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Evaluation of Full-depth Reclamation on Strength and Durability of Pavement Base Layers

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EVALUATION OF FULL-DEPTH RECLAMATION ON STRENGTH AND DURABILITY OF PAVEMENT BASE LAYERS

by

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ABSTRACT

EVALUATION OF FULL-DEPTH RECLAMATION ON STRENGTH AND DURABILITY OF PAVEMENT BASE LAYERS

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Master of Science

The purpose of this research was to determine the effect of full-depth reclamation (FDR) on the strength and durability of aggregate base layers in a coordinated approach involving both field and laboratory testing. Field comparisons between the pre-reclamation neat base and post-reclamation blended base were supplemented with laboratory experiments conducted to determine the effects of reclaimed asphalt pavement (RAP) content, compaction effort, and heating on the strength and durability of roadways reconstructed using FDR with a portable asphalt recycling machine (PARM). Also, the effect of reclamation on the spatial uniformity of the pavement structures was explored by comparing variability in the pre- and post-reclamation material properties. Test sites in Orem, Utah; San Marcos, Texas; and South Jordan, Utah, were selected for this research.

The results of field testing indicate that the FDR process significantly increased the stiffness and/or strength of the base material at two of the test locations and did not significantly change the third base material. An evaluation of spatial variability indicated that the FDR process produced equivalent or lower spatial variability with respect to both base modulus and California bearing ratio (CBR) values at one site, while the other two sites exhibited equivalent or higher spatial variability after FDR.

The results of laboratory testing for all three locations indicate that specimens compacted using the modified Proctor method exhibit significantly higher CBR values and dry densities than specimens compacted using the standard Proctor method. Also, the CBR values for specimens tested in the dry condition were significantly higher than those obtained from specimens tested at optimum moisture content. These results demonstrate the value of achieving a high level of compaction during construction and preventing water ingress into the pavement over time. The blended material exhibited a significantly lower CBR value than that of the neat material at only one location; the addition of RAP to materials at the other locations did not significantly change the CBR values of those materials. In the tube suction test (TST), most of the specimens were classified as marginally or highly moisture-susceptible, and the effect of RAP on the dielectric value in the TST was of no practical importance.

The use of PARMs in the FDR process is an acceptable, economical, and environmentally friendly approach to reconstruction of flexible pavements. To ensure satisfactory performance of FDR projects, engineers and managers should carefully follow recommended guidelines for project selection, pavement testing, material characterization, design, construction, and quality assurance testing.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Every year, thousands of miles of roadways in the United States are reconstructed. By-products of this reconstruction include millions of tons of reclaimed asphalt pavement (RAP) (*1, 2*). Currently, many ways in which RAP may be re-used are being explored, one of which is full-depth reclamation (FDR). FDR involves the pulverization and blending of the asphalt layer with the base or subgrade to create a new base layer. This method is attractive because it is comparatively easy, environmentally friendly (*1,* 2*, 3, 4, 5*), and relatively inexpensive (*4*, *5*). Indeed, a survey report of 18,000 decision-makers in the pavement industry indicated that 49 percent of the responders estimate that the use of FDR will increase between 2005 and 2010 (*6*).

As this method of reconstruction has gained popularity, new procedures and equipment for pulverization have been developed. One of these involves the use of a portable asphalt recycling machine (PARM) that easily mounts to the bucket of a front-end loader or backhoe, as shown in Figure 1.1. These machines are attractive because they can effectively pulverize to a depth of 12 in., are easily transported, and can be deployed within a matter of minutes after arrival at a job site. For these reasons, many

FIGURE 1.1 Portable asphalt recycling machine.

city and county agencies have recently begun using PARMs for street and highway reconstruction (*7*).

With the increasing use of FDR for pavement reconstruction, design engineers and street superintendents need more information about the properties of recycled materials in their jurisdictions. In particular, data demonstrating the effect of RAP content on the strength and durability of base materials is needed. Reductions or improvements in the strength of a recycled base layer compared to the original base material will require a thicker or thinner asphalt surface layer, respectively, with all other factors held constant.

While several laboratory studies (*4*, *8*, *9*, *10*, *11*) and one field study (*12*) on recycled materials have been completed, research comparing the in-situ properties of pre- and post-reclamation base materials through both field and laboratory data was not identified in the literature. Furthermore, all of the existing studies were focused on projects involving full-size reclaimers rather than PARMs. Therefore, the purpose of this research was to determine the effect of recycling on the strength and durability of aggregate base layers in a coordinated approach involving both field and laboratory testing. Field comparisons between the pre-reclamation neat base and post-reclamation blended base were supplemented with laboratory experiments conducted to determine the effects of RAP content, compaction effort, and heating on the strength and durability of roadways reconstructed using FDR with a PARM. Also, the effect of reclamation on the spatial uniformity of the pavement structures was explored by comparing variability in the pre- and post-reclamation material properties.

1.2 SCOPE

Research personnel at Brigham Young University (BYU) and the Texas Transportation Institute (TTI) performed tests on low-volume residential roadways within the municipalities of Orem, Utah; San Marcos, Texas; and South Jordan, Utah. Each roadway exhibited various degrees of deterioration and was scheduled for reconstruction using FDR with a PARM. Original average asphalt thicknesses varied from 1.8 in. to 4.6 in., and reclamation depths ranged from 6 in. to 11 in. These values correspond to a range in RAP content of 16 to 48 percent. All of the materials evaluated in this study were tested in the untreated condition, without the addition of a stabilizer. To quantify the effect of reclamation on the strength and durability of the pavement structures, field tests to determine the base modulus and California bearing ratio (CBR) values were conducted prior to and immediately following reclamation, as well as one year after reclamation. Laboratory testing included CBR and tube suction test (TST) evaluations of materials with and without RAP.

1.3 OUTLINE OF REPORT

This report contains five chapters. Chapter 1 presents the objectives and scope of the research. The results of a literature review focused on the process of FDR and the long-term performance of recycled base layers are presented in Chapter 2. In Chapter 3, descriptions of the experimental plan and field and laboratory testing procedures are presented. The results of testing and statistical analyses are explained in Chapter 4, and conclusions and recommendations are provided in Chapter 5.

CHAPTER 2

BACKGROUND

2.1 OVERVIEW

Currently, an overabundance of roads that need to be reconstructed exists in the United States. Traditionally, roads have been frequently repaired using a hot-mix asphalt overlay; however, this technique does not address one of the main problems for failed roadways, inadequate road base strength (*3*). In recent years, FDR has become a popular technique for reconstructing road bases, as it reduces costs and waste by recycling the existing asphalt and base material (*4, 5, 6, 8*). Stabilizers such as cement, lime-fly ash, or asphalt emulsions may be used to strengthen the reclaimed material, although 40 percent of all FDR projects do not use any type of chemical or bituminous stabilizer (*6*). The results of a literature review focused on the process of FDR and the long-term performance of recycled base layers are presented in the following sections.

2.2 PROCESS OF FULL-DEPTH RECLAMATION

FDR is the process of completely pulverizing the existing asphalt and blending it with the base and/or subgrade materials to create a new granular base material. The use of FDR is appropriate when certain types of pavement failures are present, including deep rutting, alligator cracking, longitudinal cracking in the wheel path, edge cracking, block cracking, transverse cracking, maintenance patching, depressions or high spots, and weak base or subgrade materials (*1*, *2*). Pulverization and blending are usually performed using large, powerful road reclaiming machines (*3*); however, smaller, more portable reclaimers that can be mounted to the bucket of a loader or backhoe are available.

The appropriate depth of FDR for a given project depends on a variety of factors, including original asphalt thickness, base and subgrade soil conditions, future traffic loading, and desired service life (*13*). Properties of the pavement layers that will be included in the reclamation process should be assessed through field and laboratory testing. In the field, samples of the pavement structure can be taken by means of coring; at least two cores per mile should be taken to obtain an estimate of the asphalt thickness (*13*). Core depths should be equal to the desired reclamation depth and should include a representative sample of asphalt, base, and subgrade as applicable (*3*). The maximum ratio of RAP to base utilized by many agencies is 50:50 (*13*, *14*), as the percentage of RAP can impact the structural properties of the blended material. In addition to coring, field testing should also be performed to assess the ability of the subgrade to provide sufficient support for compaction of the reclaimed material (*13*). Common methods for measuring the structural capacity of the subgrade are the dynamic cone penetrometer (DCP) and falling-weight deflectometer (FWD) (*13*).

In the laboratory, the sampled cores should be crushed, blended, and tested to determine the moisture content and gradation of the blended material, aggregate properties, asphalt binder content, and plasticity index (*13*). If oversized rocks, generally defined to be greater than 4 in., exist within the intended reclamation zone, the costs of FDR may be high because the progress of the contractor will be impeded by the difficult pulverization and blending process (*16*), and damage to the reclaimer may occur (*13*).

Also, if clay is discovered within the intended reclamation zone, FDR may not be an appropriate reconstruction technique, depending on available opportunities to utilize chemical stabilization or, in the event that elevation constraints are not present, to place an aggregate base overlay on top of the existing asphalt prior to reclamation so that the reclamation zone does not reach into the clay. Of course, when elevation constraints such as curb and gutter are present, for example, some blended material will need to be removed prior to grading and compaction so that sufficient space is available for a new wearing course, and this will require that the reclamation depth exceed the desired thickness of the reclaimed layer.

Following completion of field and laboratory testing, the pavement design can be prepared and specifications drafted. For low-volume roads, on which truck trafficking is negligible, calculations of required layer thicknesses are sometimes neglected in favor of applying a default agency design. With higher traffic levels, however, performing appropriate calculations to determine the structural capacity required for the new pavement becomes increasingly important to ensure that the pavement will provide satisfactory service for the specified performance period.

Once the pavement design is completed, reconstruction of the road can move forward. Use of proper construction techniques greatly reduces future maintenance costs for the pavement (*14*), so the establishment of proper construction guidelines and enforcement of quality assurance standards are important tasks. The following construction steps are typical of FDR projects (*13*):

1. Pulverization and mixing of the pavement layers
2. Initial compaction

3. Rough grading
4. Intermediate compaction
5. Intermediate grading
6. Final compaction
7. Soil density testing
8. Final grading
9. Removal of all loose material
10. Application of seal coat and wearing surface

Pulverization of the pavement should be performed at a speed appropriate for the depth of reclamation and consistent with recommendations provided by the equipment manufacturer (*7*). Reclaiming too quickly will result in larger particles, while reclaiming too slowly creates a finer mix. The maximum particle size should typically be less than 2.5 in., generally requiring that the maximum size of existing aggregates within the zone of reclamation also be less than this value, and the blended material should be dense-graded (*13*). Water can be added to the material as it is being pulverized to bring it to optimum moisture content (OMC) and reduce dust.

If the specified depth of reclamation exceeds the effective depth of compaction for the rollers available on the project, which is typically a maximum depth of 12 in. (*16*), then part of the reclaimed material must be temporarily removed so that compaction of the reclaimed layer may occur in lifts (*13*). Initial compaction should be performed using a vibratory sheep's foot compactor set to a high amplitude and low frequency (*17*), after which the area should be smoothed with a grader. Intermediate and final compaction should then be performed using a smooth-drum vibratory compactor. Once each lift is completed, as applicable, density testing with a nuclear density gauge (NDG) should be performed by an outside agency to ensure that compaction is adequate. Final grading should ensure that the road meets alignment and drainage specifications. A tack coat should then be applied, followed by an appropriate thickness of the selected wearing course. Following sound construction practices consistent with the engineering specifications and recommendations for the project is important to ensure satisfactory performance of the reconstructed pavement.

2.3 PERFORMANCE OF PAVEMENTS WITH RECYCLED BASE LAYERS

As mentioned previously, several studies on recycled materials have been completed. All of these studies concluded that the use of RAP-base mixtures is acceptable if certain criteria are met (*8, 9, 10, 11, 12, 14*). Specifically highlighted in this section are laboratory studies by Taha et al., Guthrie et al., MacGregor et al., and Kim et al., a field study by Garg and Thompson, and a questionnaire survey by Scullion et al.

Taha et al. showed that RAP contents of 0, 20, 40, and 60 percent produced CBR values above 30 percent, the minimum required CBR for pavement base materials in Oman, while RAP contents of 80 and 100 percent produced CBR values lower than 30 percent. All CBR tests performed by Taha et al. were conducted on unsoaked specimens that were compacted and tested in the laboratory at their respective OMCs. Taha et al. speculated that, as the percentage of virgin aggregate increased, the load transfer between particles improved due to better interlocking between particles and a reduction in slip surfaces associated with the presence of asphalt coatings (*1*).

Guthrie et al. found that the increase from 0 percent RAP to 25 percent RAP caused a 29 percent decrease, on average, in the soaked CBR value of two Utah base materials, while each additional 25 percent increase in RAP content caused the strength to decrease 13 to 15 percent more (*8*). Guthrie et al. also found that, as the RAP content increased from 0 to 25 percent, the stiffness decreased, but, for every subsequent 25 percent addition of RAP, the stiffness increased. However, after these specimens were heated to 140°F for 72 hours, the opposite was true; stiffness increased as RAP content increased from 0 to 25 percent, and stiffness decreased with every additional 25 percent of RAP. Guthrie et al. speculated that this reversal was due to the fact that, as the specimens were heated, the asphalt surrounding the RAP particles softened, and, upon cooling, the asphalt hardened and enhanced the inter-particle bonds. Guthrie et al. also noted that specimens tested in the soaked condition had modulus values that were between 40 percent and 90 percent lower than specimens tested after a 72-hour drying period (*8*).

MacGregor et al. found that, for aggregate specimens compacted to at least 95 percent of the standard Proctor dry unit weight and tested at OMC, an increase in RAP content increased the resilient modulus of the recycled layer, which effectively increased the structural number (SN) of the layer (*10*). MacGregor et al. concluded that, because of the increased SN, RAP was a beneficial additive to the base material tested. He also found that the addition of up to 50 percent RAP had little effect on the hydraulic conductivity of the material.

Kim et al. reported that base materials containing 50 percent RAP by weight, and compacted and tested at OMC, developed stiffnesses equivalent to those of specimens comprised of 100 percent neat base at low confining pressures, but that, at higher confining pressures, the specimens with higher RAP contents were stiffer (*11*). Specifically, specimens with 25 percent neat base and 75 percent RAP had the highest resilient modulus values. However, in the study, specimens that contained RAP exhibited more permanent deformation than neat base specimens.

In a field study conducted on a 1200-ft section (1000 ft of RAP base and 200 ft of crushed stone aggregate) of a two-lane pavement, Garg and Thompson found that the performance of RAP as a pavement base material was comparable to the performance of crushed stone base. After two years, minor rutting was the only visible distress, and FWD data indicated that the recycled base was providing adequate structural support and subgrade protection (*12*).

A questionnaire survey of 16 districts in Texas conducted by Scullion et al. indicated that more than 70 percent of the survey respondents rated the performance of recycled sections in their district as “good” or “excellent.” These condition data were not quantified but do give insight into the long-term performance of FDR pavements in Texas. Most of the agencies polled in this study typically use chemical or bituminous stabilizers, so the findings are not directly related to the focus of this research but are helpful in considering the overall use and effectiveness of FDR (*14*).

Although various researchers have investigated the effects of RAP on the strength and durability of blended materials produced by full-size reclaimers or laboratory crushers, experimental data documenting the effects on strength and durability when reclaiming with a PARM were not identified in the literature. To the extent that the properties of materials reclaimed using a full-size reclaimer are similar to those of materials reclaimed using a PARM, much of the available research becomes useful in evaluating the effectiveness of FDR using a PARM.

2.4 SUMMARY

In recent years, FDR has become a popular technique for reconstructing road bases, as it reduces costs and waste by recycling the existing asphalt and base material. The use of FDR is appropriate when certain types of pavement failures are present, including deep rutting, alligator cracking, longitudinal cracking in the wheel path, edge cracking, block cracking, transverse cracking, maintenance patching, depressions or high spots, and weak base or subgrade materials. In the design phase of a reconstruction project involving FDR, properties of the pavement layers that will be included in the reclamation process should be assessed in order to determine the design of the new pavement structure. In the construction phase, following recommended practices consistent with the engineering specifications and recommendations for the project is important to ensure satisfactory performance of the reconstructed pavement.

Pulverization and blending of the existing asphalt with the base and/or subgrade materials are usually performed using large, powerful reclaiming machines; however, smaller, more portable reclaimers that can be mounted to the bucket of a loader or backhoe are available. Various studies have been conducted on the qualities of reclaimed material. Taha et al. found that RAP contents up to 60 percent resulted in an acceptable CBR value, and MacGregor et al. reported that, as RAP content increased, the resilient modulus also increased. Kim et al. reported that, at low confining pressures, material with 50 percent RAP developed stiffnesses equivalent to 100 percent neat base material, and, at high confining pressures, the specimens with higher RAP contents were stiffer. Guthrie et al. reported increasing stiffness with increasing RAP contents above 25 percent, but the trend reversed after the specimens experienced a short duration of heating. Guthrie et al. also determined that, as RAP content increased, CBR value decreased. Through field studies, Garg and Thompson determined that the performance of RAP as a base material was comparable to crushed stone base, and a survey conducted by Scullion et al. indicated that the majority of respondents rated recycled pavements as “good” or “excellent.” The variability in the results of these studies warrants further investigation of the effects of FDR on the strength and durability of pavements.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 OVERVIEW

Field testing, laboratory testing, and statistical analyses were performed to meet the objectives of this research. In order to provide a variety of test data, three different locations were chosen for this research: Orem, Utah; San Marcos, Texas; and South Jordan, Utah. Test sites within the municipalities were selected by the street superintendents based on their reconstruction schedules and were all characterized as residential facilities with light truck trafficking. Details of the experimental methodology are described in the following sections.

3.2 FIELD TESTING

Field tests were performed at six test areas at each project location. The individual test areas were selected by dividing the project into equal-sized squares, with each square having a side length equal to the width of one lane. The squares were numbered consecutively from 1 to 30 or so, depending on the length of the project, and the total number of squares was then multiplied by each value in a set of six random numbers between 0 and 1. The products were then rounded to the nearest whole number in each case, and the squares corresponding to these rounded numbers were selected for testing. Diagrams of the Orem, San Marcos, and South Jordan test sites are presented in Figures 3.1, 3.2, and 3.3, respectively.

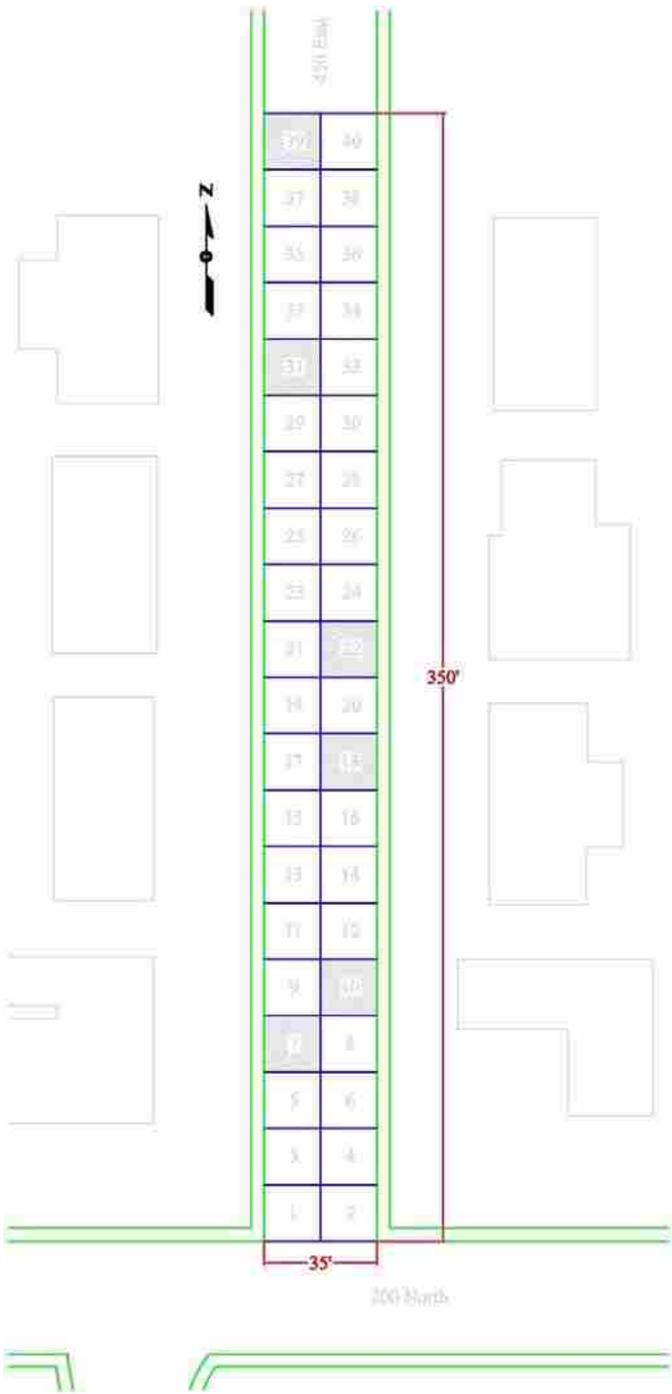

FIGURE 3.1 Orem site layout.

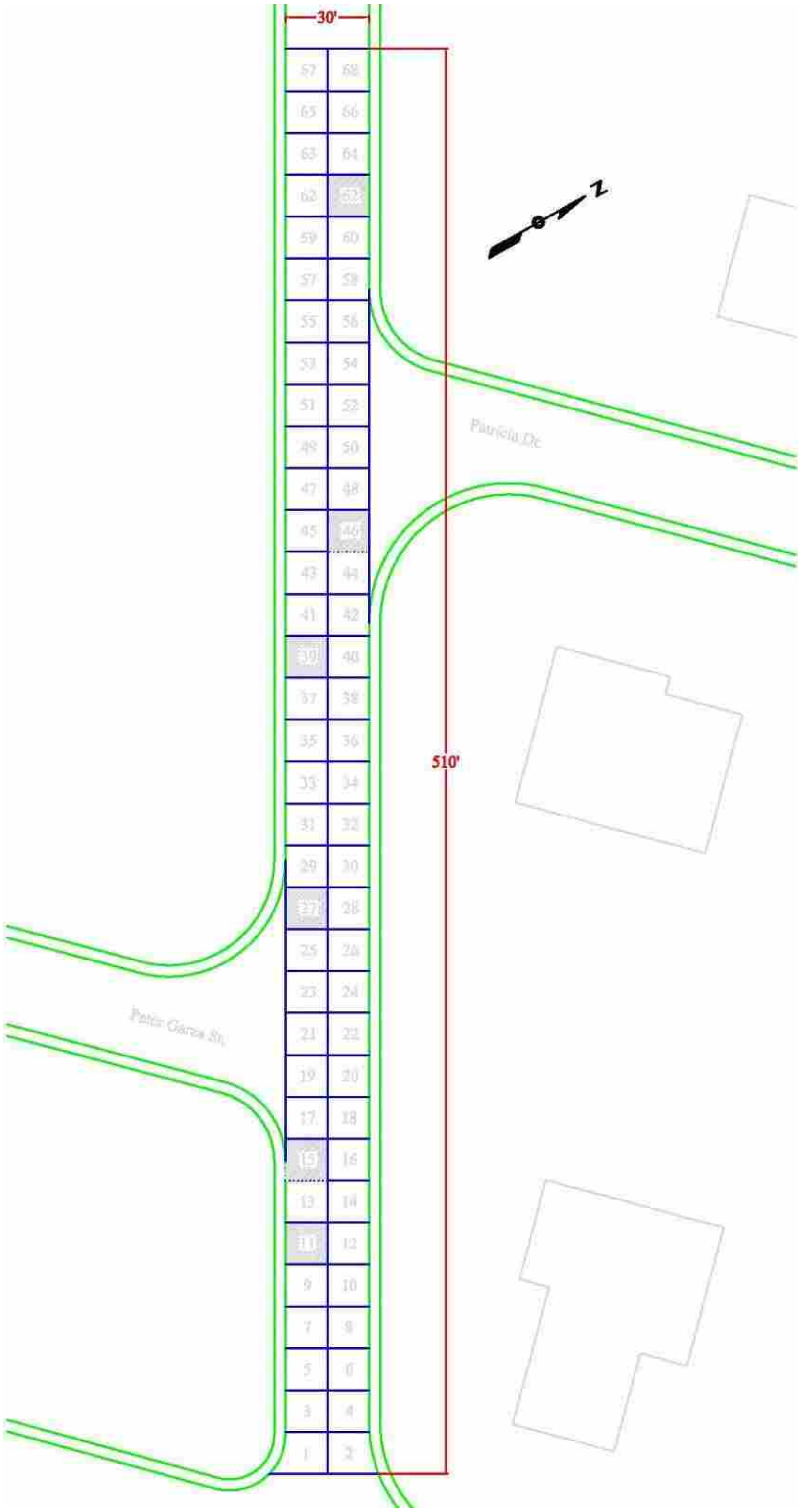

FIGURE 3.2 San Marcos site layout.

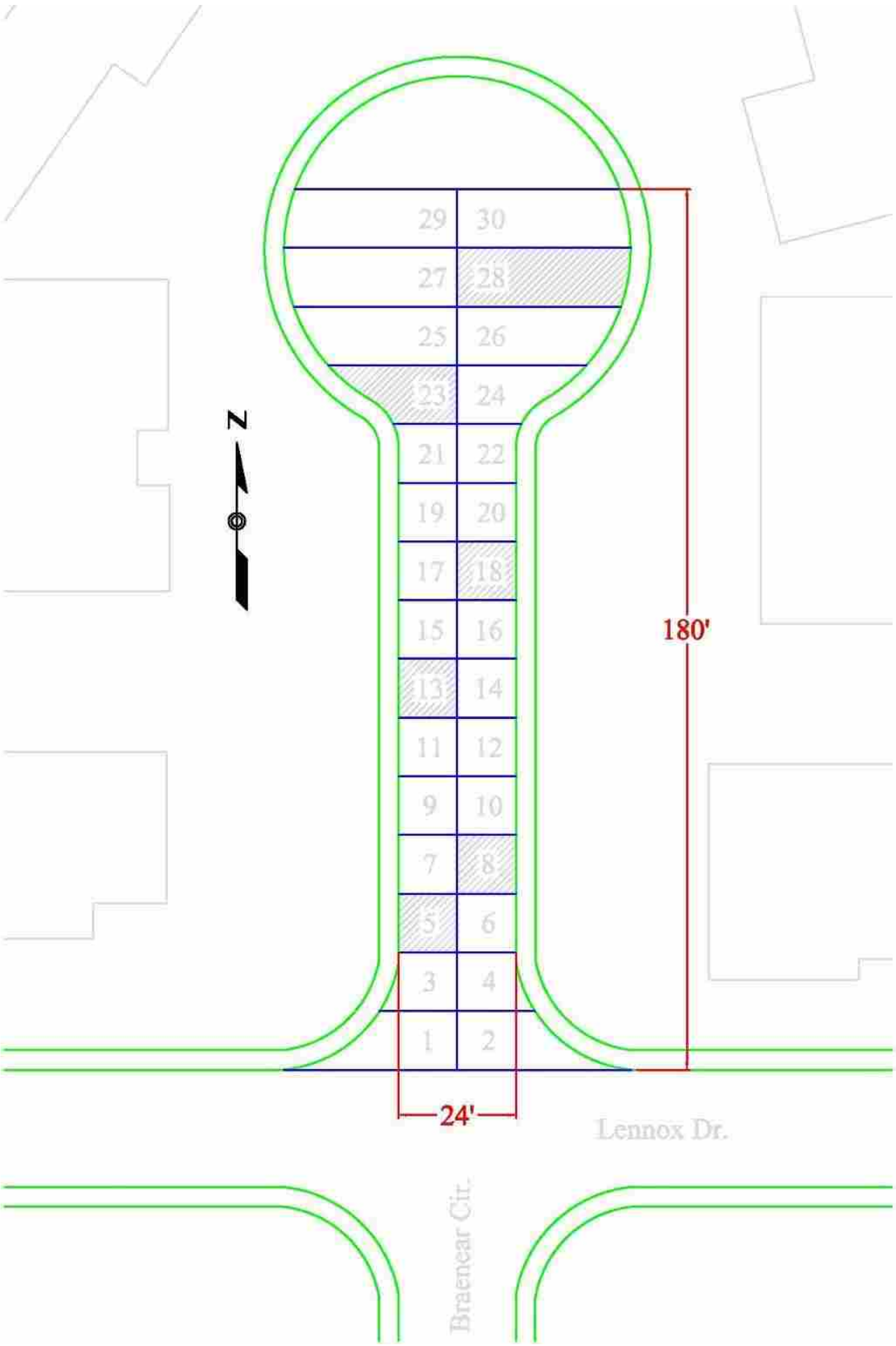

FIGURE 3.3 South Jordan site layout.

Data collected at each location prior to pulverization include the results of distress surveys of each individual test area conducted in accordance with the Long Term Pavement Performance Program guidelines (*18*), pavement layer modulus values measured using the portable falling-weight deflectometer (PFWD), and layer thickness and CBR values measured with the DCP. Figure 3.4 depicts the layout of these tests at a typical test area. As illustrated in Figure 3.5, PFWD tests were performed 4 ft from the center of each test area as measured along a line parallel to the center line of the roadway. A total of four drops were applied at each test area, the first being a seating load. To facilitate calculation of the modulus values of the pavement layers, average load and deflection data obtained from the last three drops of the PFWD were input into BAKFAA, a computer program provided by the Federal Aviation Administration for back-calculation of pavement layer properties (*19*). For situations in which asphalt was

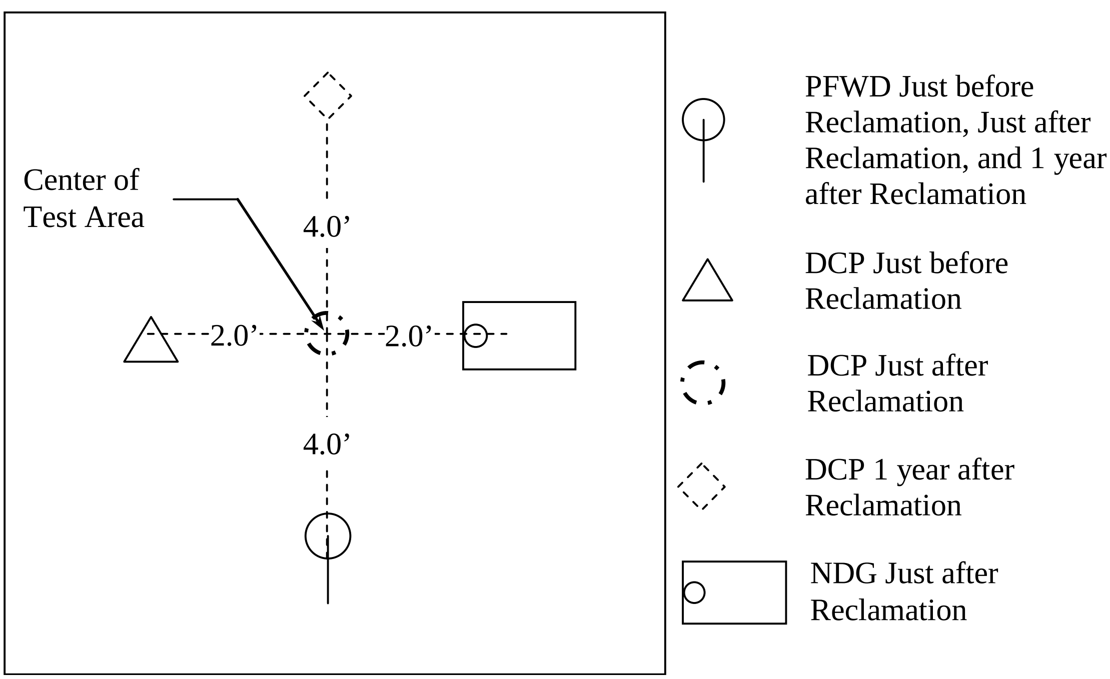

FIGURE 3.4 Standard test area layout.

FIGURE 3.5 PFWD testing just before reclamation.

present, a two-layer model was used, and the modulus of the asphalt layer was fixed based on its surface temperature measured using a spot radiometer during PFWD testing as described in Equation 3.1 (*20*):

$$\log E = 6.464 - 0.000145 \times T^{1.94824} \tag{3.1}$$

where E = modulus of asphalt, psi

T = temperature of asphalt, °F

When asphalt was not present, a one-layer model was used to compute the composite modulus of the base and subgrade together. Thus, in these back-calculations, the BAKFAA program was allowed to change only the composite modulus of the base and subgrade materials in the optimization process. In all cases, a seed modulus value of 50,000 psi was used for the base/subgrade material, and a Poisson's ratio of 0.35 was used for all layers.

For DCP tests, a 1.5-in.-diameter hole was drilled through the asphalt at a location exactly 2 ft to one side of the center of each test area. The hole through the asphalt provided a means of measuring the thickness of the existing surface course and gave access to the underlying base material for DCP testing as shown in Figure 3.6. The DCP tests involved measuring the penetration rate of the standard DCP cone tip through the subsurface materials at approximately 1-in. depth intervals. From the DCP data, the average CBR value of the base material within the depth of reclamation at each test area was calculated using Equation 3.2:

$$CBR = \frac{292}{PR^{1.12}} \qquad (3.2)$$

where CBR = California bearing ratio, %

PR = DCP penetration rate, mm/blow

Refusal, which was defined as a penetration rate less than 0.04 in. per blow, occurred on a few occasions, and new holes were drilled to facilitate retesting. Also, if the DCP leaned more than 6 in. from vertical, that test was aborted, and a new test was

FIGURE 3.6 DCP testing just before reclamation.

conducted. If refusal or lean occurred more than twice, DCP testing was abandoned at that test area.

To facilitate measurement of the in-situ density and moisture content of the base material prior to reclaiming, two sections of the asphalt at each location, one at each end, were subjected to saw-cutting for removal of the wearing course. The asphalt was carefully lifted out of place in each case to avoid disturbing the underlying base material. Figure 3.7 shows how a NDG was then situated immediately on top of the base layer. Because the street superintendents arranged the saw-cutting in advance of the testing, the

FIGURE 3.7 NDG testing just before reclamation.

locations of NDG testing did not necessarily coincide with any test areas selected through the randomization process described previously.

Following the NDG testing, samples of the exposed base material from within each tested section were removed for laboratory analysis, as shown in Figure 3.8. Six 5-gallon buckets of material were collected. The asphalt and base layers were then blended together in the field using a PARM within a day or two of the initial testing. The reclamation depths were noted, and six 5-gallon buckets of the reclaimed material were then collected, as shown in Figure 3.9, for laboratory analysis.

FIGURE 3.8 Material sampling just before reclamation.

Immediately after pulverization, compaction, and grading of the reclaimed base material, PFWD tests were performed, as shown in Figure 3.10, in the same locations within each test area as they were performed prior to reclamation. DCP tests were also performed in each test area as illustrated in Figure 3.11; however, in order to avoid penetrating the previous DCP hole, the test was moved to the center of the test area. In addition, NDG tests were performed at each of the test areas, as depicted in Figure 3.12. In each case, this test was performed 2 ft from the center of the test area on the opposite side of the pre-reclamation DCP test location as illustrated in Figure 3.4. NDG testing was not performed at the San Marcos location after reclamation due to the lack of availability of an NDG. Following the testing, an asphalt wearing course was then applied by a paving contractor, and the road was opened to traffic.

FIGURE 3.9 Material sampling just after reclamation.

One year after reclamation, each site was revisited, and testing was repeated in order to observe how the pavement properties had changed over time. Distress surveys PFWD tests, and DCP tests were conducted within the same test areas as previously defined. While the PFWD tests were performed at exactly the same locations previously evaluated, DCP testing was conducted through a hole drilled in the pavement 2 ft from the center of the test area in each case, opposite from the PFWD test, as shown in Figure 3.4. After DCP testing, the hole drilled in each test area was patched using a commercially available asphalt patch material.

FIGURE 3.10 PFWD testing just after reclamation.

FIGURE 3.11 DCP testing just after reclamation.

FIGURE 3.12 NDG testing just after reclamation.

3.3 LABORATORY TESTING

All sampled materials were transported to the BYU Highway Materials Laboratory for analysis. Testing included sieve analyses, apparent specific gravity determinations, Atterberg limits determinations, burn-off tests, standard and modified Proctor compaction tests, CBR testing, and evaluations of moisture susceptibility using the TST. In order to facilitate preparation of specimens with matching gradations, the full quantity of each of the six different samples collected during the field work was separated over the 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 following American Society for Testing and Materials (ASTM) D 422 (Standard Test Method for Particle-Size Analysis of Soils). Sieving of materials retained on the No. 16 sieve was accomplished using a large tray shaker, while sieving of finer materials was performed using a 12-in.-diameter sieve shaker. Particles larger than 3/4 in. were discarded and therefore not used in the preparation of samples. A master gradation was developed for each material after this manner, and replicate samples were created for the various laboratory tests based on these particle-size distributions. In addition, washed sieve analyses were performed to enable classification of each material using the American Association of State Highway and Transportation Officials (AASHTO) and Unified soil classification systems.

Compaction tests were performed to determine the OMC and maximum dry density (MDD) for each material at each of two levels of compaction energy. The individual samples of base material were weighed out according to the appropriate master gradation, mixed with a pre-determined amount of water, and then soaked for 24 hours prior to compaction. Each sample was compacted using either the standard or modified Proctor procedure as outlined in ASTM D 698 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3))) Method B and ASTM D 1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2700 kN-m/m^3))) Method B, respectively. For a 4-in.-diameter specimen, the standard Proctor procedure requires compaction of specimens in three lifts of 25 blows per lift of a 5.5-lb hammer dropped from a height of 12 in. The modified Proctor procedure requires compaction of specimens in five lifts of 25 blows per lift of a 10-lb hammer dropped from a height of 18 in. After each lift was compacted, the surface was scarified to facilitate interlayer bonding. After the final lift of a specimen was compacted, five additional blows were given to the specimen surface using a finishing hammer to both level and flatten the top. At least three specimens of each material were prepared in this manner to determine the individual OMCs and MDDs. After compaction, the moisture content of each specimen was determined by drying the specimens at 140°F to constant weight. A temperature of 140°F was used in this research to prevent volatilization of asphalt cement from the RAP particles that might otherwise occur at a more typical oven temperature of 230°F and was consistently applied to all specimens whether or not they contained any RAP.

Once compaction testing was complete, strength and durability testing proceeded as outlined in Figure 3.13. Strength testing was performed in accordance with ASTM D 1883 (Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils). For each material, a total of 18 specimens were prepared, nine using the standard Proctor procedure and nine using the modified Proctor procedure. In order to allow the moisture in the specimens to equilibrate, each sample was moistened to the appropriate OMC, compacted to MDD 24 hours prior to testing, and sealed in a plastic bag. Three rounds of CBR testing were then conducted. First, the CBR test was performed at room temperature, or about 68°F, on three standard and three modified specimens of each material at OMC. Second, to simulate heating that occurs in the field during hot summers (8), three standard specimens and three modified specimens were sealed to prevent moisture loss and heated at 140°F for 72 hours. The CBR test was then performed after the specimens had cooled but while they were still wet. Finally, three

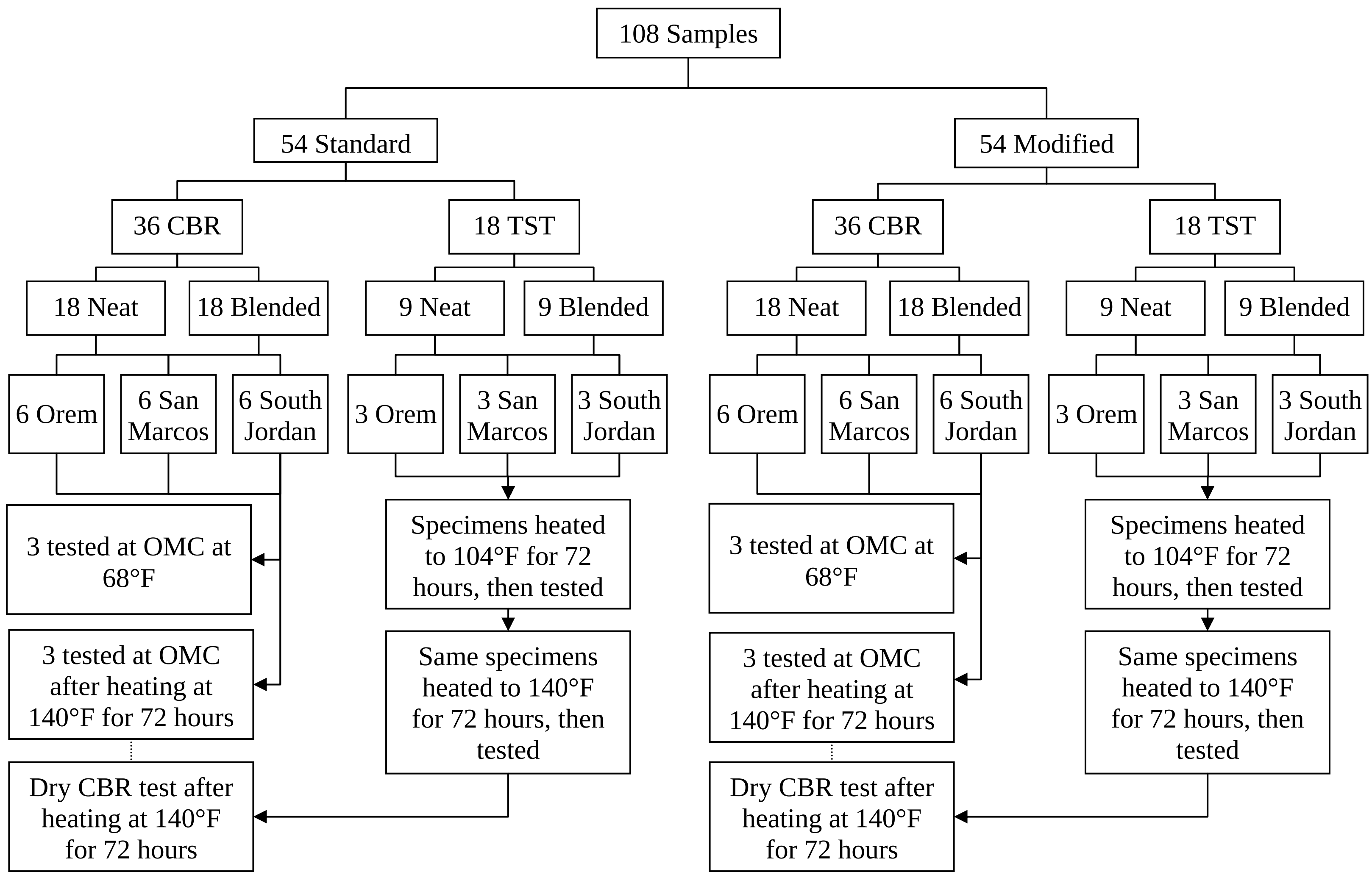

FIGURE 3.13 Specimen preparation matrix.

standard and three modified specimens were heated unsealed at 140°F for 72 hours, and the CBR test was performed on each specimen in an oven-dried condition. All CBR testing was performed using the compression machine depicted in Figure 3.14. A standard piston having a cross-sectional area of 3 $in.^2$ was pressed into the top of each specimen at a constant rate of 0.05 in. per minute. CBR values were then calculated using the load readings recorded at 0.1 and 0.2 in. of penetration as specified in Equations 3.3 and 3.4, in which the value of 7.4833 is a constant associated with the proving ring used in the testing:

FIGURE 3.14 Compression machine used in CBR test.

$$CBR_{0.1} = \frac{7.4833 \cdot L_{0.1}}{1000} \tag{3.3}$$

where $CBR_{0.1}$ = CBR value at 0.1 in. of penetration, %

$L_{0.1}$ = load reading at 0.1 in. of penetration

$$CBR_{0.2} = \frac{7.4833 \cdot L_{0.2}}{1500} \tag{3.4}$$

where $CBR_{0.2}$ = CBR value at 0.2 in. of penetration, %

$L_{0.2}$ = load reading at 0.2 in. of penetration

The larger of the resulting values was recorded as the CBR for the specimen (*20*).

As a measure of durability, the TST was performed in general accordance with the Texas Department of Transportation (TxDOT) Test Method Tex-144-E (Tube Suction Test), with modification to the specimen size. Each specimen mold was prepared by cutting a standard 6-in.-diameter plastic test cylinder to 6 in. in height and drilling 0.0625 in.-diameter holes every 0.5 in. in a line around the circumference of the base of the cylinder at a height of 0.25 in. from the bottom. Four holes were also drilled in the bottom of the cylinder, one in each quadrant. The plastic mold was placed within a metal cylinder to prevent buckling of the plastic during compaction. For each material, six specimens were evaluated in the TST, three prepared using the standard Proctor procedure and three prepared using the modified Proctor procedure. Immediately following compaction, the specimens were dried in an oven at 104°F for 72 hours, and initial dielectric readings were taken, five around the perimeter of the surface of each specimen and one in the center as shown in Figure 3.15. The specimens were then

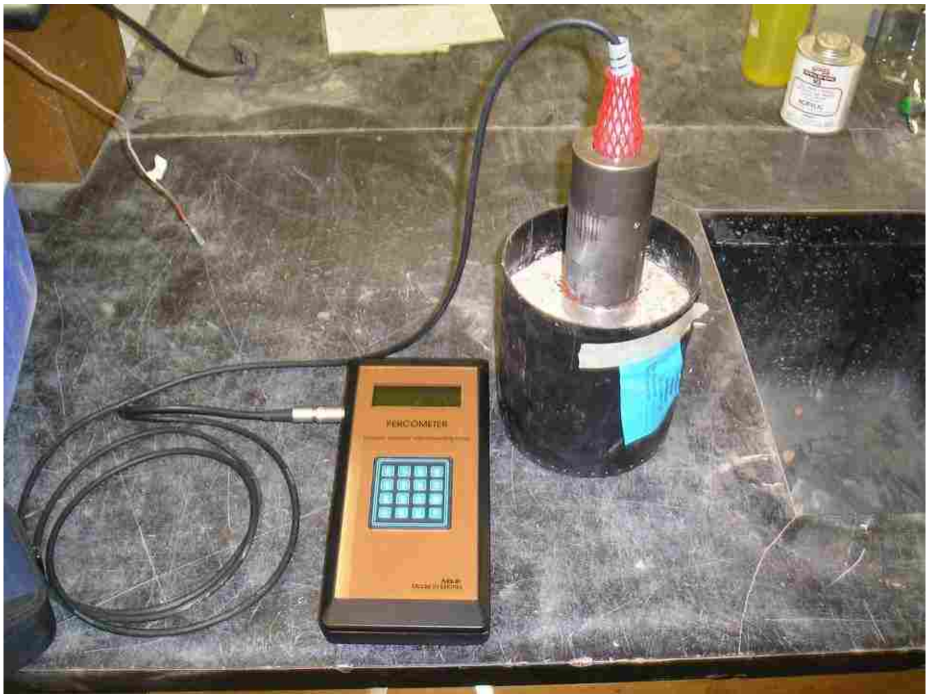

FIGURE 3.15 Surface dielectric probe used in TST.

placed in a 0.5-in.-deep water bath inside closed ice chests to maintain constant temperature and to prevent water from evaporating during the testing. Each ice chest contained three specimens. Dielectric readings for each specimen were measured daily through a total of 10 days of soaking. After the final dielectric values were measured, the wet weight of each specimen was also recorded to facilitate computation of moisture content. A daily average dielectric value for each specimen in the TST was calculated by omitting the highest and lowest dielectric values and averaging the remaining four readings, and the average dielectric value for the final day of testing was used to characterize the moisture susceptibility of the specimen. The specimens were then dried at 140°F for 72 hours to again simulate summer heating, and, subsequently, the TST was re-conducted in the same manner on the very same specimens.

3.4 STATISTICAL ANALYSES

Once all field and laboratory data were collected and reduced, statistical methods were used for analysis. The primary analysis technique used in this research was a fixed-effects analysis of variance (ANOVA). The null hypothesis in the ANOVA is that the mean values of the populations of interest are the same, and the alternative hypothesis is that the mean value of at least one population is different than those of the others. When the *p*-value computed in the ANOVA was greater than the standard error rate of 0.05 in this research, insufficient data existed to reject the null hypothesis. However, when the *p*-value was less than or equal to 0.05, the null hypothesis was rejected and the alternative accepted. In these cases, Tukey's mean separation procedure was utilized to determine which means were different from the others when more than two means were analyzed. Plots of the significant main effects and two-way interactions were then prepared for each analysis.

3.5 SUMMARY

In order to assess the differences in strength and durability between neat and blended base materials, BYU research personnel conducted both field and laboratory testing in connection with FDR projects at each of three different test locations: Orem, Utah; San Marcos, Texas; and South Jordan, Utah. In all three cases, pavement reconstruction was performed using a PARM. Evaluations of each pavement structure, including distress surveys, PFWD tests, DCP tests, and NDG tests, were conducted prior to reclamation. The neat base material was then sampled to facilitate strength and durability testing in the laboratory using the CBR test and TST, respectively. Following the FDR process, the blended base material was also sampled for laboratory testing, and the compacted, reclaimed layer was subsequently subjected to PFWD, DCP, and NDG testing prior to placement of a new asphalt wearing course. After one year of service, distress surveys were again performed, and each facility was retested using the PFWD and DCP. Field and laboratory data were then subjected to statistical analyses to address the research objectives.

CHAPTER 4

RESULTS

4.1 OVERVIEW

The results of field and laboratory testing, as well as the results of statistical analyses, are presented in the following sections.

4.2 FIELD TESTING

Each test site had different asphalt thicknesses and reclamation depths as detailed in Table 4.1. The RAP content therefore also varied at each site as shown in Table 4.1. This variation allowed for an investigation of the effect of RAP and binder content on the properties of the reconstructed pavements. The results of the field testing, including PFWD, DCP, and NDG testing, are presented in the following sections. A discussion of the spatial variability associated with selected in-situ properties is also provided.

TABLE 4.1 RAP Contents at Test Sites

Location	Average Asphalt Thickness (in.)	Reclamation Depth (in.)	RAP Content (%)
Orem	1.8	11.0	16
San Marcos	2.0	6.0	33
South Jordan	4.6	9.5	48

4.2.1 Distress Surveys

The results of the distress surveys performed before reclamation are displayed in Table 4.2 and Appendix A. The Orem pavement had extensive fatigue cracking, longitudinal and transverse cracking, and patching. The San Marcos pavement also experienced extensive fatigue cracking and patching. The South Jordan pavement had very little distress, just minor raveling in four of the test areas. None of the test areas at any of the locations exhibited any visual distress one year after reclamation; therefore, no data for the one-year distress surveys are presented in this report.

TABLE 4.2 Distress Survey Results

Location	Test Area	Fatigue Cracking (ft^2)	Longitudinal Cracking (ft)	Transverse Cracking (ft)	Patching (ft^2)	Potholes (ft^2)	Raveling (ft^2)
Orem	1	35.0	4.6	9.0	45.0	-	1.3
	2	110.0	30.0	7.0	-	-	62.0
	3	-	22.0	15.0	3.0	-	-
	4	153.0	-	-	-	-	-
	5	-	-	-	66.0	-	-
	6	117.0	-	1.5	33.0	-	-
San Marcos	1	20.0	-	-	15.0	32.0	-
	2	18.0	-	-	-	-	-
	3	12.0	-	-	-	-	-
	4	47.5	-	-	-	-	-
	5	-	11.0	-	104.0	-	-
	6	3.0	10.0	-	179.0	-	-
South Jordan	1	-	-	-	-	-	17.0
	2	-	-	-	-	-	-
	3	-	-	-	-	-	42.0
	4	-	-	-	-	-	23.5
	5	-	-	-	-	-	9.5
	6	-	-	-	-	-	-

4.2.2 Portable Falling-Weight Deflectometer

Modulus values backcalculated using deflection data from the PFWD are presented in Table 4.3 for the Orem, San Marcos, and South Jordan locations. PFWD data from test area 2 at San Marcos are missing due to an underground concrete structure that adversely influenced the readings, and PFWD data collected just before reclamation at South Jordan were lost due to equipment power failure.

TABLE 4.3 PFWD Test Results

Location	Test Area	Base Modulus (ksi)		
		Just before Reclamation	Just after Reclamation	1 Year after Reclamation
Orem	1	30.5	17.5	35.8
	2	20.4	13.5	38.2
	3	19.0	20.0	33.2
	4	11.1	17.2	39.2
	5	14.9	25.1	34.1
	6	16.6	9.9	38.6
San Marcos	1	26.4	40.4	15.7
	2	-	-	-
	3	32.8	59.6	70.1
	4	27.9	37.4	51.5
	5	17.6	62.3	63.6
	6	25.0	27.6	12.0
South Jordan	1	-	14.5	24.1
	2	-	19.8	26.5
	3	-	14.4	30.2
	4	-	27.7	32.6
	5	-	25.7	33.3
	6	-	33.7	66.4

4.2.3 Dynamic Cone Penetrometer

CBR values obtained using the DCP are displayed in Table 4.4. Data from test area 2 at San Marcos are missing for the same reason previously mentioned with respect

TABLE 4.4 DCP Test Results

Location	Test Area	CBR (%)		
		Just before Reclamation	Just after Reclamation	1 Year after Reclamation
Orem	1	69.8	29.6	45.4
	2	46.9	14.2	93.7
	3	75.3	30.7	69.6
	4	47.4	46.1	69.6
	5	10.9	22.5	-
	6	28.9	32.0	20.8
San Marcos	1	167.7	76.8	161.9
	2	-	-	-
	3	166.5	152.2	522.0
	4	94.0	97.3	323.4
	5	62.4	78.4	497.2
	6	70.5	73.4	144.6
South Jordan	1	55.9	45.5	38.5
	2	43.0	34.9	38.0
	3	73.5	39.1	49.1
	4	49.8	43.6	52.6
	5	78.9	41.3	77.8
	6	62.9	28.9	94.0

to the PFWD data. The reason that DCP data are not shown for one of the test areas in Orem is because in that instance the DCP experienced refusal or excessive lean more than twice.

4.2.4 Nuclear Density Gauge

The in-situ density and moisture content data obtained from the NDG are presented in Tables 4.5 and 4.6 for the neat and blended base materials, respectively. The relative compaction was calculated by dividing the measured in-situ dry density by the dry density determined in the laboratory for the neat or blended material from each location. No NDG data were obtained after reclamation at the San Marcos location

TABLE 4.5 NDG Test Results Just before Reclamation

Location	Moisture Content (%)	Wet Density (lb/ft^3)	Dry Density (lb/ft^3)	Relative Compaction (%)	
				Standard Proctor	Modified Proctor
Orem	4.2	136.5	131.0	89.0	87.1
	5.3	142.9	135.7	92.2	90.3
San Marcos	6.7	142.5	133.6	97.9	95.7
	4.2	132.1	126.8	92.9	90.8
South Jordan	8.8	127.4	117.1	83.0	81.4
	10.4	122.6	111.1	78.7	77.2

TABLE 4.6 NDG Test Results Just after Reclamation

Location	Test Area	Moisture Content (%)	Wet Density (lb/ft^3)	Dry Density (lb/ft^3)	Relative Compaction (%)	
					Standard Proctor	Modified Proctor
Orem	1	9.0	135.0	123.8	87.4	86.2
	2	10.5	140.0	126.7	89.5	88.2
	3	7.9	138.7	128.5	90.7	89.4
	4	8.1	136.8	126.6	89.4	88.1
	5	10.6	135.9	122.9	86.8	85.5
	6	9.3	132.5	121.2	85.6	84.3
San Marcos	1	-	-	-	-	-
	2	-	-	-	-	-
	3	-	-	-	-	-
	4	-	-	-	-	-
	5	-	-	-	-	-
	6	-	-	-	-	-
South Jordan	1	6.3	134.7	126.7	93.6	91.0
	2	5.9	133.8	126.3	93.3	90.7
	3	6.8	128.0	119.8	88.5	86.1
	4	6.1	122.1	115.1	85.1	82.7
	5	5.6	124.0	117.4	86.8	84.3
	6	7.3	127.7	119.0	88.0	85.5

because an NDG was not available at the time of testing. The low MDD for the in-situ material could be a result of numerous factors, such as low water content or insufficient compaction effort.

4.3 LABORATORY TESTING

The results of laboratory testing, including material characterization, compaction properties, and strength and moisture-susceptibility tests, are presented in the following sections.

4.3.1 Material Characterization

Material characterization included washed sieve analyses, specific gravity determinations, Atterberg limits determinations, and burn-off testing. The results of the washed sieve analyses are shown in Tables 4.7, 4.8, and 4.9 for Orem, San Marcos, and South Jordan, respectively, and Figures 4.1, 4.2, and 4.3 display the results in graphical form. Overall, both the Orem and San Marcos materials were slightly finer after reclamation, as shown in Figure 4.1 and 4.2. However, because the South Jordan location was characterized by a gap-graded neat base material, the more dense-graded blended base was finer than the neat material only for grains larger than about the No. 16 sieve size as shown in Figure 4.3; the neat material was finer at smaller grain sizes.

TABLE 4.7 Particle-Size Distributions for Orem Materials

Sieve Size	Percent Passing (%)	
	Neat Base	Blended Base
3/4 in.	100.0	100.0
1/2 in.	87.9	89.5
3/8 in.	74.9	80.3
No. 4	54.9	59.1
No. 8	40.5	43.1
No. 16	28.6	31.6
No. 30	20.2	24.1
No. 50	14.5	17.4
No. 100	10.0	10.5
No. 200	4.5	4.3

TABLE 4.8 Particle-Size Distributions for San Marcos Materials

Sieve Size	Percent Passing (%)	
	Neat Base	Blended Base
3/4 in.	100.0	100.0
1/2 in.	89.0	88.7
3/8 in.	80.7	78.9
No. 4	60.2	57.2
No. 8	44.6	48.8
No. 16	33.6	37.7
No. 30	26.0	30.3
No. 50	20.1	22.3
No. 100	15.4	17.3
No. 200	13.5	14.5

TABLE 4.9 Particle-Size Distributions for South Jordan Materials

Sieve Size	Percent Passing (%)	
	Neat Base	Blended Base
3/4 in.	100.0	100.0
1/2 in.	79.9	90.3
3/8 in.	68.1	82.3
No. 4	47.3	57.8
No. 8	36.4	39.6
No. 16	31.2	29.3
No. 30	28.1	24.0
No. 50	24.6	19.5
No. 100	17.6	13.5
No. 200	10.6	8.8

Table 4.10 presents the results of the specific gravity determinations, Atterberg limit determinations, and AASHTO and Unified soil classifications for the neat and blended base materials from each test location. The blended materials from Orem and San Marcos had lower specific gravities than the neat materials, probably due to the presence of asphalt cement, which has a specific gravity of approximately 1.0. For none of the materials except the neat base from San Marcos could the plastic limit be

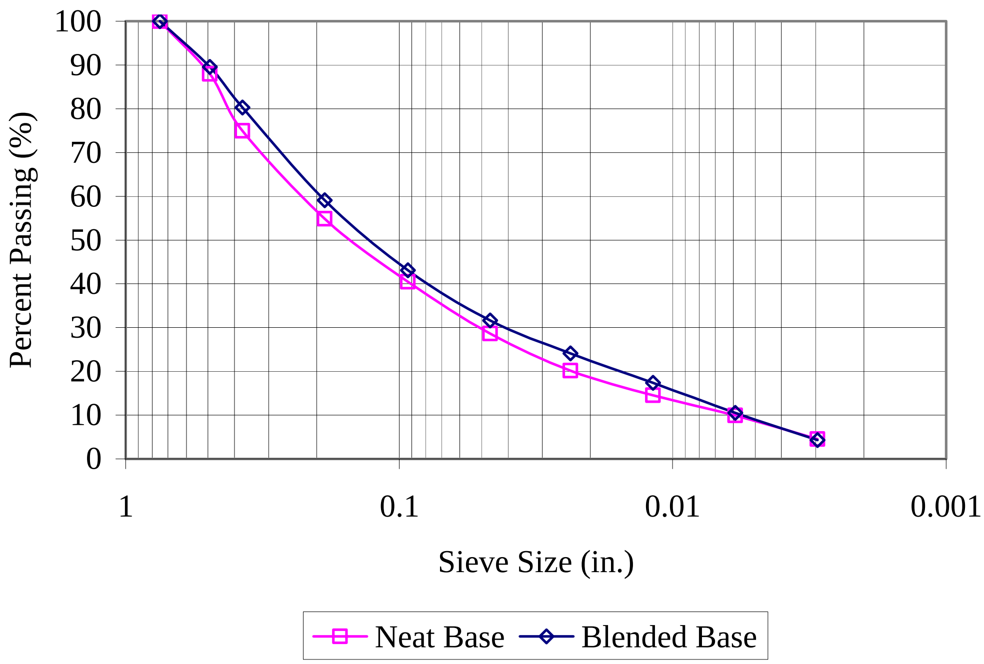

FIGURE 4.1 Particle-size distributions for Orem materials.

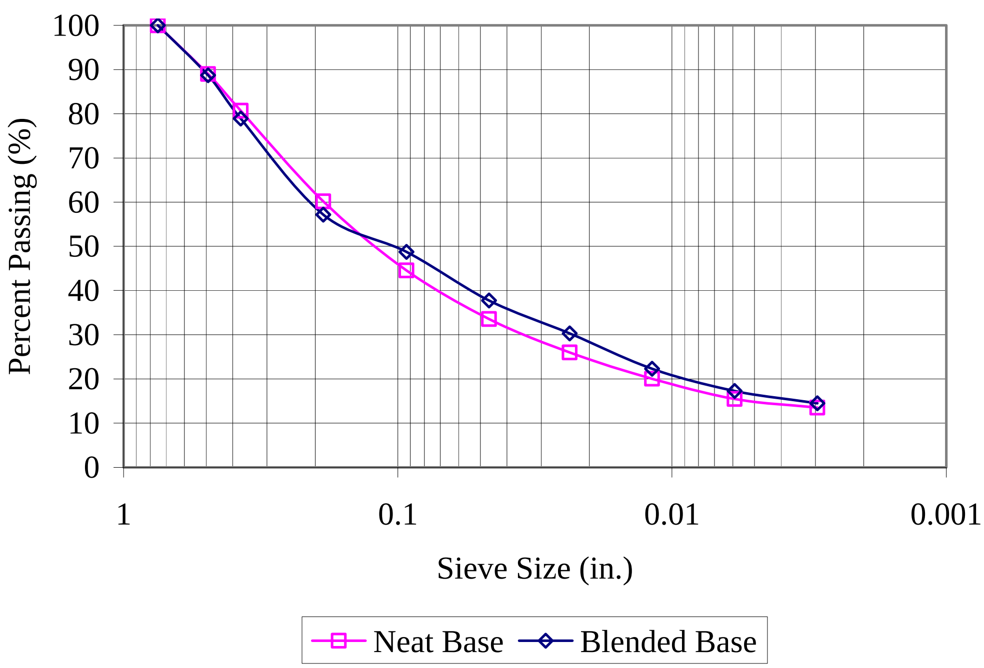

FIGURE 4.2 Particle-size distributions for San Marcos materials.

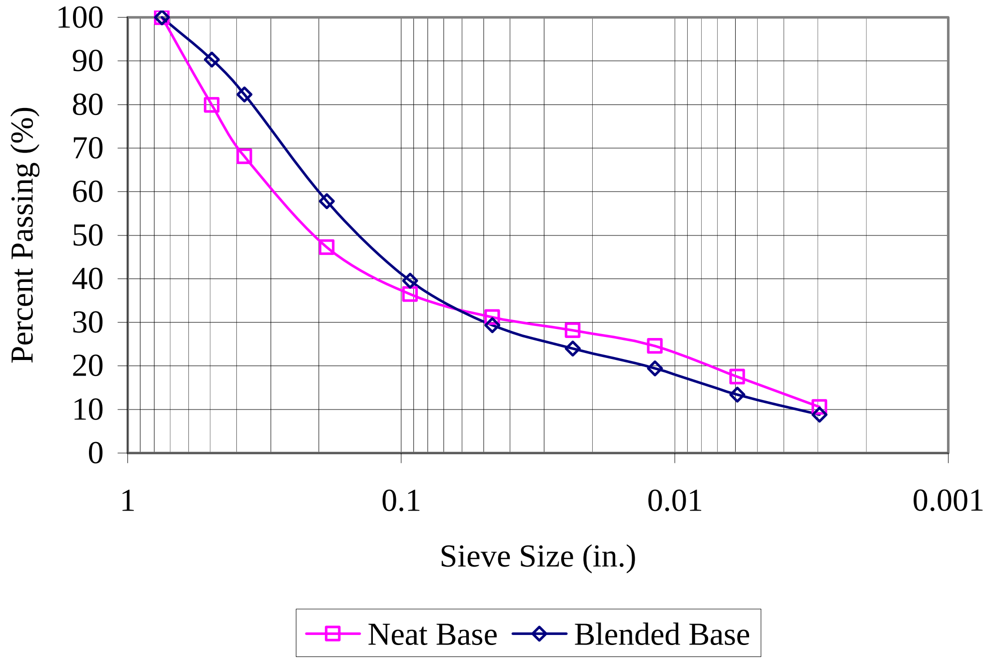

FIGURE 4.3 Particle-size distributions for South Jordan materials.

TABLE 4.10 Material Characteristics and Soil Classifications

Location	Material	Specific Gravity	Plasticity Index	Soil Classification	
				AASHTO	Unified
Orem	Neat	2.67	NP	A-1-a	SW
	Blended	2.61	NP	A-1-a	SW
San Marcos	Neat	2.60	6	A-1-a	SW
	Blended	2.52	NP	A-1-a	SW
South Jordan	Neat	2.57	NP	A-1-a	SW-SM
	Blended	2.61	NP	A-1-a	SW-SM

determined; therefore, the liquid limit test was performed only on the neat base from San Marcos, and all the others were characterized as non-plastic. The plastic and liquid limits for the San Marcos neat base were measured to be 23 and 29, respectively, yielding a plasticity index of 6.

The results of the burn-off tests are displayed in Table 4.11. The percentage of RAP in each material, as shown in Table 4.1, is directly correlated with the asphalt binder content shown in Table 4.11. As expected, the Orem material had the lowest asphalt binder content, and the South Jordan material had the highest asphalt binder content.

TABLE 4.11 Burn-Off Test Results

Location	Asphalt Binder Content in Blended Material (%)
Orem	1.9
San Marcos	3.1
South Jordan	3.3

4.3.2 Compaction Properties

Table 4.12 lists the OMC and MDD values determined for each of the tested materials using standard and modified Proctor compaction efforts. The OMC of the

TABLE 4.12 Compaction Test Results

Location	Compaction Level	Material Description	OMC (%)	MDD (pcf)
Orem	Standard	Neat	7.2	147.2
		Blended	8.2	141.6
	Modified	Neat	6.1	150.3
		Blended	6.3	143.7
San Marcos	Standard	Neat	11.5	136.5
		Blended	12.3	136.6
	Modified	Neat	8.7	139.6
		Blended	10.1	137.6
South Jordan	Standard	Neat	8.9	141.1
		Blended	9.1	135.2
	Modified	Neat	7.7	143.9
		Blended	7.6	139.2

blended base was generally higher than that of the neat base. This trend of increasing OMC with the presence of RAP differs from the findings of previous research in which OMC was shown to decrease with increasing RAP content (*8*). Because the previous research was performed on material processed using a full-size reclaimer as opposed to the PARM utilized in this study, the different trends may be attributable to different gradations produced by the different reclaimers. Similar to previous research, however, the MDD of the blended base was typically lower than the MDD of the neat base evaluated in this study. Furthermore, in all cases, the OMC associated with modified Proctor compaction was lower than that associated with standard Proctor compaction, and the MDD determined using modified Proctor compaction was higher than that determined using standard Proctor compaction.

4.3.3 Strength and Moisture Susceptibility

Regarding strength, the results of the laboratory CBR tests are shown in Tables 4.13 to 4.15. Table 4.13 contains the CBR test results of the tests performed on specimens at OMC. Table 4.14 contains the CBR test results of the tests performed on specimens that were sealed at OMC, heated at 140°F for 72 hours, and tested wet. Table 4.15 contains the CBR test results of the tests performed on specimens that were heated unsealed at 140°F for 72 hours and tested dry. The CBR values of the wet specimens tested at OMC ranged from 4 to 26 percent. The CBR values of the wet specimens tested at OMC after being heated to 140°F for 72 hours ranged from 3 to 27 percent. Finally, the CBR values of the dry specimens tested after being heated to 140°F for 72 hours ranged from 33 to 112 percent. The CBR values for both sample sets tested in the

TABLE 4.13 CBR Test Results for Wet Specimens at OMC

Location	Compaction Effort	Base Material	Specimen Number	Moisture Content (%)	CBR (%)
Orem	Standard	Neat	1	7.2	9
			2	7.3	10
			3	7.2	22
		Blended	1	8.3	7
			2	8.3	8
			3	8.3	11
	Modified	Neat	1	6.0	13
			2	6.0	22
			3	5.9	16
		Blended	1	6.1	13
			2	6.1	25
			3	6.1	20
San Marcos	Standard	Neat	1	11.6	8
			2	11.6	10
			3	11.5	7
		Blended	1	12.3	8
			2	12.4	9
			3	12.4	7
	Modified	Neat	1	7.5	23
			2	7.7	10
			3	7.5	26
		Blended	1	8.9	11
			2	9.1	10
			3	8.9	10
South Jordan	Standard	Neat	1	8.9	5
			2	9.0	5
			3	9.0	5
		Blended	1	9.2	13
			2	9.2	8
			3	9.1	9
	Modified	Neat	1	7.5	7
			2	7.5	10
			3	7.5	4
		Blended	1	7.2	9
			2	7.2	7
			3	7.6	11

TABLE 4.14 CBR Test Results for Wet Specimens at OMC after Heating at 140°F for 72 Hours

Location	Compaction Effort	Base Material	Specimen Number	Moisture Content (%)	CBR (%)
Orem	Standard	Neat	1	7.2	14
			2	7.1	13
			3	7.1	16
		Blended	1	8.2	15
			2	8.2	12
			3	8.2	14
	Modified	Neat	1	6.1	14
			2	6.0	23
			3	6.0	27
		Blended	1	6.2	18
			2	6.2	22
			3	6.3	15
San Marcos	Standard	Neat	1	10.9	8
			2	11.1	9
			3	11.2	10
		Blended	1	11.7	9
			2	11.8	6
			3	11.7	9
	Modified	Neat	1	8.4	20
			2	8.4	16
			3	8.5	11
		Blended	1	9.5	17
			2	9.5	15
			3	9.5	14
South Jordan	Standard	Neat	1	9.0	6
			2	8.8	3
			3	8.8	6
		Blended	1	8.9	14
			2	9.1	9
			3	9.0	13
	Modified	Neat	1	7.7	8
			2	7.7	10
			3	7.7	13
		Blended	1	7.5	12
			2	7.5	15
			3	7.5	10

TABLE 4.15 CBR Test Results for Dry Specimens after Heating at 140°F for 72 Hours

Location	Compaction Effort	Base Material	Specimen Number	Moisture Content (%)	CBR (%)
Orem	Standard	Neat	1	7.3	81
			2	7.3	62
			3	7.3	59
		Blended	1	8.4	57
			2	8.4	44
			3	8.5	55
	Modified	Neat	1	6.1	112
			2	6.2	43
			3	6.1	85
		Blended	1	6.4	64
			2	6.4	56
			3	6.4	58
San Marcos	Standard	Neat	1	11.8	55
			2	11.7	37
			3	11.8	50
		Blended	1	12.5	40
			2	12.5	55
			3	12.5	47
	Modified	Neat	1	8.6	40
			2	8.9	69
			3	8.7	66
		Blended	1	9.1	52
			2	9.4	56
			3	9.5	53
South Jordan	Standard	Neat	1	9.1	41
			2	9.1	33
			3	9.1	45
		Blended	1	9.3	37
			2	9.3	48
			3	9.4	38
	Modified	Neat	1	7.6	75
			2	7.7	60
			3	7.5	62
		Blended	1	7.8	37
			2	7.6	50
			3	7.7	51

wet condition yielded almost identical ranges of CBR values, whereas the CBR values for the specimens that were allowed to dry out were much higher. This indicates that the specimens gained substantial strength as they dried at elevated temperatures.

Regarding moisture susceptibility, Tables 4.16 and 4.17 show test results for specimens that were heated at 104°F and 140°F for 72 hours, respectively. Specimens with dielectric values less than 10 are considered non-moisture-susceptible and are considered good for use as a road base. Specimens with dielectric values between 10 and 16 are considered marginally moisture-susceptible, and specimens with dielectric values above 16 are considered highly moisture-susceptible (*23*, *24*). As shown in Table 4.16, the measured final dielectric values for the specimens dried at 104°F for 72 hours ranged from 8.4 to 18.0, indicating that most of these specimens were classified as marginally or highly moisture-susceptible in the TST. Only three of the specimens had final dielectric values below 10.

Table 4.17 shows that the measured final dielectric values for the specimens dried at 140°F for 72 hours ranged from 10.6 to 21.5, indicating that all of these specimens were classified as marginally or highly moisture-susceptible in the TST. These results suggest that heating at 140°F did not improve the moisture-susceptibility ratings of the specimens compared to heating at 104°F.

TABLE 4.16 TST Results for Specimens Dried at 104°F for 72 Hours

Location	Compaction Effort	Base Material	Specimen Number	Moisture Content (%)	Dielectric Value
Orem	Standard	Neat	1	6.0	17.6
			2	5.3	14.9
			3	5.8	14.0
		Blended	1	7.2	12.0
			2	7.3	11.4
			3	7.3	12.1
	Modified	Neat	1	5.2	11.9
			2	5.3	13.7
			3	5.4	14.7
		Blended	1	6.4	12.5
			2	6.4	10.4
			3	6.3	8.4
San Marcos	Standard	Neat	1	11.1	16.5
			2	11.2	12.1
			3	11.1	13.7
		Blended	1	11.6	17.7
			2	11.8	16.1
			3	11.7	18.0
	Modified	Neat	1	10.3	11.1
			2	10.4	11.0
			3	10.5	16.3
		Blended	1	9.1	10.6
			2	9.4	11.9
			3	9.6	13.5
South Jordan	Standard	Neat	1	6.8	11.2
			2	7.2	13.8
			3	7.4	10.5
		Blended	1	7.4	10.6
			2	7.7	12.6
			3	7.9	11.5
	Modified	Neat	1	6.5	10.4
			2	6.6	10.2
			3	6.2	11.5
		Blended	1	6.8	8.8
			2	6.7	9.6
			3	6.8	10.0

TABLE 4.17 TST Results for Specimens Dried at 140°F for 72 Hours

Location	Compaction Effort	Base Material	Specimen Number	Moisture Content (%)	Dielectric Value
Orem	Standard	Neat	1	4.7	13.2
			2	3.8	12.2
			3	4.0	12.9
		Blended	1	7.1	14.6
			2	7.1	13.5
			3	7.2	12.7
	Modified	Neat	1	3.7	16.0
			2	3.5	15.4
			3	3.6	14.7
		Blended	1	6.0	18.2
			2	6.1	15.4
			3	6.0	17.1
San Marcos	Standard	Neat	1	10.9	14.1
			2	10.9	11.0
			3	10.8	10.6
		Blended	1	11.4	21.5
			2	11.5	16.8
			3	11.4	17.5
	Modified	Neat	1	10.1	16.8
			2	10.2	16.1
			3	10.1	17.7
		Blended	1	8.9	13.0
			2	9.2	15.8
			3	9.4	16.4
South Jordan	Standard	Neat	1	6.8	13.8
			2	7.1	13.3
			3	7.1	16.5
		Blended	1	7.6	11.7
			2	7.4	11.0
			3	7.6	13.2
	Modified	Neat	1	6.2	12.9
			2	6.0	13.2
			3	5.0	15.4
		Blended	1	6.5	14.5
			2	6.3	11.5
			3	6.6	12.1

4.4 STATISTICAL ANALYSES

The results of statistical analyses performed on the field and laboratory data are described in the following sections.

4.4.1 Field Data

At the completion of field testing, a statistical analysis was performed in order to determine if a significant difference existed between the properties of the neat base and those of the blended base at each location. The variables analyzed included base modulus and CBR values. Table 4.18 reports the level of significance, or *p*-value, calculated for each variable. *P*-values less than or equal to 0.05 indicate that the pre-reclamation neat base material, the post-reclamation blended base material tested immediately after compaction, and/or the post-reclamation blended base material tested after one year of service life are significantly different. *P*-values less than or equal to 0.05 are shown in bold-face font. According to Table 4.18, only the base modulus value for Orem and the base CBR value for San Marcos were characterized by significant differences. Plots of the mean values for these variables are given in Figures 4.4 and 4.5 respectively, for all three locations.

TABLE 4.18 Significance Levels for Field Main Effects

Location	*P* -Values	
	Base Modulus	Base CBR
Orem	**<0.001**	0.097
San Marcos	0.227	**0.009**
South Jordan	0.099	0.058

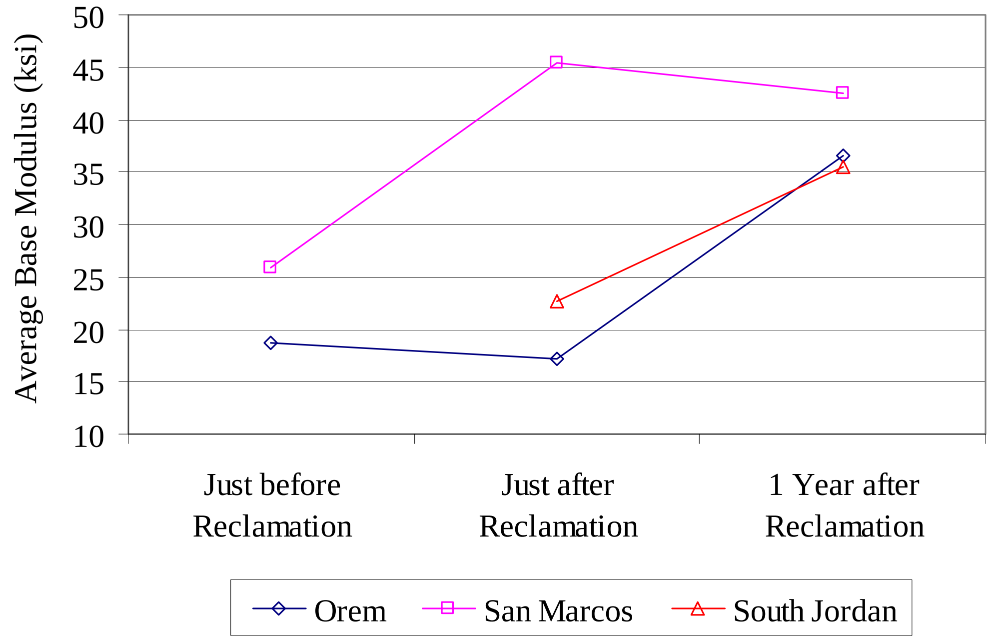

FIGURE 4.4 Average base modulus values.

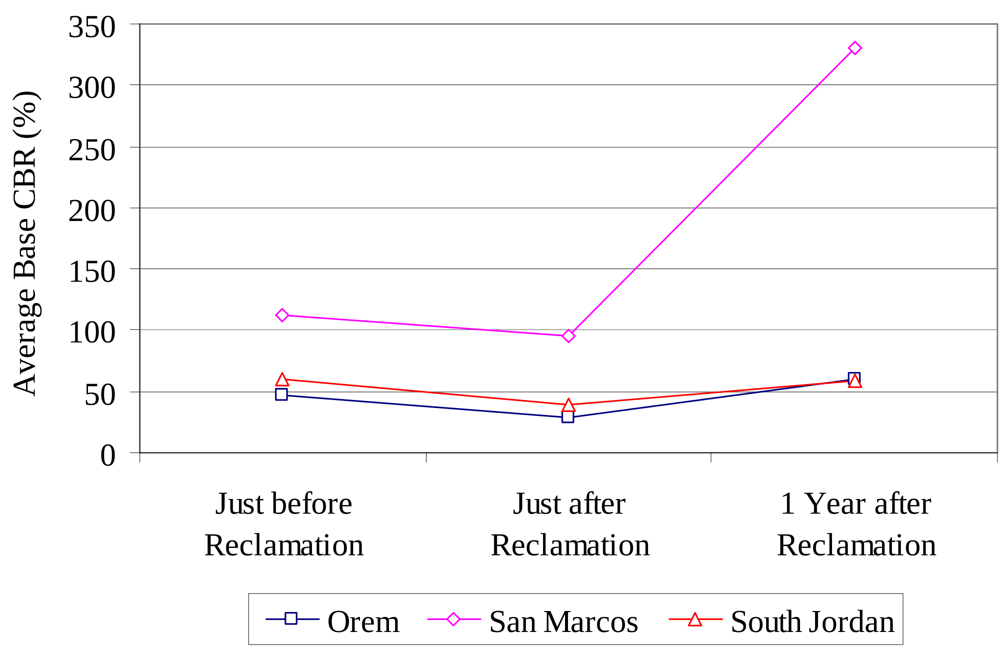

FIGURE 4.5 Average base CBR values.

Tukey's mean separation procedure was then applied in order to determine which time period (just before, just after, or one year after reclamation) differed significantly from the others in each case in which significant differences were identified. For the Orem material, which had the lowest RAP content at 16 percent, the base modulus just before reclamation and the base modulus just after reclamation were both significantly different than the base modulus one year after reclamation. In fact, the Orem material exhibited a 94.8 percent higher average base modulus one year after reclamation than just before reclamation. These benefits were achieved despite the fact that the Orem material just after reclamation had an average relative compaction of only 87.0 percent with respect to the modified Proctor value determined in the laboratory, which was lower than the average relative compaction of 88.7 percent associated with the pre-reclamation condition. A higher level of post-reclamation compaction would have produced even greater benefit.

For the San Marcos material, which had an intermediate RAP content of 33 percent, the base CBR value just before reclamation and the base CBR value just after reclamation were both significantly different than the base CBR value one year after reclamation. Even more impressive than the results obtained at the Orem location, the San Marcos material exhibited a 193.9 percent higher CBR value one year after reclamation than just before reclamation. No nuclear density gauge data were taken at San Marcos just after reclamation, so comparing the quality of compaction before and after reclamation is not possible.

For the South Jordan material, which had the highest RAP content at 48 percent, the statistical analyses indicated a lack of significant differences across the three time periods. This occurred despite the fact that the average relative compaction with respect to the modified Proctor value determined in the laboratory was 86.7 percent after reclamation, a definite improvement over the average relative compaction of 79.3 percent characteristic of the base material before reclamation. The absence of a statistically significant improvement in the structural quality of the base material after reclamation may be attributable to the comparatively higher RAP content at this location, which would be consistent with the findings of previous research (*8*).

Comparisons of the standard deviations corresponding to the modulus and CBR values of the neat and blended base materials previously presented in Tables 4.3 and 4.4 for each location are presented in Figures 4.6 and 4.7. In these charts, lower standard deviations correspond to lower spatial variability, or greater uniformity, on the project. The data show that the FDR process produced equivalent or decreased spatial variability

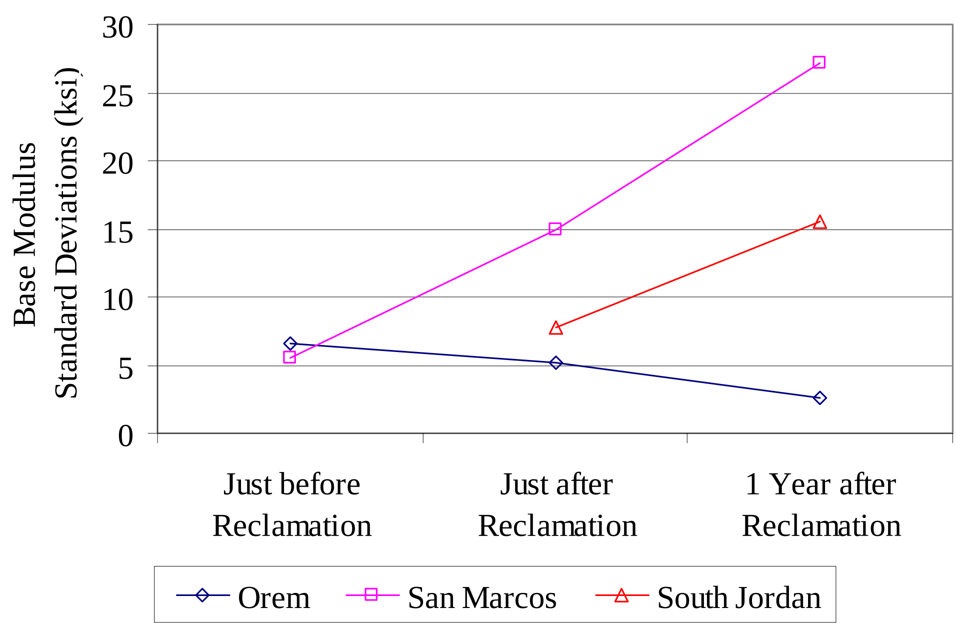

FIGURE 4.6 Base modulus standard deviations.

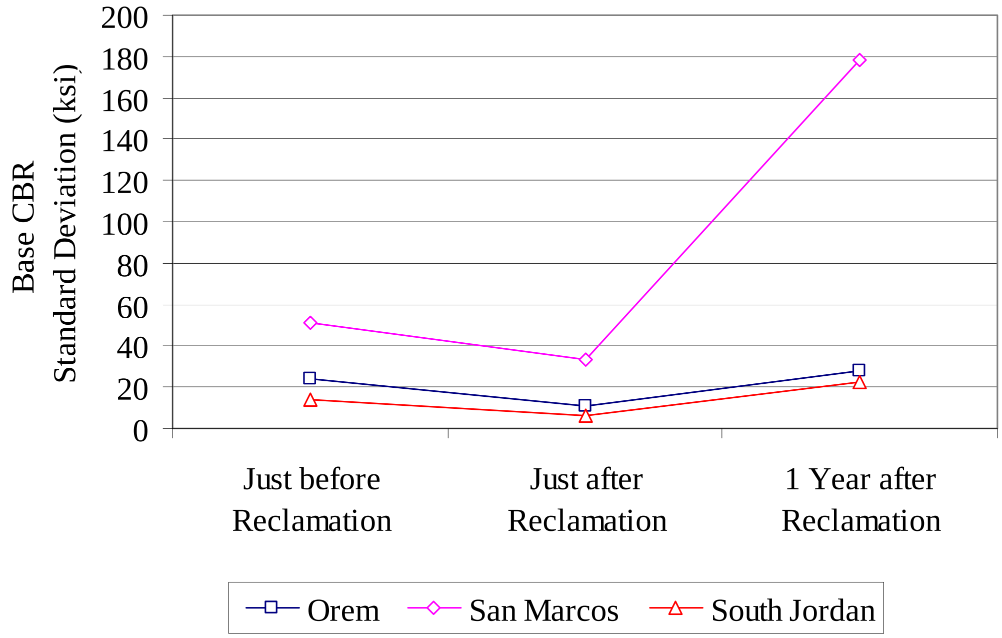

FIGURE 4.7 Base CBR standard deviations.

with respect to both base modulus and CBR values at the Orem location, while the San Marcos location exhibited increased spatial variability with respect to both types of measurements one year after reclamation despite the fact that the spatial variability in base CBR just after reclamation was somewhat lower than that associated with the pre-reclamation condition. The available base modulus data for the South Jordan location indicate increasing variability after reclamation, while the CBR data suggest that the FDR process did not markedly affect the spatial variability on the project.

4.4.2 Laboratory Data

At the completion of laboratory testing, a fixed-effects ANOVA was performed on each of the dependent variables, which included CBR, dry density, and moisture content for the CBR analysis and dielectric value, dry density, and moisture content for the TST analysis. The independent variables in the analysis were compaction level, condition, material type, and temperature. Table 4.19 summarizes the levels of each factor included in the statistical analysis. Initially, a full-model statistical analysis including all main effects and two- and three-way interactions was performed on each set of data collected during laboratory testing. Factors with *p*-values greater than 0.15 were considered insignificant and were removed from the model. Once insignificant factors had been identified and removed, a reduced-model analysis was then performed on the remaining factors. Tables 4.20, 4.21, and 4.22 report the reduced-model *p*-values associated with each independent variable for the tests conducted on the Orem, San Marcos, and South Jordan materials, respectively. Bold-face font indicates *p*-values less than or equal to 0.05, italicized font indicates *p*-values for main effects that were greater than 0.15 but were necessarily included because they contributed to an interaction with a *p*-value less than or equal to 0.15, and hyphens indicate values that were greater than 0.15 in the full-model analysis and were therefore excluded in the reduced-model analysis. In this report, only the statistically significant main effects are discussed in detail, although

TABLE 4.19 Levels of Experimental Factors

Factor	Levels
Compaction Effort	Standard
	Modified
Condition (CBR Specimens Only)	OMC
	Dry
Material Type	Neat
	Blended
CBR Temperature	68°F
	140°F
TST Temperature	104°F
	140°F

TABLE 4.20 Significance Levels for Orem Laboratory Main Effects and Interactions

Factor	*P*- Values					
	CBR Test			TST		
	CBR	Moisture Content	Dry Density	Dielectric Value	Moisture Content	Dry Density
Compaction Effort	**0.0388**	**<0.0001**	**<0.0001**	*0.2514*	**<0.0001**	**<0.0001**
Condition	**<0.0001**	**<0.0001**	0.1379	-	**-**	**-**
Material Type	**0.0123**	**<0.0001**	**<0.0001**	**0.0471**	**<0.0001**	**<0.0001**
Temperature	**-**	*0.5358*	**0.0187**	**0.0016**	**<0.0001**	**-**
Compaction Effort * Condition	-	**<0.0001**	-	-	-	-
Compaction Effort * Material Type	-	**<0.0001**	-	-	**0.0039**	0.1129
Compaction Effort * Temperature	-	**<0.0001**	0.1057	**0.0002**	-	-
Condition * Material Type	**0.0341**	**0.0496**	0.1014	-	-	-
Condition * Temperature	-	-	-	-	-	-
Material Type * Temperature	-	-	-	**0.0003**	**<0.0001**	-
Compaction Effort * Condition * Material Type	**-**	**<0.0001**	-	-	-	-
Compaction Effort * Condition * Temperature	**-**	**-**	-	-	-	-
Compaction Effort * Material Type * Temperature	**-**	**-**	0.1014	-	-	-
Condition * Material Type * Temperature	-	-	-	-	-	-

TABLE 4.21 Significance Levels for San Marcos Laboratory Main Effects and Interactions

Factor	*P*- Values					
	CBR Test			TST		
	CBR	Moisture Content	Dry Density	Dielectric Value	Moisture Content	Dry Density
Compaction Effort	**0.0006**	**<0.0001**	**<0.0001**	0.1391	**<0.0001**	**<0.0001**
Condition	**<0.0001**	**<0.0001**	**<0.0001**	-	-	-
Material Type	-	**<0.0001**	*0.9770*	**0.0397**	**0.0011**	-
Temperature	-	0.0721	**0.0205**	0.0767	**0.0002**	-
Compaction Effort * Condition	-	**<0.0001**	-	-	-	-
Compaction Effort * Material Type	-	**0.0018**	**0.0050**	**0.0013**	-	-
Compaction Effort * Temperature	-	**<0.0001**	**<0.0001**	**0.0255**	-	-
Condition * Material Type	-	**<0.0001**	**0.0103**	-	-	-
Condition * Temperature	-	-	-	-	-	-
Material Type * Temperature	-	**0.0111**	**0.0018**	-	-	-
Compaction Effort * Condition * Material Type	-	**<0.0001**	**0.0136**	-	-	-
Compaction Effort * Condition * Temperature	-	-	-	-	-	-
Compaction Effort * Material Type * Temperature	-	-	**0.0322**	-	-	-
Condition * Material Type * Temperature	-	-	-	-	-	-

TABLE 4.22 Significance Levels for South Jordan Laboratory Main Effects and Interactions

Factor	*P*- Values					
	CBR Test			TST		
	CBR	Moisture Content	Dry Density	Dielectric Value	Moisture Content	Dry Density
Compaction Effort	**<0.0001**	**<0.0001**	**<0.0001**	**-**	**<0.0001**	**<0.0001**
Condition	**<0.0001**	**<0.0001**	0.0875	-	-	-
Material Type	0.1061	0.0543	**<0.0001**	**0.0286**	**0.0001**	**<0.0001**
Temperature	-	*0.5092*	*0.2559*	**0.0004**	**0.0091**	-
Compaction Effort * Condition	**0.0001**	**<0.0001**	**-**	-	-	-
Compaction Effort * Material Type	**0.0003**	-	**0.0002**	-	-	**0.0153**
Compaction Effort * Temperature	-	**0.0124**	0.0562	-	0.0971	-
Condition * Material Type	**0.0002**	**0.0070**	**0.0198**	**-**	-	-
Condition * Temperature	-	-	-	-	-	-
Material Type * Temperature	-	-	**0.0122**	-	-	-
Compaction Effort * Condition * Material Type	**0.0106**	**0.0094**	**-**	-	-	-
Compaction Effort * Condition * Temperature	-	-	-	-	-	-
Compaction Effort * Material Type * Temperature	-	-	-	-	-	-
Condition * Material Type * Temperature	-	-	-	-	-	-

plots of the statistically significant two-way interactions are provided in Appendices B, C, and D for the Orem, San Marcos, and South Jordan locations, respectively. No analyses of the three-way interactions are provided, as describing those more complex relationships is beyond the scope of this research.

Figures 4.8 to 4.13 display the least square mean (LSM) values for each of the dependent variables for which statistically significant main effects were identified in the analyses. For ease of comparison, data for all three locations are plotted on the same graph in each case.

As shown in Figure 4.8, the LSM CBR values were significantly higher for the specimens compacted using the modified Proctor method than for those compacted using the standard Proctor method. Increases in CBR value of 20.5, 26.6, and 35.4 percent

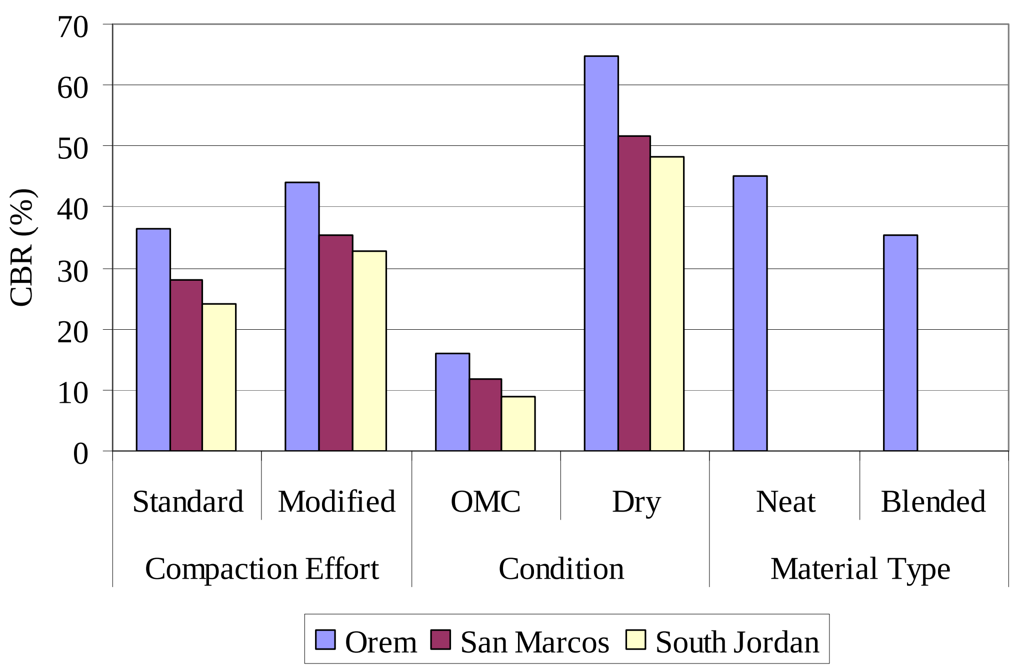

FIGURE 4.8 Least square means for main effects of compaction effort, condition, and material type on CBR value.

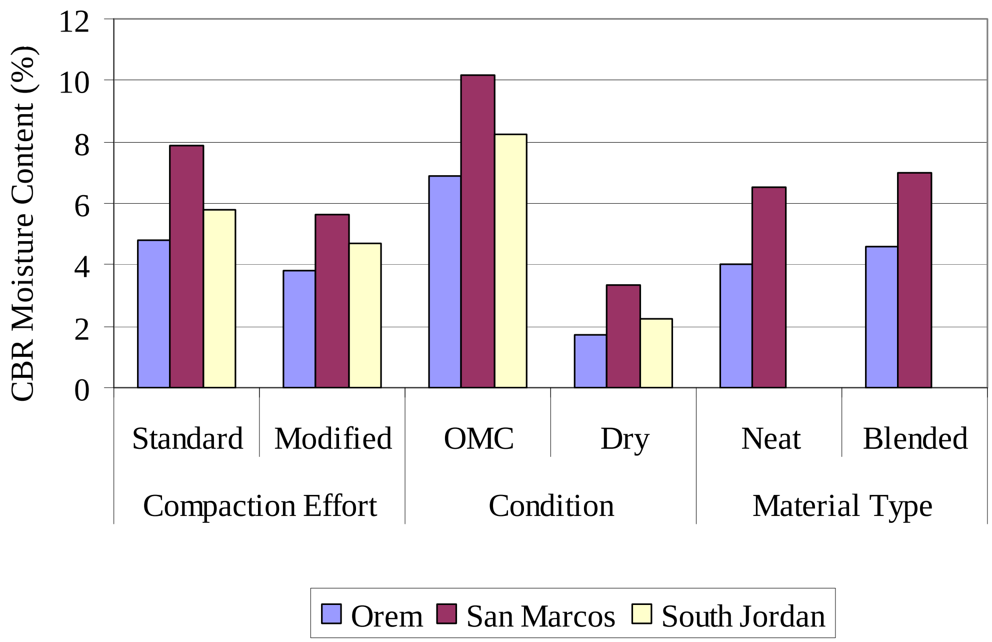

FIGURE 4.9 Least square means for main effects of compaction effort, condition, and material type on CBR test moisture content.

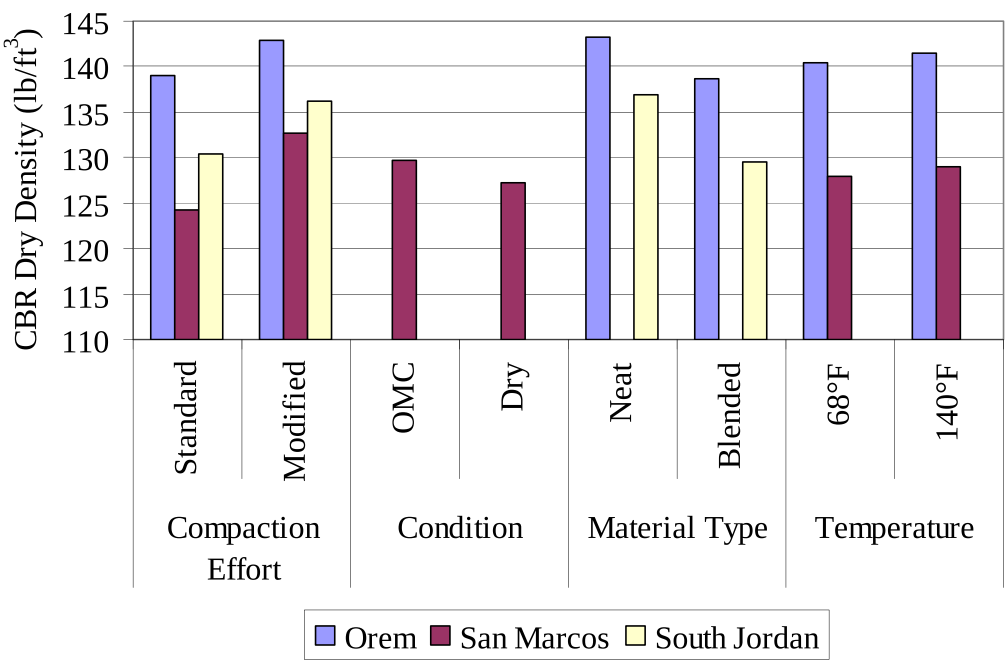

FIGURE 4.10 Least square means for main effects of compaction effort, condition, material type, and temperature on CBR test dry density.

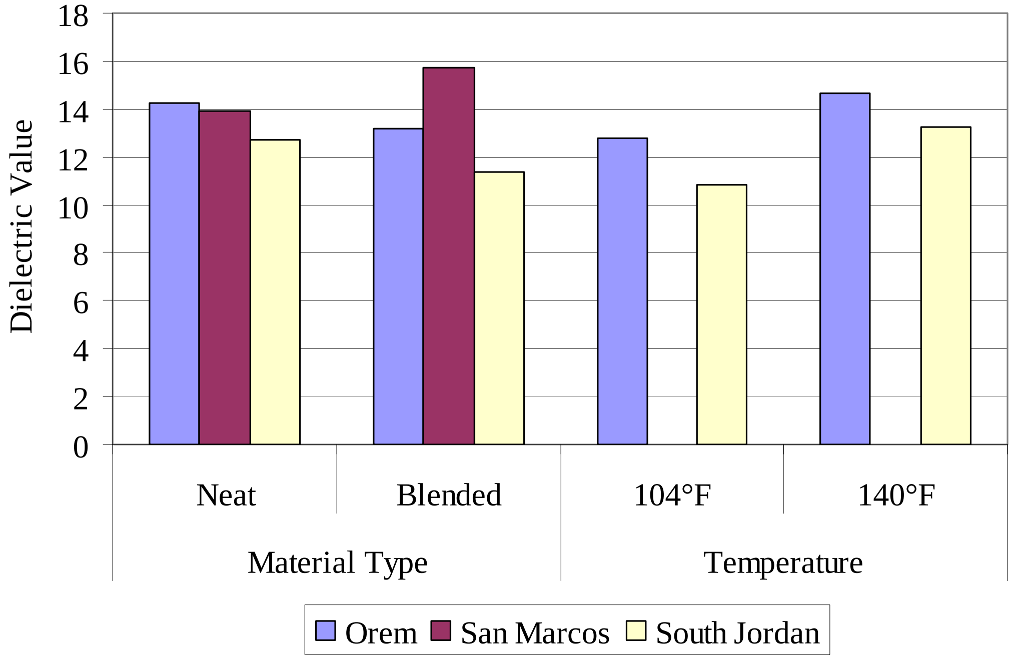

FIGURE 4.11 Least square means for main effects of material type and temperature on dielectric value.

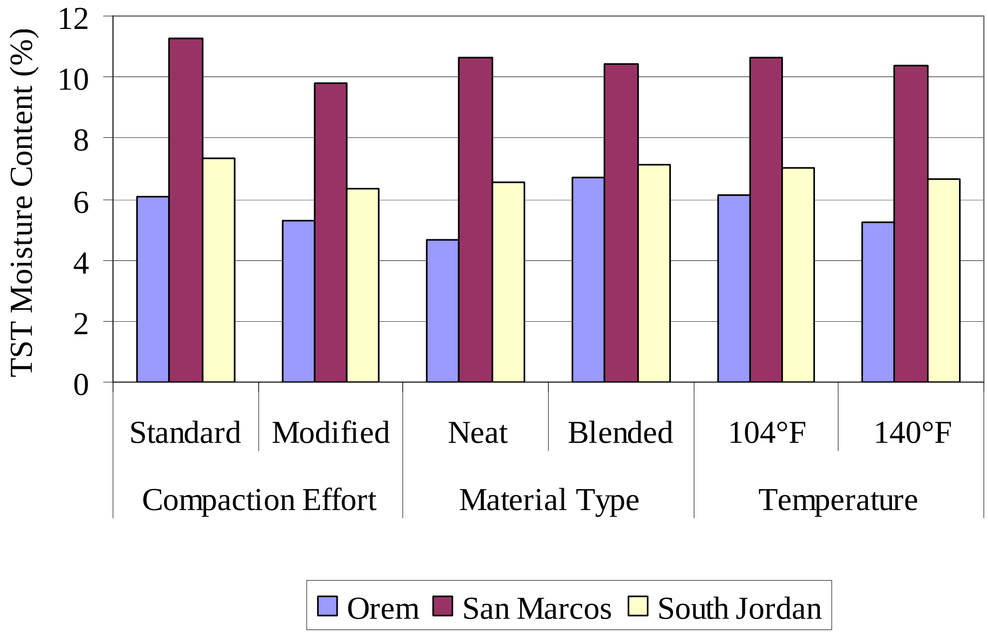

FIGURE 4.12 Least square means for main effects of compaction effort, material type, and temperature on TST moisture content.

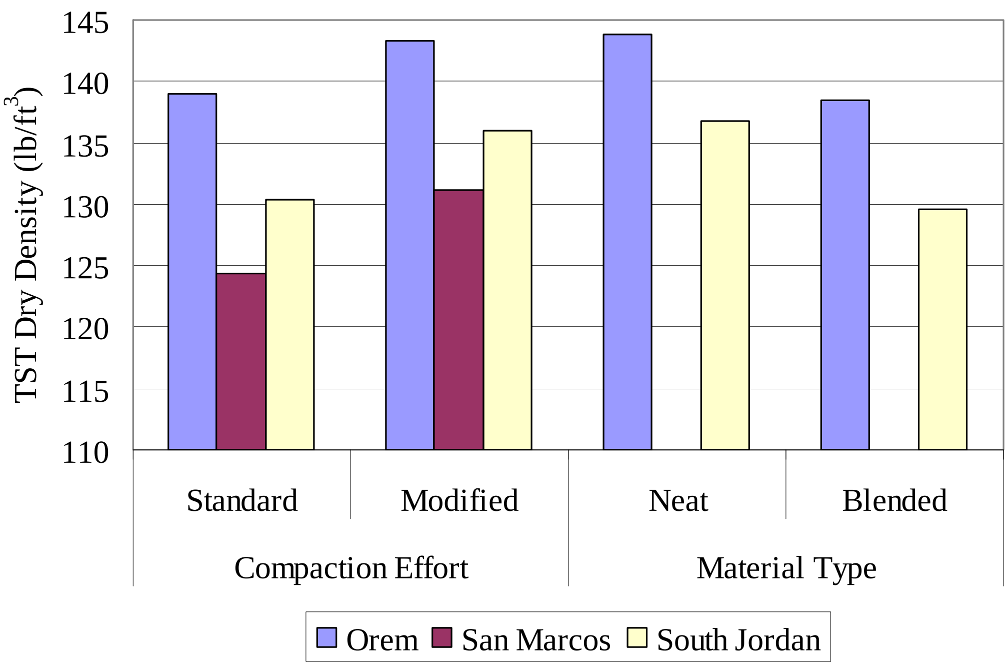

FIGURE 4.13 Least square means for main effects of compaction effort and material type on TST dry density.

were exhibited by the Orem, San Marcos, and South Jordan materials, respectively. Also, the CBR values for specimens tested in the dry condition were significantly higher than those obtained from specimens tested at OMC. Increases in CBR value of 306.2, 335.2, and 440.5 percent were experienced by the Orem, San Marcos, and South Jordan materials, respectively. Clearly, providing a high level of compaction during construction and preventing water ingress over time by maintaining the wearing course in good condition and ensuring positive drainage yield improvements in the CBR value of the reclaimed layer. Concerning material type, the blended material exhibited an average CBR value lower by 21.6 percent than that of the neat material at the Orem location; this behavior is consistent with the findings of Guthrie et al. (*8*) and shows that additions of RAP lead to reductions in CBR values.

As shown in Figure 4.9, the LSM CBR test moisture contents were significantly lower for the specimens compacted using the modified Proctor method than for those compacted using the standard Proctor method. Decreases in CBR test moisture contents of 20.3, 28.7, and 18.3 percent were exhibited by the Orem, San Marcos, and South Jordan materials, respectively. The standard compaction effort leaves more voids within the specimen, thus allowing for higher moisture contents. Also, as was expected, the CBR test moisture contents for specimens tested in the dry condition were significantly lower than those of specimens tested at OMC. Decreases in CBR test moisture contents of 74.7, 67.2, and 72.9 percent were experienced by the Orem, San Marcos, and South Jordan materials, respectively. Concerning material type, the blended material exhibited an average CBR test moisture content higher by 13.7 and 6.7 percent than that of the neat material at the Orem and San Marcos locations, respectively, suggesting that the addition of RAP facilitated higher degrees of water ingress.

As shown in Figure 4.10, the LSM CBR test dry densities were significantly higher for the specimens compacted using the modified Proctor method than for those compacted using the standard Proctor method; this was expected due to the higher compaction energy associated with the modified method. Increases in CBR test dry densities of 2.8, 6.9, and 4.5 percent were exhibited by the Orem, San Marcos, and South Jordan materials, respectively. Also, the average CBR test dry density for the San Marcos specimens tested in the dry condition was lower by 1.8 percent than that associated with the corresponding specimens tested at OMC; this may be attributable to specimen shrinkage during drying caused by water evaporation from the aggregate matrix and is probably not of practical importance. Concerning material type, the blended material exhibited a CBR test dry density lower by 3.1 and 5.4 percent than that of the neat material at the Orem and South Jordan locations, respectively, consistent with the MDD values computed for these materials in this research. Regarding temperature, the specimens heated to 140°F were characterized by a CBR test dry density higher by 0.73 and 0.74 percent than that of the specimens heated to 68°F at the Orem and San Marcos locations, respectively; this may also be attributable to drying shrinkage and is also probably not of practical importance.

As shown in Figure 4.11, the LSM dielectric values of the Orem and South Jordan blended materials were lower by 7.6 and 10.3 percent, respectively, than those of the neat materials, but the average dielectric value of the San Marcos blended material was higher by 13.1 percent than that of the neat material. While statistically significant in each individual case, the reversal in trends among the materials is probably not of practical importance because, since all of the dielectric values are between 10 and 16, all of the specimens would be classified the same as marginally moisture-susceptible. Regarding temperature, the Orem and South Jordan specimens heated to 140°F were characterized by dielectric values higher by 14.8 percent and 21.8 percent, respectively, than those of the specimens heated to 104°F; again, this effect is probably not of practical importance.

As shown in Figure 4.12, the LSM TST moisture contents were significantly lower for the specimens compacted using the modified Proctor method than for those compacted using the standard Proctor method. Decreases in TST moisture contents of 12.2, 13.4, and 13.0 percent were exhibited by the Orem, San Marcos, and South Jordan materials, respectively. As with the CBR test moisture contents, this suggests that the standard compaction effort leaves more voids within the specimen, thus allowing for higher moisture contents. Also, the TST moisture contents of the Orem and South Jordan blended materials were higher by 43.0 and 8.1 percent, respectively, than those of the neat materials, but the average TST moisture content of the San Marcos blended material was lower by 2.0 percent than that of the neat material. Remarkably, these trends in TST moisture content are exactly the opposite of those associated with dielectric value. Additional information about the moisture profiles of individual test specimens would be needed to develop an explanation for this occurrence. Regarding temperature, TST moisture contents were lower for specimens heated to 140°F than for specimens heated to 104°F. Decreases in TST moisture content of 15.1, 2.4, and 4.6 percent were exhibited by the Orem, San Marcos, and South Jordan materials, respectively. Because these differences correspond to changes of less than 1 percentage point, they are probably not of practical importance.

As shown in Figure 4.13, the LSM TST dry densities were significantly higher for the specimens compacted using the modified Proctor method than for those compacted using the standard Proctor method; this was expected due to the higher compaction energy associated with the modified method. Increases in TST dry densities of 3.2, 5.5, and 4.3 percent were exhibited by the Orem, San Marcos, and South Jordan materials, respectively. Concerning material type, the blended material exhibited a TST dry density lower by 3.8 and 5.3 percent than that of the neat material at the Orem and South Jordan locations, respectively, consistent with the MDD values computed for these materials in this research.

4.5 SUMMARY

The reclaimed base materials consisted of 16, 33, and 48 percent RAP at the Orem, Utah; San Marcos, Texas; and South Jordan, Utah, test sites, respectively. Before reclamation, the test sites at each location exhibited various degrees of pavement distress, but none of the test sites at any of the locations exhibited any visual distress one year after reclamation.

All of the neat and blended materials sampled from the sites established for this research were classified as A-1-a in the AASHTO soil classification method and as SW for the Orem and San Marcos materials and SW-SM for the South Jordan materials in the Unified soil classification system. Concerning gradation, both the Orem and San Marcos materials were slightly finer after reclamation, and the South Jordan material was more dense-graded after reclamation. In this research, the OMC of the blended base at each location was generally higher than that of the neat base, and the MDD of the blended base was typically lower than that of the neat base.

The CBR values of the materials tested at OMC ranged from 4 to 26 percent when tested at room temperature and from 3 to 27 percent after being heated in a sealed condition at 140°F for 72 hours, respectively. In a dry condition achieved by heating in an unsealed condition at 140°F for 72 hours, the specimens exhibited CBR values ranging from 33 to 112 percent. Therefore, CBR values were much more sensitive to moisture content than to temperature within the ranges of these factors investigated in this study, and improvements in CBR values due to summer heating of reclaimed materials should not be expected unless drying also occurs.

In the TST, the measured final dielectric values for the specimens dried at 104°F for 72 hours ranged from 8.4 to 18.0, indicating that most of these specimens were classified as marginally or highly moisture-susceptible in the TST; only three of the specimens had final dielectric values below 10. The measured final dielectric values for the specimens dried at 140°F for 72 hours ranged from 10.6 to 21.5, indicating that all of these specimens were classified as marginally or highly moisture-susceptible in the TST. These results suggest that heating at 140°F did not improve the moisture-susceptibility ratings of the specimens compared to heating at 104°F.

The results of the ANOVA and Tukey's analyses of field data indicate that the base modulus of the Orem material was significantly higher one year after reclamation than just before reclamation and that the San Marcos CBR value was significantly higher one year after reclamation than just before reclamation. These results show that the FDR process significantly increased the stiffness and/or strength of the base material at these locations. The South Jordan material did not experience a significant change in either base modulus value or CBR value, suggesting that the FDR process did not significantly improve or degrade the South Jordan material.

An evaluation of spatial variability indicated that the FDR process produced equivalent or decreased spatial variability with respect to both base modulus and CBR values at the Orem location, while the San Marcos location exhibited increased spatial variability with respect to both types of measurements one year after reclamation. The available base modulus data for the South Jordan location indicate increasing variability after reclamation, while the CBR data suggest that the FDR process did not markedly affect spatial variability on that project.

The results of the laboratory tests for all three locations indicate that specimens compacted using the modified Proctor method exhibit significantly higher CBR values, lower CBR test moisture contents, higher CBR test dry densities, lower TST moisture contents, and higher TST dry densities than specimens compacted using the standard Proctor method. Also, the CBR values for specimens tested in the dry condition were significantly higher than those obtained from specimens tested at OMC; the CBR test moisture contents for the former specimens were significantly lower than those of specimens tested at OMC. Clearly, providing a high level of compaction during construction and preventing water ingress over time by maintaining the wearing course in good condition and ensuring positive drainage yield improvements in the CBR value of the reclaimed layer. Concerning material type, the blended material exhibited a significantly lower CBR value than that of the neat material only at the Orem location, although the CBR test moisture contents of the blended materials at both the Orem and San Marcos locations were significantly higher than those of the neat materials. Also, the blended materials at the Orem and South Jordan locations were both characterized by lower dry densities than those of the neat materials. The effect of material type on dielectric value in the TST was not of practical importance, nor was any of the effects of temperature on any of the dependent variables of practical importance.

CHAPTER 5

CONCLUSION

5.1 SUMMARY

With the increasing use of FDR for pavement reconstruction, design engineers and street superintendents need more information about the properties of recycled materials in their jurisdictions. In particular, data demonstrating the effect of RAP content on the strength and durability of the base material is needed. While several studies on recycled materials have been completed, research comparing the in-situ properties of pre- and post-reclamation base materials through both field and laboratory data was not identified in the literature. Furthermore, all of the existing studies were focused on projects involving full-size reclaimers rather than PARMs. Therefore, the purpose of this research was to determine the effect of recycling on the strength and durability of aggregate base layers in a coordinated approach involving both field and laboratory testing. Field comparisons between the pre-reclamation neat base and post-reclamation blended base were supplemented with laboratory experiments conducted to determine the effects of RAP content, compaction effort, and heating on the strength and durability of roadways reconstructed using FDR with a PARM. Also, the effect of reclamation on the spatial uniformity of the pavement structures was explored by comparing variability in the pre- and post-reclamation material properties.

In order to assess the differences in strength and durability between neat and blended base materials, BYU research personnel conducted both field and laboratory testing in connection with FDR projects at each of three different test locations: Orem, Utah; San Marcos, Texas; and South Jordan, Utah. In all three cases, pavement reconstruction was performed using a PARM. Evaluations of each pavement structure, including distress surveys, PFWD tests, DCP tests, and NDG tests, were conducted prior to reclamation. The neat base material was then sampled to facilitate strength and durability testing in the laboratory using the CBR test and TST, respectively. Following the FDR process, the blended base material was also sampled for laboratory testing, and the compacted, reclaimed layer was subsequently subjected to PFWD, DCP, and NDG testing prior to placement of a new asphalt wearing course. After one year of service, distress surveys were again performed, and each facility was retested using the PFWD and DCP. Field and laboratory data were then subjected to statistical analyses to address the research objectives.

5.2 FINDINGS

The reclaimed base materials consisted of 16, 33, and 48 percent RAP at the Orem, Utah; San Marcos, Texas; and South Jordan, Utah, test sites, respectively. Before reclamation, the test sites at each location exhibited various degrees of pavement distress, but none of the test sites at any of the locations exhibited any visual distress one year after reclamation.

All of the neat and blended materials sampled from the sites established for this research were classified as A-1-a in the AASHTO soil classification method and as SW for the Orem and San Marcos materials and SW-SM for the South Jordan materials in the

Unified soil classification system. Concerning gradation, both the Orem and San Marcos materials were slightly finer after reclamation, and the South Jordan material was more dense-graded after reclamation. In this research, the OMC of the blended base at each location was generally higher than that of the neat base, and the MDD of the blended base was typically lower than that of the neat base.

The results of the statistical analyses of field data indicate that the base modulus value of the Orem material was significantly higher one year after reclamation than just before reclamation and that the San Marcos CBR value was significantly higher one year after reclamation than just before reclamation. These results show that the FDR process significantly increased the stiffness and/or strength of the base materials at these locations. The South Jordan material did not experience a significant change in either base modulus value or CBR value, suggesting that the FDR process did not significantly improve or degrade the South Jordan material.

An evaluation of spatial variability indicated that the FDR process produced equivalent or decreased spatial variability with respect to both base modulus and CBR values at the Orem location, while the San Marcos location exhibited increased spatial variability with respect to both types of measurements one year after reclamation. The available base modulus data for the South Jordan location indicate increasing variability after reclamation, while the CBR data suggest that the FDR process did not markedly affect spatial variability on that project.

The results of the laboratory tests for all three locations indicate that specimens compacted using the modified Proctor method exhibit significantly higher CBR values, lower CBR test moisture contents, higher CBR test dry densities, lower TST moisture contents, and higher TST dry densities than specimens compacted using the standard Proctor method. Also, the CBR values for specimens tested in the dry condition were significantly higher than those obtained from specimens tested at OMC. Clearly, providing a high level of compaction during construction and preventing water ingress over time by maintaining the wearing course in good condition and ensuring positive drainage yield improvements in the CBR value of the reclaimed layer. The blended material exhibited a significantly lower CBR value than that of the neat material only at the Orem location; the addition of RAP to the San Marcos and South Jordan materials did not significantly change the CBR values of those materials. In the TST, most of the specimens were classified as marginally or highly moisture-susceptible, and the effect of RAP on the dielectric value in the TST was of no practical importance.

5.3 RECOMMENDATIONS

The use of PARMs in the FDR process is an acceptable, economical, and environmentally friendly approach to reconstruction of flexible pavements. To ensure satisfactory performance of FDR projects, engineers and managers should carefully follow recommended guidelines for project selection, pavement testing, material characterization, design, construction, and quality assurance testing.

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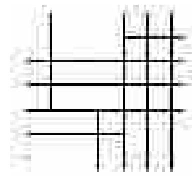
APPENDIX A:

DISTRESS SURVEYS

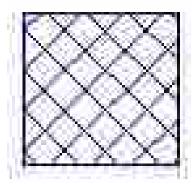
1. Fatigue Cracking
L = Low Severity
M = Moderate Severity
H = High Severity



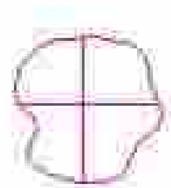
2. Longitudinal Cracking
L = Low Severity
M = Moderate Severity
H = High Severity

3. Transverse Cracking
L = Low Severity
M = Moderate Severity
H = High Severity

4. Patching
L = Low Severity
M = Moderate Severity
H = High Severity



5. Potholes
L = Low Severity
M = Moderate Severity
H = High Severity



6. Raveling
No Severity Levels

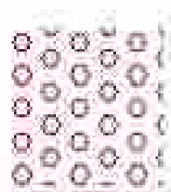


FIGURE A.1 Distress survey key.

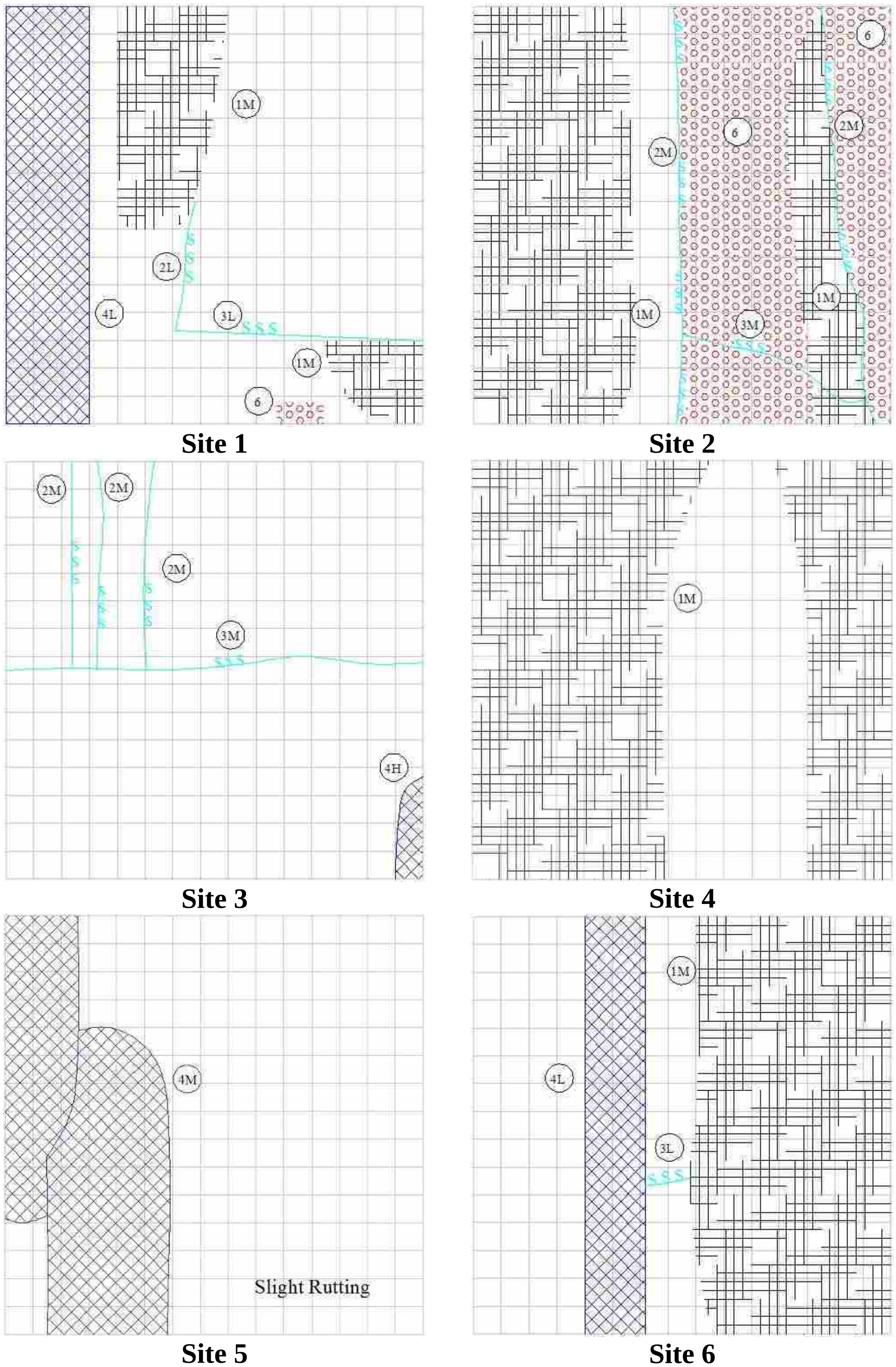


FIGURE A.2 Orem pre-reclamation distress surveys.

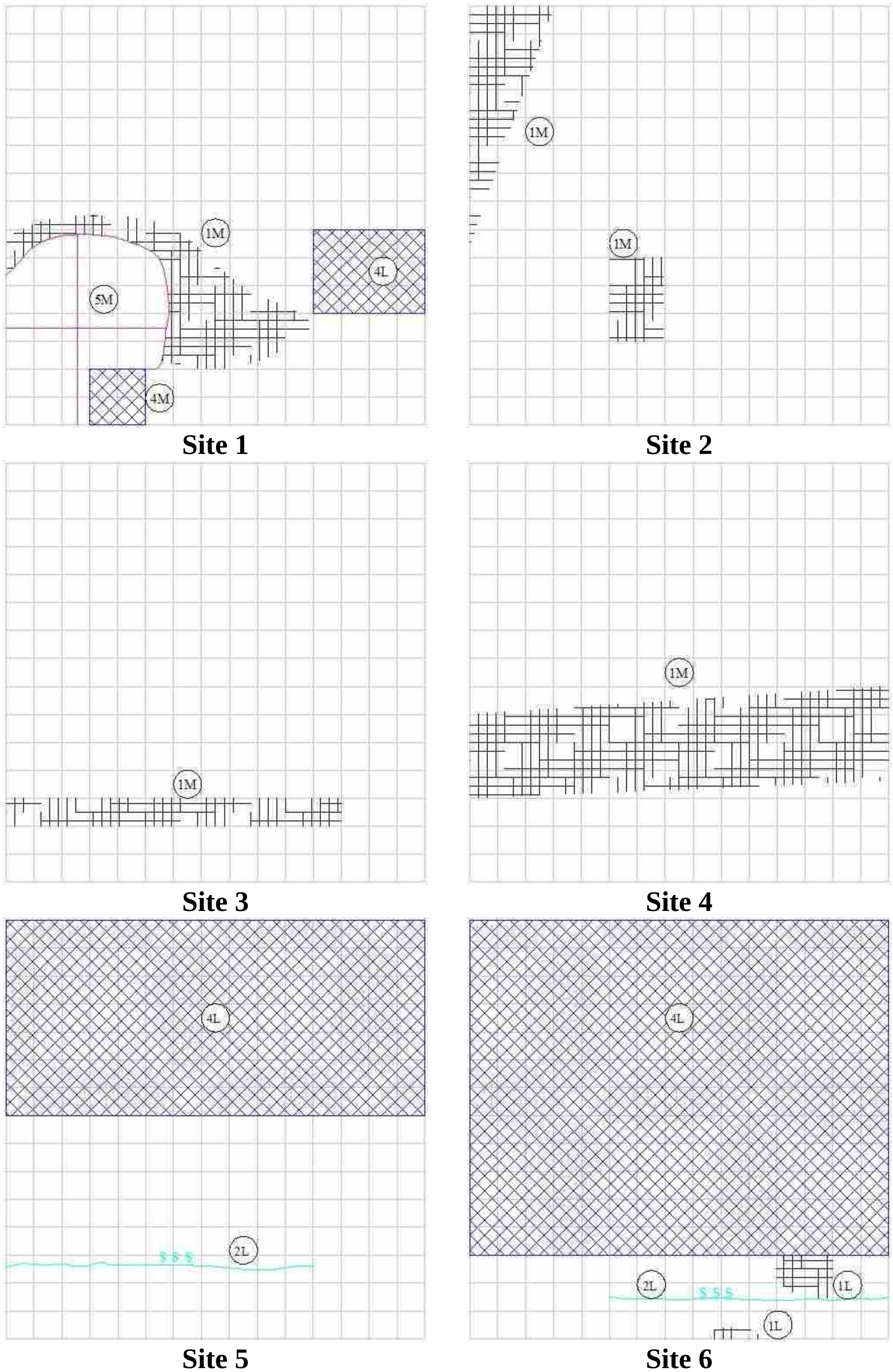


FIGURE A.3 San Marcos pre-reclamation distress surveys.

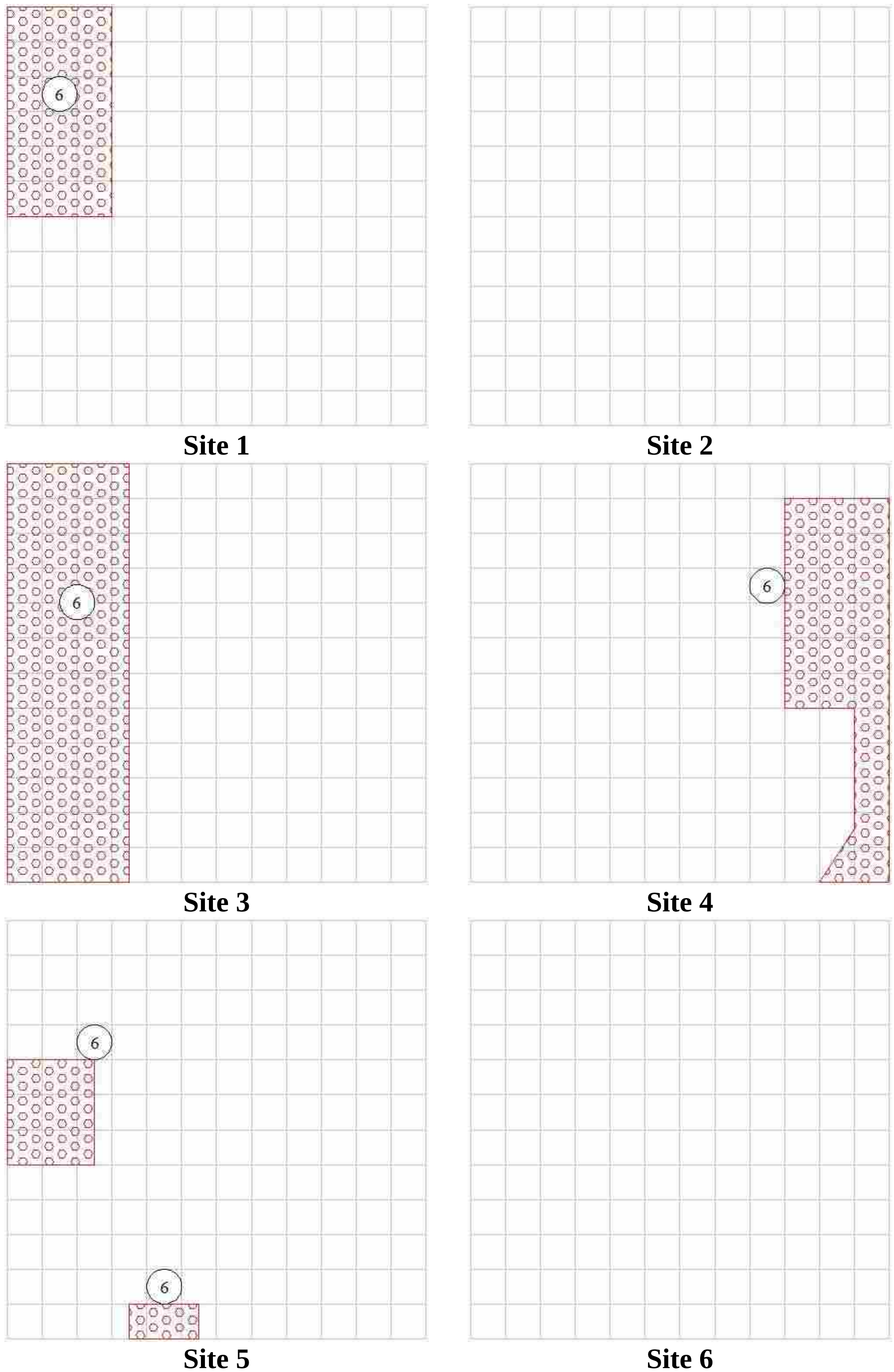


FIGURE A.4 South Jordan pre-reclamation distress surveys.

APPENDIX B:

OREM STATISTICAL INTERACTIONS

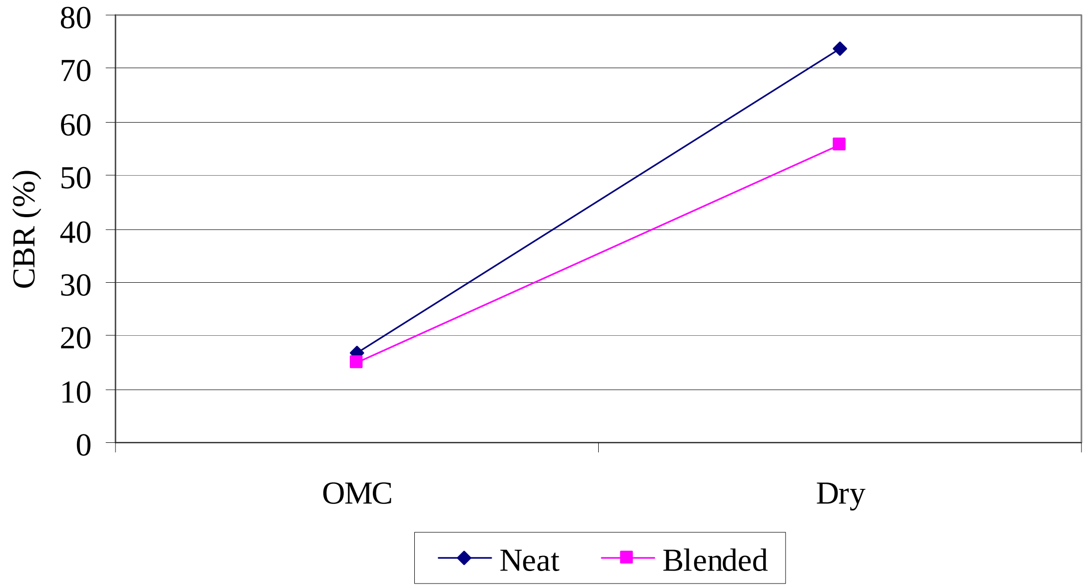


FIGURE B.1 Least square means for interactions between condition and material type on CBR value for Orem.

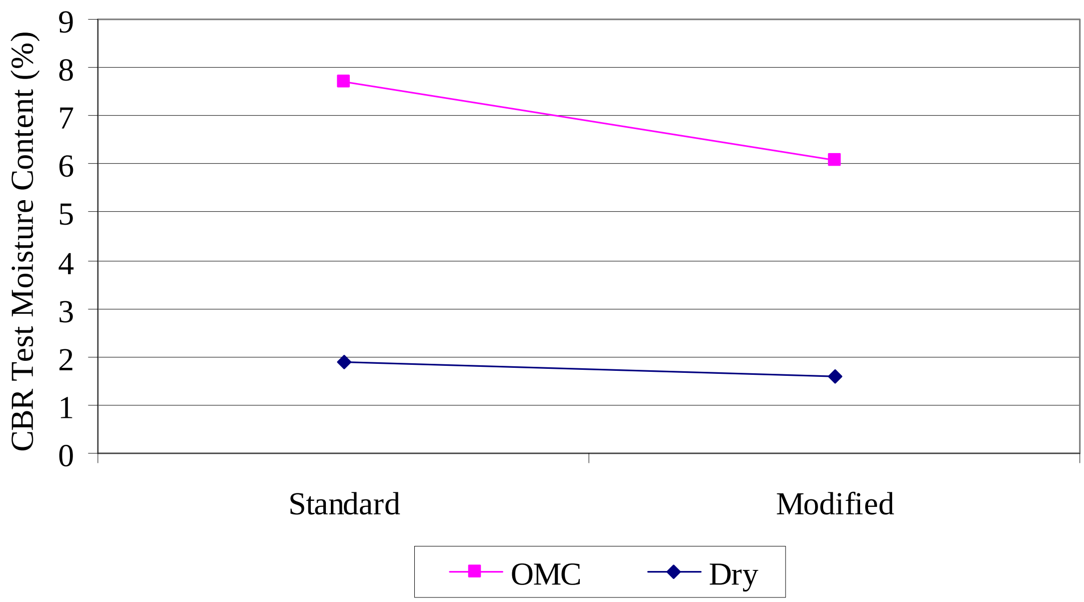


FIGURE B.2 Least square means for interactions between compaction effort and condition on CBR test moisture content for Orem.

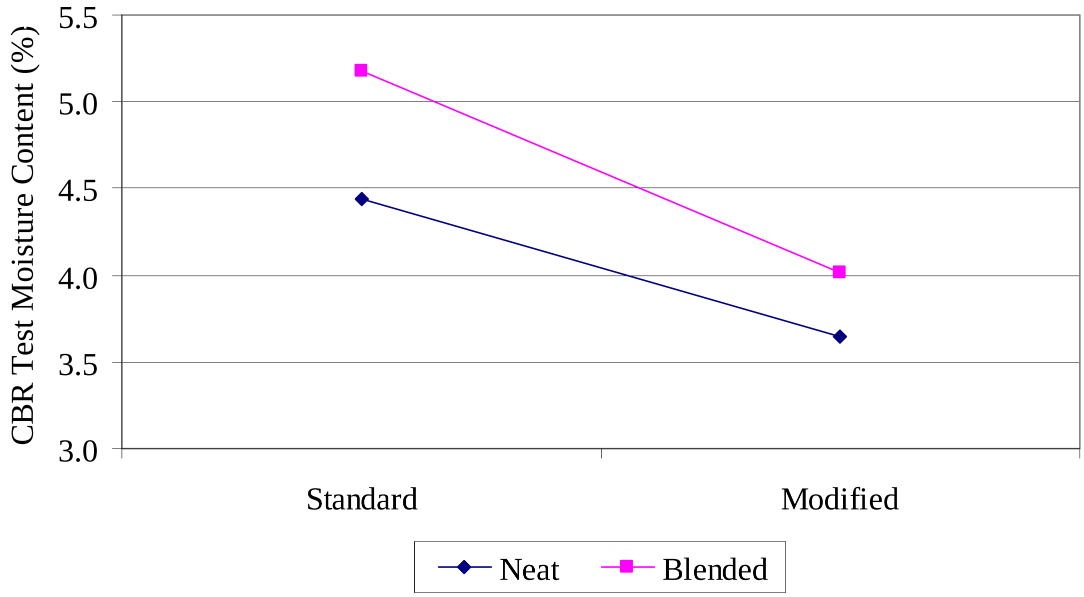


FIGURE B.3 Least square means for interactions between compaction effort and material type on CBR test moisture content for Orem.

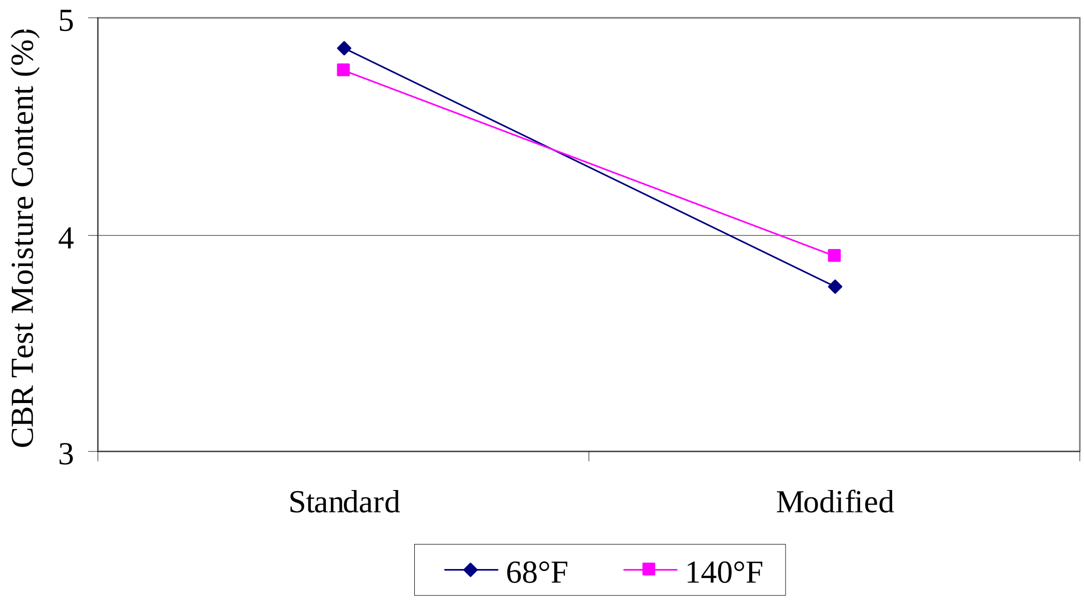


FIGURE B.4 Least square means for interactions between compaction effort and temperature on CBR test moisture content for Orem.

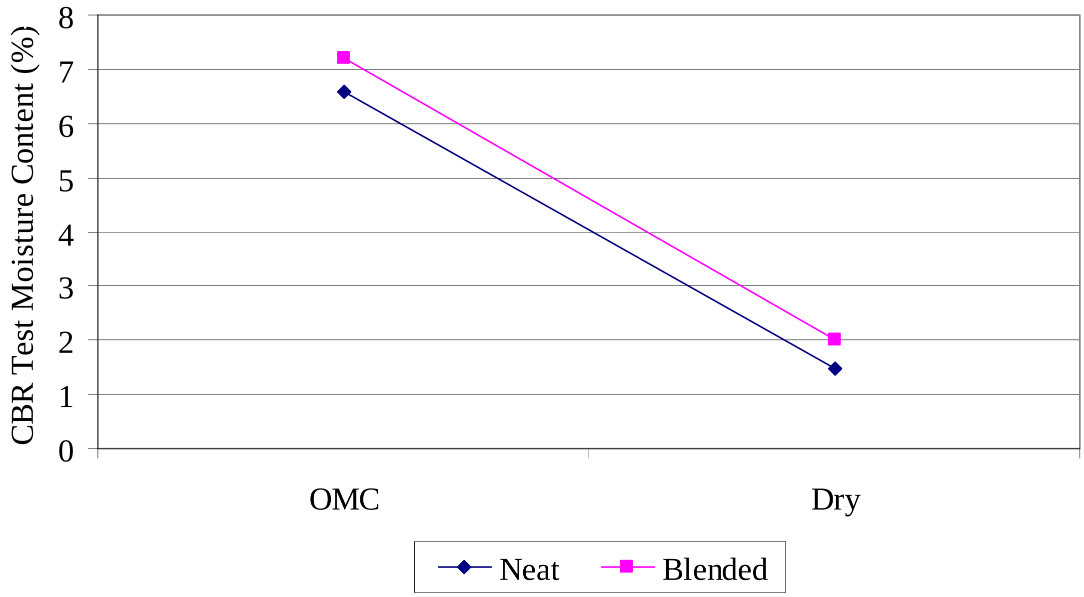


FIGURE B.5 Least square means for interactions between condition and material type on CBR test moisture content for Orem.

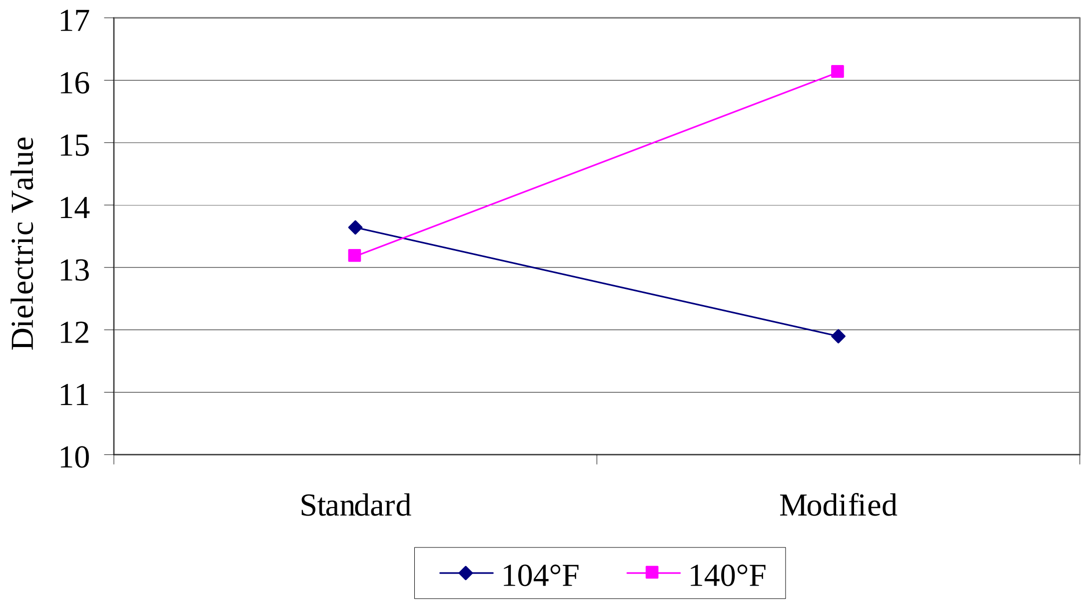


FIGURE B.6 Least square means for interactions between compaction effort and temperature on dielectric value for Orem.

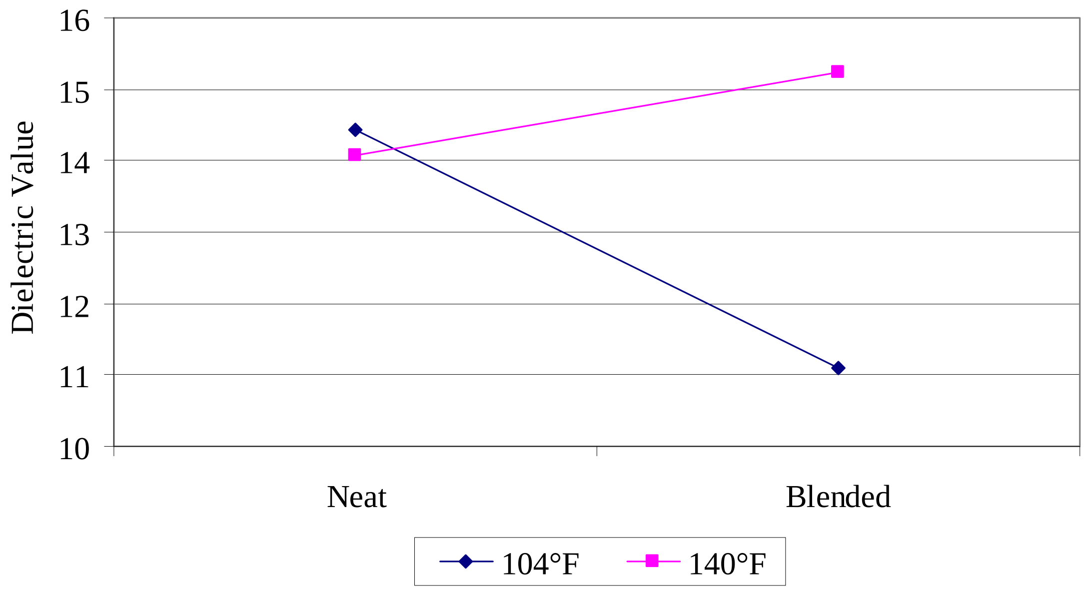


FIGURE B.7 Least square means for interactions between material type and temperature on dielectric value for Orem.

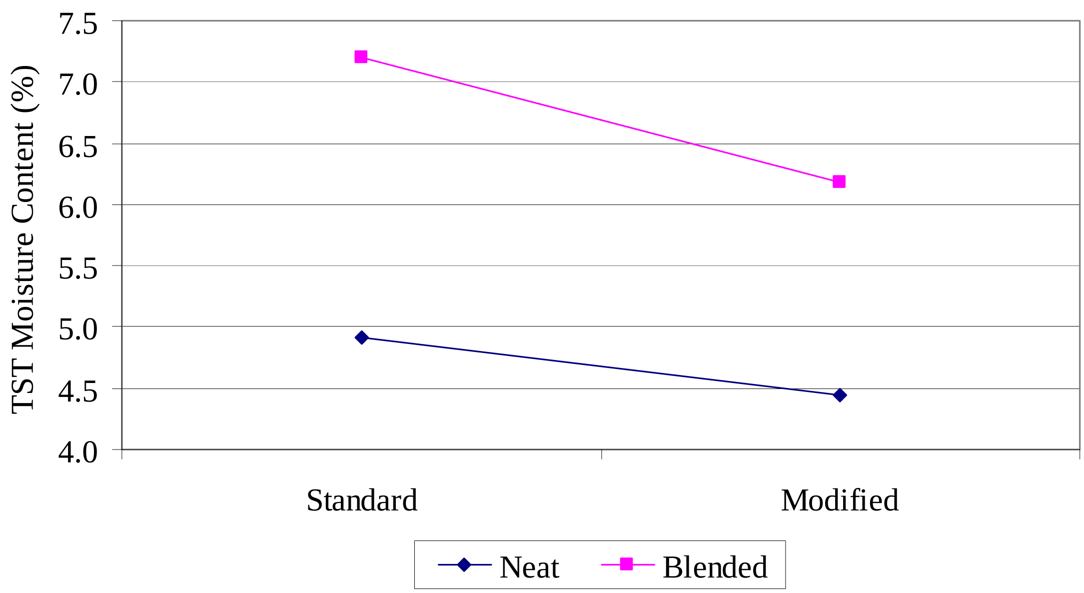


FIGURE B.8 Least square means for interactions between compaction effort and material type on TST moisture content for Orem.

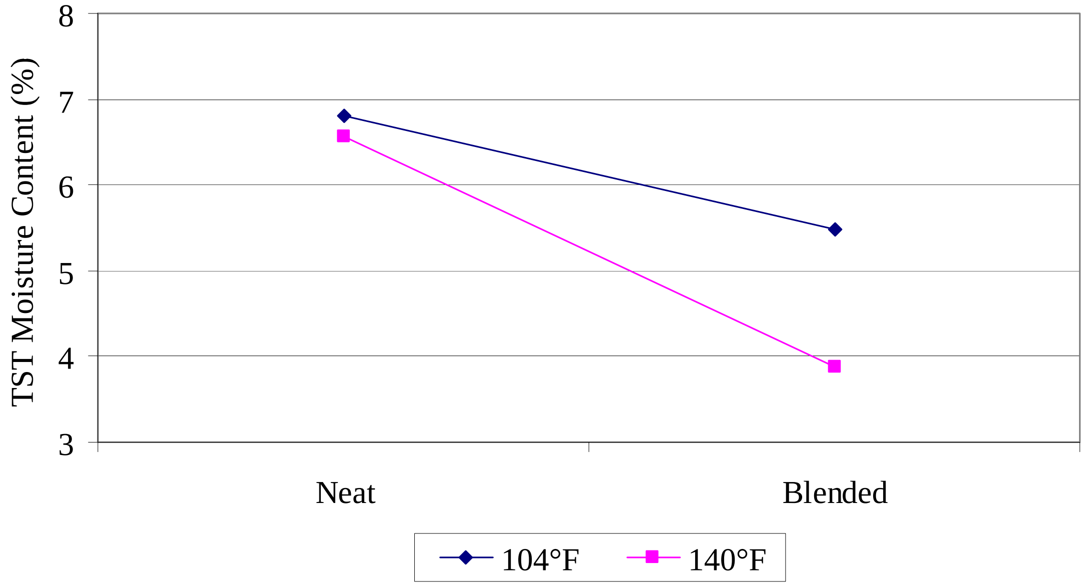


FIGURE B.9 Least square means for interactions between material type and temperature on TST moisture content for Orem.

APPENDIX C:

SAN MARCOS STATISTICAL INTERACTIONS

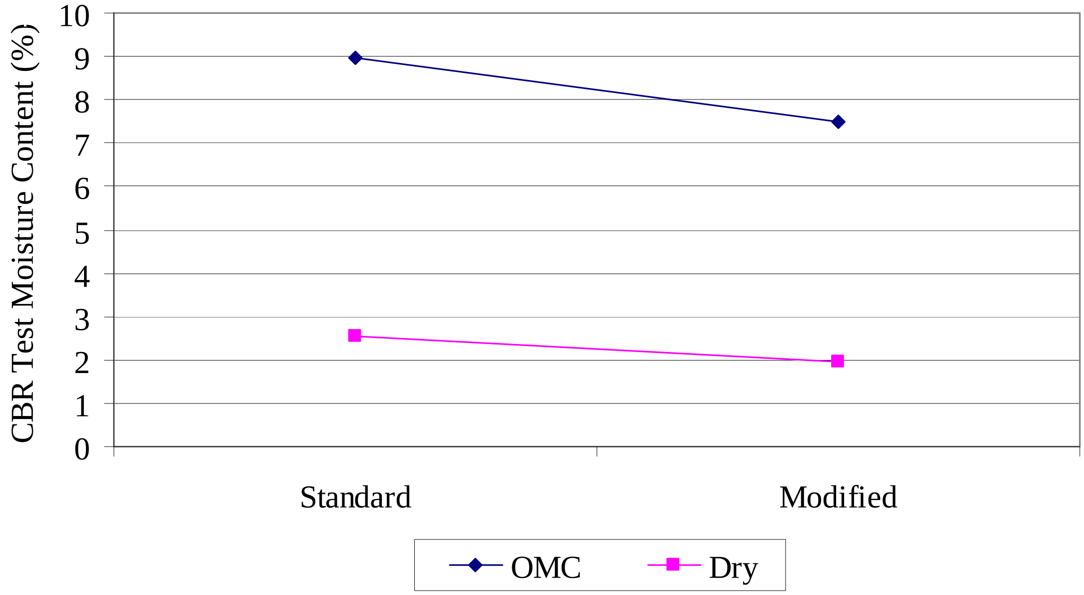


FIGURE C.1 Least square means for interactions between compaction effort and condition on CBR test moisture content for San Marcos.

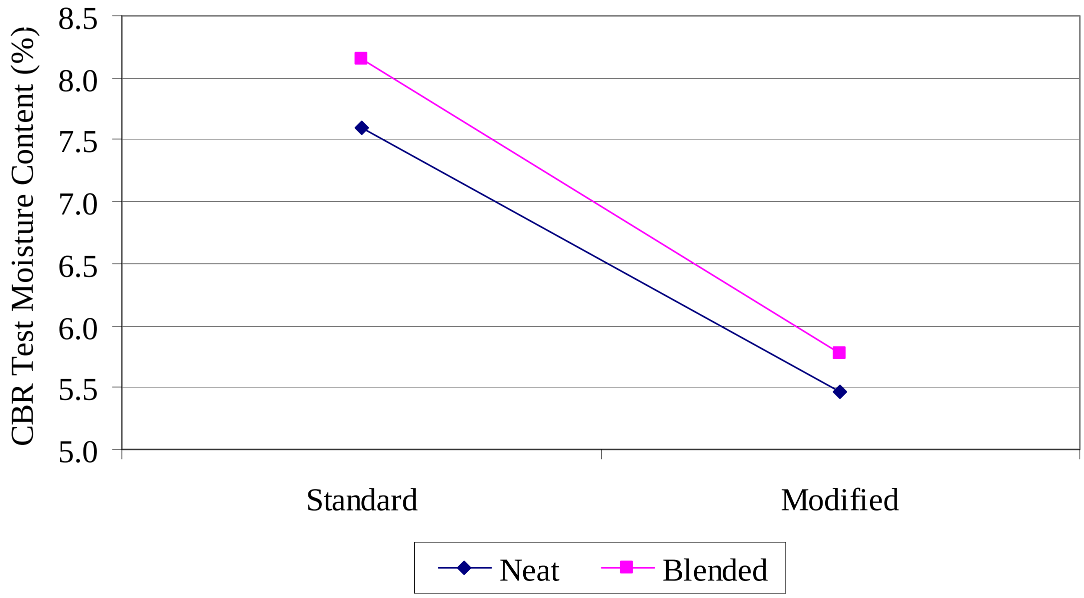


FIGURE C.2 Least square means for interactions between compaction effort and material type on CBR test moisture content for San Marcos.

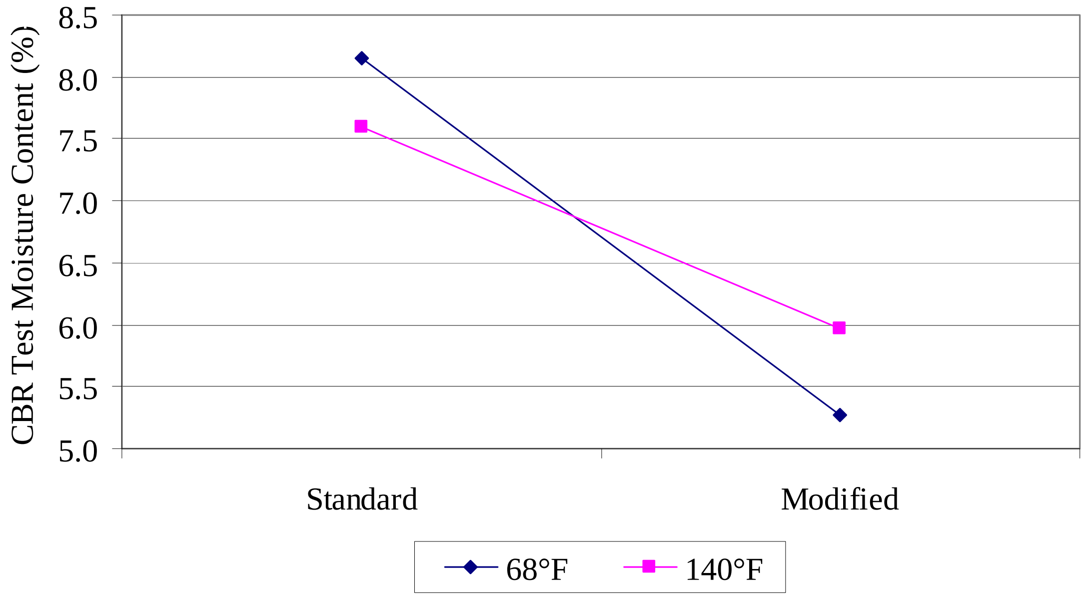


FIGURE C.3 Least square means for interactions between compaction effort and temperature on CBR test moisture content for San Marcos.

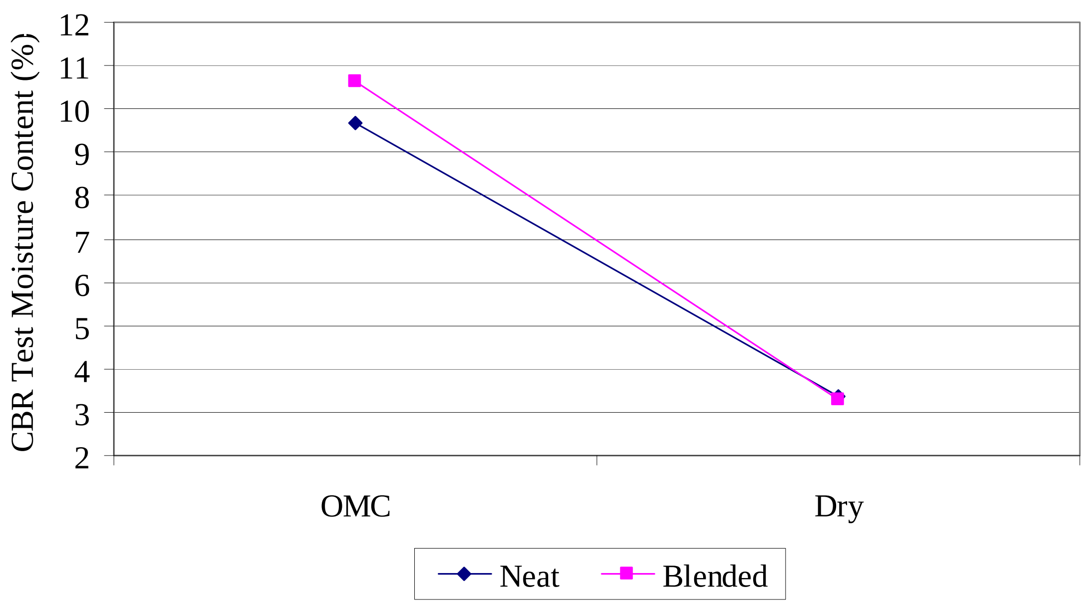


FIGURE C.4 Least square means for interactions between condition and material type on CBR test moisture content for San Marcos.

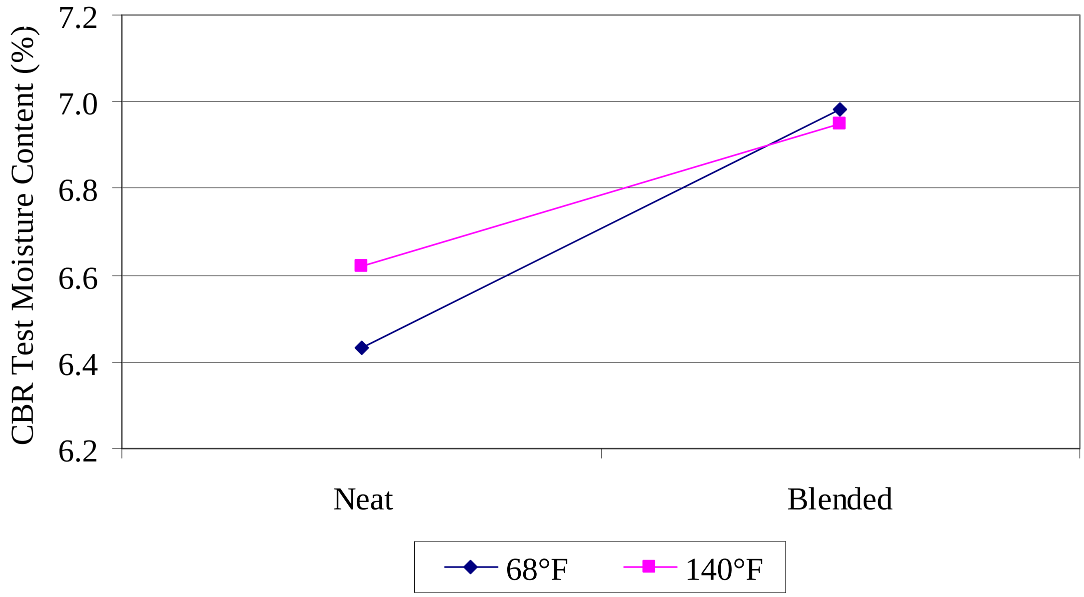


FIGURE C.5 Least square means for interactions between material type and temperature on CBR test moisture content for San Marcos.

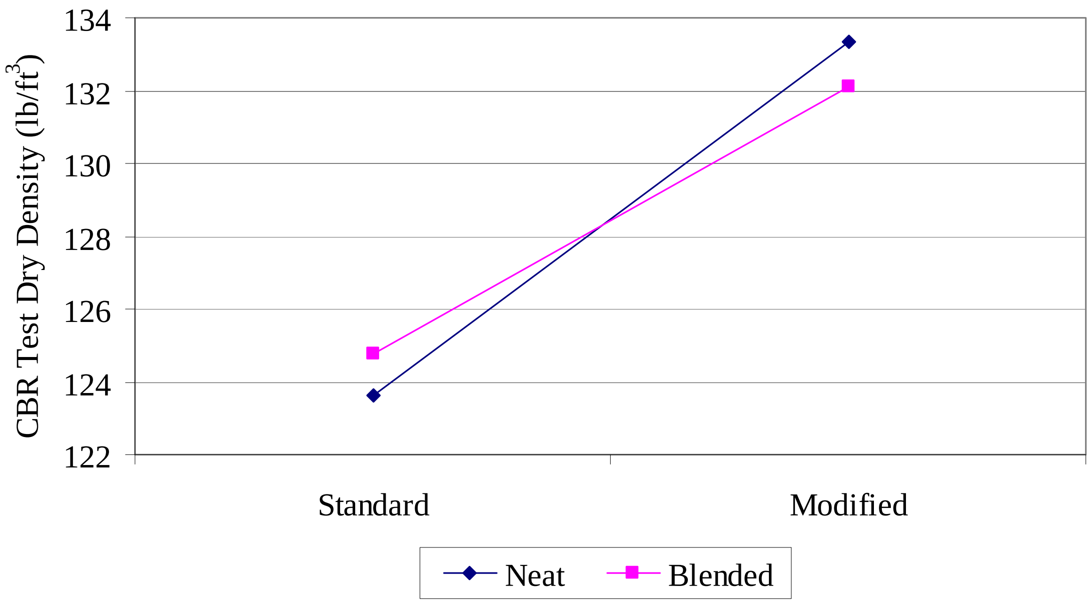


FIGURE C.6 Least square means for interactions between compaction effort and material type on CBR test dry density for San Marcos.

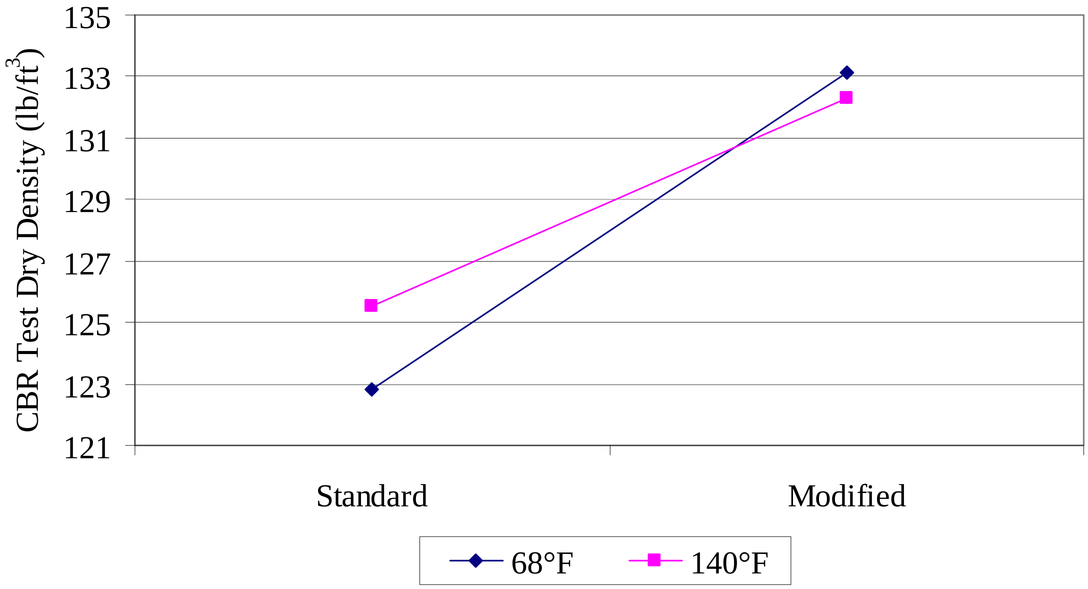


FIGURE C.7 Least square means for interactions between compaction effort and temperature on CBR test dry density for San Marcos.

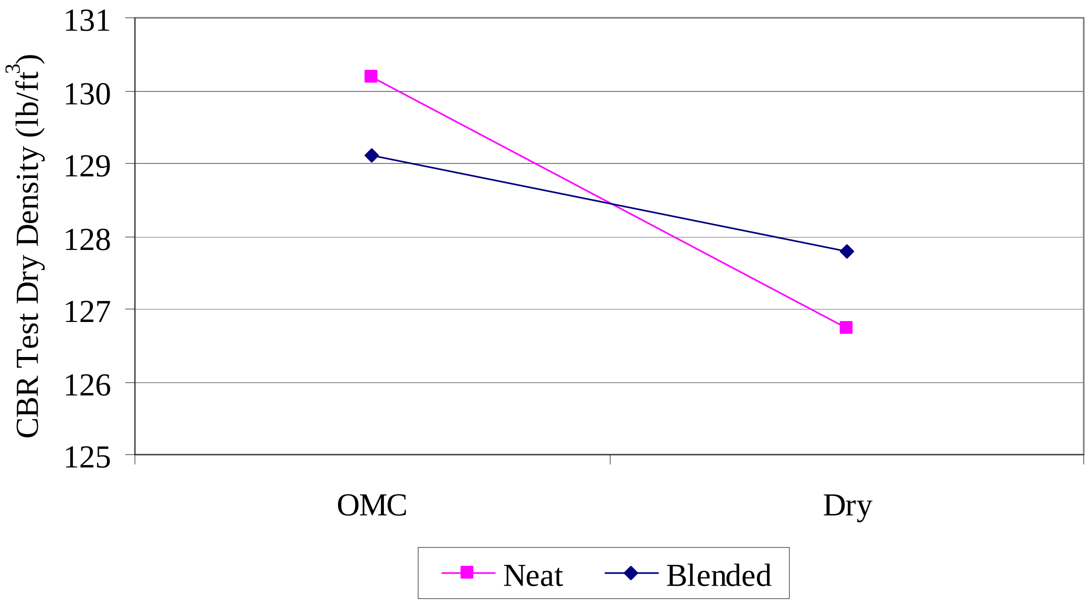


FIGURE C.8 Least square means for interactions between condition and material type on CBR test dry density for San Marcos.

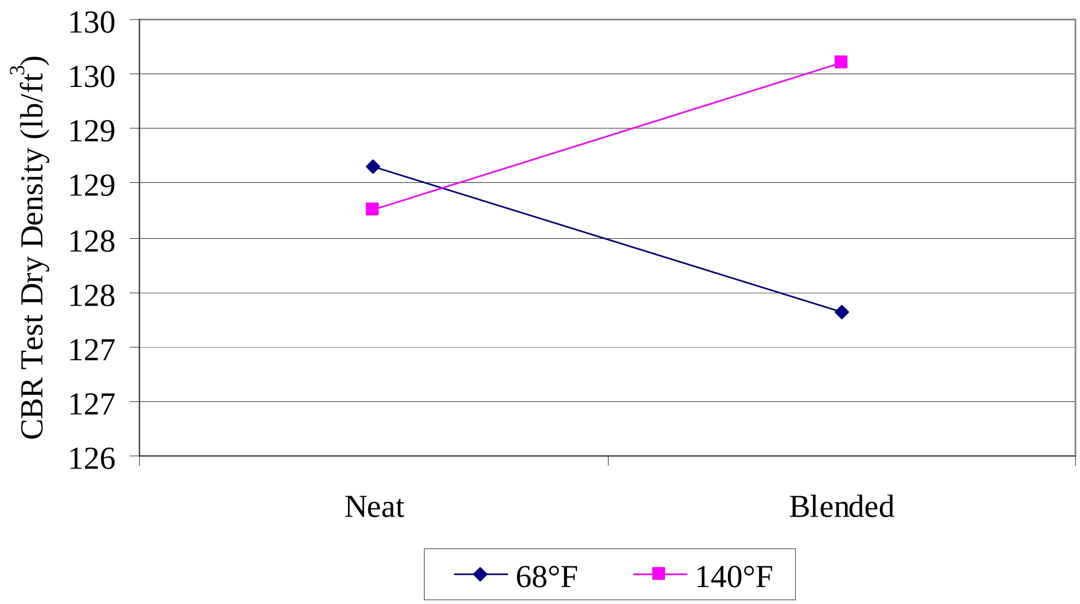


FIGURE C.9 Least square means for interactions between material type and temperature on CBR test dry density for San Marcos.

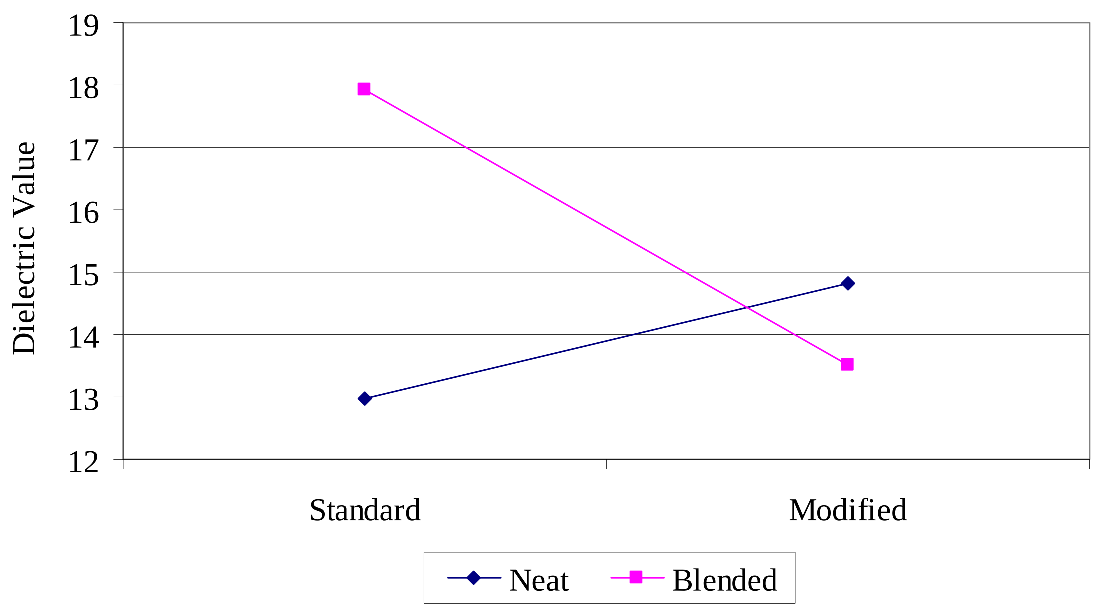


FIGURE C.10 Least square means for interactions between compaction effort and material type on dielectric value for San Marcos.

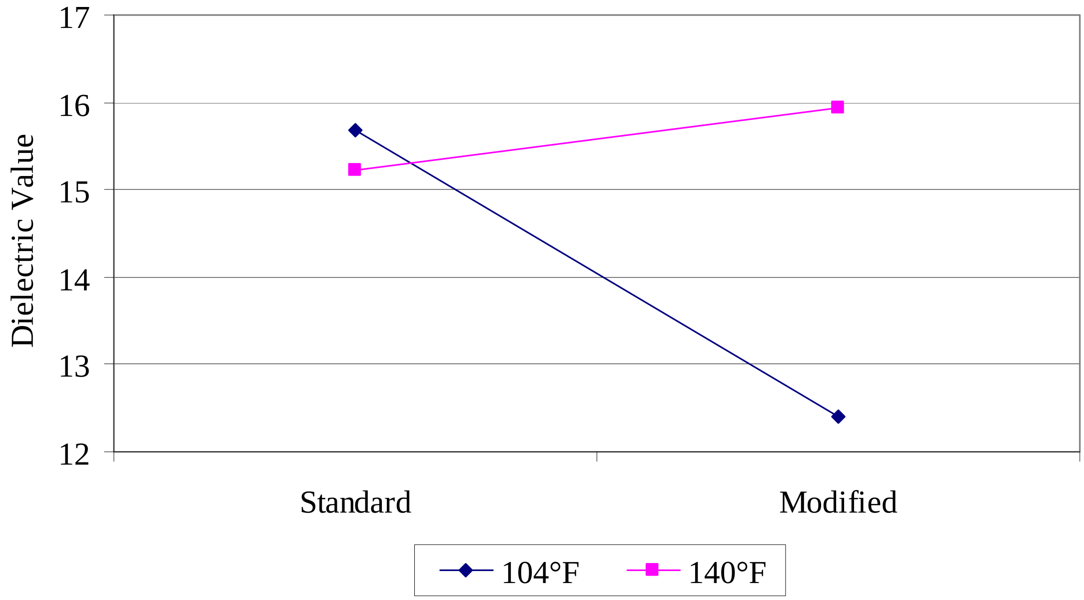


FIGURE C.11 Least square means for interactions between compaction effort and temperature on dielectric value for San Marcos.

APPENDIX D:

SOUTH JORDAN STATISTICAL INTERACTIONS

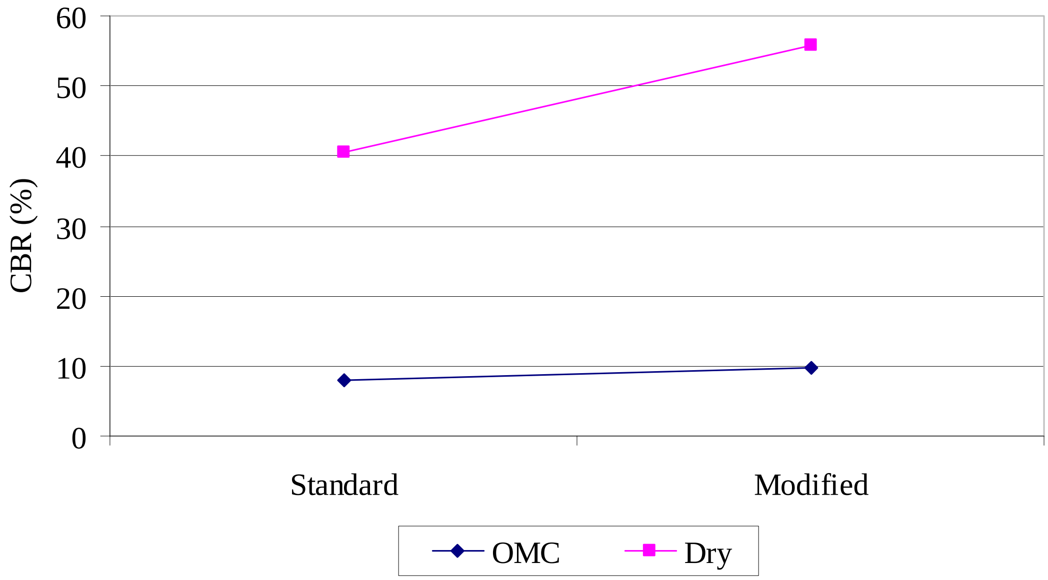


FIGURE D.1 Least square means for interactions between compaction effort and condition on CBR value for South Jordan.

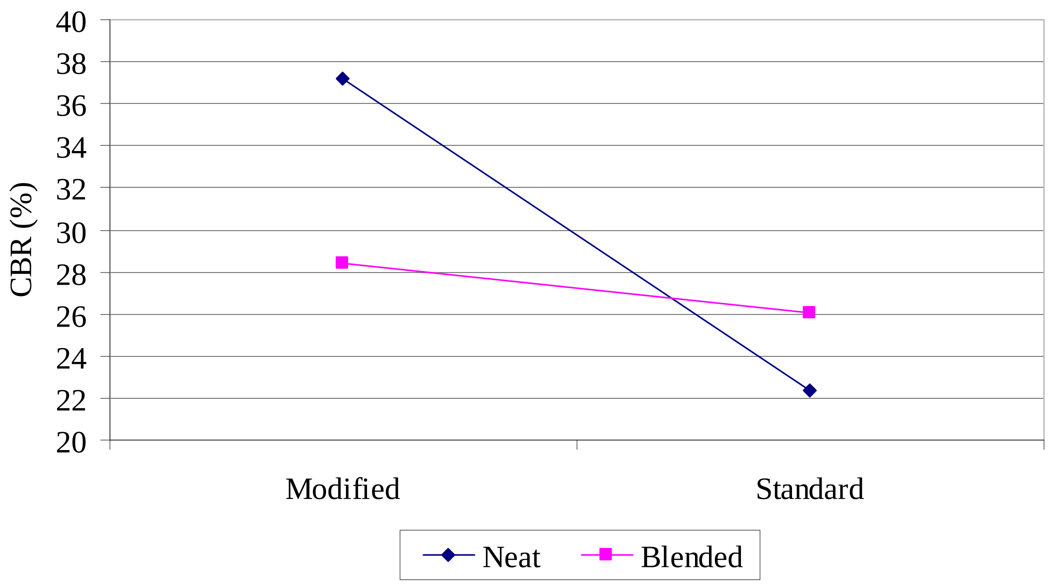


FIGURE D.2 Least square means for interactions between compaction effort and material type on CBR value for South Jordan.

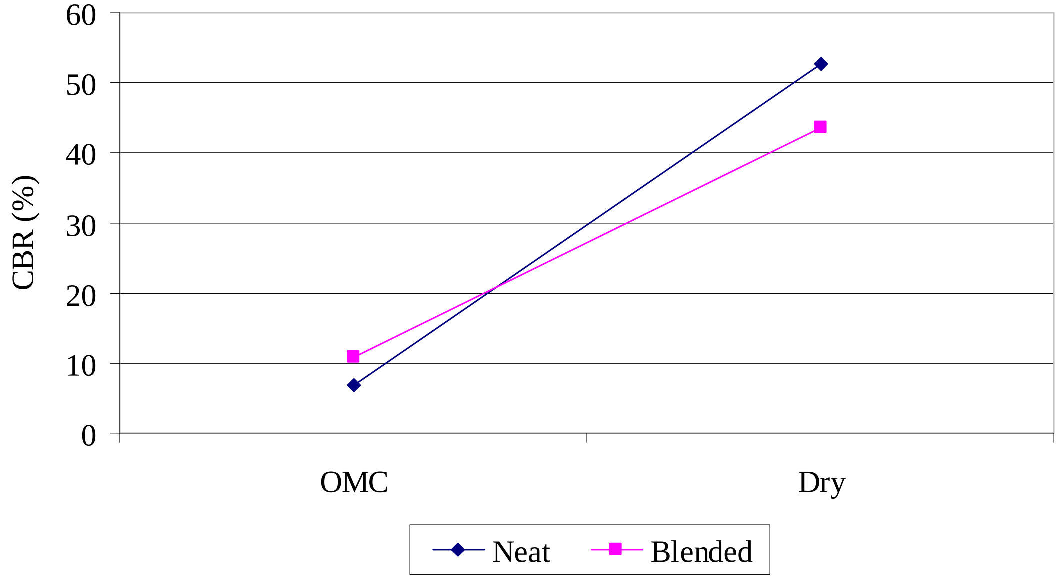


FIGURE D.3 Least square means for interactions between condition and material type on CBR for South Jordan.

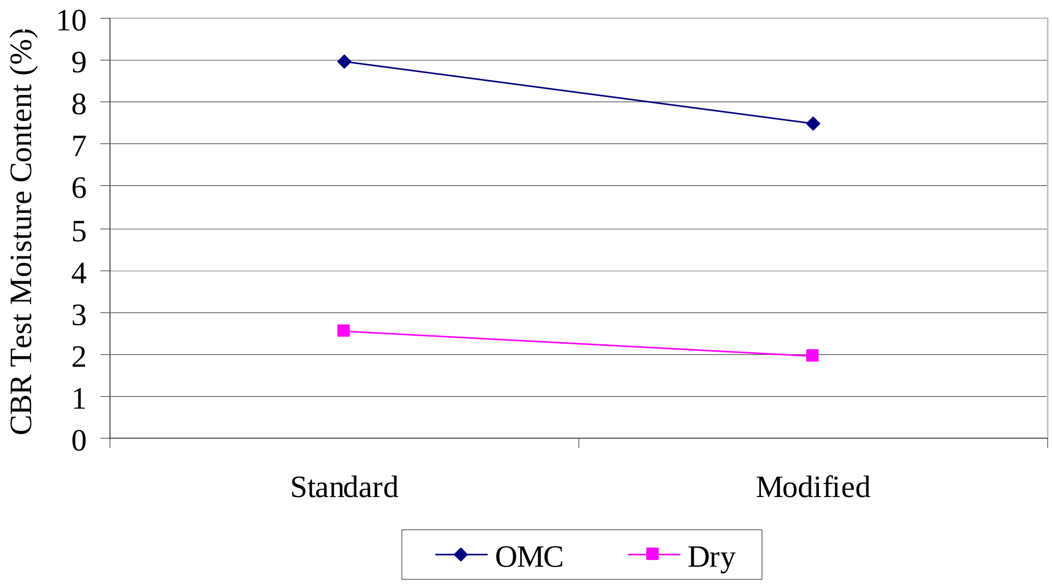


FIGURE D.4 Least square means for interactions between compaction effort and condition on CBR test moisture content for South Jordan.

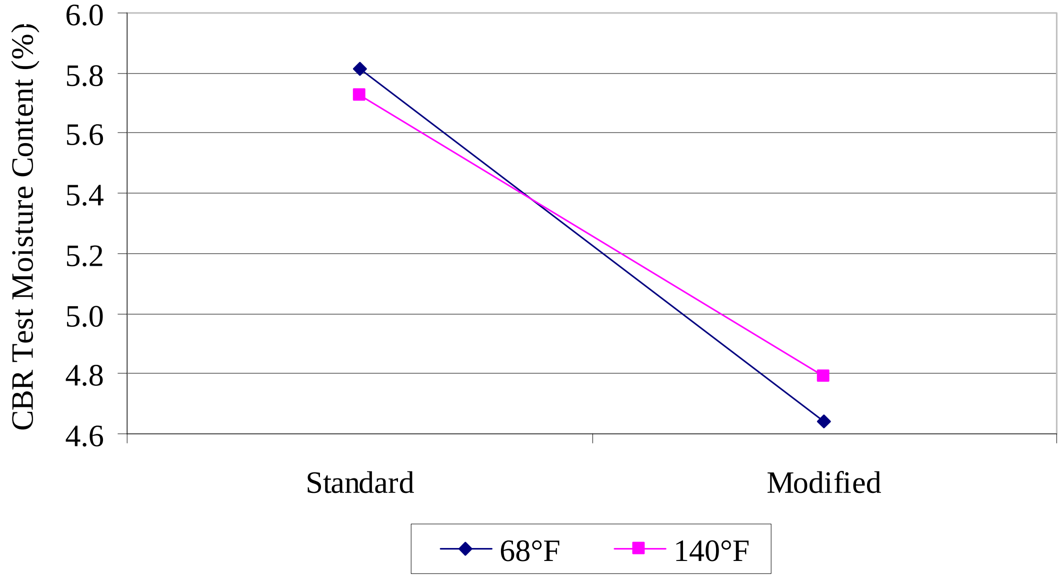


FIGURE D.5 Least square means for interactions between compaction effort and temperature on CBR test moisture content for South Jordan.

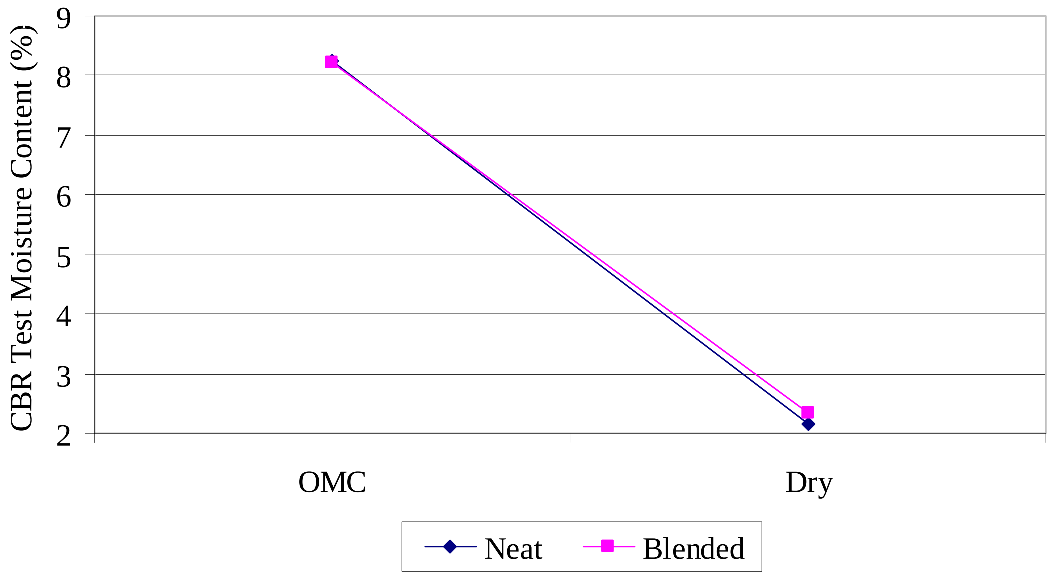


FIGURE D.6 Least square means for interactions between condition and material type on TST test moisture content for South Jordan.

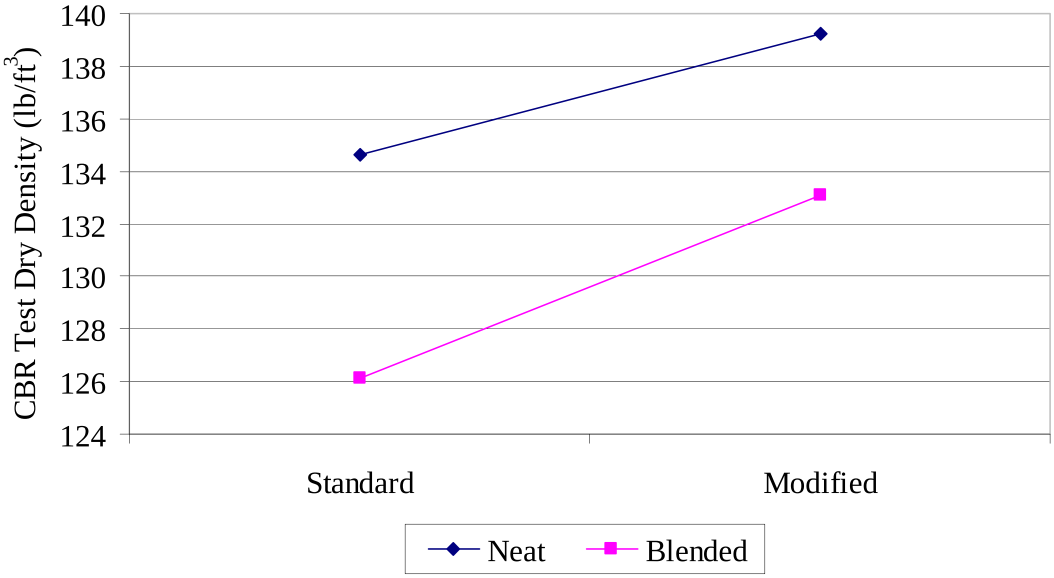


FIGURE D.7 Least square means for interactions between compaction effort and material type on CBR test dry density for South Jordan.

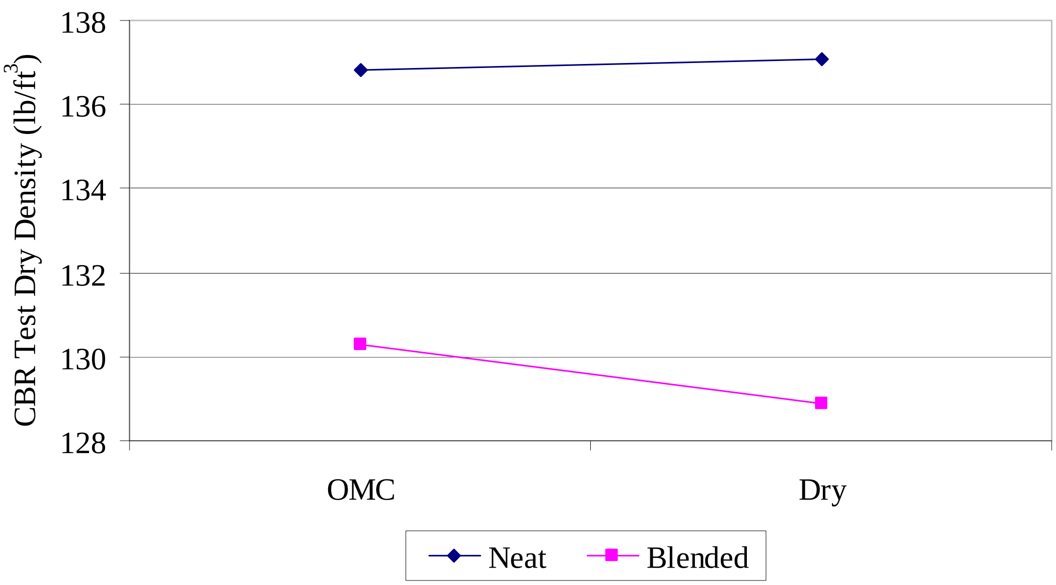


FIGURE D.8 Least square means for interactions between condition and material type on CBR test dry density for South Jordan.

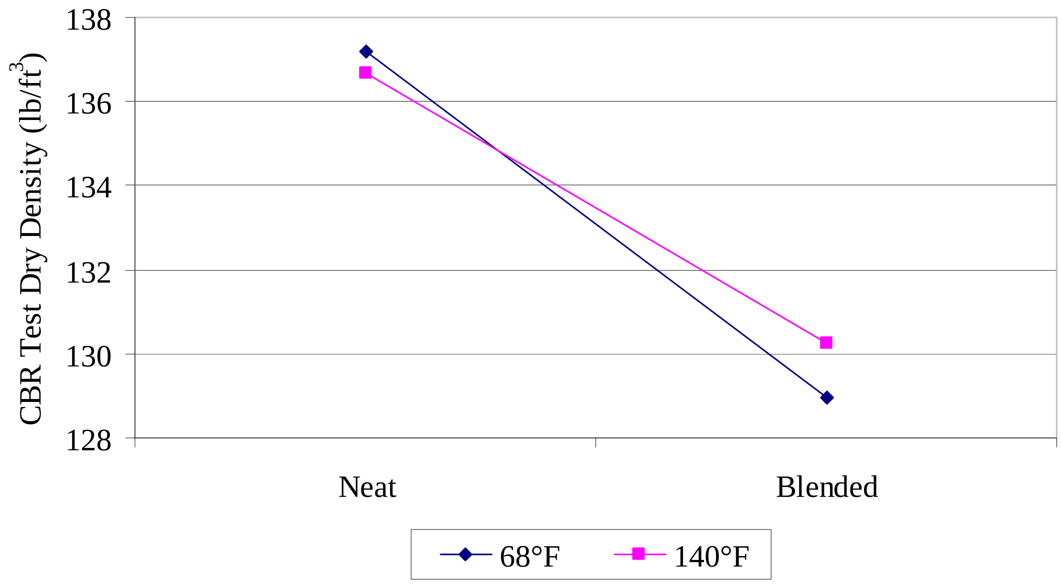


FIGURE D.9 Least square means for interactions between material type and temperature on CBR test dry density for South Jordan.

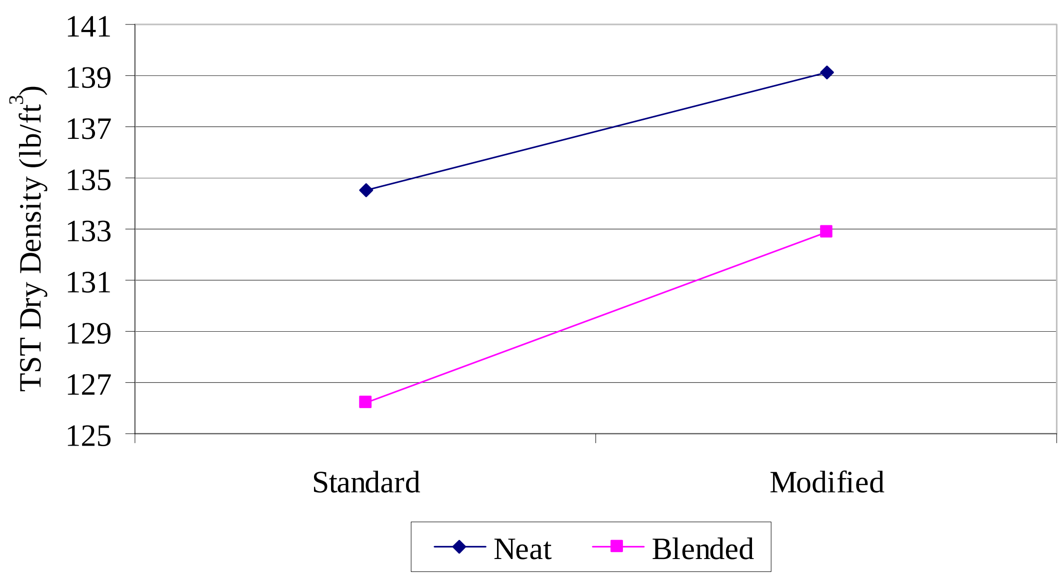


FIGURE D.10 Least square means for interactions between compaction effort and material type on TST dry density for South Jordan.