ramp, the $N_{DCPT}$ values recorded for 0 to 6 inch penetration and 6 to 12 inch penetration satisfied this criterion. In the NW ramp, in some of the stations the recorded $N_{DCPT}$ values were slightly lower than the values specified by the criterion developed by Kim et al. (*18*).

In addition to the DCPTs, INDOT performed nuclear gauge tests at five stations in the SW ramp subgrade. The results of the nuclear gauge tests performed by INDOT are summarized in Table 4.3. As shown in Table 4.4, the moisture content values recorded by the nuclear gauge tests were lower than the recommended range of 14 to 17%. Nonetheless, based on the maximum dry unit weight values recorded by the nuclear gauge, the relative compaction values for the subgrade at these five stations ranged between 102.6 and 106.7%. INDOT requires a minimum relative compaction of 100% for field compaction of subgrade soil, and hence, the stabilized subgrade met INDOT criterion. After compaction, the subgrade was monitored and checked for possible cracks or signs of distress. Cracks or signs of distress were not observed on the compacted subgrade before construction of the

TABLE 4.2
**DCPT results for the subgrade soils stabilized with 7% steel slag-3% Class-C fly ash mixture for the SW ramp**

| | | **DCPT Test Results—SW Ramp** | | |
|---|---|---|---|---|
| | **Test Date:** | **5/20/2010** | **5/24/2010** | **5/24/2010** |
| | **Test Time:** | **2.00 pm** | **2.00 pm** | **3.00 pm** |
| | **Test Time Delay:** | **~3 hrs after compaction** | **~96 hr after compaction** | **~96 hr after compaction** |
| **Station No.** | **Penetration** | **$N_{DCPT}$** | **$N_{DCPT1}$** | **$N_{DCPT2}$** |
| 300 + 90 ft | 0 to 6 inches | — | 13 | 11 |
| | 6 to 16 inches | — | 18 | 18 |
| 301 + 05 ft | 0 to 6 inches | 8 | 20 | 16 |
| | 6 to 16 inches | 18 | 21 | 20 |
| 301 + 20 ft | 0 to 6 inches | 11 | 14 | 14 |
| | 6 to 16 inches | 24 | 18 | 16 |
| 301 + 35 ft | 0 to 6 inches | 11 | 16 | 14 |
| | 6 to 16 inches | 19 | 32 | 32 |
| 301 + 65 ft | 0 to 6 inches | 13 | 20 | 15 |
| | 6 to 16 inches | 19 | 19 | 17 |
| 301 + 80 ft | 0 to 6 inches | 13 | 24 | 17 |
| | 6 to 16 inches | 16 | 24 | 29 |
| 301 + 95 ft | 0 to 6 inches | 18 | 23 | 24 |
| | 6 to 16 inches | 19 | 21 | 23 |
| 302 + 10 ft | 0 to 6 inches | 15 | 17 | 23 |
| | 6 to 16 inches | 20 | 18 | 22 |
| 302 + 23 ft | 0 to 6 inches | 12 | 10 | 11 |
| | 6 to 16 inches | 17 | 12 | 13 |

TABLE 4.3

**DCPT results for the subgrade soils stabilized with 7% steel slag-3% Class-C fly ash mixture for the NW ramp**

| DCPT Test Results—NW Ramp | | |
|---|---|---|
| | **Test Date:** | **5/20/2010** |
| | **Test Time:** | **3.00 pm** |
| | **Test Time Delay:** | **~1 hr after compaction** |
| **Station No(1)** | **Penetration** | **$N_{DCPT}$** |
| 0 + 15 ft | 0 to 6 inches | 8 |
| | 6 to 16 inches | 10 |
| 0 + 30 ft | 0 to 6 inches | 5 |
| | 6 to 16 inches | 15 |
| 0 + 45 ft | 0 to 6 inches | 15 |
| | 6 to 16 inches | 7 |
| 0 + 60 ft | 0 to 6 inches | 8 |
| | 6 to 16 inches | 13 |
| 0 + 75 ft | 0 to 6 inches | 10 |
| | 6 to 16 inches | 12 |
| 0 + 90 ft | 0 to 6 inches | 6 |
| | 6 to 16 inches | 6 |

(1) At the time of testing, INDOT station numbers were not provided to us, therefore the 1st electricity/utility box located along the ramp which was closest to 109th Avenue was deemed as station 0+00, with the station numbers increasing as we moved along the ramp in the North direction

base course and concrete placement. The stabilized subgrade performed satisfactorily.

## 4.7 Pavement Construction

After completing the subgrade stabilization process and performing field quality control tests to ensure proper compaction of the subgrade, pavement construction work started. Prior to the placement of concrete, an aggregate base course was placed on the finished subgrade and reinforcements were placed on top of the base course (*26*). Figure 4.13 (a) and (b) show the placement of reinforcements and the leveling of the base course, respectively. When required, the base material was also sprayed with water to prevent the concrete from losing too much water due to the heat from the sun. Concrete was transferred to the site by trucks, shifted to the conveyer belt and poured on the reinforced base course (see Figure 4.14). A vibratory-type concrete placement equipment was used for spreading and initial leveling of concrete. Figure 4.15 shows the concrete before and after the pass of the

TABLE 4.4

**Nuclear gauge test results reported by INDOT for the subgrade soils stabilized with 7% steel slag-3% Class-C fly ash mixture in the SW ramp**

| Nuclear Gauge Density Tests on the SW Ramp<br>Test Date : 5/20/2010 | | | | |
|---|---|---|---|---|
| **Stations** | **Wet Unit Weight** | **Moisture Content** | **Dry Unit Weight** | **Relative Compaction(1)** |
| | $\gamma_{wet}$ | $wc$ | $\gamma_{d,max}$ | |
| | **kN/m$^3$** | | **kN/m$^3$** | |
| | **(pcf)** | % | **(pcf)** | % |
| 301 + 05 ft | 20.83<br>(132.6) | 12.4 | 18.54<br>(118) | 102.6 |
| 301 + 35 ft | 21.33<br>(135.8) | 11.9 | 19.04<br>(121.2) | 105.4 |
| 301 + 65 ft | 21.55<br>(137) | 13.4 | 19.02<br>(121.1) | 105.3 |
| 301 + 95 ft | 21.27<br>(135.4) | 13.9 | 18.66<br>(118.8) | 103.3 |
| 302 + 10 ft | 21.68<br>(138) | 12.5 | 19.28<br>(122.7) | 106.7 |

(1) Relative compaction is the ratio of the maximum dry unit weight measured at the field to the maximum compacted dry unit weight obtained from the standard Proctor compaction tests.

(a) (b)

**Figure 4.13** Pavement work prior to placement of concrete: (a) placement of reinforcement and (b) leveling of the base course.

**Figure 4.14** Preparation and pouring of concrete pavement.

vibratory equipment. The concrete was further leveled to ensure that the surface was free of any lumps or cracks. The pictures taken during the leveling process are presented in Figure 4.16.

After completing the leveling of the concrete, the surface of the concrete was gridded. Tinning allows proper drainage of the excess water on the concrete surface and also provides better traction for the vehicles. The tinned concrete surface is shown in Figure 4.17.

After completion of tinning, the pavement surface was coated with 1600-white, water-based, wax-based concrete curing compound. This compound has white pigments that form a premium grade membrane that optimizes the concrete's water retention potential, something that is essential for the cementitious reactions to occur. In addition, these white pigments reflect the sun's rays, and hence, prevent excessive heat build-up. This process also aids in keeping the surface of the concrete cooler. The drying time of the compound varies based on the weather and job site conditions. Typically, the compound is expected to dry within 2 hours. Figure 4.18 shows a picture of the concrete pavement after the application of the curing compound.

(a) (b)

**Figure 4.15** Placement of concrete: (a) before and (b) after the initial leveling by the vibratory equipment.

**Figure 4.16** Final leveling of the concrete surface.

**Figure 4.17** Tinned concrete surface.

**Figure 4.18** Concrete surface after spraying with the concrete curing compound.

## 5. SUMMARY AND CONCLUSIONS

### 5.1 Summary

The main objectives of this study were to design suitable steel slag-Class-C fly ash mixtures that could replace lime in subgrade stabilization applications and to demonstrate the cost-effective use of the selected mixture in an INDOT subgrade stabilization project. For this purpose, a clayey subgrade soil collected from the proposed implementation site was characterized through a series of tests in the laboratory. For stabilizing the clayey soil, two types of mixtures were considered: (i) steel slag-Class-C fly ash mixtures, and (ii) steel slag-blast-furnace slag mixtures. In order to design a suitable mixtures, laboratory tests were performed on soil-5% steel slag-5% Class-C fly ash, soil-7% steel slag-3% Class-C fly ash, soil-8% steel slag-2% Class-C fly ash and soil-7% steel slag-3% blast furnace slag mixtures (all percentages by weight of soil). The laboratory tests performed on the mixtures included unconfined compression, compaction and long-term swelling tests. Based on the laboratory tests results, the subgrade mixture selected was the 7% steel slag-3% Class-C fly ash mixture.

The suitability of the 7% steel slag-3% Class-C fly ash mixture as a lime replacement alternative was demonstrated in the stabilization of the *in situ* subgrade soils of some sections of the I-65 ramps near the intersection of 109th Avenue and I-65, in Crown Point, Indiana. Construction guidelines were prepared for the subgrade stabilization work. The stabilization process was monitored in the field. Field compaction quality control was done by performing DCPTs and nuclear gauge tests.

### 5.2 Conclusions

Based on the findings of the present study, the following conclusions are drawn:

1. The soil collected from the implementation site was classified as lean clay (CL) according to the USCS classification system. The PI, LL, and PL of the *in situ* soil were in the ranges of 12–13, 28–35, and 16–22, respectively.
2. The soil collected from the implementation site was classified as A-6, with a group index of 7 according to the AASHTO classification system (AASHTO M145) (*7*). AASHTO gives a general rating of fair-to-poor for A-6 soils as subgrade material.
3. The optimum moisture content and maximum dry unit weight of the *in situ* clayey soil were 13% and 18.56 kN/m$^3$ (118.2 pcf), respectively.
4. The compacted soil samples reached a maximum swelling strain of about 0.41% after approximately 13 days of soaking and started shrinking after that. Eventually, the soil samples reached equilibrium at approximately 0.24% swelling strain after 35 days of soaking.
5. The unconfined compressive strength of the *in situ* soil samples compacted to 95 to 101% relative compaction ranged between 214 and 329 kPa. The average unconfined compressive strength of the samples tested was 282.9 kPa (41 psi).
6. The unconfined compressive strength test results showed that the *in situ* clayey soil at the implementation site required improvement to support the loads from the pavement since INDOT requires a minimum unconfined compressive strength of 552 kPa (80 psi) for subgrade soils.
7. The PI, LL and PL values of the soil-7% steel slag-3% Class-C fly ash mixture were 13, 35 and 22, respectively. These results indicated that blending the *in situ* soil with the 7% steel slag-3% Class-C fly ash mixture resulted in an increase in LL and PL. No significant change was observed in the PI of the soil-7% steel slag-3% Class-C fly ash mixture when compared to that of the *in situ* clayey soil.
8. The PI, LL and PL of the soil-7% steel slag-3% blast furnace slag mixture were 14, 39 and 25, respectively. These results indicated that blending the *in situ* soil with the 7% steel slag-3% blast furnace slag mixture resulted in an increase in LL and PL. No significant change was observed in the PI of the soil-7% steel slag-3% blast furnace slag mixture when compared to that of the *in situ* clayey soil.
9. The optimum moisture content and maximum dry unit weight of the soil-7% steel slag-3% fly ash mixture were 15% and 18.04 kN/m$^3$ (114.8 pcf), respectively.
10. The optimum moisture content and maximum dry unit weight of the soil-7% steel slag-3% blast furnace slag mixture were 16% and 16.94 kN/m$^3$ (107.7 pcf), respectively.
11. Both the soil-steel slag-Class-C fly ash and soil-steel slag-blast furnace mixtures exhibited higher optimum moisture content and lower maximum dry unit weight than those observed for the *in situ* clayey soil.
12. The two-day unconfined compressive strength of the compacted soil-7% steel slag-3% Class-C fly ash and soil-7% steel slag-3% blast furnace slag mixtures were 820 kPa (119 psi) and 602 kPa (87 psi), respectively.
13. The unconfined compressive strength gain rate of the soil-7% steel slag-3% Class-C fly ash mixture was higher than that of the soil-7% steel slag-3% blast furnace slag mixture. These results indicated the occurrence of stronger cementitious reactions in the soil-steel slag-Class-C fly ash mixture.
14. The maximum swelling strains of the soil-7% steel slag-3% Class-C fly ash and soil-7% steel slag-3% blast furnace slag mixtures were 0.13% and 0.052%, respectively. These results showed that both the steel slag-Class-C fly ash and steel slag-blast furnace slag mixtures were effective in reducing the swelling potential of the *in situ* clayey soil.
15. The soil-7% steel slag-3% Class-C fly ash mixture was selected as the most suitable and cost-effective subgrade material for an INDOT implementation project. Field compaction quality control was done by performing DCPTs and nuclear gauge tests.
16. The $N_{DCPT}$ values recorded for 0 to 6 inch and 6 to 16 inch penetration at various stations in the SW ramp were in the ranges of 8 to 18 and 16 to 24, respectively, 3 hours after subgrade compaction.
17. The $N_{DCPT}$ values corresponding to 0 to 6 inch and 6 to 16 inch penetration were in the ranges of 11 to 24 and 12 to 32, respectively, about 96 hours after subgrade compaction.
18. The $N_{DCPT}$ values recorded for 0 to 6 inch and 6 to 16 inch penetration at various stations in the NW ramp were in the ranges of 5–15 and 6–15, respectively, approximately 1 hour after subgrade compaction.

19. $N_{DCPT}$ values recorded at all stations in the NW and SW ramps fell in the range specified by U.S. DOTs.
20. The subgrade was monitored and checked for possible cracks or signs of distress. Cracks or signs of distress were not observed on the subgrade before the base course and concrete placement. The stabilized subgrade performed satisfactorily.

## 5.3 Recommendations and Future Work

Based on the work performed in this research study, the following are recommendations for future research:

1. The long-term performance of the pavement constructed in connection with the implementation project that was part of this study should be monitored.
2. The effectiveness of steel slag-Class-C fly ash mixtures to stabilize high-plasticity clays should be investigated by performing laboratory tests on mixtures with varying percentages of steel slag and Class-C fly ash.
3. The short- and long-term environmental impact of using slag-Class-C fly ash mixtures in subgrade stabilization projects should be assessed.
4. Design of stabilizing mixtures that are effective in suppressing the expansive behavior of natural soils found in Indiana should be explored in a research project.
5. A set of stabilizing mixtures should be designed for use with soils that are found routinely in INDOT projects. These mixtures could be designed in such a way as to account for the possible inherent variability of the materials that are by-products of the steel and iron industry.

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## About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

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