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Variability in Construction of Cement-Treated Base Layers: Probabilistic Analysis of Pavement Life Using Mechanistic-Empirical Approach

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Variability in Construction of Cement-Treated Base Layers:

Probabilistic Analysis of Pavement Life Using

Mechanistic-Empirical Approach

Tyler Jeremy Rogers

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Variability in Construction of Cement-Treated Base Layers:
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The primary objective of this research was to quantify the improvement in service life of a flexible pavement constructed using full-depth reclamation (FDR) in conjunction with cement stabilization when specified reductions in the spatial variability of specific construction-related parameters are achieved. This study analyzed pavement data obtained through field and laboratory testing of a reconstruction project in northern Utah. Data analyses included multivariate regression, Monte Carlo simulation, and mechanistic-empirical analyses of a model pavement structure.

The results of the research show a steadily increasing trend in 28-day unconfined compressive strength of the cement-treated base (CTB) layer with increasing reductions in variability for cement content, moisture content, and reclaimed asphalt pavement (RAP) content across each of five different reliability levels. The most significant increases in CTB strength occurred with reductions in the standard deviations of moisture content and RAP content. Decreasing the variability of cement content did not provide significant additional strength to the CTB layer. Therefore, when involved on FDR projects, members of the pavement industry should focus energy on reducing the variability of both moisture content and RAP content, which both significantly impact pavement life, to achieve high-quality, long-lasting pavements.

Keywords: construction variability, construction-related parameters, mechanistic-empirical approach, full-depth reclamation (FDR), cement-treated base (CTB), reclaimed asphalt pavement (RAP), unconfined compressive strength (UCS), pavement life, Monte Carlo simulation, spatial variability, cement stabilization, moisture content

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BRIGHAM YOUNG UNIVERSITY

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The thesis of Tyler J. Rogers is acceptable in its final form including (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory and ready for submission.

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1 INTRODUCTION

1.1 Problem Statement

While many pavement distresses are induced and/or exacerbated by heavy traffic loads, deterioration may be accelerated by variability in initial construction practices, material properties, and in-situ conditions. A consensus exists among the engineering community that variability, or lack of uniformity, with respect to target design parameters or design specifications negatively impacts pavement performance (*1*, *2*, *3*). However, little research has been performed to document the magnitude of typical construction-related variability and map it to pavement life.

Of particular interest to this research is the construction-related variability associated with full-depth reclamation (FDR) in conjunction with cement stabilization. Research suggests that minimizing the variability of parameters during construction of cement-treated base (CTB) will improve pavement performance (*4*). The primary objective of this research was to quantify the improvement in service life of a flexible pavement constructed using these technologies when specified reductions in the spatial variability of specific construction-related parameters are achieved. As members of the pavement industry focus energy on reducing the variability of parameters that significantly impact pavement life, engineers should be able to develop more useful project specifications, the occurrence of contractor penalties should be reduced, and owners should benefit from high-quality, long-lasting pavements.

1.2 Scope

Data used in this study were collected through field and laboratory testing at a pavement reconstruction site along the westbound lanes of Interstate 84 (I-84) near Peterson, Utah, during the summer of 2005. The reconstruction project involved FDR in conjunction with cement stabilization. The scope of this research was limited to the CTB layer along the westbound lane of I-84 between milepost 94 and milepost 94.5.

Previous analysis of the I-84 data was performed at Brigham Young University (BYU) in 2006 and suggests that the primary construction parameters most useful in predicting the 28-day unconfined compressive strength (UCS) of the CTB layer are cement content, 28-day moisture content, and reclaimed asphalt pavement (RAP) content (*4*). UCS testing was emphasized in the previous research due to the fact that it is a primary parameter in CTB design (*5*); UCS results may also be of particular use in developing quality control measures and construction pay factors. During the present study, the previously developed regression model for estimating 28-day UCS was refined to better predict CTB layer strength.

After a new regression model was obtained, a Monte Carlo simulation program was created to facilitate an analysis of how the distribution of CTB strength over the project would be affected by specified reductions in spatial variability among cement content, 28-day moisture content, and RAP content. Individual distributions were derived from I-84 field and laboratory data, and numerous simulations were performed with systematic reductions in the standard deviations of these construction parameters. Each simulation consisted of 100,000 iterations in order to provide an adequate distribution of estimated 28-day UCS results.

Estimates of the increase in pavement life due to reductions in the variability of these construction parameters were obtained through mechanistic-empirical (M-E) analysis. Because the I-84 facility is still in service, evaluating the accuracy of M-E models available for predicting pavement life was not possible; instead, the emphasis of this research was on assessing the relative effects on pavement service life of reductions in the spatial variability of cement content, 28-day moisture content, and RAP content. Because the data collected in this study are specific to a particular construction site, the findings of this research may not be readily applicable to CTB layers constructed using different materials or in different climatic conditions.

1.3 Outline

This report contains five chapters. Chapter 1 presents the problem statement and scope of the research. Chapter 2 provides background information on the FDR process and the construction parameters determined to significantly affect pavement performance. The experimental methodology utilized in the research is explained in Chapter 3. Chapter 4 provides the results of the research and the analyses performed, and Chapter 5 presents findings and recommendations developed from the study.

2 BACKGROUND

2.1 Overview

As a pavement approaches the end of its expected life, the urgency to perform pavement maintenance, rehabilitation, and replacement is amplified. An increasingly popular method of pavement reconstruction is FDR in conjunction with cement stabilization. Pavement reconstruction through the use of FDR provides economic, environmental, and engineering benefits to contractors, state and local agencies, and tax payers (*6*).

A major advantage of cement stabilization is the ability to distribute traffic loads over a larger area. Strong cementitious bonds formed during the cement hydration process reduce point loads by distributing the stresses and strains on the underlying pavement layers over a larger footprint. Cement stabilization also helps pavement base layers resist consolidation and movement during heavy loading, nearly eliminating rutting in the base and underlying layers (*7*).

In recognition of these benefits, pavement engineers develop specifications to control the parameters in pavement design, but contractors are ultimately responsible for completing construction projects according to these specifications (*4*). If contractors build projects with little deviation from appropriate design specifications, owners receive high-quality projects with the intended pavement life; however, large deviations from design specifications can result in poor pavement performance, which can eliminate the benefits of a carefully engineered roadway (*8*). The following sections discuss the process of FDR with cement stabilization and describe the effects of variability in key factors shown in previous research to be significant predictors of CTB strength (*4*).

2.2 Full-Depth Reclamation with Cement Stabilization

When an asphalt pavement fails, determining the proper rehabilitation method is necessary to ensure that the desired service life will be achieved. While FDR corrects most distresses, it is most appropriate for pavements with structural damage in the base and/or subgrade layers. FDR should be used when full-depth patching is required on more than 15 to 20 percent of the total pavement surface area (*9*).

FDR with cement stabilization is a recycling technique for flexible pavements in which cement is mixed with the deteriorated asphalt surface layer and a portion of the existing base material to create a new base course. Milling and removing excess asphalt from the existing surface layer may be required in order to provide a uniform distribution of RAP in the mix. During the first pass of the reclaimer, the entire depth of the remaining asphalt and specified thickness of base material is pulverized, creating a blend of RAP and existing base material. If necessary, grading is performed following the first pass of the reclaimer.

After grading, a binding agent such as portland cement is added to the new base layer to provide additional strength (*4*). Cement is spread onto the surface of the recycled base layer in a powder or slurry form using an appropriate distribution truck. The cement is mixed together with the recycled base and water through the entire depth of the recycled material during the second pass of the reclaimer. Water is typically injected directly into the mixing chamber. The base layer is then compacted and graded to final elevation. The recommended time between mixing and compaction depends on base material type, cement content, wind speed, air temperature, and relative humidity (*10*). While a maximum time between mixing and compaction can be calculated, minimizing the delay time between these construction steps is very important. To ensure that cement hydration continues to occur, water is ideally added to the surface of the new CTB layer for several days following compaction; alternatively, a prime coat may be placed within a short time after construction to prevent the evaporation of water from the CTB layer. A hot mix asphalt (HMA) layer or bituminous surface treatment is commonly applied to complete the FDR process (*9*).

2.3 Variability in Cement-Treated Base Construction

While construction-related variability stems from both material properties and contractor performance, the focus of this research is on the former. Therefore, spatial uniformity in compositional attributes of a given CTB layer is of primary concern; high-quality CTB construction is achieved when soil/aggregate and RAP materials are uniformly mixed with portland cement and sufficient water to allow for compaction to the target maximum dry density (MDD) (*7*). Variability in construction parameters such as cement content, moisture content, and RAP content can significantly affect the mechanical properties of the CTB layer (*4*). The impact of each of these parameters on pavement performance is explained in the following sections.

2.3.1 Cement Content

Cement is added during the FDR process to increase the structural capacity and durability of the reclaimed layer. When proper construction procedures are followed, higher cement contents correspond to higher CTB strengths. Too little cement provides insufficient stabilization and may allow excessive pavement deflections under heavy traffic loading, while overly stabilized CTB layers are too stiff and brittle and prone to shrinkage cracking (*5*). Cracking creates avenues for water ingress into the base layer, causes accelerated pavement damage by increasing erosion and susceptibility to deterioration under freeze-thaw cycling, and decreases the strength and stiffness of affected layers (*11*). Thus, cement contents should not be too low or too high.

Optimum cement content varies depending on the gradation and material type of the base layer but is typically specified as a percentage by mass of dry soil/aggregate based on results of testing performed in accordance with American Society for Testing and Materials (ASTM) D559 (Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures) or ASTM D560 (Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures) (*4*). According to the Portland Cement Association (PCA), well-graded sandy and gravelly materials with 10 to 35 percent non-plastic fines have the most favorable characteristics for CTB construction, and they require the least amount of cement for adequate hardening (*12*). Aggregate or soil types with finer gradations require more cement to achieve desired strengths (*5*).

When cement is applied dry, a spreader truck is typically used for cement placement. Spreader trucks should be operated at a slow constant speed to ensure an even distribution of cement powder onto the ground from the hopper (*7*). Spreader trucks may also have an adjustable gate to improve the precision and uniformity of cement placement. The appropriate gate opening and truck speed is determined by trial runs and driver experience (*4*).

Cement content is commonly measured in the field using collection trays or sheets placed at pre-determined locations on the pulverized base prior to cement spreading (*13*). Following cement spreading, the sheet or tray is collected, and the cement content is calculated by dividing the weight of accumulated cement by the area of the sheet. Ultimately, variability in cement content is a result of the construction equipment, the experience of the paving contractor, and the cement distribution method (*4*).

2.3.2 Moisture Content

Both the water existing in the base material before cement treatment and the water added during cement mixing are important because water content directly affects both the compaction characteristics and the strength of the CTB layer. While the average moisture content existing in the base material before cement treatment depends to a large measure upon the air temperature, relative humidity, amount of recent precipitation, and wind speed (*10*), which should all be comparatively uniform over the length of a typical project, other factors, such as the presence of underwater springs, drainage features, and shaded areas, can cause pronounced spatial variability in the water content of the base layer (*4*). Consequently, the amount of mixing water that should be added by the contractor to achieve the optimum moisture content (OMC) may vary significantly along the construction corridor.

OMC varies depending on the gradation and material type of the base layer and on the level of desired compaction energy. ASTM D1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3))) and ASTM D698 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft^3 (600 kN-m/m^3))) are commonly specified for determination of the OMC and corresponding MDD for a given material treated at a given cement content. Because contractors cannot easily monitor existing moisture contents in a roadbed, deviations from OMC inevitably result. Too little or too much water leads to lower dry density and reduced structural capacity (*4*).

OMC is usually specified as a percentage by mass of dry soil/aggregate and stabilizer, and moisture contents are typically determined in the laboratory through oven drying of sampled materials. Following compaction of a CTB layer, water is added to the CTB surface to prevent moisture from evaporating so that cement hydration can continue. Clean potable water free of large amounts of alkalis, acids, or organic matter should be used in CTB construction (*12*).

2.3.3 Reclaimed Asphalt Pavement Content

Both the content and characteristics of RAP can influence the mechanical properties of a CTB layer. A systematic laboratory evaluation of the effect of RAP content on the amount of cement required to achieve a 7-day UCS of approximately 400 psi indicated that increased RAP contents require increased cement contents when all other factors are held constant; the authors of that study hypothesized that the asphalt cement coating on RAP particles interrupts the formation of strong cementitious bonds between aggregates (*14*). The characteristics of RAP that affect pavement strength include the amount and composition of asphalt cement and the angularity, type, and gradation of aggregate (*15*).

Although maximum RAP contents are often specified in FDR projects, control of the RAP content is difficult. Due to variations in asphalt thickness (*16*), the upper portion of the existing asphalt surface layer may need to be milled and removed from selected locations prior to FDR in order to achieve the target RAP content specified by the engineer. Milling and removal of part of the asphalt layer may also be necessary in areas where elevation constraints such as curb and gutter restrict the pavement profile. One source recommends that only aged asphalt surfaces with high viscosity should be incorporated into the base layer in the FDR process; otherwise, the surface layer should be removed altogether (*12*).

RAP content is usually measured in the laboratory using burn-off testing following ASTM D6307 (Standard Test Method for Asphalt Content of Hot-Mix Asphalt by Ignition Method), which determines gravimetric asphalt contents in tested samples. RAP contents in recycled base materials can be determined by dividing the measured asphalt contents by the asphalt content of a pure RAP sample obtained from the same site.

2.4 Summary

FDR with cement stabilization is an increasingly popular method of pavement reconstruction in which cement is mixed with the deteriorated asphalt surface layer and a portion of the existing base material to create a new base course. Variability in construction parameters that can significantly affect the mechanical properties of CTB material include cement content, 28-day moisture content, and RAP content. Mixing the base with inadequate cement does not provide the CTB layer with sufficient strength to resist heavy traffic loads, while the addition of too much cement makes the CTB layer excessively stiff and prone to shrinkage cracking. Moisture content directly affects both the compaction characteristics and strength of the CTB layer. When too much or too little water is added to the stabilized layer, the base will have a lower density and, therefore, lower structural capacity than would have been obtained if compacted at OMC. Insufficient moisture may also inhibit the hydration process. A laboratory evaluation of RAP indicated that increased RAP contents require increased cement contents when all other factors are held constant; the authors of that study hypothesized that the asphalt cement coating on RAP particles interrupts the formation of strong cementitious bonds between aggregates. High-quality CTB construction is achieved when soil/aggregate and RAP materials are uniformly mixed with portland cement and sufficient water to allow for maximum compaction.

3 EXPERIMENTAL METHODOLOGY

3.1 Overview

Data used in this study were collected through field and laboratory testing associated with a pavement reconstruction site along the westbound lanes of I-84 near Peterson, Utah, during the summer of 2005; the reconstruction project involved FDR in conjunction with cement stabilization. A map of the site location is shown in Figure 3-1. Records provided by Utah Department of Transportation (UDOT) personnel show that the pre-construction pavement

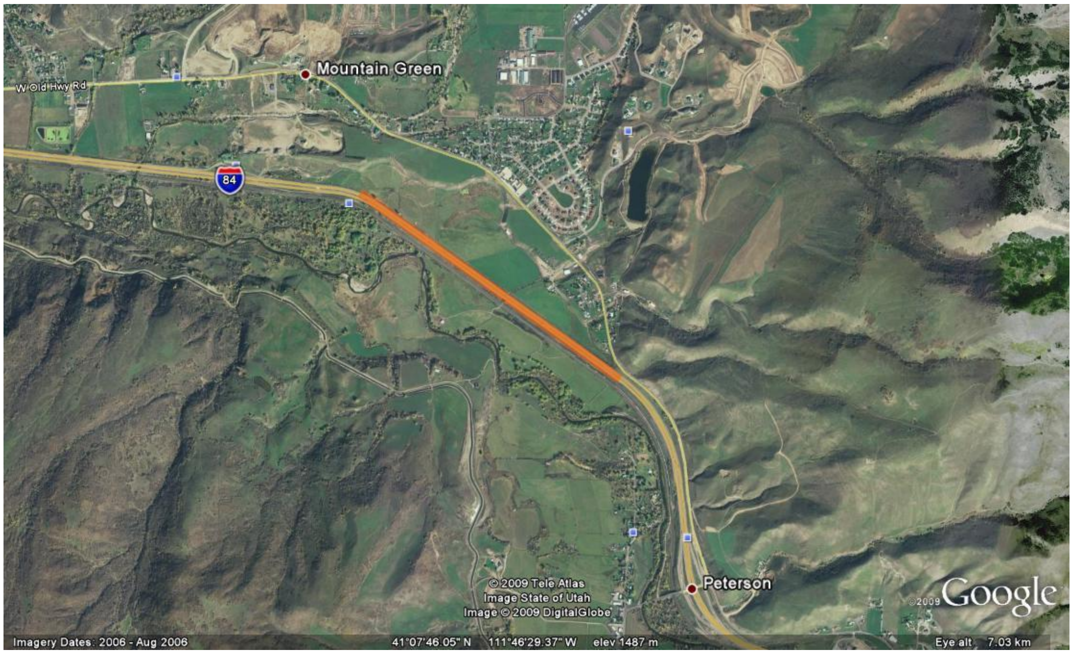

Figure 3-1 Location of I-84 reconstruction site.

structure consisted of 4 layers: a 9-in. asphalt layer (*16*), a 5-in. untreated base layer, and a 4-in. granular borrow layer overlying the native subgrade soil (*17*).

During the 2005 reconstruction project, the upper 5 in. of asphalt was milled and removed. The remaining 4 in. of asphalt was pulverized and mixed with 4 in. of the original base material to achieve a total reclamation depth of 8 in. with a single pass of a reclaimer. Following the first pass of the reclaimer, 2 percent Type II portland cement by mass of dry aggregate was placed in dry form on the surface of the reclaimed base layer with a cement spreader truck. During the second pass of the reclaimer, the cement was mixed with the reclaimed base material and water, consistent with UDOT specifications (*16*). Within a short time after compaction, the CTB layer was sealed with a prime coat to retard water evaporation and therefore enhance cement hydration. An HMA surface course containing a stiffening modifier was placed over the CTB layer to complete the pavement structure.

The finished pavement structure consisted of five layers: an asphalt layer with a design thickness of 5.5 in. and an estimated modulus of 700 ksi; a CTB layer with an average RAP content of 59 percent by mass, a design thickness of 8 in., and an average modulus of 546 ksi determined from 28-day UCS measurements (*4*); a remnant of the original base layer with a minimal thickness of just 1 in. and an estimated modulus of 30 ksi, assumed to be similar to the underlying material (*18*); a granular subbase material with a thickness of 4 in. and an assumed modulus of 30 ksi, consistent with current UDOT default values (*18*); and a subgrade soil estimated by UDOT personnel from falling-weight deflectometer testing to have a modulus of 10 ksi (*17*). The following sections describe the multivariate regression, Monte Carlo simulation, and M-E analyses utilized in this study.

3.2 Multivariate Regression

Field data were previously obtained from 30 locations randomly selected from three construction sections on I-84. Each section measured 1,000 ft in length by 40 ft in width (*4*). Random sampling was necessary in order to maintain the validity of the data and make statistical inferences from the results. Previous regression analyses of the collected data by other researchers indicated that the primary construction parameters most correlated to the UCS of the CTB layer are cement content, moisture content, and RAP content (*4*). UCS testing was emphasized in the previous research due to the fact that it is a primary parameter in CTB design (*5*); UCS results may also be of particular use in developing quality control measures and construction pay factors. The previously developed regression model is shown in Equation 3-1 (*4*):

$$UCS_{28} = 1551.7 - 100 \cdot MC_{28} - 6.3 \cdot RAP - 72 \cdot Cem \quad (\mathrm{R}^2 = 0.7315) \tag{3-1}$$

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

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

RAP = recycled asphalt pavement content, %

Cem = cement content, %

The R^2 value, or coefficient of determination, is the proportion of variation in the dependent variable, 28-day UCS in this case, that can be explained by variation in the independent variables, namely, moisture content, RAP content, and cement content; an R^2 value of 1.0 represents a perfect correlation (*19*).

In the current study, the previously developed regression model for estimating 28-day UCS was refined using a commercial software package to achieve a higher R^2 value through the introduction of variable transformations. A stepwise regression for all independent variables and their squared terms was performed to determine which variables should be added to the previously developed 28-day UCS equation. The stepwise regression process begins with a constant-mean model containing no independent variables and proceeds with iteratively adding and/or removing independent variables to/from the model until the best-fit model is identified (*20*); in this research, independent variables were included in the model only if their level of significance, or *p*-value, was less than or equal to 0.05. The independent variables evaluated in the analysis included RAP content; percentages finer than the 0.75-in., 0.50-in., 0.375-in., No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200 sieves; fineness modulus; cement content; time between mixing and compaction by research personnel; dry density; and moisture content during curing. As in the original analysis, the new analysis also excluded a zero-valued observation of cement content at a location over which the contractor failed to spread cement (*4*).

3.3 Monte Carlo Simulation

After the regression model was refined, a Monte Carlo simulation program was created to facilitate an analysis of how the distribution of CTB strength over the project would be affected by specified reductions in spatial variability among the independent variables in the model. The Monte Carlo simulations involved repeated random sampling from the specified distributions of the independent variables, which were each assumed to have a normal distribution consistent with previous research (*8*). Each independent variable included in the Monte Carlo simulation was assigned an appropriate lower limit, but upper limits were not specified.

The Monte Carlo simulation process utilized in this research consisted of five steps per iteration. First, a pseudo-random number greater than zero and less than or equal to one (*21*) was generated using the linear-congruential method, in which a new seed value was produced for the uniformly distributed random number generator each time the program was run. Second, the Box-Muller transformation was used to convert the random number into a standard normal deviate, or *Z*-value, associated with a standard normal distribution (*22*); a standard normal distribution has a mean of zero and a standard deviation of one (*23*). Third, the standard normal deviate was multiplied by the standard deviation specified for the distribution of the independent variable of interest and added to the mean of the same distribution to compute the value of the independent variable for the given iteration (*24*). If this value was greater than or equal to the lower limit specified for the given independent variable, the value was retained; otherwise, steps one to three were repeated. Fourth, steps one to three were repeated for each independent variable in the model so that values for each variable were determined for the given iteration. Fifth, the values of the independent variables were used in the regression model to compute a 28-day UCS value for the given iteration; if this value was greater than or equal to the specified lower limit of 85 psi determined for CTB strength, which reflects the strength of the untreated base material (*14*), this value was then converted to modulus using Equation 3-2 (*25*):

$$E_2 = \frac{UCS + 1142.6}{0.0028} \tag{3-2}$$

where E_2 = CTB modulus of elasticity, psi

UCS = unconfined compressive strength of CTB layer, psi

Otherwise, all five steps were repeated. The program automatically terminated when 100,000 predicted values of modulus were obtained (*2*).

Several different Monte Carlo simulations were performed in this research, one for the baseline case defined to represent the actual field conditions measured during I-84 construction and two additional simulations for each of the independent variables included in the regression model. In the latter simulations, the measured standard deviation of the independent variable of interest was reduced by 25 and 50 percent, in turn, while the distributions of the other independent variables were held constant. These reductions in standard deviation were included to reflect 25 and 50 percent reductions in spatial variability hypothetically accomplished by the contractor, as a reduction in standard deviation represents lesser variance from the mean, or greater uniformity in construction of the CTB layer in this application (*8*). The computer programming code utilized in the Monte Carlo simulation for the baseline case is given in Figure A-1 of the Appendix.

3.4 Mechanistic-Empirical Analysis

Estimates of the increase in pavement life due to the improved uniformity of the specified construction parameters were obtained through M-E analyses. Because the I-84 facility is still in service, evaluating the accuracy of M-E models available for predicting pavement life was not possible; instead, the emphasis of this research was on assessing the relative effects on pavement service life of proposed reductions in the spatial variability of certain construction parameters.

Five reliability levels were evaluated in the M-E analyses. In this case, reliability was defined as the probability that a given CTB modulus would be equal to or greater than a specified value. From the output of each of the Monte Carlo simulations that was performed in this research, the CTB modulus values associated with the 25th, 20th, 15th, 10th, and 5th percentiles were selected for reliability levels of 75, 80, 85, 90, and 95 percent, respectively. Percentiles were used for reliability instead of *Z*-values because the predicted CTB modulus values did not follow a normal distribution; the left tail in the distribution was missing due to the minimum 28-day UCS constraint set at 85 psi in the Monte Carlo program.

M-E analyses were then performed for each reliability level associated with each Monte Carlo simulation. KENLAYER software was used to calculate critical stresses and strains in the model reconstructed pavement structure, which is presented in Table 3-1. The pavement structure analyzed in KENLAYER is identical to the reconstructed pavement structure described previously except for the fact that the 1-in.-thick existing base layer was assumed to have properties similar to the 4-in.-thick granular base layer and was therefore combined with that layer for simplicity. As the focus of this research is the CTB layer, the modulus values for all other layers were held constant in the analyses. In each analysis, all layers were assumed to be linear elastic with constant modulus values through time, all layer interfaces were assumed to be fully bonded, and the load was specified to be an equivalent single axle load (ESAL). An ESAL is defined as an 18-kip single axle with four wheels, each of which has an effective contact radius of 3.78 in. and a contact pressure of 100 psi; dual wheels are separated 13.5 in. center-to-center (*26*). The horizontal tensile strain at the bottom of the asphalt layer, the horizontal tensile

Table 3-1 Layer Properties of Model Pavement Structure

Layer	Material	Thickness (in.)	Modulus (ksi)	Poisson's Ratio
1	Asphalt	5.5	700	0.35
2	Cement-Treated Base	8	Variable	0.20
3	Granular Base	5	30	0.35
4	Subgrade	NA	10	0.40

stress at the bottom of the CTB layer, and the vertical compressive strain at the top of the subgrade were all computed at radial distances of 0 in., 3.78 in., and 6.75 in. as measured from the center of one of the dual wheels towards the center of the other dual wheel for analysis.

Pavement life was then calculated using the three transfer functions shown in Equations 3-3, 3-4, and 3-5:

$$N_f = f_1(\varepsilon_t)^{-f_2}(\mathrm{E}_1)^{-f_3} \tag{3-3}$$

where N_f = allowable number of load repetitions to asphalt fatigue cracking failure

ε_t = horizontal tensile strain at the bottom of the asphalt layer, in./in.

E_1 = elastic modulus of the asphalt layer, psi

f_1 = 0.0796 (calibration factor)

f_2 = 3.291 (calibration factor)

f_3 = 0.854 (calibration factor)

$$N_d = f_4(\varepsilon_c)^{-f5} \tag{3-4}$$

where N_d = allowable number of load repetitions to subgrade rutting failure

ε_c = vertical compressive strain at the top of the subgrade layer, in./in.

$f_4 = 1.365 \text{ x } 10^{-9}$ (calibration factor)

f_5 = 4.477 (calibration factor)

$$\log N_f = \frac{0.972 \cdot (\beta_{c1}) - \left(\frac{\sigma_t}{R}\right)}{0.0825 \cdot (\beta_{c2})} \tag{3-5}$$

where N_f = allowable number of load repetitions to CTB fatigue cracking failure

R = flexural tensile strength of CTB layer, psi

σ_t = horizontal tensile stress at the bottom of the CTB layer, psi

$ß_{c1}$ = 1.0645 (calibration factor)

$ß_{c2}$ = 0.9003 (calibration factor)

Developed by the Asphalt Institute (AI), Equations 3-3 and 3-4 calculate the allowable number of passes of the load in question before more than 20 percent of the pavement surface area exhibits fatigue cracking and before rutting exceeds 0.5 in., respectively (*26*). Equation 3-5 was developed by the American Coal Ash Association (ACAA) to predict the allowable number of passes of the load in question until fatigue failure of chemically stabilized materials occurs (*27*); the calibration factors were determined through research at the Texas Transportation Institute (TTI) (*28*). The flexural tensile strength was determined in each case by multiplying the 28-day UCS of the CTB layer by 33 percent (*29*). The results obtained from the three transfer functions were compared, and the lowest number of allowable ESALs was specified as the expected pavement life in each evaluation.

3.5 Summary

Data used in this study were collected through field and laboratory testing from a pavement reconstruction site along the westbound lanes of I-84 near Peterson, Utah, during the summer of 2005. Previous regression analyses of the collected data indicated that the primary construction parameters most correlated to the 28-day UCS of the CTB layer are cement content, moisture content, and RAP content. The previously developed regression model for estimating 28-day UCS was refined in the current study to achieve a higher R^2 value.

After a new regression model was developed, a Monte Carlo simulation program was created to facilitate an analysis of how the distribution of CTB strength over the project would be affected by specified reductions in spatial variability among the independent variables in the new regression model. Several different Monte Carlo simulations were performed in this research, one for the baseline case defined to represent the actual field conditions measured during I-84 construction and two additional simulations for each of the independent variables included in the regression model. In the latter simulations, the measured standard deviation of the independent variable of interest was reduced by 25 and 50 percent, in turn, while the distributions of the other independent variables were held constant. These reductions in standard deviation were included to reflect 25 and 50 percent reductions in spatial variability hypothetically accomplished by the contractor.

Estimates of the increase in pavement life due to the improved uniformity of the specified construction parameters were obtained through M-E analyses. The M-E analyses were performed at five different reliability levels associated with each Monte Carlo simulation: 75, 80, 85, 90, and 95 percent. KENLAYER software was used to calculate critical stresses and strains in the model reconstructed pavement structure, and pavement life was then calculated using AI and ACAA transfer functions. The lowest number of allowable ESALs was specified as the expected pavement life in each evaluation.

4 RESULTS

4.1 Overview

Results of the multivariate regression, Monte Carlo simulation, and M-E analyses are given in the following sections. Because the data collected and analyzed in this study are specific to a particular construction site, the findings of this research may not be readily applicable to CTB layers constructed using different materials or in different climatic conditions.

4.2 Multivariate Regression

The refined regression equation developed in this research for predicting 28-day UCS is given in Equation 4-1:

$$UCS_{28} = 243.5 - 68.6 \cdot Cem - 101.3 \cdot MC_{28} + 40 \cdot RAP - 0.4 \cdot RAP^2 \quad (\mathrm{R}^2 = 0.7653) \qquad (4\text{-}1)$$

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

Cem = cement content, %

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

RAP = recycled asphalt pavement content, %

With the introduction of the RAP^2 term, the R^2 value increased by 0.0338 compared to the original equation. Figure 4-1 displays the relationship between the measured and predicted 28-day UCS values.

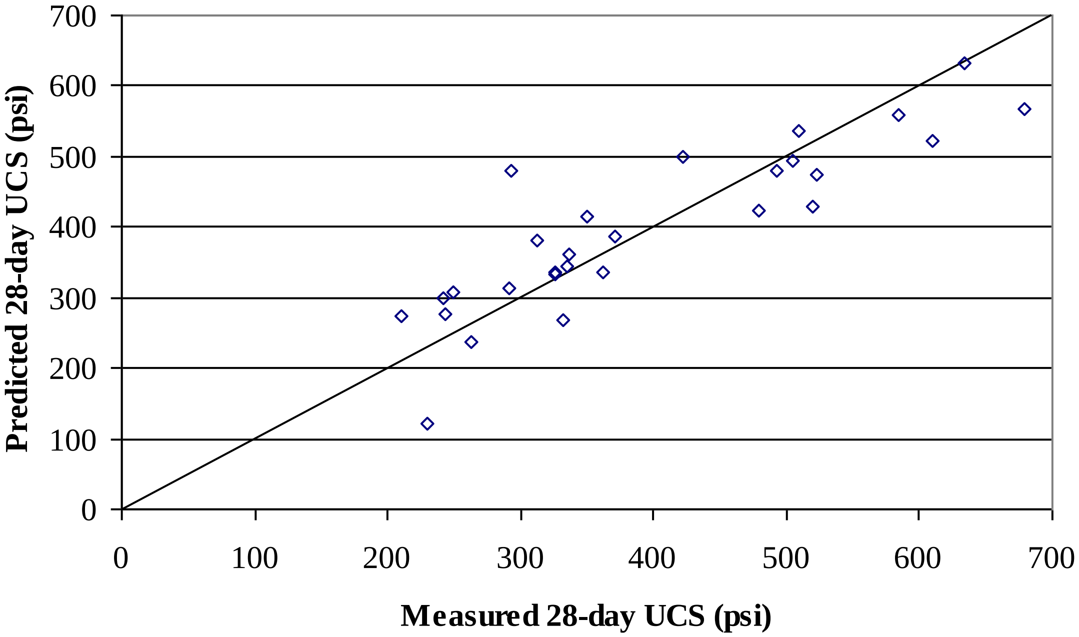

Figure 4-1 Relationship between measured and predicted 28-day UCS values.

4.3 Monte Carlo Simulation

The lower limits for all independent variables in the Monte Carlo program were set to zero, as negative values of cement content, moisture content, and RAP content are not possible. The means and standard deviations of these three independent variables included in the new regression model are shown in Table 4-1, and Table 4-2 displays the 28-day UCS and CTB modulus values that resulted from the seven Monte Carlo simulations performed in this research.

The results of the Monte Carlo program show a steadily increasing trend in 28-day UCS of the CTB layer with increasing reductions of variability for each reliability level. The steadily increasing trend shows that reducing the variability in cement content, moisture content, and RAP content provides additional strength and stiffness to the CTB layer.

Table 4-1 Means and Standard Deviations for Independent Variables

Independent Variable	Mean	Standard Deviation	Standard Deviation Reduced by 25%	Standard Deviation Reduced by 50%
Cement Content	1.42	0.58	0.43	0.29
28-day Moisture Content	6.85	1.14	0.86	0.57
RAP Content	59.06	7.88	5.91	3.94

Table 4-2 Critical Stresses and Strains in Model Pavement Structure

Parameter	Reduction in Variability (%)	Reliability (%)	CTB 28-day UCS (psi)	CTB Modulus (psi)	Critical Tensile Strain at Bottom of Asphalt, ε_t (10^{-6} psi)	Critical Tensile Stress at Bottom of CTB, σ_t (psi)	Critical Compressive Strain on Top of Subgrade, ε_c (10^{-6} psi)
Baseline	0	75	309	518,501	19.82	38.94	165.0
		80	286	510,372	20.34	38.64	166.0
		85	260	500,913	20.96	38.29	167.1
		90	228	489,336	21.74	37.86	168.6
		95	181	472,624	22.93	37.22	170.7
Cement Content	25	75	310	518,809	19.80	38.95	164.9
		80	288	510,787	20.31	38.66	165.9
		85	262	501,579	20.92	38.32	167.0
		90	230	490,357	21.67	37.90	168.4
		95	185	474,033	22.83	37.27	170.5
	50	75	312	519,378	19.77	38.97	164.9
		80	290	511,516	20.27	38.68	165.8
		85	263	502,156	20.88	38.34	166.9
		90	231	490,728	21.65	37.91	168.4
		95	186	474,379	22.80	37.29	170.5
28-day Moisture Content	25	75	323	523,387	19.52	39.12	164.4
		80	303	516,232	19.97	38.86	165.3
		85	279	507,734	20.51	38.55	166.3
		90	249	496,958	21.22	38.15	167.6
		95	204	481,082	22.32	37.54	169.6
	50	75	338	528,659	19.20	39.31	163.8
		80	321	522,746	19.56	39.09	164.5
		85	300	515,370	20.02	38.83	165.4
		90	273	505,469	20.66	38.46	166.5
		95	229	489,808	21.71	37.88	168.5
RAP Content	25	75	318	521,818	19.62	39.06	164.6
		80	297	514,125	20.10	38.78	165.5
		85	272	505,074	20.68	38.45	166.6
		90	241	494,042	21.42	38.04	168.0
		95	196	477,908	22.55	37.42	170.0
	50	75	327	524,921	19.43	39.17	164.2
		80	306	517,476	19.89	38.90	165.1
		85	282	508,836	20.44	38.59	166.1
		90	252	498,120	21.15	38.19	167.4
		95	208	482,514	22.22	37.60	169.4

4.4 Mechanistic-Empirical Analysis

The predicted CTB modulus values at the five reliability levels in each of the seven models were input and separately analyzed in KENLAYER, requiring a total of 35 KENLAYER analyses. Tables 4-2 and 4-3 present the critical stresses and strains computed in the M-E analyses, as well as the corresponding numbers of ESALs calculated using the AI and ACAA transfer functions. In every case, the governing mode of failure was CTB cracking.

Figures 4-2, 4-3, and 4-4 give a graphical display of the pavement life estimates as a function of reliability level and reduction in variability for each of the independent variables. In all cases, the differences in pavement life among the three levels of reduction in standard deviation are most manifest at lower reliability levels. In addition, because higher failure rates are tolerated at lower reliability levels, estimated pavement lives increase substantially from the high to the low reliability levels investigated in this study. On average, for all three independent variables, the projected pavement life increases by 171,960 to 5,556,042 ESALs as reliability decreases from 95 to 75 percent, respectively. Conversely, the increase in pavement life as a percentage of the baseline case increases with increasing reliability. In this case, the average pavement life increases by 41 to 566 percent as reliability increases from 75 to 95 percent, respectively.

Concerning the relative significance of reductions in variability for the three independent variables of interest, the data clearly demonstrate that reducing the variability in moisture content provides the greatest increase in pavement life; this emphasizes the importance of the role of moisture for satisfactory compaction of the CTB layer and for adequate cement hydration. Minimizing the variability in RAP content also yields a significant increase in pavement life, suggesting that efforts by the contractor to adhere to RAP content specifications will provide a

Table 4-3 Pavement Life Estimates from Transfer Functions

Parameter	Reduction in Variability (%)	Reliability (%)	CTB Flexural Tensile Strength (psi)	Allowable Load Repetitions (ESALs)			Estimated Pavement Life (ESALs)	Increase in Estimated Pavement Life Relative to Baseline Variability (ESALs)	Increase in Estimated Pavement Life Relative to Baseline Variability (%)
				Fatigue Cracking, N_f	CTB Failure, N_f	Permanent Deformation, N_d			
Baseline	0	75	102	2,434,620,244	13,391,719	117,342,958	13,391,719	-	-
		80	95	2,235,714,635	6,764,465	114,211,212	6,764,465	-	-
		85	86	2,025,352,613	2,631,058	110,883,541	2,631,058	-	-
		90	75	1,795,883,649	615,711	106,534,754	615,711	-	-
		95	60	1,506,987,318	30,356	100,791,330	30,356	-	-
Cement Content	25	75	102	2,442,722,881	13,716,547	117,661,878	13,716,547	324,828	2
		80	95	2,246,601,185	7,021,030	114,519,747	7,021,030	256,565	4
		85	86	2,038,125,168	2,829,830	111,181,111	2,829,830	198,773	8
		90	76	1,815,046,118	711,484	107,102,381	711,484	95,773	16
		95	61	1,528,820,110	41,500	101,321,728	41,500	11,144	37
	50	75	103	2,454,942,887	14,331,168	117,661,878	14,331,168	939,448	7
		80	96	2,261,224,356	7,495,090	114,829,303	7,495,090	730,625	11
		85	87	2,051,002,949	3,010,994	111,479,659	3,010,994	379,937	14
		90	76	1,820,570,035	749,186	107,102,381	749,186	133,475	22
		95	61	1,535,450,288	44,705	101,321,728	44,705	14,349	47
28-day Moisture Content	25	75	107	2,559,942,885	19,282,868	119,272,476	19,282,868	5,891,149	44
		80	100	2,374,953,605	11,179,755	116,392,524	11,179,755	4,415,290	65
		85	92	2,175,305,978	5,292,102	113,291,689	5,292,102	2,661,044	101
		90	82	1,944,823,965	1,671,127	109,410,220	1,671,127	1,055,417	171
		95	67	1,646,822,384	165,308	103,751,200	165,308	134,952	445
	50	75	111	2,703,055,718	27,656,515	121,240,951	27,656,515	14,264,796	107
		80	106	2,542,754,636	18,414,430	118,948,209	18,414,430	11,649,966	172
		85	99	2,355,488,980	10,420,391	116,077,807	10,420,391	7,789,334	296
		90	90	2,123,760,151	4,241,280	112,683,703	4,241,280	3,625,570	589
		95	76	1,804,063,677	658,520	106,818,107	658,520	628,164	2,069
RAP Content	25	75	105	2,517,253,321	17,211,477	118,625,020	17,211,477	3,819,757	29
		80	98	2,324,776,017	9,391,063	115,764,130	9,391,063	2,626,598	39
		85	90	2,117,008,164	4,076,756	112,381,206	4,076,756	1,445,698	55
		90	79	1,885,699,463	1,164,683	108,248,777	1,164,683	548,972	89
		95	65	1,592,186,943	91,820	102,662,735	91,820	61,464	202
	50	75	108	2,599,174,005	21,487,994	119,924,260	21,487,994	8,096,275	60
		80	101	2,406,535,488	12,354,991	117,025,096	12,354,991	5,590,526	83
		85	93	2,199,919,188	5,871,921	113,903,693	5,871,921	3,240,863	123
		90	83	1,966,087,800	1,917,664	109,996,657	1,917,664	1,301,953	211
		95	69	1,671,339,425	212,043	104,300,726	212,043	181,687	599

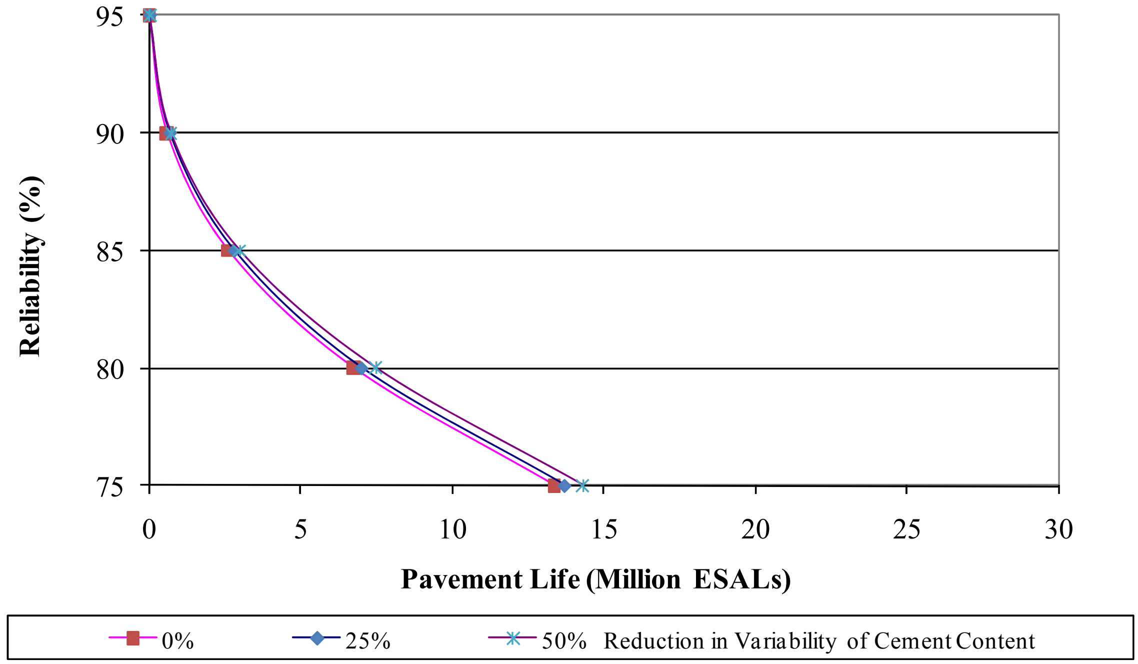

Figure 4-2 Interaction among pavement life, reliability, and reduction in variability of cement content.

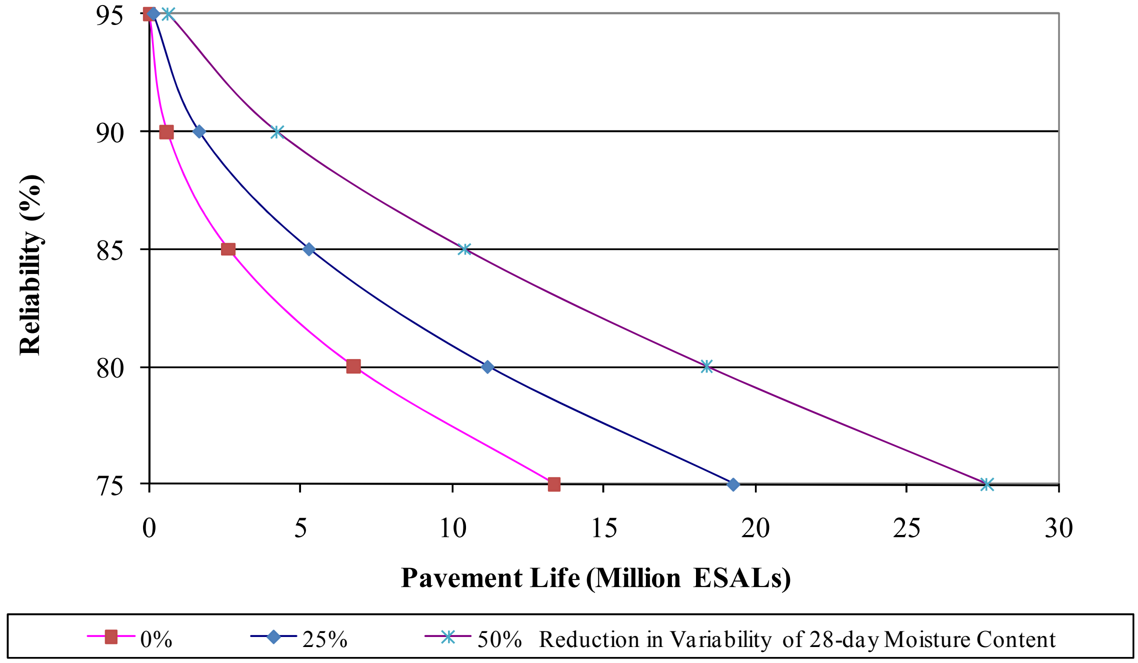

Figure 4-3 Interaction among pavement life, reliability, and reduction in variability of 28-day moisture content.

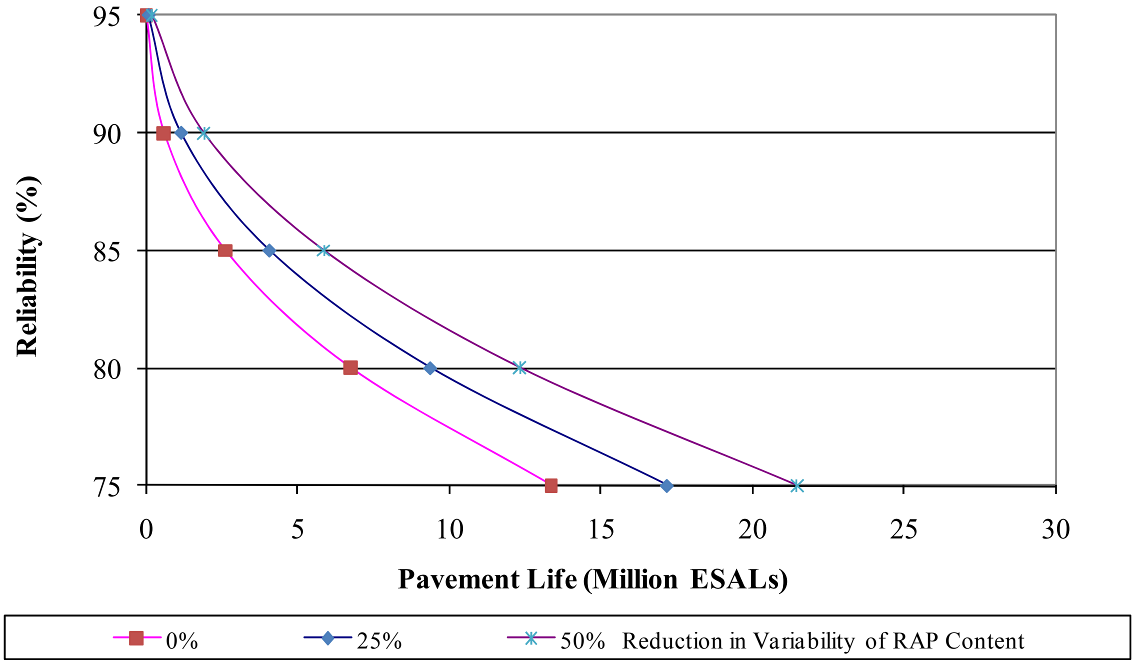

Figure 4-4 Interaction among pavement life, reliability, and reduction in variability of RAP content.

payoff in extending pavement life. In contrast, reductions in the variability of cement content provide comparatively little improvement in pavement life across all reliability levels; notably, both the mean and standard deviation associated with the baseline condition for cement content were the lowest among the three independent variables. Figures 4-5, 4-6, 4-7, 4-8, and 4-9 provide a different view of the data, showing pavement life estimates as a function of reduction in variability and independent variable type for each reliability level.

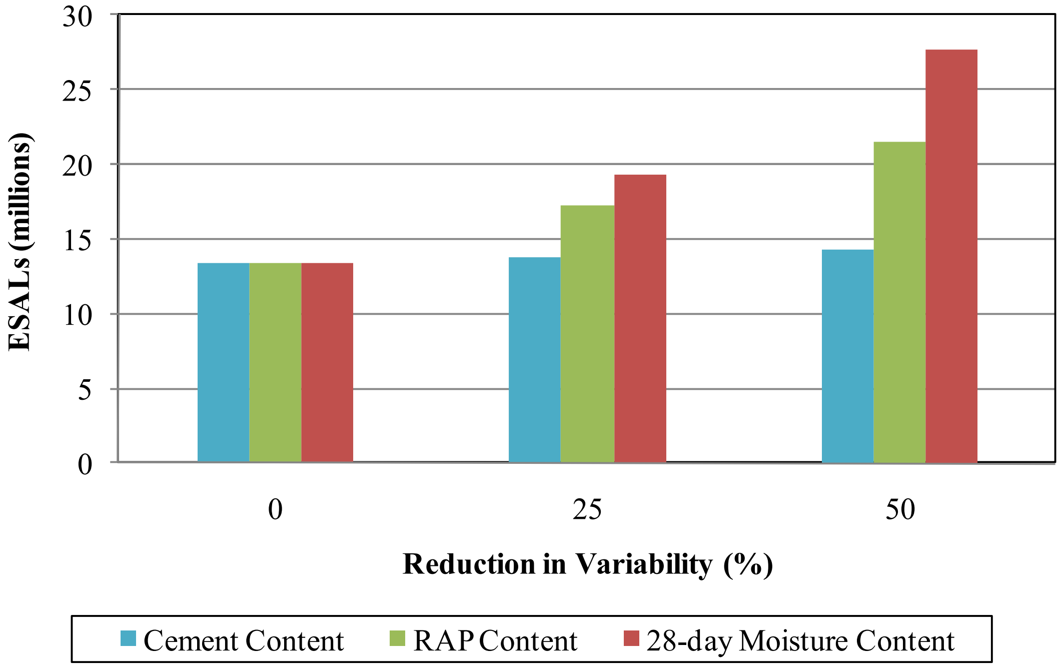

Figure 4-5 Interaction among pavement life, reliability, and reduction in variability at 75 percent reliability.

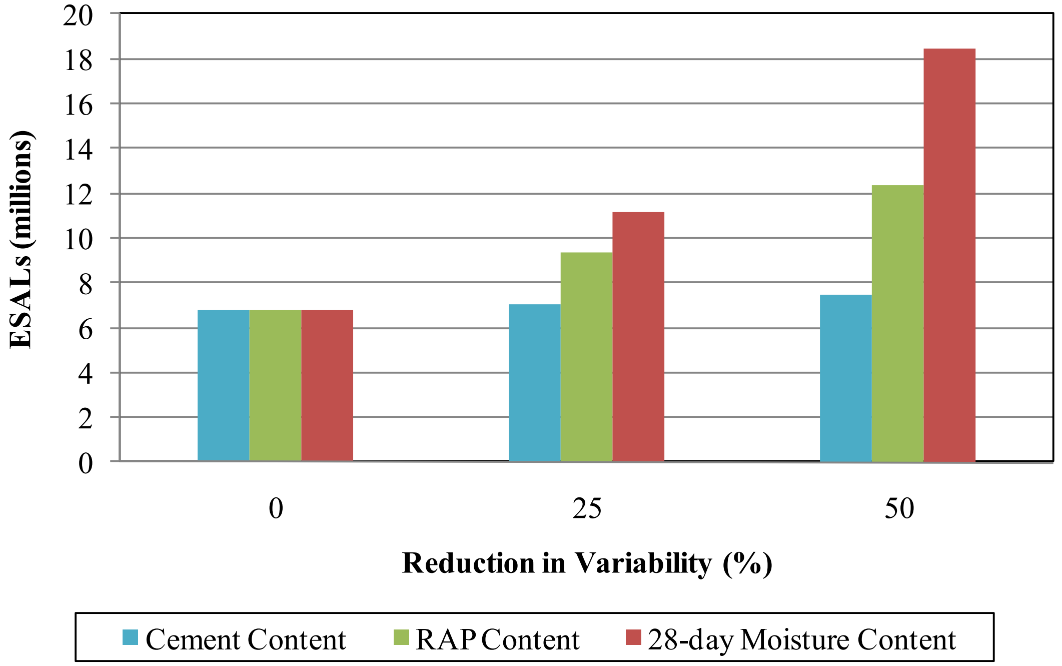

Figure 4-6 Interaction among pavement life, reliability, and reduction in variability at 80 percent reliability.

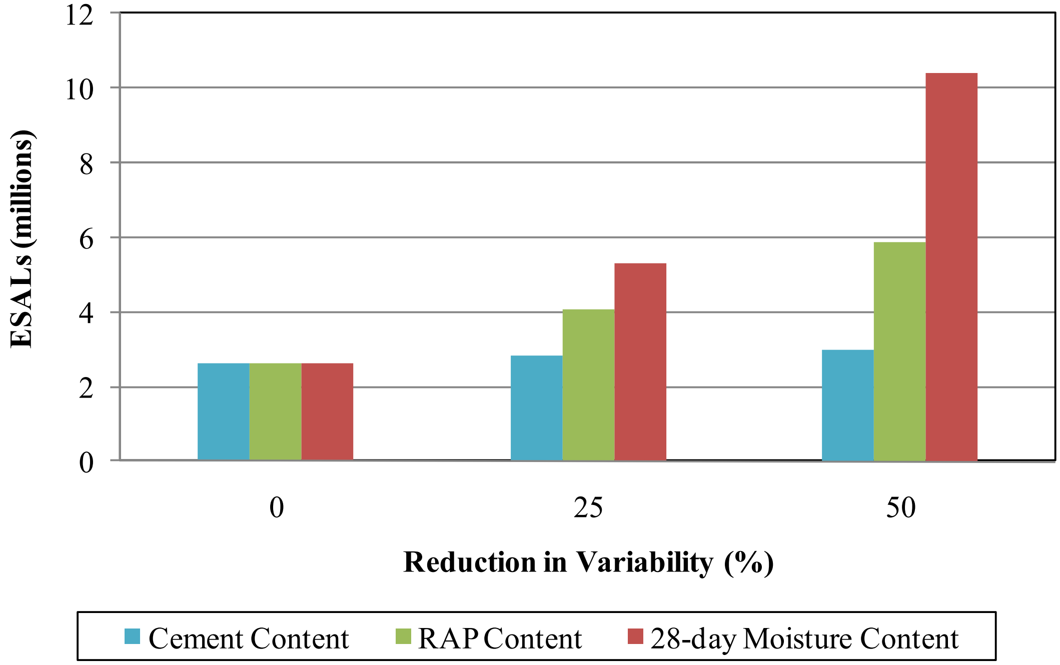

Figure 4-7 Interaction among pavement life, reliability, and reduction in variability at 85 percent reliability.

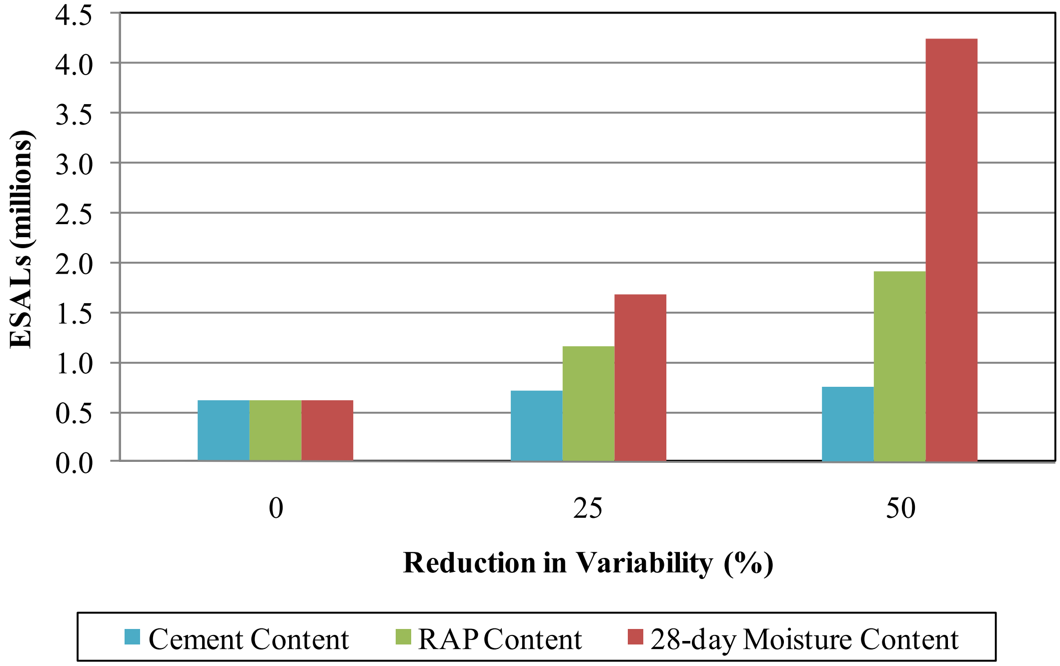

Figure 4-8 Interaction among pavement life, reliability, and reduction in variability at 90 percent reliability.

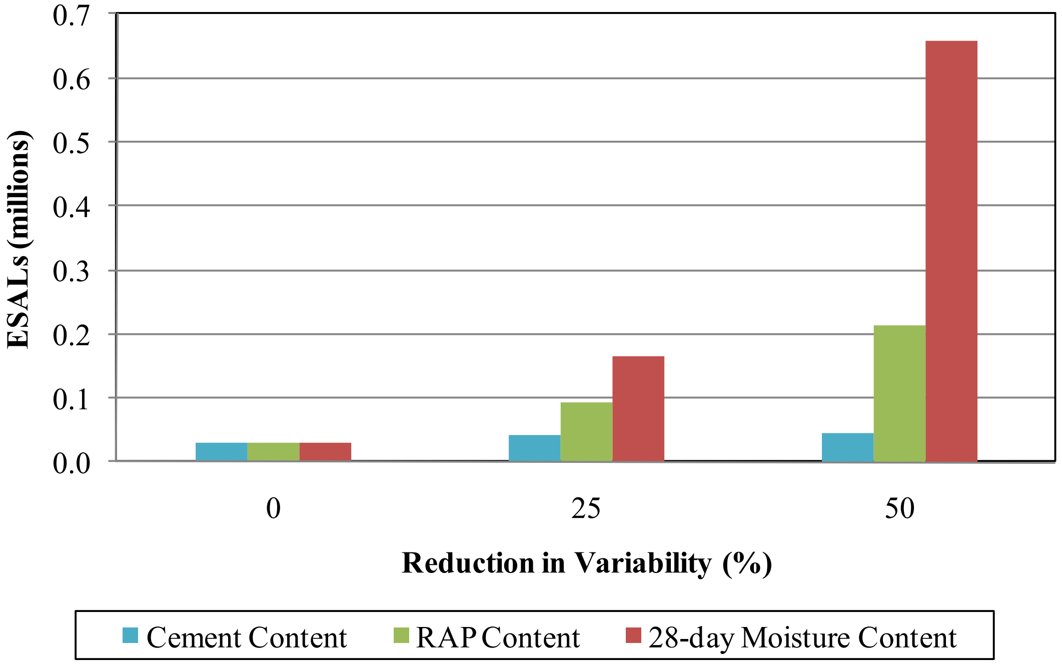

Figure 4-9 Interaction among pavement life, reliability, and reduction in variability at 95 percent reliability.

4.5 Summary

Multivariate regression of I-84 field and laboratory data, Monte Carlo simulations, and M-E analyses were performed in this study. The multivariate regression produced a refined model for predicting 28-day UCS; the addition of the RAP^2 term improved the R^2 value of the new regression model compared to one developed in previous research. The results of the Monte Carlo program show a steadily increasing trend in 28-day UCS of the CTB layer with increasing reductions of variability for each reliability level.

The M-E analyses involved evaluating predicted CTB modulus values at five reliability levels in each of the seven models that were input and separately analyzed in KENLAYER. A total of 35 KENLAYER analyses were performed. For all analyses, the governing mode of failure was determined to be CTB cracking.

In all cases, the differences in pavement life among the three levels of reduction in standard deviation are most manifest at lower reliability levels. In addition, because higher failure rates are tolerated at lower reliability levels, estimated pavement lives increase substantially from the high to the low reliability levels investigated in this study. On average, for all three independent variables, the projected pavement life increases by 171,960 to 5,556,042 ESALs as reliability decreases from 95 to 75 percent, respectively. Conversely, the increase in pavement life as a percentage of the baseline case increases with increasing reliability. In this case, the average pavement life increases by 41 to 566 percent as reliability increases from 75 to 95 percent, respectively.

Concerning the relative significance of reductions in variability for the three independent variables of interest, the data clearly demonstrate that reducing the variability in moisture content provides the greatest increase in pavement life. Minimizing the variability in RAP content also yields a significant increase in pavement life. In contrast, reductions in the variability of cement content provide comparatively little improvement in pavement life across all reliability levels; notably, both the mean and standard deviation associated with the baseline condition for cement content were the lowest among the three independent variables.

5 CONCLUSION

5.1 Summary

The primary objective of this research was to quantify the improvement in service life of a flexible pavement constructed using FDR in conjunction with cement stabilization when specified reductions in the spatial variability of specific construction-related parameters are achieved. Data used in this study were collected through field and laboratory testing at a pavement reconstruction site along the westbound lanes of I-84 near Peterson, Utah, during the summer of 2005.

Previous analysis of the I-84 data suggests that the primary construction parameters most useful in predicting the 28-day UCS of the CTB layer are cement content, 28-day moisture content, and RAP content. During the present study, the previously developed regression model for estimating 28-day UCS was refined to better predict CTB layer strength. After a new regression model was developed, a Monte Carlo simulation program was created to facilitate an analysis of how the distribution of CTB strength over the project would be affected by specified reductions of 25 and 50 percent in spatial variability among the independent variables in the new regression model. Estimates of the increase in pavement life due to the improved uniformity of the specified construction parameters were then obtained through M-E analyses at five different reliability levels associated with each Monte Carlo simulation: 75, 80, 85, 90, and 95 percent. KENLAYER software was used to calculate critical stresses and strains in the model reconstructed pavement structure, and pavement life was then calculated using AI and ACAA transfer functions. The lowest number of allowable ESALs was specified as the expected pavement life in each evaluation.

5.2 Findings

The results of the Monte Carlo program show a steadily increasing trend in 28-day UCS of the CTB layer with increasing reductions of variability for each reliability level. In all cases, the differences in pavement life among the three levels of reduction in standard deviation are most manifest at lower reliability levels. In addition, because higher failure rates are tolerated at lower reliability levels, estimated pavement lives increase substantially from the high to the low reliability levels investigated in this study. On average, for all three independent variables, the projected pavement life increases by 171,960 to 5,556,042 ESALs as reliability decreases from 95 to 75 percent, respectively. Conversely, the increase in pavement life as a percentage of the baseline case increases with increasing reliability. In this case, the average pavement life increases by 41 to 566 percent as reliability increases from 75 to 95 percent, respectively.

Concerning the relative significance of reductions in variability for the three independent variables of interest, the data clearly demonstrate that reducing the variability in moisture content provides the greatest increase in pavement life. Minimizing the variability in RAP content also yields a significant increase in pavement life. In contrast, reductions in the variability of cement content provide comparatively little improvement in pavement life across all reliability levels; notably, both the mean and standard deviation associated with the baseline condition for cement content were the lowest among the three independent variables.

5.3 Recommendations

The results of this research indicate that contractors involved in FDR projects similar to that evaluated in this study should focus their efforts on achieving greater spatial uniformity in moisture content and RAP content within CTB layers. Those responsible for quality assurance on such projects may consider attaching pay factors to measurements of uniformity in these parameters to encourage greater attention to these details by contractors. Because the data collected in this study are specific to a particular construction site, additional research may be warranted on FDR projects constructed using different materials or in different climatic conditions.

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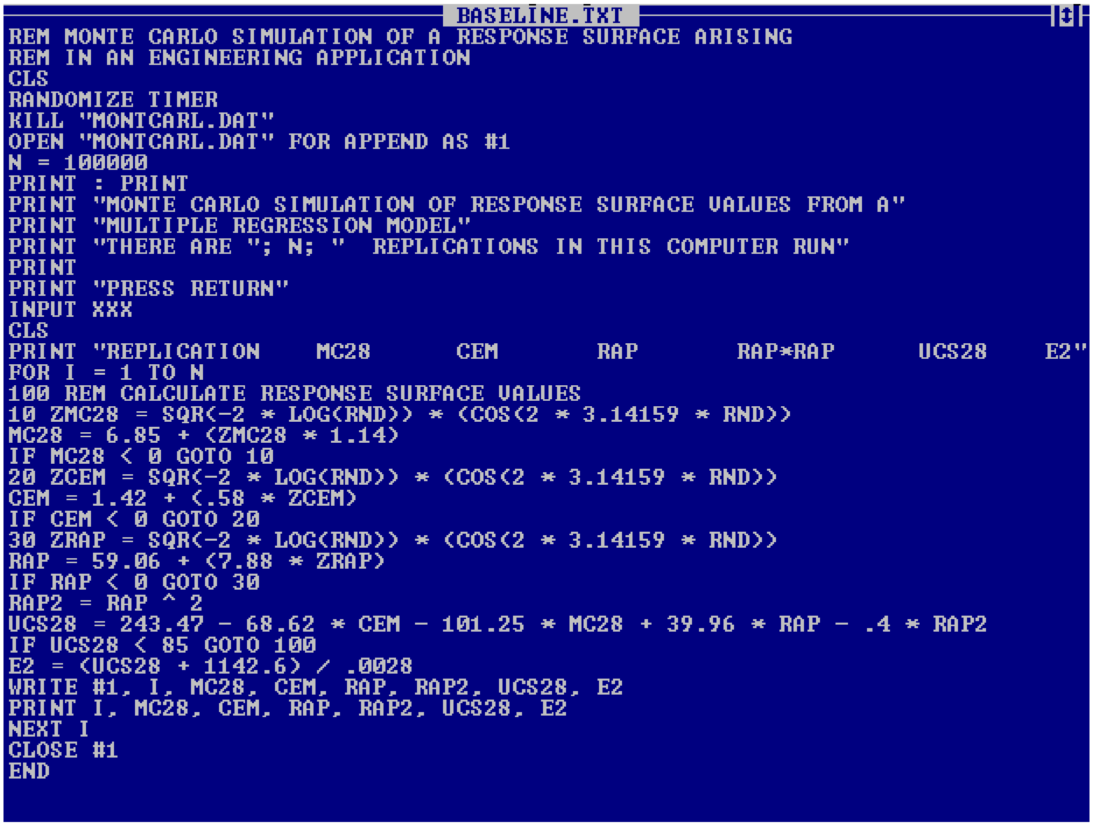
APPENDIX



```
REM MONTE CARLO SIMULATION OF A RESPONSE SURFACE ARISING
REM IN AN ENGINEERING APPLICATION
CLS
RANDOMIZE TIMER
KILL "MONTCARL.DAT"
OPEN "MONTCARL.DAT" FOR APPEND AS #1
N = 100000
PRINT : PRINT
PRINT "MONTE CARLO SIMULATION OF RESPONSE SURFACE VALUES FROM A"
PRINT "MULTIPLE REGRESSION MODEL"
PRINT "THERE ARE "; N; "  REPLICATIONS IN THIS COMPUTER RUN"
PRINT
PRINT "PRESS RETURN"
INPUT XXX
CLS
PRINT "REPLICATION    MC28      CEM       RAP       RAP*RAP      UCS28    E2"
FOR I = 1 TO N
100 REM CALCULATE RESPONSE SURFACE VALUES
10 ZMC28 = SQR(-2 * LOG(RND)) * (COS(2 * 3.14159 * RND))
MC28 = 6.85 + (ZMC28 * 1.14)
IF MC28 < 0 GOTO 10
20 ZCEM = SQR(-2 * LOG(RND)) * (COS(2 * 3.14159 * RND))
CEM = 1.42 + (.58 * ZCEM)
IF CEM < 0 GOTO 20
30 ZRAP = SQR(-2 * LOG(RND)) * (COS(2 * 3.14159 * RND))
RAP = 59.06 + (7.88 * ZRAP)
IF RAP < 0 GOTO 30
RAP2 = RAP ^ 2
UCS28 = 243.47 - 68.62 * CEM - 101.25 * MC28 + 39.96 * RAP - .4 * RAP2
IF UCS28 < 85 GOTO 100
E2 = (UCS28 + 1142.6) / .0028
WRITE #1, I, MC28, CEM, RAP, RAP2, UCS28, E2
PRINT I, MC28, CEM, RAP, RAP2, UCS28, E2
NEXT I
CLOSE #1
END
```

Figure A-1 Monte Carlo computer programming code for baseline case.