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Contractor Variability in Construction of Cement Treated Base Layers

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VARIABILITY IN CONSTRUCTION OF

CEMENT-TREATED BASE LAYERS

by

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ABSTRACT

VARIABILITY IN CONSTRUCTION OF

CEMENT-TREATED BASE LAYERS

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The primary purposes of this research were to identify construction factors most correlated to specific mechanical properties of cement-treated base (CTB) layers and to determine which construction factors exhibit comparatively high variability within individual construction sections of the two pavement reconstruction projects included in this study. In addition, differences between construction sections tested in this research were evaluated. The research focused on the construction of CTB layers in two pavement reconstruction projects in northern Utah, one along Interstate 84 (I-84) near Morgan and one along U.S. Highway 91 (US-91) near Richmond.

The significant predictor variables associated with California bearing ratio (CBR), Clegg impact value (CIV), 7-day unconfined compressive strength (UCS), and 28-day UCS at the I-84 sites include reclaimed asphalt pavement (RAP) content; cement content;

amounts of aggregate particles finer than the No. 8, No. 50, and No. 200 sieves; 7-day moisture content, and 28-day moisture content. The significant predictors of the same response variables on US-91 were in-situ moisture content, cement content, amount of aggregate particles finer than the No. 50 sieve, time between mixing and compaction in the field, dry density in the field, 7-day dry density, 7-day moisture content, 28-day dry density, and 28-day moisture content.

The factors that were found to be the most variable on both I-84 and US-91 were CBR, cement content, time between mixing and compaction in the field, and time between mixing and compaction for each of the manually compacted specimens. On I-84, 16 of 27 factors were found to be significantly different between the sites, while 17 of 26 factors were found to be significantly different between the sites on US-91.

The results of this research suggest that tighter specifications are warranted with respect to RAP content, cement content, and time between mixing and compaction. Concerning full depth recycling (FDR) projects, milling plans should be utilized to achieve improved uniformity in RAP content, and inspection protocols for encouraging improved control of cement content should be implemented during construction to ensure high-quality work. Compaction should be performed as soon as possible after mixing to minimize the adverse effects of cement hydration on the ability to achieve maximum dry density in the field.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

In the pavement industry, the use of cement stabilization in conjunction with full-depth recycling (FDR) for pavement rehabilitation and reconstruction is increasing. The reuse of deteriorated asphalt in pavement construction can provide a very economical alternative to removing damaged asphalt, but using reclaimed asphalt pavement (RAP) may require the addition of a stabilizing agent such as Portland cement to achieve the desired engineering properties (*1*). When stabilization is specified, the optimum type and amount of stabilizer for use in construction should be determined using appropriate laboratory testing, and the pavement should then be constructed according to the resulting specifications.

Although engineers and contractors may carefully adhere to accepted standards of practice for pavement design and construction, the extent to which a newly constructed or reconstructed pavement structure exhibits the expected performance depends on variability in in-situ conditions, material characteristics, construction procedures, and climatic factors. For example, with respect to construction of cement-treated base (CTB) in conjunction with FDR, variability in the mechanical properties of the pavement can be caused by differences in RAP content; aggregate gradation; moisture content; cement content; and the quality of mixing, compaction, and curing of the finished layer. Consequently, the engineer may ideally assume that all sections of a pavement project will be constructed uniformly and provide equal service life. Such an assumption is usually invalid. Instead, in many cases, variability in the construction process yields variability in pavement performance, including premature failure of some sections.

Although knowledge of the variability associated with CTB construction would prove very beneficial to pavement designers, the literature is generally absent of such information; existing publications focus mainly on laboratory testing and field performance of CTB materials. Therefore, the primary purposes of this research were to identify construction factors most correlated to specific mechanical properties of CTB layers and to determine which construction factors exhibit comparatively high variability within individual construction sections of CTB projects. In addition, differences between construction sections tested in this research were evaluated. Information addressing variability in construction of CTB layers is expected to assist both pavement engineers and contractors in re-evaluating existing specifications and/or developing new specifications and methods that will ultimately lead to higher quality pavements that more consistently meet design expectations.

1.2 SCOPE

The research conducted in this study focused on the construction of CTB layers in two pavement reconstruction projects in northern Utah, one along Interstate 84 (I-84) near Morgan and one along U.S. Highway 91 (US-91) near Richmond. The I-84 project utilized FDR in conjunction with cement stabilization, while the US-91 project involved cement stabilization of new aggregate delivered to the site from a local quarry. The specifications for both projects required the addition of 2 percent Portland cement by weight of dry aggregate and 8-in.-thick CTB layers. The projects were performed by different contractors during the summer of 2005.

Testing at I-84 and US-91 was conducted during June and July, respectively, of 2005. Within each corridor, three individual construction sections each 1,000 ft in length and 40 ft in width were evaluated. The specific mechanical properties of interest in this research included California bearing ratio (CBR), Clegg impact value (CIV), 7-day unconfined compressive strength (UCS), and 28-day UCS. CBR and CIV were chosen because they are two forms of on-site quality control testing available to contractors and owners, and UCS was chosen because it is the primary design parameter utilized in CTB design. CBR and CIV were measured in the field using a dynamic cone penetrometer (DCP) and heavy Clegg hammer, respectively, while UCS values were determined through laboratory testing of specimens manually compacted in the field from the processed material. Because the data collected in this study are specific to these two projects, the findings of this research may not be readily applicable to CTB layers constructed using different materials or in different climatic conditions.

1.3 OUTLINE OF REPORT

This report contains five chapters. Chapter 1 describes the problem statement and scope of the research, and Chapter 2 discusses several construction factors that can influence the mechanical properties of CTB layers. Chapter 3 explains the experimental methodology utilized in the research, and Chapter 4 presents the research results and statistical analyses. Chapter 5 of this report offers conclusions and recommendations derived from the study.

CHAPTER 2

FULL-DEPTH RECLAMATION WITH CEMENT STABILIZATION

2.1 OVERVIEW

The highway system is a national resource that has allowed the United States to achieve economical, social, and military sophistication. Although engineers must continue to expand the nation's transportation systems to meet the growing transportation demands of this nation, the building of virgin roadways has been largely completed within the continental United States (*2*). Numerous roadways are now approaching or have already exceeded their design life expectancies, and maintenance, rehabilitation, and reconstruction (MR&R) of these existing pavements have necessarily become the primary tasks of the highway construction industry.

Because roadway construction is expensive, finding economical ways of extending pavement service life is a constant necessity for contractors and departments of transportation (DOTs) (*3*). In particular, this research focuses on the use of cement stabilization as an economically attractive method for increasing the strength and durability of aggregate base materials (*4*). The cement binds the aggregate particles together, and the improvement in structural capacity then permits applications of greater traffic loads than may have been previously possible.

The amount of Portland cement that is blended with the aggregate base material cannot be excessive, however, because cement hydration causes shrinkage stresses in the layer that can lead to transverse cracking and block cracking of the layer. Cracking creates avenues for water ingress into the base layer, causes accelerated pavement damage by increasing erosion and susceptibility to deterioration under freeze-thaw cycling, and decreases the strength and stiffness of affected layers (*5*). In addition to cement content, other factors associated with pavement base layer construction may also impact pavement performance, including aggregate gradation; reclaimed asphalt pavement (RAP) content; moisture content; cement content; and the quality of mixing, compaction, and curing of the finished layer.

Although pavement engineers are usually responsible for developing and implementing appropriate specifications for controlling these factors, highway contractors are ultimately responsible for meeting the specifications and providing high-quality projects. The following sections describe the process of cement-treated base (CTB) construction and then address specific variables associated with the procedure.

2.2 PROCESS OF CTB CONSTRUCTION

In any form of construction, substantial work takes place even before ground breaking occurs on the site. In roadway construction, the structural requirements of the pavement must be calculated, the type and thickness of each layer must be determined, and the method of construction must be specified. As stated previously, the use of full-depth recycling (FDR) in conjunction with cement stabilization is an attractive pavement reconstruction method when economic, environmental, and engineering perspectives are considered.

If FDR is utilized, the existing asphalt layer should be pulverized with the underlying base material to the depth specified by the engineer, which is usually accomplished using a reclaimer as shown in Figure 2.1. To achieve target RAP contents in the reclaimed layer, asphalt milling may be required in certain areas prior to pulverization. Following pulverization, the layer should be graded and compacted to approximate final elevations. Material may need to be added or removed to satisfy the profile and cross-section design requirements for the facility. If FDR is not used, the existing asphalt should be removed by milling or another means to expose the base layer in preparation for cement stabilization.

For new construction, the base material may be placed normally for in-situ cement treatment, or it may be blended with cement in a pug mill prior to delivery to the site. For in-situ cement stabilization, the cement should be spread over the prepared base layer in a powder or slurry form and mixed with the aggregate to the specified depth of

FIGURE 2.1 Pulverization process (*6*).

treatment (*7*). The use of a spreader truck for placement of cement powder is illustrated in Figure 2.2.

The cement content is determined by the engineer, usually from the results of testing performed according to American Society for Testing and Materials (ASTM) D 559 or ASTM D 560, and is monitored by the driver of the cement truck; the truck may be equipped with automatic gates for improving the accuracy and uniformity of cement placement, but the driver may instead rely on experience and trial runs to determine appropriate gate openings and ground speeds for different conditions. After being placed, the cement is mixed, as shown in Figure 2.3, with the underlying base material, and water is added as needed to bring the aggregate to the optimum moisture content (OMC) previously determined in the laboratory.

FIGURE 2.2 Cement placement process.

FIGURE 2.3 Cement mixing process.

Compaction should then follow as soon as possible after mixing so that the cement hydration does not substantially prohibit the contractor from achieving the density specified for the project. The compaction process is depicted in Figure 2.4, and the use of a water truck to maintain ideal curing conditions for the CTB layer is shown in Figure 2.5. If the base becomes too dry due to evaporation, the cement may not fully hydrate, and shrinkage cracking may occur. Final grading is displayed in Figure 2.6.

FIGURE 2.4 Compaction process.

FIGURE 2.5 Watering process.

FIGURE 2.6 Grading process.

2.3 VARIABILITY IN CTB CONSTRUCTION

Several construction variables can impact the performance of CTB layers, including RAP content, aggregate gradation, aggregate moisture content, cement content, compaction density, and curing. Each of these variables and their possible effects on pavement performance are described in the following sections.

2.3.1 RAP Content in Conjunction with FDR Projects

Recycling of pavement materials has become a viable alternative to consider in the rehabilitation and maintenance of roads (*8*). RAP is typically produced by milling existing asphalt pavement or by crushing chunks of deteriorated pavement previously removed from a site (*9*). When it is used for CTB, RAP is typically recycled in place. Several factors should be considered when determining whether or not to use RAP on a particular project. Two of the major reasons supporting the use of recycling are lack of quality aggregate in the area and cost of disposing the old asphalt (*10*). No concrete evidence is present to prove whether RAP is actually beneficial to CTB or not; however, recent research indicates that increased RAP contents do require increased cement contents in order to achieve comparable UCS values when all other factors are held constant. This finding suggests that strong cementitious bonds between aggregate particles coated with asphalt cement do not readily form (*11*). Some studies show that, because of the angular nature of the RAP particles after they are crushed, compaction is more difficult and leads to excess air voids in the base. These air voids allow water infiltration that can weaken the base, especially in the presence of freeze-thaw cycling associated with cold climates. If the project is in a hot climate instead, problems can also arise with the asphalt in the RAP particles melting and creating larger pieces of aggregate. This can be detrimental to the final compaction of the base because a well-graded mix is required to achieve optimum compaction (*12*). One source claims that if the existing surface still retains most of its original viscosity, that surface should be removed instead of being incorporated into the base layer (*7*).

2.3.2 Gradation

Aggregate particle size can affect both OMC and maximum dry density, which in turn impact the compaction characteristics of the material. In addition, finer gradations generally exhibit increased cement demand (*13*). Well-graded sandy and gravelly materials with between 10 and 35 percent non-plastic fines are generally considered to be the most favorable for CTB construction and require the least amount of cement for adequate hardening (*7*). While particle-size distributions can be controlled to tight tolerances at aggregate processing facilities, in-situ recycling of asphalt in the FDR method can lead to significant variability in aggregate gradation. Although several passes of the reclaimer may be required to obtain the proper gradation after pulverization, additional passes may not be performed in the interest of time, resulting in improper particle-size distributions (*14*). Because the asphalt is pulverized and mixed with the existing base, variability in the recycled layer depends to a great degree on the variability associated with material composition, thickness, and mechanical properties of the original pavement layers. These uncontrollable factors can cause contractors difficulty in satisfying gradation specifications.

2.3.3 Moisture Content

With regard to CTB construction, both the water existing in the base material and the water added during mixing are variables that can affect the compaction characteristics, and, ultimately, the strength of the CTB layer. While the average moisture content existing in the base material depends to a large measure upon the air temperature, relative humidity, amount of recent precipitation, and wind speed, which should all be comparatively uniform over the length of a project, other factors, such as the presence of underwater springs, drainage features, and shaded areas, can cause spatial variability in the water content of the base layer. Consequently, the amount of mixing water that should be added by the contractor to achieve the OMC may vary greatly along the construction corridor. Because contractors cannot easily monitor existing moisture contents in a roadbed, deviations from OMC inevitably result. Too little or too much water leads to lower dry density and reduced structural capacity.

Although nuclear density gauges are commonly used for measuring both in-situ water content and density in the field, accurate detection of water in materials containing RAP can be difficult with this equipment (*15*). Furthermore, not all water that is present in the aggregate will affect the quality of the layer. Water absorbed in the aggregate, for example, will not change the amount of water required for cement hydration. For these reasons, determining the exact amount of water that should be added in the field can be challenging.

2.3.4 Cement Content

As suggested earlier, the optimum cement content is a function of both material type and gradation (*16*). CTB material should contain enough cement to strip the fines of their water affinity but not enough to bond all the aggregate particles into a solid mass (*17*). Identifying the optimum cement content for each CTB material is therefore crucial to achieving satisfactory pavement performance. If too little cement is added, the base will not be stable enough, it will flex under heavy traffic loading, and the bituminous material placed over the base will eventually crack. If too much cement is mixed into the base, the layer will be too stiff and brittle and likely prone to shrinkage cracking; these cracks can propagate into the surface layer as well (*5*). Variability in cement content depends upon the method of cement distribution, the type of equipment utilized, and the skill and diligence of the contractor in providing uniform cement treatment.

2.3.5 Compaction Density

Compaction density has been used as a primary measure of pavement quality for decades. The denser the base is compacted, the more stable it will be, and the longer the resulting road will last. Although water content plays an important role in achieving adequate compaction density in all situations, the use of cement stabilization in construction of a base layer also involves a time constraint. As soon as cement powder comes into contact with water, it begins to hydrate. Because the hydration process binds aggregate particles together with time, they become less mobile relative to one another and therefore resist reconfiguration into a denser structure upon compaction. For this reason, greater time delays between mixing and compaction are typically associated with lower densities; the Portland Cement Association suggests that compaction should normally be completed within 2 hours of mixing to avoid significant hardening of uncompacted material (*7*). If the process of hydration advances too far before compaction is completed, the material may need to be removed and replaced.

The type of compaction equipment used can also affect the density reached. Some of the different types of compaction equipment include sheep's foot rollers, tamping rollers, vibratory steel drums, and pneumatic tire rollers, each of which may be more suited to a particular project than another (*18*). However, each unique combination of equipment type and material type may require a different number of passes to reach optimum density than other combinations. In general, however, when compaction begins immediately after mixing of a CTB, control of water content is improved, and required densities are obtained more easily.

2.3.6 Curing

CTB layers gain strength over time as the cement continues to cure. As illustrated in Figure 2.5, watering during the construction process is therefore important to ensure that adequate moisture is available for cement hydration. Unfortunately, however, not all CTB construction sections are cured sufficiently, especially beyond the first few days after construction, and subsequent drying often leads to shrinkage cracking mentioned previously (*17*). Furthermore, because most roadway construction projects follow very tight time schedules necessary to minimize inconvenience to the traveling public, many contractors do not provide adequate CTB curing time before reopening the facility to traffic. Early trafficking of the affected layer often causes premature pavement damage.

2.4 SUMMARY

Several construction variables can impact the performance of CTB layers, including RAP content, aggregate gradation, aggregate moisture content, cement content, compaction density, and curing. Elevated RAP contents can cause excess air voids in the base material and may interfere with the formation of cementitious bonds between aggregate particles (*11*). The particle-size distribution can affect OMC, maximum dry density, and cement demand. The existing moisture content and mixing water content must be closely monitored because too little or too much water leads to lower dry density and reduced structural capacity of the pavement. Too little cement provides insufficient stabilization and may allow excessive pavement deflections under heavy traffic loading, while overly stabilized CTB layers are too stiff and brittle and prone to shrinkage cracking. Compaction density is critical because greater compaction density correlates to greater strength and layer stability. CTB layers should be watered frequently, especially during the first few days after construction, to ensure adequate curing, and the length of curing should be as long as possible to minimize failure due to premature trafficking of the layer. As discussed previously, all of these factors can directly impact the performance of pavements constructed using CTB layers and were therefore evaluated in this research.

CHAPTER 3

METHODOLOGY

3.1 OVERVIEW

The research conducted in this study focused on the construction of CTB layers in two pavement reconstruction projects in northern Utah, one along Interstate 84 (I-84) near Morgan and one along U.S. Highway 91 (US-91) near Richmond as shown in Figures 3.1 and 3.2, respectively. The I-84 project utilized FDR in conjunction with cement stabilization, while the US-91 project involved cement stabilization of new aggregate delivered to the site from a local quarry. The specifications for both projects required the addition of 2 percent Portland cement by weight of dry aggregate and 8-in.-thick CTB layers. The projects were performed by different contractors during the summer of 2005. The following sections describe the field and laboratory testing conducted in this research.

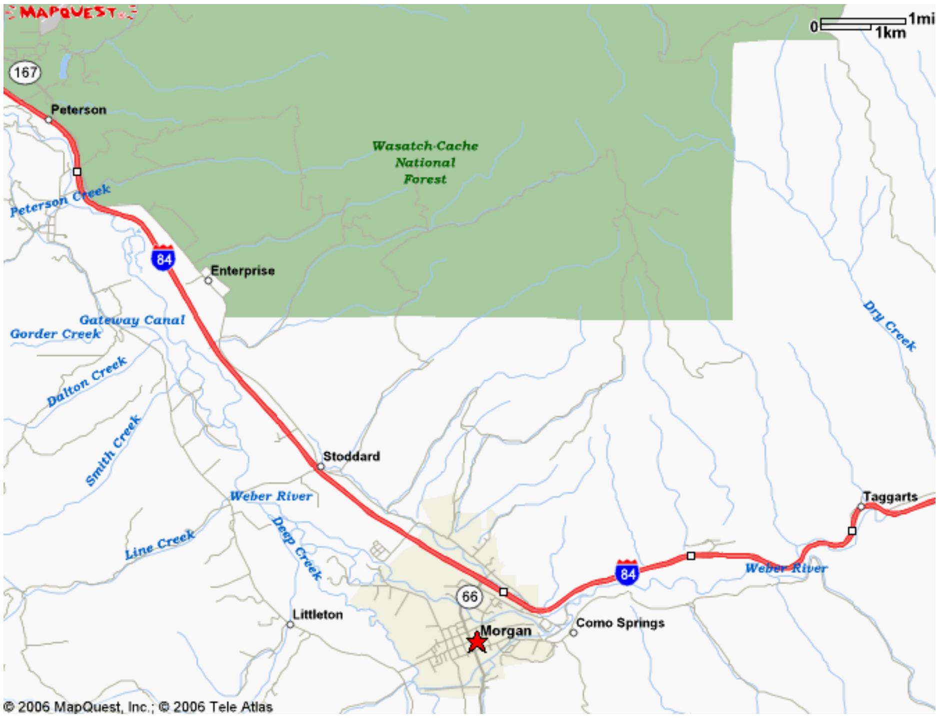

FIGURE 3.1 I-84 corridor.

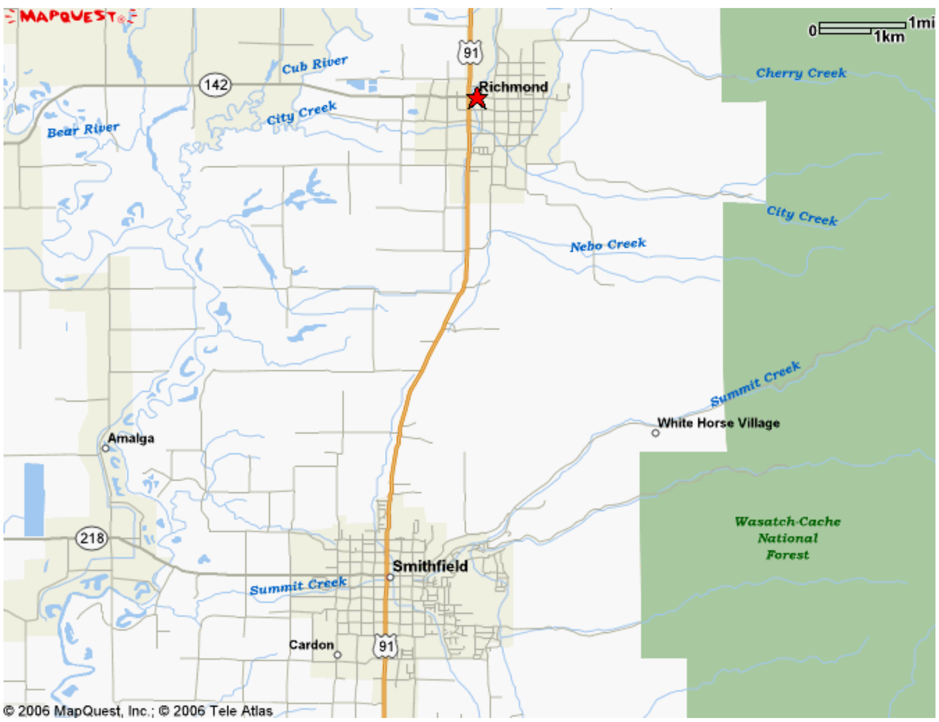

FIGURE 3.2 US-91 corridor.

3.2 FIELD TESTING

Within each corridor, three individual construction sections each 1,000 ft in length and 40 ft in width were evaluated at 10 locations each. The length of the construction section was determined by the distance over which one truckload of cement was spread by the contractor. The locations of the sections within each corridor were determined by the contractor's position during the days during which the research personnel were available to conduct the testing. However, the locations of individual test locations within each section were determined using random sampling techniques, where every possible test area within a given section had an equal chance of being selected. Figure 3.3 depicts the typical layout of a construction section, including the 10 randomly selected test locations. All of the sampling and testing conducted in the research were performed at the same locations at each site.

At each site on both projects, aggregate samples were collected at various stages of the construction process. One sample, as shown in Figure 3.4, was taken after the reclaimer operator had already pulverized the old asphalt and blended it with the existing base. This sample was processed later in the laboratory to calculate in-situ moisture content and to determine the gradation of the recycled base material.

To facilitate calculation of the actual amounts of cement being placed at each site, one rectangular plastic sheet with an area of 1.25 square feet was placed at each test area and tacked down with roofing nails as shown in Figure 3.5. The research assistants were careful to avoid placing the sheets in the wheel paths of the cement truck to ensure that the sheets would remain undisturbed in their original positions during the cement spreading process.

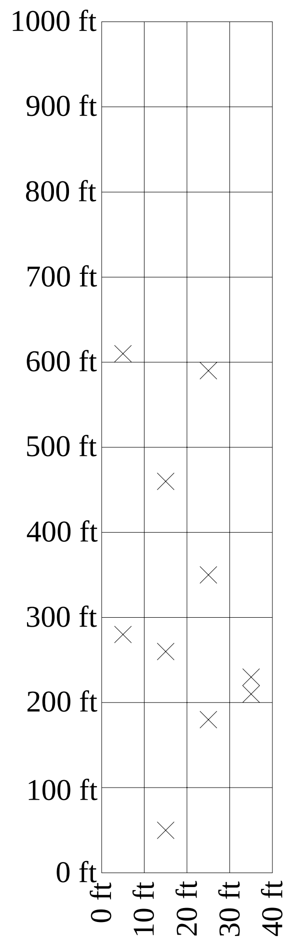

FIGURE 3.3 Layout of typical test site.

Once the cement truck placed the cement, the plastic sheets were carefully retrieved, as shown in Figure 3.6, and the cement from each location was transferred into a plastic bag and weighed as shown in Figure 3.7. The cement was then returned to the location from which it was retrieved. The cement content was calculated by dividing the weight of cement in pounds by the total area of the plastic sheet in square feet. This number was compared to the target percentage that was specified for the project.

FIGURE 3.4 Sampling base material before cement placement.

FIGURE 3.5 Placing cement collection sheet.

FIGURE 3.6 Retrieving cement collection sheet.

After the cement was placed on the prepared base, the reclaimer operator mixed the cement into the base to a target depth of 8 in. During this process, water was injected in regulated quantities directly into the mixing chamber to facilitate compaction of the CTB and curing of the cement. The time of mixing at each test location was recorded by research personnel to facilitate measurement of the time delay between mixing of the cement and water into the base and compaction of the blended CTB layer; the effect of time delay on the mechanical properties of the CTB was later assessed. Immediately following mixing, another sample of material was taken as shown in Figure 3.8. One

FIGURE 3.7 Measuring weight of retrieved cement.

sample was used for on-site compaction of specimens by research assistants, as shown in Figure 3.9.

The specimens were compacted in 4-in.-diameter steel molds to a target height of 4.6 in. using the modified Proctor compaction method. Figure 3.10 shows a completed specimen being extruded from the metal form in which it was compacted. Two specimens were compacted from the CTB material sampled from each test location and then placed in sealed plastic bags to prevent moisture loss during curing for a period of 7 or 28 days before being subjected to unconfined compressive strength (UCS) testing in

FIGURE 3.8 Sampling base material after cement mixing.

the laboratory. Each bag was labeled with the location of sampling and the time of compaction; recording the time allowed the researchers to also assess the effect of time delay between mixing and compaction on the strength of the specimens.

After the CTB layer was compacted and graded for the final time, non-destructive quality control testing was performed. Several pieces of equipment were used, including a dynamic cone penetrometer (DCP), heavy Clegg hammer, and nuclear density gauge.

The DCP, as shown in Figure 3.11, consists of a standard cone tip attached to a metal pole that was driven into the ground by a manually operated falling weight. The

FIGURE 3.9 Compacting cement-treated specimens.

penetration rate was recorded and later used to calculate the California bearing ratio (CBR) of the layer at the time of testing.

The Clegg hammer, as shown in Figure 3.12, consists of a 44-lb weight with an accelerometer attached to the top that measured the rate of deceleration of the weight when dropped through the guide tube from a height of 12 in. (*19*). Stiffness was calculated by the device by averaging the deceleration measured in four consecutive drops and then reporting the number in units of gravities on an attached digital display.

FIGURE 3.10 Extruding cement-treated specimens.

The nuclear density gauge, as shown in Figure 3.13, was utilized to measure the moisture content and dry density of the CTB layer at each test location. The tip of the probe was set at a depth of 6 in. below the CTB surface, and a 60-second test was conducted.

FIGURE 3.11 Dynamic cone penetrometer.

FIGURE 3.12 Clegg hammer.

FIGURE 3.13 Nuclear density gauge.

3.3 LABORATORY TESTING

Samples returned to the laboratory were subjected to a variety of tests, including moisture analyses, sieve analyses, asphalt content measurements, and UCS determinations. All of the testing was performed at the Brigham Young University Highway Materials Laboratory.

Moisture content was determined as a percentage of the dry weight of the given aggregate sample. Samples obtained from I-84 prior to the placement of cement were subjected to oven drying at 140°F for a period of 48 hours to minimize volatilization of the asphalt cement present in the RAP, while those obtained from US-91 were dried at 230°F for 24 hours.

After drying the samples, research personnel performed sieve analyses on approximately 5 lb of each sample. The samples were separated over ten different sieve sizes, including 3/4 in., 1/2 in., 3/8 in., No. 4, No. 8, No.16, No. 30, No. 50, No. 100, and No. 200 sieves, in addition to the pan. For each sample, the total weight retained on each of the sieves and pan was compared with the original weight to ensure that the sample did not lose more than 1 percent of its original weight during the testing process, which would make the test invalid. Based on the results of the sieve analyses, the fineness modulus of each sample was computed.

As depicted in Figure 3.14, a burn-off oven was then utilized to measure the asphalt content in the samples collected from I-84, which were recombined following sieve analyses. The burn-off testing was performed at a temperature of 1000°F until constant weight was achieved, which usually required approximately 90 minutes of heating, and the asphalt content was then reported as a percentage of the original weight of the sample. Manual weight measurements were performed to verify the automated calculations shown on the computer print-out from the burn-off oven. A sample of pure RAP that had been obtained from previous research on I-84 was also subjected to burn-off testing in this study to facilitate calculation of RAP content in each of the blended samples containing both RAP and base.

As previously indicated, one of the two specimens prepared for UCS testing was allowed to cure for 7 days, while the other was allowed to cure for 28 days. Curing was accomplished at room temperature in sealed plastic bags. After the specified curing period, the height and weight of each specimen were measured, and the specimens were

FIGURE 3.14 Burn-off oven.

then capped with high-strength gypsum to create flat, level specimen ends as shown in Figure 3.15.

Once the gypsum caps were sufficiently hardened, which required about an hour after the second cap had been placed, the specimens were subjected to computer-controlled compression testing at a constant strain rate of 0.05 in. per minute. Figure 3.16 shows the typical test setup. The computer then reported the maximum strength of each specimen in kips. Figure 3.17 shows a splitting failure of one of the specimens in the loading machine.

FIGURE 3.15 Preparing gypsum caps for UCS testing.

Following UCS testing, specimens were dried at 230°F for 24 hours to facilitate moisture content determination. From these data and the original heights and weights, the dry density of each specimen was then computed.

FIGURE 3.16 Unconfined compressive strength testing.

FIGURE 3.17 Splitting failure of cement-treated specimen.

3.4 SUMMARY

The research conducted in this study focused on the construction of CTB layers in two pavement reconstruction projects in northern Utah, one along I-84 near Morgan and one along US-91 near Richmond. Three construction sections each 1,000 ft in length and 40 ft in width were established along each project corridor, and ten locations within each section were randomly selected for evaluation. All sampling and testing performed in this study were performed at those locations.

Samples of the reclaimed layer were obtained both before and after cement placement, and specimens were manually compacted on site for UCS testing in the laboratory after a curing period of 7 or 28 days. The time delay between mixing and compaction of the CTB was recorded for each test location in the field and for each specimen compacted for UCS testing. In addition, DCP, Clegg hammer, and nuclear density gauge tests were performed to assess the quality of the CTB layer after final compaction and grading were complete. In the laboratory, moisture analyses, sieve analyses, asphalt content measurements, and UCS determinations were performed on the collected samples.

CHAPTER 4

RESULTS

4.1 OVERVIEW

Test results obtained from samples collected before and after cement was blended into the base layer are presented in the following "pre-treatment" and "post-treatment" sections, respectively. The results from I-84 are presented first in each section, and the results for US-91 are presented second. The collected data and statistical analyses are then discussed. In all tables throughout this chapter, the presence of a hyphen indicates that the data were not measured or were not available.

4.2 PRE-TREATMENT DATA

Pre-treatment data include in-situ moisture content (IM), particle-size distribution, and cement content (Cem) for all samples, as well as asphalt content for samples obtained from I-84. Tables 4.1, 4.2, and 4.3 contain the moisture content, cement content, asphalt content, and reclaimed asphalt pavement (RAP) content at each test location for I-84 sites A, B, and C, respectively, while Tables 4.4, 4.5, and 4.6 present the moisture content and cement content for US-91 sites A, B, and C, respectively. Also included in the tables are calculations of average value, standard deviation, and coefficient of variation (CV).

Based on maximum dry density values of 129.9 lb/ft^3 and 138.3 lb/ft^3 for I-84 and US-91, respectively, the corresponding target cement contents were 1.73 lb/ft^2 and 1.84 lb/ft^2. Therefore, test sites A and C within both the I-84 and US-91 corridors were not sufficiently stabilized, while test site B on each project received the specified level of cement treatment. The asphalt content in the pure RAP sample was 5.9 percent.

TABLE 4.1 Pre-Treatment Data for I-84 Site A

Test Location	Moisture Content (%)	Cement Content (lb/ft^2)	Asphalt Content (%)	RAP Content (%)
1	7.0	2.4	3.6	59.8
2	6.3	0.9	3.5	58.3
3	5.3	0.0	3.0	50.0
4	5.2	1.2	3.0	49.4
5	5.3	1.5	4.3	71.0
6	5.5	2.1	3.8	63.1
7	5.6	2.0	4.0	65.4
8	4.4	1.2	4.1	67.4
9	6.5	1.8	3.4	56.4
10	4.8	0.1	3.4	56.6
Average	5.6	1.3	3.6	59.7
Std. Dev.	0.8	0.8	0.4	7.1
CV (%)	14.5	61.4	12.2	11.9

TABLE 4.2 Pre-Treatment Data for I-84 Site B

Test Location	Moisture Content (%)	Cement Content (lb/ft^2)	Asphalt Content (%)	RAP Content (%)
1	4.5	1.5	4.4	70.9
2	5.5	1.0	4.1	65.9
3	5.4	2.3	2.9	49.8
4	5.1	1.7	3.1	51.6
5	4.5	2.0	4.1	66.8
6	6.2	2.3	3.9	63.7
7	3.2	1.3	4.1	68.3
8	3.9	1.6	3.9	61.5
9	4.9	1.8	3.9	63.2
10	2.7	2.2	3.7	60.7
Average	4.6	1.7	3.8	62.2
Std. Dev.	1.1	0.4	0.5	6.8
CV (%)	23.6	24.6	12.3	11.0

TABLE 4.3 Pre-Treatment Data for I-84 Site C

Test Location	Moisture Content (%)	Cement Content (lb/ft^2)	Asphalt Content (%)	RAP Content (%)
1	6.5	0.3	3.5	58.0
2	3.1	1.7	3.4	53.3
3	4.1	1.0	3.0	49.8
4	3.9	1.2	3.3	53.6
5	3.4	1.0	4.1	64.0
6	2.8	1.4	2.8	46.1
7	2.4	0.7	4.2	67.2
8	2.9	1.2	3.9	63.6
9	2.1	2.0	2.6	43.8
10	3.4	1.3	3.0	47.6
Average	3.5	1.1	3.4	54.7
Std. Dev.	1.2	0.5	0.5	8.2
CV (%)	35.8	42.2	16.3	15.0

TABLE 4.4 Pre-Treatment Data for US-91 Site A

Test Location	Moisture Content (%)	Cement Content (lb/ft^2)
1	2.4	0.5
2	2.0	1.4
3	2.0	1.8
4	2.4	0.9
5	1.8	1.3
6	2.2	0.7
7	2.3	1.4
8	2.5	1.0
9	2.1	2.5
10	1.2	0.9
Average	2.1	1.2
Std. Dev.	0.4	0.6
CV (%)	17.9	48.2

TABLE 4.5 Pre-Treatment Data for US-91 Site B

Test Location	Moisture Content (%)	Cement Content (lb/ft^2)
1	2.1	0.7
2	1.5	6.5
3	1.5	2.9
4	2.4	0.6
5	1.9	1.3
6	2.0	2.1
7	1.5	1.7
8	1.6	0.6
9	1.7	0.4
10	2.8	1.4
Average	1.9	1.8
Std. Dev.	0.4	1.8
CV (%)	22.6	101.2

TABLE 4.6 Pre-Treatment Data for US-91 Site C

Test Location	Moisture Content (%)	Cement Content (lb/ft^2)
1	2.0	0.9
2	2.1	1.0
3	2.0	1.0
4	2.3	0.5
5	2.6	1.0
6	2.4	0.6
7	2.9	2.5
8	2.6	1.1
9	2.4	1.1
10	2.8	2.8
Average	2.4	1.2
Std. Dev.	0.3	0.8
CV (%)	12.7	62.4

Tables 4.7, 4.8, and 4.9 contain the sieve analysis results for I-84 sites A, B, and C, respectively, and Tables 4.10, 4.11, and 4.12 contain the sieve analysis results for US-91 sites A, B, and C, respectively. Figures 4.1 to 4.6 provide graphical depictions of the particle-size distributions presented in Tables 4.7 to 4.12. The legend in each figure designates the test location.

As a bulk quantitative measure of particle-size distribution, the fineness modulus (FM) was computed for each gradation. Tables 4.13 and 4.14 present the fineness modulus values for I-84 and US-91, respectively. Also included in the tables are calculations for average value, standard deviation, and CV.

TABLE 4.7 Dry Sieve Analysis Data for I-84 Site A

Percent Passing (%)	Test Location									
	1	2	3	4	5	6	7	8	9	10
3/4 in.	99.0	96.5	95.7	99.0	98.5	98.6	96.9	97.8	100.0	98.2
1/2 in.	95.0	86.4	84.0	87.2	92.2	91.6	87.8	89.1	87.9	87.3
3/8 in.	89.2	76.9	71.3	77.3	84.8	83.3	78.6	77.5	77.1	76.1
No. 4	69.6	57.7	51.6	56.6	62.3	63.2	56.5	55.2	58.2	56.2
No. 8	55.4	45.5	40.7	45.0	45.6	48.8	42.3	40.2	46.1	43.9
No. 16	44.5	33.6	33.4	37.2	34.6	38.5	31.3	30.5	35.2	36.1
No. 30	31.9	23.9	24.7	29.0	24.5	27.9	20.4	21.1	23.7	28.0
No. 50	19.8	14.6	13.7	16.7	13.6	15.5	11.2	10.9	14.2	16.4
No. 100	9.3	6.5	5.5	6.7	5.6	6.4	4.6	4.2	6.5	6.3
No. 200	4.0	2.4	1.9	2.5	2.0	2.2	1.7	1.5	2.5	2.3
Pan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 4.8 Dry Sieve Analysis Data for I-84 Site B

Percent Passing (%)	Test Location									
	1	2	3	4	5	6	7	8	9	10
3/4 in.	98.9	98.6	98.4	97.4	99.1	96.4	97.7	99.5	97.7	97.0
1/2 in.	89.9	87.8	90.2	87.3	92.7	87.2	88.3	87.7	91.2	87.6
3/8 in.	77.6	78.4	79.4	76.5	82.5	78.1	78.8	74.3	80.7	76.9
No. 4	54.0	54.8	58.1	53.5	59.6	55.6	55.5	49.8	56.6	54.4
No. 8	39.7	39.9	45.2	41.3	44.5	41.3	39.5	36.0	42.2	41.1
No. 16	29.4	28.9	36.9	33.3	33.1	30.4	29.5	26.8	32.7	32.9
No. 30	20.5	18.2	27.4	24.3	22.0	19.1	20.8	17.8	23.0	25.0
No. 50	11.2	9.2	16.1	13.7	10.9	10.1	11.7	8.7	12.2	15.4
No. 100	4.5	3.8	7.1	6.0	4.2	4.4	4.6	6.7	4.6	6.7
No. 200	1.5	1.4	2.7	2.3	1.5	1.6	1.6	1.2	1.6	2.3
Pan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 4.9 Dry Sieve Analysis Data for I-84 Site C

Percent Passing (%)	Test Location									
	1	2	3	4	5	6	7	8	9	10
3/4 in.	95.1	97.2	96.0	95.5	93.2	88.7	92.9	98.6	94.6	95.1
1/2 in.	87.4	81.1	84.5	85.6	79.1	78.0	83.6	87.2	81.1	80.9
3/8 in.	77.5	71.7	73.3	74.1	67.0	68.2	73.4	78.3	70.9	71.2
No. 4	56.5	47.6	52.2	53.9	42.4	51.3	52.7	55.9	52.8	52.8
No. 8	43.5	34.4	39.9	41.6	29.3	41.7	38.7	40.3	41.9	41.9
No. 16	34.3	25.9	31.5	33.1	21.9	35.1	29.6	30.7	34.7	35.1
No. 30	23.2	18.4	23.1	24.8	15.7	28.2	21.9	22.8	27.4	28.3
No. 50	13.3	10.0	12.7	14.1	8.4	17.6	12.7	13.9	17.2	17.4
No. 100	5.8	4.1	5.1	5.8	3.0	7.2	5.0	5.8	7.4	6.8
No. 200	2.3	1.6	2.0	2.1	1.0	2.4	1.6	2.1	3.0	2.2
Pan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 4.10 Dry Sieve Analysis Data for US-91 Site A

Percent Passing (%)	Test Location									
	1	2	3	4	5	6	7	8	9	10
3/4 in.	99.1	100.0	99.3	98.7	97.7	98.7	99.4	98.1	98.3	98.3
1/2 in.	89.4	89.3	85.2	89.8	84.5	86.5	90.4	90.7	90.1	88.9
3/8 in.	79.7	74.7	70.6	77.8	73.5	74.2	81.1	78.4	79.8	77.6
No. 4	57.9	49.1	45.3	52.6	48.0	51.0	60.0	55.2	57.3	57.2
No. 8	44.8	37.3	33.7	39.1	35.5	38.2	46.4	41.9	44.1	43.9
No. 16	36.6	30.1	27.1	31.2	28.6	30.3	36.2	33.2	34.9	34.3
No. 30	28.2	23.5	21.2	24.2	22.4	23.4	26.9	25.4	26.9	25.8
No. 50	18.7	16.1	14.3	16.2	15.3	15.8	17.5	17.2	17.8	17.2
No. 100	9.9	8.6	7.4	7.9	8.2	8.3	9.2	9.3	8.4	8.9
No. 200	4.3	3.8	3.1	3.0	3.6	3.7	4.1	4.5	3.3	1.5
Pan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 4.11 Dry Sieve Analysis Data for US-91 Site B

Percent Passing (%)	Test Location									
	1	2	3	4	5	6	7	8	9	10
3/4 in.	99.3	99.2	96.2	97.6	99.5	99.3	96.9	96.5	98.8	100.0
1/2 in.	90.3	84.6	87.3	86.2	87.5	90.0	87.5	85.6	85.7	91.3
3/8 in.	73.8	73.7	73.8	75.0	74.3	76.7	74.5	71.4	69.5	82.3
No. 4	48.9	51.5	46.7	53.4	50.9	50.7	52.0	45.6	45.4	58.4
No. 8	35.7	38.9	33.9	40.7	37.6	37.6	39.1	32.2	32.3	42.7
No. 16	27.6	30.9	26.3	31.6	28.5	29.2	31.1	23.8	23.9	31.2
No. 30	21.1	24.2	20.4	23.9	21.6	22.4	24.5	17.6	17.4	22.4
No. 50	14.2	16.7	14.2	15.7	14.5	15.1	17.2	11.7	11.6	14.4
No. 100	7.3	9.2	7.8	7.7	7.6	7.8	9.6	6.0	5.7	7.3
No. 200	3.5	4.0	3.5	3.3	3.5	3.2	4.5	2.4	2.8	2.9
Pan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 4.12 Dry Sieve Analysis Data for US-91 Site C

Percent Passing (%)	Test Location									
	1	2	3	4	5	6	7	8	9	10
3/4 in.	98.4	97.6	96.9	98.6	98.7	98.2	98.6	98.9	97.8	99.6
1/2 in.	88.8	87.3	90.0	86.2	88.9	85.8	85.8	87.5	86.0	91.0
3/8 in.	76.2	77.1	79.4	72.1	77.5	73.7	72.5	77.4	74.7	78.1
No. 4	51.8	57.1	54.9	49.0	52.1	50.5	51.4	55.0	52.6	52.4
No. 8	38.8	43.1	40.1	35.8	37.3	37.4	38.5	41.4	39.5	38.8
No. 16	29.9	32.6	29.9	27.2	27.4	27.7	28.8	32.2	29.9	29.5
No. 30	22.4	23.8	22.2	20.2	19.8	20.0	21.0	24.4	22.2	22.1
No. 50	14.7	15.3	14.7	13.4	12.7	12.9	13.3	15.9	14.7	14.3
No. 100	7.1	7.7	7.4	6.7	6.0	6.4	6.3	7.5	7.3	6.8
No. 200	2.7	3.0	3.0	2.6	2.3	2.7	2.4	2.9	3.0	2.7
Pan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

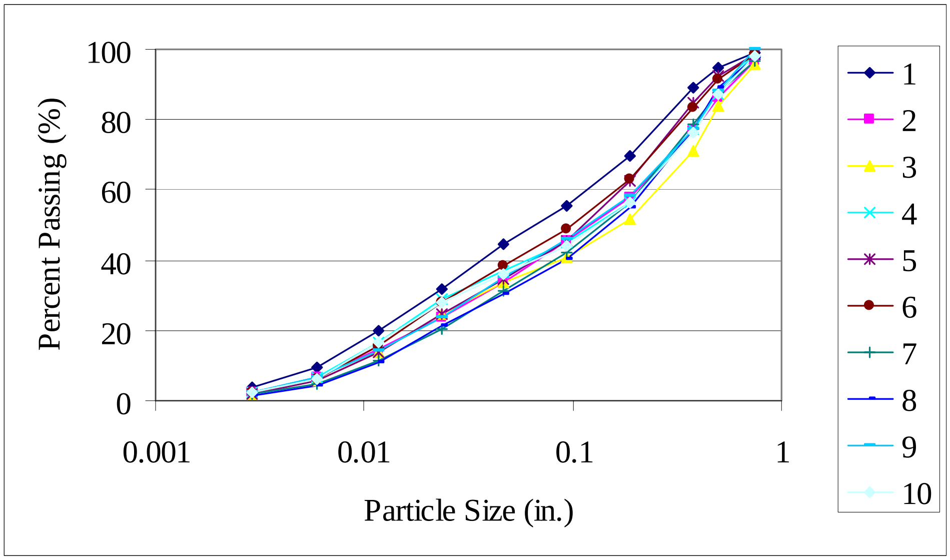

FIGURE 4.1 Particle-size distributions for I-84 site A.

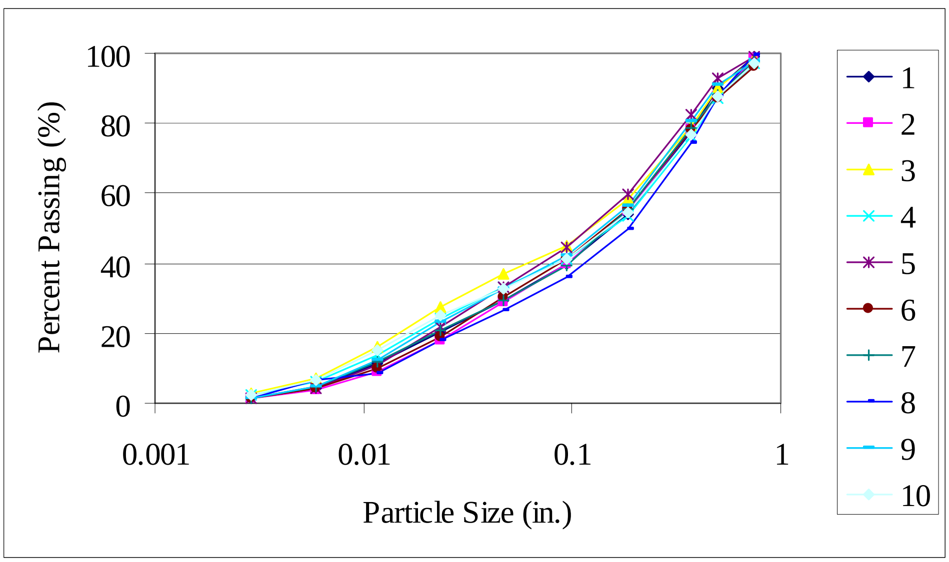

FIGURE 4.2 Particle-size distributions for I-84 site B.

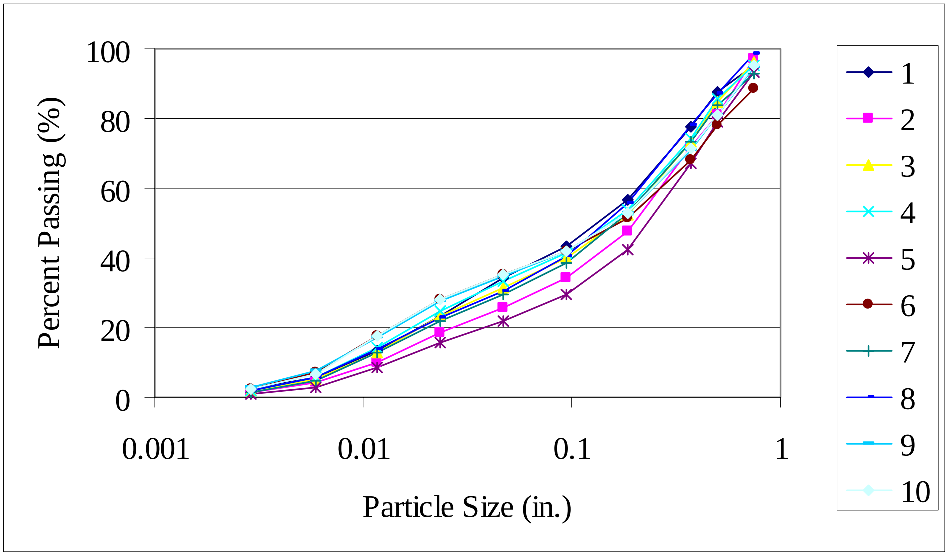

FIGURE 4.3 Particle-size distributions for I-84 site C.

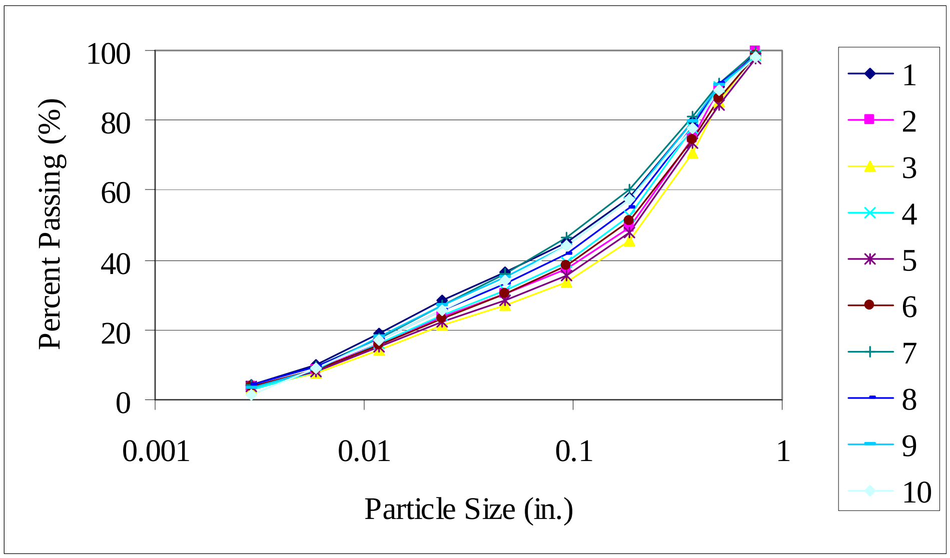

FIGURE 4.4 Particle-size distributions for US-91 site A.

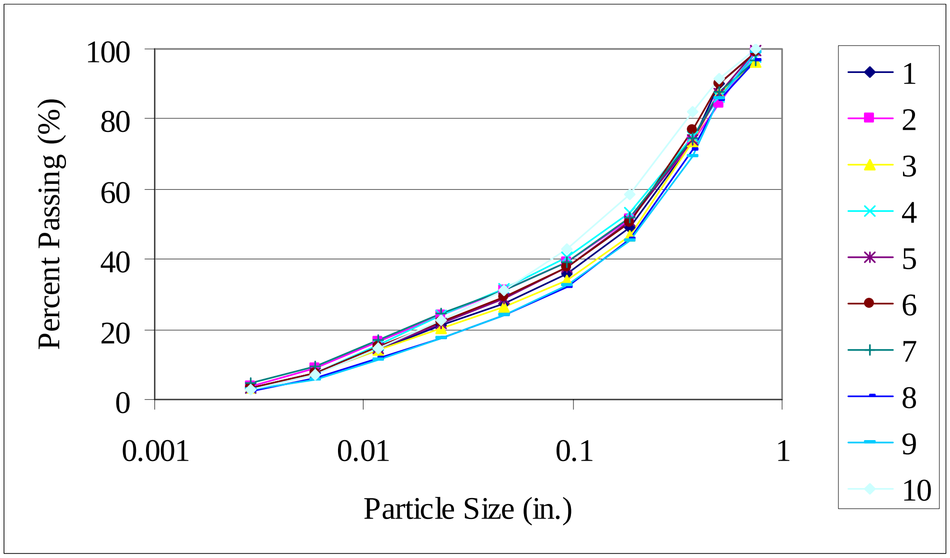

FIGURE 4.5 Particle-size distributions for US-91 site B.

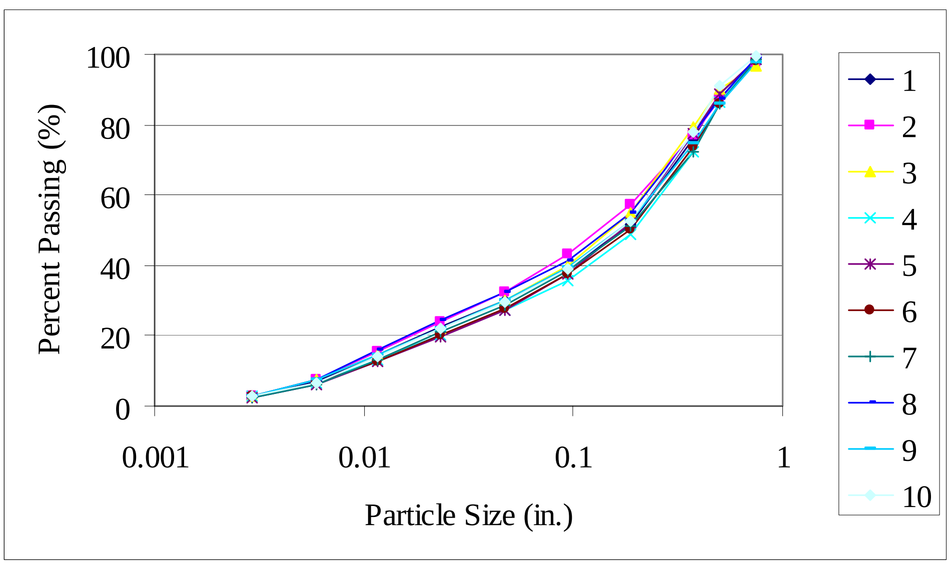

FIGURE 4.6 Particle-size distributions for US-91site C.

TABLE 4.13 Fineness Modulus Values for I-84

Test Location	Fineness Modulus		
	Site A	Site B	Site C
1	3.81	4.64	4.51
2	4.45	4.68	4.91
3	4.63	4.31	4.66
4	4.32	4.54	4.57
5	4.31	4.44	5.19
6	4.18	4.65	4.62
7	4.58	4.62	4.73
8	4.63	4.80	4.54
9	4.39	4.50	4.53
10	4.39	4.51	4.51
Average	4.37	4.57	4.68
Std. Dev.	0.24	0.14	0.22
CV (%)	5.60	3.03	4.67

TABLE 4.14 Fineness Modulus Values for US-91

Test Location	Fineness Modulus		
	Site A	Site B	Site C
1	4.25	4.72	4.61
2	4.61	4.56	4.46
3	4.81	4.81	4.54
4	4.52	4.54	4.77
5	4.71	4.65	4.68
6	4.60	4.61	4.73
7	4.23	4.55	4.70
8	4.41	4.95	4.47
9	4.32	4.95	4.61
10	4.37	4.41	4.58
Average	4.48	4.68	4.62
Std. Dev.	0.20	0.18	0.11
CV (%)	4.39	3.87	2.29

4.3 POST-TREATMENT DATA

Post-treatment data include both field and laboratory test results. Field data include time between mixing and compaction (T F), California bearing ratio (CBR), Clegg impact value (CIV), moisture content in the field (MC F), and dry density in the field (DD F), and laboratory data include moisture content (MC 7, MC 28), dry density (DD 7, DD 28), and unconfined compressive strength (UCS 7, UCS 28) for specimens cured for 7 and 28 days. Tables 4.15, 4.16, and 4.17 provide post-treatment field data for I-84 sites A, B, and C, respectively, while Tables 4.18, 4.19, and 4.20 provide post-treatment field data for US-91 sites A, B, and C, respectively. Similarly, Tables 4.21, 4.22, and 4.23 contain laboratory data for I-84 sites A, B, and C, respectively, while Tables 4.24, 4.25, and 4.26 contain laboratory data for US-91 sites A, B, and C, respectively. Also included in each of the tables are calculations for average value, standard deviation, and CV.

TABLE 4.15 Post-Treatment Field Data for I-84 Site A

Test Location	Time between Mixing and Compaction (min)	CBR	CIV	Moisture Content (%)	Dry Density (lb/ft^3)
1	5	44	23.3	9.5	118.4
2	2	42	14.5	9.7	118.1
3	2	14	10.8	7.7	124.8
4	2	28	14.7	10.5	118.1
5	1	31	16.2	11.1	117.5
6	2	35	13.1	11.0	116.8
7	0	66	16.6	12.5	118.3
8	1	110	19.2	10.3	115.9
9	0	49	17.5	11.2	120.1
10	10	46	16.4	13.0	117.2
Average	3	47	16.2	10.7	118.5
Std. Dev.	3	26	3.4	1.5	2.5
CV (%)	120	57	21.1	14.2	2.1

TABLE 4.16 Post-Treatment Field Data for I-84 Site B

Test Location	Time between Mixing and Compaction (min)	CBR	CIV	Moisture Content (%)	Dry Density (lb/ft^3)
1	13	55	17.2	10.4	117.9
2	1	38	13.5	12.0	111.7
3	6	32	13.8	10.6	111.1
4	6	30	13.3	11.1	118.3
5	14	28	13.0	11.0	114.6
6	20	94	16.8	10.7	120.8
7	14	50	17.1	9.2	113.6
8	25	54	15.9	9.9	115.9
9	2	101	16.8	8.2	113.0
10	32	55	18.8	8.4	117.6
Average	13	54	15.6	10.2	115.5
Std. Dev.	10	25	2.0	1.2	3.2
CV (%)	76	47	13.1	12.0	2.7

TABLE 4.17 Post-Treatment Field Data for I-84 Site C

Test Location	Time between Mixing and Compaction (min)	CBR	CIV	Moisture Content (%)	Dry Density (lb/ft^3)
1	0	45	17.7	10.2	120.1
2	0	42	13.6	11.4	120.4
3	4	31	14.9	8.8	116.7
4	4	35	16.7	8.3	117.5
5	1	52	19.1	-	121.6
6	2	37	14.9	8.0	118.5
7	2	32	11.7	7.8	117.0
8	0	65	19.4	9.8	122.9
9	2	34	15.3	9.4	119.6
10	13	39	14.4	6.2	126.5
Average	3	41	15.8	8.9	120.1
Std. Dev.	4	10	2.4	1.5	3.0
CV (%)	139	25	15.5	17.2	2.5

TABLE 4.18 Post-Treatment Field Data for US-91 Site A

Test Location	Time between Mixing and Compaction (min)	CBR	CIV	Moisture Content (%)	Dry Density (lb/ft^3)
1	1	79	22.6	6.9	137.0
2	1	64	18.1	7.2	131.0
3	1	41	22.4	7.1	136.6
4	1	49	20.1	5.6	131.0
5	2	54	21.9	6.2	132.6
6	0	58	20.0	5.7	129.7
7	0	61	24.0	6.8	132.5
8	0	51	22.6	7.6	131.8
9	1	55	18.7	6.2	131.2
10	0	53	18.0	6.6	133.7
Average	1	57	20.8	6.6	132.7
Std. Dev.	1	10	2.1	0.7	2.4
CV (%)	96	18	10.3	9.9	1.8

TABLE 4.19 Post-Treatment Field Data for US-91 Site B

Test Location	Time between Mixing and Compaction (min)	CBR	CIV	Moisture Content (%)	Dry Density (lb/ft^3)
1	61	36	22.0	6.6	127.3
2	47	47	15.7	4.0	124.3
3	47	33	18.1	5.1	128.2
4	39	35	21.8	4.2	128.4
5	42	36	17.3	4.7	121.6
6	36	29	19.6	4.9	128.4
7	45	51	18.6	4.7	122.5
8	45	49	13.1	4.7	122.4
9	21	44	17.6	7.2	127.5
10	34	52	18.6	5.0	124.4
Average	42	41	18.2	5.1	125.5
Std. Dev.	10	8	2.6	1.0	2.7
CV (%)	25	20	14.5	19.8	2.2

TABLE 4.20 Post-Treatment Field Data for US-91 Site C

Test Location	Time between Mixing and Compaction (min)	CBR	CIV	Moisture Content (%)	Dry Density (lb/ft^3)
1	3	41	22.3	5.4	127.6
2	2	78	23.3	5.4	128.4
3	2	74	21.6	4.5	127.8
4	3	75	21.4	4.3	128.7
5	0	30	21.5	6.6	126.2
6	2	51	18.8	6.3	132.1
7	2	57	18.6	5.8	129.6
8	4	61	17.6	5.3	128.8
9	5	55	22.0	6.1	131.8
10	3	114	25.3	6.9	129.8
Average	3	64	21.2	5.7	129.1
Std. Dev.	1	23	2.3	0.9	1.8
CV (%)	52	37	11.0	15.0	1.4

TABLE 4.21 Post-Treatment Laboratory Data for I-84 Site A

Test Location	7-Day Cure			28-Day Cure		
	Moisture Content (%)	Dry Density (lb/ft^3)	UCS (psi)	Moisture Content (%)	Dry Density (lb/ft^3)	UCS (psi)
1	3.1	-	197	4.0	127.8	633
2	5.0	-	244	6.7	128.3	293
3	4.2	-	45	4.2	-	72
4	8.8	125.1	146	8.8	124.5	210
5	8.7	126.5	158	8.4	127.0	230
6	7.0	131.0	438	-	-	478
7	7.1	129.1	228	6.9	128.1	291
8	6.1	-	153	7.3	127.8	242
9	5.1	-	349	7.5	124.9	335
10	5.7	-	413	8.7	126.6	362
Average	6.1	127.9	237	6.9	126.9	315
Std. Dev.	1.8	2.6	126	1.8	1.5	154
CV (%)	30.4	2.0	53	25.5	1.1	49

TABLE 4.22 Post-Treatment Laboratory Data for I-84 Site B

Test Location	7-Day Cure			28-Day Cure		
	Moisture Content (%)	Dry Density (lb/ft^3)	UCS (psi)	Moisture Content (%)	Dry Density (lb/ft^3)	UCS (psi)
1	5.5	129.5	376	5.8	125.8	313
2	6.7	-	217	7.6	127.1	250
3	7.4	131.4	305	6.9	131.0	371
4	7.2	-	606	8.4	126.1	243
5	6.9	129.2	218	6.6	125.2	325
6	7.5	128.0	310	7.7	125.9	263
7	8.2	125.5	436	5.3	126.6	493
8	5.2	138.0	452	6.5	128.9	480
9	5.2	129.9	510	5.4	129.2	423
10	7.8	124.8	402	7.7	126.1	333
Average	6.8	129.5	383	6.8	127.2	349
Std. Dev.	1.1	4.1	125	1.1	1.9	91
CV (%)	16.1	3.1	33	15.5	1.5	26

TABLE 4.23 Post-Treatment Laboratory Data for I-84 Site C

Test Location	7-Day Cure			28-Day Cure		
	Moisture Content (%)	Dry Density (lb/ft^3)	UCS (psi)	Moisture Content (%)	Dry Density (lb/ft^3)	UCS (psi)
1	6.9	129.5	442	7.2	128.6	522
2	8.0	127.7	193	7.8	128.9	326
3	6.5	122.5	401	6.1	130.2	585
4	7.2	130.1	419	7.2	124.6	520
5	6.9	130.1	299	6.8	129.1	349
6	6.5	130.7	456	6.0	131.5	509
7	6.1	129.1	409	5.8	128.2	505
8	4.9	129.5	496	5.2	129.1	679
9	7.5	124.5	234	7.2	129.5	336
10	6.9	132.9	497	6.3	132.4	610
Average	6.7	128.7	385	6.5	129.2	494
Std. Dev.	0.8	3.0	106	0.8	2.1	121
CV (%)	12.3	2.4	28	12.5	1.6	24

TABLE 4.24 Post-Treatment Laboratory Data for US-91 Site A

Test Location	7-Day Cure			28-Day Cure		
	Moisture Content (%)	Dry Density (lb/ft^3)	UCS (psi)	Moisture Content (%)	Dry Density (lb/ft^3)	UCS (psi)
1	8.1	132.7	228	8.5	131.5	441
2	6.7	136.4	581	6.4	136.2	925
3	6.3	136.0	530	6.4	137.4	933
4	7.1	135.2	251	7.2	134.1	608
5	6.5	136.3	624	5.7	136.0	1133
6	6.1	136.2	851	6.2	135.8	1146
7	5.5	136.1	634	5.9	136.1	1182
8	6.6	137.1	433	6.6	136.1	824
9	5.7	138.9	762	5.5	137.4	1557
10	6.5	135.9	389	7.2	134.8	604
Average	6.5	136.1	528	6.5	135.5	935
Std. Dev.	0.7	1.5	205	0.9	1.7	334
CV (%)	11.2	1.1	39	13.4	1.3	36

TABLE 4.25 Post-Treatment Laboratory Data for US-91 Site B

Test Location	7-Day Cure			28-Day Cure		
	Moisture Content (%)	Dry Density (lb/ft^3)	UCS (psi)	Moisture Content (%)	Dry Density (lb/ft^3)	UCS (psi)
1	4.8	137.5	1032	4.7	136.2	1187
2	4.8	141.5	1042	4.7	140.1	1539
3	5.7	139.3	691	6.7	136.1	997
4	4.0	135.1	518	4.9	130.3	715
5	5.6	137.0	578	6.3	138.3	1017
6	4.3	132.3	639	15.8	125.8	1471
7	4.2	-	858	4.7	135.9	1354
8	4.7	-	789	5.3	135.1	1077
9	6.2	136.8	760	7.1	135.2	835
10	5.5	140.4	890	5.5	134.9	1265
Average	5.0	137.5	780	6.6	134.8	1146
Std. Dev.	0.7	2.9	179	3.4	4.0	268
CV (%)	14.5	2.1	23	51.0	3.0	23

TABLE 4.26 Post-Treatment Laboratory Data for US-91 Site C

Test Location	7-Day Cure			28-Day Cure		
	Moisture Content (%)	Dry Density (lb/ft^3)	UCS (psi)	Moisture Content (%)	Dry Density (lb/ft^3)	UCS (psi)
1	6.3	137.3	596	6.7	136.8	970
2	6.5	126.6	622	6.7	136.0	905
3	6.9	134.4	509	6.9	134.6	724
4	4.8	133.0	506	4.7	135.5	1066
5	6.3	-	232	7.5	136.0	326
6	8.3	134.4	668	5.5	135.6	1181
7	6.1	132.1	666	6.1	131.5	1012
8	5.4	-	557	5.8	137.2	1192
9	6.0	134.0	731	5.9	132.9	1209
10	5.6	134.7	828	5.1	134.1	860
Average	6.2	133.3	591	6.1	135.0	945
Std. Dev.	0.9	3.1	161	0.9	1.8	268
CV (%)	14.9	2.3	27	14.1	1.3	28

4.4 STATISTICAL ANALYSES

After the data were collected, several statistical analyses were performed, including multivariate regression, CV comparisons, analysis of variance (ANOVA), and Tukey's mean separation procedure. The data were separated by highway and analyzed using a statistical software program to meet the research objectives as described in the following sections.

4.4.1 Multivariate Regression

A stepwise regression analysis was performed to determine the most significant predictor variables for each of four separate response variables, including CBR, CIV, 7-day UCS, and 28-day UCS, which were of primary interest in this research. CBR and CIV were chosen because they are two forms of on-site quality control testing available to contractors and owners, and UCS was chosen because it is the primary design parameter utilized in CTB design.

In a stepwise regression process, the utility of each of the potential predictor variables is evaluated. The predictor variables found to be the most influential on the response variable are used in the formation of the regression model. Those predictor variables are given a *p*-value, or level of significance. In this research, predictor variables having *p*-values less than 0.15 were included in the regression models. Once a given regression model is formed, a coefficient of determination, or R^2 value, can be computed for the model. The R^2 value reflects the percentage of variation in the response variable that is explained by variation in the predictor variables included in the regression model, where an R^2 value of 1 represents a perfect model (*20*).

For I-84, the predictor variables that were used in the regression analysis for both CBR and CIV were RAP content, in-situ moisture content, cement content, fineness modulus, percent passing values associated with each of the ten sieves, time between mixing and compaction in the field, moisture content in the field, and dry density in the field. The common predictor variables that were used in the regression analysis for 7-day UCS and 28-day UCS were RAP content, cement content, fineness modulus, and percent passing values for each of the ten sieves. The unique variables used to predict 7-day UCS were moisture content, dry density, and time between mixing and compaction associated with the specimens cured for 7 days (T 7). Likewise, moisture content, dry density, and time between mixing and compaction associated with the specimens cured for 28 days were used to predict 28-day UCS (T 28). The regression analyses resulted in the following Equations 4.1 to 4.4 for I-84:

$$CBR = -25.81 + 1.24 \cdot RAP \tag{4.1}$$

where CBR = California bearing ratio

RAP = recycled asphalt pavement, %

$$CIV = 2.929 + 5.47 \cdot P_{200} + 0.290 \cdot RAP - 0.37 \cdot P_8 \tag{4.2}$$

where CIV = Clegg impact value

P_{200} = percent passing the No. 200 sieve, %

RAP = recycled asphalt pavement, %

P_8 = percent passing the No. 8 sieve, %

$$UCS_7 = 729.9 - 80 \cdot MC_7 + 13.4 \cdot P_{50} \quad (4.3)$$

where UCS_7 = 7-day unconfined compressive strength, psi

MC_7 = 7-day moisture content, %

P_{50} = percent passing the No. 50 sieve, %

$$UCS_{28} = 1551.7 - 100 \cdot MC_{28} - 6.3 \cdot RAP - 72 \cdot Cem \quad (4.4)$$

where UCS_{28} = 7-day unconfined compressive strength, psi

MC_{28} = 7-day moisture content, %

RAP = recycled asphalt pavement, %

Cem = cement content, %

Equation 4.1 indicates that the addition of RAP increases the CBR value of a CTB within the range of values investigated in this study, which is contradictory to earlier research performed on this material (*11*). Equation 4.2 indicates that increasing both the amount of particles finer than the No. 200 sieve and the RAP content leads to a higher CIV, but increasing the amount of particles finer than the No. 8 sieve leads to a lower CIV. Equation 4.3 indicates that higher moisture contents decrease the 7-day UCS, reflecting the fact that excess water, or water above the optimum moisture content (OMC), yields lower dry densities for a given compaction effort, and that increases in the amount of particles finer than the No. 50 sieve yield increases in UCS. Equation 4.4 indicates that increases in moisture, RAP, and cement contents all decrease the 28-day UCS. While the effects of moisture and RAP are consistent with theory and previous research, the effect of cement is contrary to expectation. The author proposes that increasing cement content yields lower CTB strength only to the extent that cement hydration begins binding aggregate particles together before the mixture is compacted to maximum density; the formation of cementitious products within the CTB would reduce the mobility of individual aggregate particles and therefore resist densification during compaction. If the proposed explanation is correct, this effect would be most pronounced on projects in which significant time delay occurs between mixing and compaction of the CTB or in climatic conditions that cause accelerated cement hydration.

Table 4.27 presents the *p*-values associated with the significant predictor variables and the R^2 values associated with each of the regression models developed from the I-84 data. The table shows that RAP content was a significant predictor variable for three of the four response variables evaluated in this research, while no other predictor variable was used more than once. The R^2 values provided in the table indicate that the equation for 28-day UCS offers the best predictions, while the equation for CBR offers the least valuable predictions.

TABLE 4.27 *P*-Values and R^2 Values for I-84

Response Variable	Predictor Variable *p*-Values							R^2
	RAP	Cement Content	No. 8	No. 50	No. 200	7-Day Moisture Content	28-Day Moisture Content	
CBR	0.017							19.43
CIV	0.000		0.055		0.001			48.93
7-Day UCS				0.102		0.001		51.03
28-Day UCS	0.002	0.008					0.000	73.15

Except for RAP content, the same predictor variables that were utilized for I-84 were utilized for US-91. The regression analyses resulted in the following Equations 4.5 to 4.8 for US-91:

$$CBR = 60.17 - 0.43 \cdot TF \tag{4.5}$$

where CBR = California bearing ratio

TF = time between mixing and compaction in the field, min

$$CIV = -24.35 + 0.31 \cdot DDF + 2.33 \cdot IM \tag{4.6}$$

where CIV = Clegg impact value

DDF = dry density in the field, lb/ft^3

IM = in-situ moisture in the field, %

$$UCS_7 = -2907 + 33 \cdot DD_7 - 48 \cdot P_{50} - 52 \cdot MC_7 + 43 \cdot Cem \tag{4.7}$$

where UCS_7 = 7-day unconfined compressive strength, psi

DD_7 = 7-day dry density, lb/ft^3

P_{50} = percent passing the No. 50 sieve, %

MC_7 = 7-day moisture content, %

Cem = cement content, %

$$UCS_{28} = -4670 - 202 \cdot MC_{28} + 51 \cdot DD_{28} \tag{4.8}$$

where UCS_{28} = 28-day unconfined compressive strength, psi

MC_{28} = 28-day moisture content, %

DD_{28} = 28-day dry density, lb/ft^3

Equation 4.5 indicates that for US-91 the time between mixing and compaction in the field was the most important indicator of CBR, where increased time delay causes lower CBR values. This finding emphasizes the critical nature of timely compaction. Equation 4.6 indicates that higher values of dry density in the field and in-situ moisture in the field lead to a higher CIV within the range of values evaluated in this study; in particular, the in-situ moisture contents for the US-91 CTB were generally lower than the OMC for that material, so, unlike most of the I-84 sites, inadequate water was available at some sites to facilitate adequate compaction. Equation 4.7 indicates that increasing dry density and cement content increase the 7-day UCS, while increasing moisture content and the amount of particles finer than the No. 50 sieve decrease the 7-day UCS. Similarly, Equation 4.8 indicates that increasing moisture content decreases the 28-day UCS, while increasing dry density increases the 28-day UCS.

Table 4.28 presents the *p*-values associated with the significant predictor variables and the R^2 values associated with each of the regression models developed from the US-91 data. As with the I-84 data, the R^2 values provided in the table indicate that the equation for 28-day UCS offers the best predictions, while the equation for CBR offers the least valuable predictions.

TABLE 4.28 *P*-Values and R-Squared Values for US-91

Response Variable	Predictor Variable *p*-Values									R^2
	In-Situ Moisture Content	Cement Content	No. 50	Time b/n Mix. and Comp. in the Field	Dry Density in the Field	7-Day Moisture Content	7-Day Dry Density	28-Day Moisture Content	28-Day Dry Density	
CBR				0.007						23.51
CIV	0.022				0.009					38.90
7-Day UCS		0.124	0.013			0.102	0.026			59.18
28-Day UCS								0.000	0.005	66.00

4.4.2 Coefficient of Variation Comparisons

After the multivariate regression was performed, CV comparisons were performed to identify the most variable factors investigated in the research. The CV represents the ratio of the standard deviation to the mean. Because the CV is a ratio of the standard deviation to the mean, it is a useful statistical calculation for comparing the degree of variation from one data series to another, even if the means are drastically different from each other (*21*). Table 4.29 presents the average CVs for each factor for I-84 and US-91.

Table 4.29 indicates that several of the properties vary substantially. Those that have a CV of above 40 percent, for example, are CBR, cement content, time between mixing and compaction in the field, and time between mixing and compaction for each of the manually compacted specimens. Because both the cement content and the time between mixing and compaction are significant predictors of three of the four mechanical properties of interest in this study, including CBR, 7-day UCS, and 28-day UCS, and because both factors are directly in control of the contractor, the variability in these properties is of practical importance in this research.

TABLE 4.29 Average CV for I-84 and US-91

Variable	Average CV (%)	
	I-84	US-91
CBR	43	25
CIV	17	12
RAP	13	-
IM	25	18
Cem	43	71
3/4 in.	2	1
1/2 in.	3	2
3/8 in.	5	4
No. 4	7	7
No. 8	9	9
No. 16	12	9
No. 30	15	9
No. 50	20	9
No. 100	23	11
No. 200	28	17
FM	4	4
TF	112	58
MC F	14	15
DD F	2	2
UCS 7	38	30
MC 7	19	14
DD 7	2	2
T 7	31	45
UCS 28	33	29
MC 28	18	26
DD 28	1	2
T 28	45	44

4.4.3 Analysis of Variance

An ANOVA was performed in this study to determine if significant differences existed between the three sites on each of the two corridors. This method of evaluation compares multiple population means while controlling the possibility of incorrectly claiming that significant differences exist (*22*). In this research, the *p*-values generated in the ANOVA were compared to the standard error rate of 0.05; *p*-values above 0.05 indicated that insufficient evidence existed to detect a significant difference between the sites, while *p*-values less than or equal to 0.05 indicated that at least one site was different from the others (*23*).

Table 4.30 presents the *p*-values associated with each variable evaluated in the ANOVA. For I-84, 16 of the 27 properties were found to be significantly different between the sites. For US-91, 17 of the 26 properties were found to be significantly different between the sites. Determination of the specific sites that were different than the others was performed using Tukey's mean separation procedure as described in the following section.

TABLE 4.30 ANOVA Results for I-84 and US-91

Variable	*p* -Values	
	I-84	US-91
CBR	0.453	0.010
CIV	0.874	0.018
RAP	0.086	-
IM	0.000	0.020
Cem	0.090	0.469
3/4 in.	0.000	0.546
1/2 in.	0.000	0.612
3/8 in.	0.001	0.281
No. 4	0.003	0.211
No. 8	0.005	0.102
No. 16	0.029	0.013
No. 30	0.093	0.003
No. 50	0.095	0.002
No. 100	0.328	0.001
No. 200	0.141	0.024
FM	0.008	0.045
TF	0.001	0.000
MC F	0.034	0.002
DD F	0.005	0.000
UCS 7	0.014	0.013
MC 7	0.681	0.001
DD 7	0.895	0.026
T 7	0.000	0.020
UCS 28	0.008	0.209
MC 28	0.413	0.064
DD 28	0.023	0.822
T 28	0.000	0.026

4.4.4 Tukey's Mean Separation Procedure

Given that the ANOVA results only indicated whether or not significant differences existed between sites, Tukey's mean separation procedure was utilized to identify those specific sites that were significantly different from the others. Tables 4.31 and 4.32 report the significant differences identified between sites at I-84 and US-91, respectively. The results of all three possible pairwise comparisons are shown in each table, in which an entry of "x" designates a significant difference in a given factor between two sites.

TABLE 4.31 Tukey's Analysis for I-84

Variable	Significant Difference between Sites			
	AB	BC	AC	None
CBR				x
CIV				x
RAP				x
IM			x	
Cem				x
3/4 in.		x	x	
1/2 in.		x	x	
3/8 in.		x	x	
No. 4			x	
No. 8			x	
No. 16			x	
No. 30				x
No. 50				x
No. 100				x
No. 200				x
FM			x	
TF		x		
MC F			x	
DD F			x	
UCS 7	x		x	
MC 7				x
DD 7				x
T 7	x	x		
UCS 28		x	x	
MC 28				x
DD 28			x	
T 28		x		

TABLE 4.32 Tukey's Analysis for US-91

Variable	Significant Difference between Sites			
	AB	BC	AC	None
CBR		x		
CIV		x		
IM		x		
Cem				x
3/4 in.				x
1/2 in.				x
3/8 in.				x
No. 4				x
No. 8				x
No. 16	x			
No. 30	x		x	
No. 50	x		x	
No. 100	x		x	
No. 200			x	
FM	x			
TF	x	x		
MC F	x			
DD F	x	x	x	
UCS 7				x
MC 7	x	x		
DD 7		x		
T 7			x	
UCS 28				x
MC 28				x
DD 28				x
T 28			x	

Table 4.31 indicates that significant differences occurred between sites A and C on I-84 more frequently than between other sites, while Table 4.32 indicates that significant differences occurred between sites A and B on US-91 more frequently than between other sites. Therefore, Utah Department of Transportation (DOT) personnel

may expect that differences in CTB performance may be most pronounced between these sites.

4.5 SUMMARY

Test results obtained from samples collected before and after cement treatment were analyzed in this research. Pre-treatment data include in-situ moisture content, particle-size distribution, and cement content for all samples, as well as asphalt content for samples obtained from I-84. Post-treatment data include both field and laboratory test results. Field data include time between mixing and compaction, CBR, CIV, moisture content in the field, and dry density in the field, and laboratory data include moisture content, dry density, and UCS for specimens cured for 7 and 28 days.

After the data were collected, several statistical analyses were performed, including multivariate regression, CV comparisons, ANOVA, and Tukey's mean separation procedure. A stepwise regression analysis was performed to determine the most significant predictor variables for each of four separate response variables, including CBR, CIV, 7-day UCS, and 28-day UCS, which were of primary interest in this research. After the multivariate regression was performed, CV comparisons were performed to identify the most variable factors investigated in the research. An ANOVA was performed in this study to determine if significant differences existed between the three sites on each of the two corridors, and Tukey's mean separation procedure was utilized to identify those specific sites that were significantly different from the others.

CHAPTER 5

CONCLUSION

5.1 FINDINGS

The primary purposes of this research were to identify construction factors most correlated to specific mechanical properties of cement-treated base (CTB) layers and to determine which construction factors exhibit comparatively high variability within individual construction sections of the two pavement reconstruction projects included in this study. In addition, differences between construction sections tested in this research were evaluated.

The significant predictor variables associated with California bearing ratio (CBR), Clegg impact value (CIV), 7-day unconfined compressive strength (UCS), and 28-day UCS at the I-84 sites include reclaimed asphalt pavement (RAP) content; cement content; amounts of aggregate particles finer than the No. 8, No. 50, and No. 200 sieves; 7-day moisture content, and 28-day moisture content. RAP content was found to be a predictor variable three times more often than any other variable, which is significant because it can be controlled by the contractor through the use of milling prior to full-depth reclamation (FDR). The significant predictors of the four response variables on US-91 were in-situ moisture content, cement content, amount of aggregate particles finer than the No. 50 sieve, time between mixing and compaction in the field, dry density in the field, 7-day dry density, 7-day moisture content, 28-day dry density, and 28-day moisture content. Therefore, on both I-84 and US-91 sites, cement content was indicated as being a significant predictor.

The factors that were found to be the most variable on both I-84 and US-91 were CBR, cement content, time between mixing and compaction in the field, and time between mixing and compaction for each of the manually compacted specimens. While preparation of the manually compacted specimens was the responsibility of the research personnel involved with the project, both the cement content and the time between mixing and compaction in the field were directly in the control of the contractor, and variability in these factors was probably responsible for the comparatively high variability in CBR values measured at the sites. Like RAP content, both cement content and time delay can be controlled by the contractor through the use of proper equipment, skilled operators, and careful scheduling.

On I-84, 16 of the 27 factors were found to be significantly different between the sites, where differences between sites A and C occurred most frequently. On US-91, 17 of the 26 factors were found to be significantly different between the sites; in this case, differences between sites A and B occurred most frequently. These data indicate that improvements in CTB construction specifications may be warranted to ensure more uniform performance of the pavement sections. Therefore, Utah Department of Transportation (DOT) personnel may expect that differences in CTB performance may be most pronounced between these sites.

5.2 RECOMMENDATIONS

The results of this research suggest that tighter specifications are warranted with respect to RAP content, cement content, and time between mixing and compaction. Concerning FDR projects, milling plans should be utilized to achieve improved uniformity in RAP content, and inspection protocols for encouraging improved control of cement content should be implemented during construction to ensure high-quality work. Compaction should be performed as soon as possible after mixing to minimize the adverse effects of cement hydration on the ability to achieve maximum dry density in the field.

For the purpose of evaluating the efficacy of tighter specifications, further research should be performed to assess the effects of construction improvements on variability in properties of CTB layers. Additional research should also be performed to investigate variability in properties of CTB layers constructed in other climatic conditions by different contractors and using other aggregate base materials and cement contents. Minimizing variability in construction of CTB layers will ultimately lead to higher quality pavements that more consistently meet design expectations.

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