POOLED FUND STUDY OF PREMATURE CONCRETE PAVEMENT DETERIORATION

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Participating Agencies:

American Concrete Paving Assoc.
Iowa DOT
Kansas DOT
Louisiana DOTD
Minnesota DOT
Nebraska DOT
Portland Cement Asociation
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Pooled Fund Study of Premature Concrete Pavement Deterioration

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Region 7 Pooled Fund Study
Lead State Iowa

Iowa Department of Transportation
Research Project HR-1063

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Abstract

Recently, a number of roads have begun to exhibit the onset of deterioration at relatively early ages. Since this deterioration appears to be the result of materials issues, data concerning raw materials, design, and paving conditions have been collected and analyzed for correlation between independent variables and deterioration. This analysis shows that there is a positive and statistically significant correlation between deterioration and the following variables: alkali and sulfate content of the cementitious materials, impermeable base course, paving temperature, and the presence of fly ash. This study also concludes that there is a significant need for improvement in data collection and maintenance by many organizations responsible for the production of concrete.

Preface

Since widely changing attitudes toward deterioration of concrete have overwhelming economic and industrial implications, it is important to consider the applicability of statistical analysis to the resolution of this problem. Statistical analysis is a powerful tool for dealing with large numbers of variables and identifying key factors and their importance. However, it is severely limited by the quality and completeness of the data on which it is performed, and historical data, like that which is used in this study, is inherently flawed.

This study will present results which show statistically significant correlation between deterioration and a number of key variables. It will also show the relative significance of each of these results. Conversely, each of these results will have a level of "uncertainty". It is important that the reader consider this "uncertainty" combined with the amount of variation in the data which will not be explained by the analysis. While the results obtained by this study may be important, they are by no means conclusive.

It is the opinion of the authors that this study should serve as the groundwork for identifying future areas of study in the search for conclusive results. However, drastic changes in current practice or specifications are not warranted without further study.

Disclaimer

I. Introduction and Objectives

Recently a number of young pavements have exhibited the onset of premature deterioration which can be generally related to materials, as opposed to structural, issues. The objective of this study, as stated in the call for proposals has been to "collect data and from and analysis of that data identify the variables that are present in those pavements exhibiting premature deterioration." More specific definition of the problem and background can be found in the project proposal in appendix A.

a) Approach

The approach for achieving this objective has been a multiple step process including the following activities.

- Survey Development- A survey was developed with the participating states in order to facilitate the collection of data for use in statistical analysis. This step has included the formulation of a list of a large number of variables which can affect concrete durability. This list was then refined and approved by the participating states, and questions were written to solicit the appropriate data.
- Data Collection- Data was collected by the individual states over a number of months.
- Database Formulation- Data received from the states was entered into a common format.
- Statistical Analysis- Multiple regression analysis was performed on the data.
- Evaluation of Statistical Models- Models were evaluated to ensure that they were both statistically valid and physically realistic.

These steps will be discussed in detail, followed by the results and conclusions derived from the statistical analysis. It is important to note that this project, and the relevant discussion will not include conclusions concerning the mechanisms involved.

b) Formation of Technical Advisory Group

The successful completion of this study was highly dependent on the collection of accurate and relevant data and an analysis of this data based on a physical understanding of the system in the real world. The technical advisory group was formed to be an integral part in both of these tasks. First, the members of the technical advisory group and their organizations provided all of the data used in this study. Second, the expertise of the technical advisory group was utilized in every step of the process, including the identification of possible important variables, the design and completion of the survey, and the eventual evaluation of the final analysis and conclusions drawn. The Technical Advisory Group includes representatives from the following organizations:

American Concrete Paving Association
Iowa Department of Transportation
Kansas Department of Transportation
Louisiana Transportation Research Center
Minnesota Department of Transportation
Portland Cement Association
Nebraska Department of Roads
Wisconsin Department of Transportation

c) Literature Review

For purposes of brevity, the literature review and corresponding bibliography are included in the project proposal in appendix A.

II. Data Collection

a) Survey Development

Development and execution of data collection procedures constituted one of the major tasks in this study, and this data serves as the foundation for all results obtained by statistical analysis. However, numerous obstacles made this process complex and difficult. These obstacles have included a lack of complete and properly maintained records, a vast number of possible important variables, and difficulties arising in efforts to quantify the levels of actual deterioration.

Cognizant of these issues, an initial survey was developed by the Northwestern research team. The survey focused on the variables known to affect pavement durability as well as other factors often left unexamined (e.g. base course permeability and weather conditions). Survey development at Northwestern was augmented at an early stage with individual visits to each of the funding agencies. The meetings provided a forum for reviewing and understanding the goals of the project from each state's prospective. As a result of these discussions, additional questions were incorporated into the data collection survey. Along with review if the initial form of the survey, a protocol for pavement site selection and deterioration quantification were developed.

In accordance with the site selection protocol, only pavements constructed during or after 1983 were selected. A pavement "site" was defined as a pavement constructed by one contractor having a common cement and aggregate mix design. Deterioration was quantified using the SHRP P338 distress manual as a guide supplemented with additional pictures of pattern cracking of varying severity. Following the SHRP procedure, a deteriorated site was not necessarily a "failed" site, only one experiencing a given percentage of premature deterioration based on the age of the pavement. Sites were not to be included where failure was knowingly a result of inadequate structural design. A minimum of 12 sites were to be chosen by each state with no less than four of those sites being classified as "non-deteriorated". The purpose of having non-deteriorated sites provides the needed bench mark for statistical analysis (i.e. finding a correlation between variables in deteriorated pavements can only occur with sufficient data from non-deteriorated pavements.) A copy of the protocol for site selection is given in Appendix B.

The survey was revised and expanded by the Northwestern research team following meetings with individual states. The final form of the survey was adopted by the entire pooled fund study group during the May 1996 meeting at Northwestern. The survey contains 7 sections as listed below in Table 2.1with at total of 137 questions. A copy of the final survey can be found in Appendix B.

Table 2.1. Premature deterioration survey sections.

Section	Subject of Section
I	Pavement Site and Construction Background
II	Composition of Construction Materials
III	Processing
IV	Structural and Geotechnical Issues
V	External Effects
VI	Properties of Hardened Concrete
VII	Damage Characterization

Initially, one survey (corresponding to one pavement project site) was completed by each state to familiarize both the Northwestern group and the states with the collection process. The initial surveys were reviewed at Northwestern and refined. Following the initial data collection and review period, the states were asked to complete the survey for each of their pavement sites. All survey data used for analysis were received at Northwestern by September, 1996.

The development of the data collection survey was by definition an iterative process occurring over several months and reviewed continuously by all parties involved. The ability of this study to provide statistically valid results lies in the accuracy and completeness of the data. Accounting for the conditions mentioned previously of missing records and in some cases, a general lack of data, this approach and its execution was the best and most complete option available.

b) Database Development

The development of a database containing the information gathered from the surveys was one of the original goals for this study. Moreover, the development of comprehensive pavement databases containing information covering all aspects of construction practices and material specifications has been the goal of several agencies for some time. The need for comprehensive pavement databases has most notably lead to the formation of ACI Committee 126 titled "Database Formats for Concrete Materials Properties." The goal of the database from this study is not only to provide a simple and logical method to categorize information for statistical analysis, but to provide a lasting source of information to be used by the funding agencies for a variety of purposes in the future.

As the surveys were returned from the states, the data was examined and in many cases standardized. Standardization was required especially in the damage characterization sections where subjective responses were prevalent. In the specific case of the damage assessment section (VII), pictures of the damaged sites along with the responses from states were evaluated independently by the Northwestern research team. Damage was rated on a scale from 0.00 to 3.00. Examples of 3 different levels of damage are included in appendix B. The individual evaluations were then compared and averaged to give a mean value for damage. In most cases, the differences among the independent Northwestern team members' evaluations were small and in no case were the differences greater than 0.8.

All data was entered into Microsoft Excel spreadsheets due to the programs widespread use by both the states and the Northwestern research team. Each section of the survey was divided by spreadsheets with questions listed numerically in columns. The data for each state was grouped together and entered by ascending pavement site number. This format allowed for simple transfers into the statistical analysis program. In total, there are 54 individual pavement sites in the databases (Iowa 12, Kansas 12, Nebraska 20, Minnesota 7, and Wisconsin 3.) Multiplied by the individual questions and subsets of questions, there are approximately 10,000 individual data values. An example of the database spread sheets is given below in Table 2.2. The complete database is now the property of the pooled study group and Northwestern University.

Table 2.2. Selection from pooled study database.

(Section II. Composition of Construction Materials, Question 61, Iowa sites 1-5.)

Survey Question			61				
			Final Mix Composition (in wt. percentages)				
Site No.	State	Sate Site No.	Cement	Water	Coarse Agg.	Fine Agg.	Plasticizer
1	IA	1	12.00%	7.00%	43.00%	36.00%	0.30%
2	IA	2	15.00%	7.00%	41.00%	35.00%	0.00%
3	IA	3	12.50%	7.00%	43.00%	35.00%	0.30%
4	IA	4	15.00%	6.00%	43.00%	35.00%	0.30%
5	IA	5	13.10%	6.60%	38.00%	39.00%	0.30%

The development of the survey and subsequent database encompassed the first 9 months of this study (Figure 2.1). As previously mentioned the quality and quantity of data from the surveys is one of the most important factors in arriving at statistically and physically valid results. To summarize, a comprehensive survey was developed that led

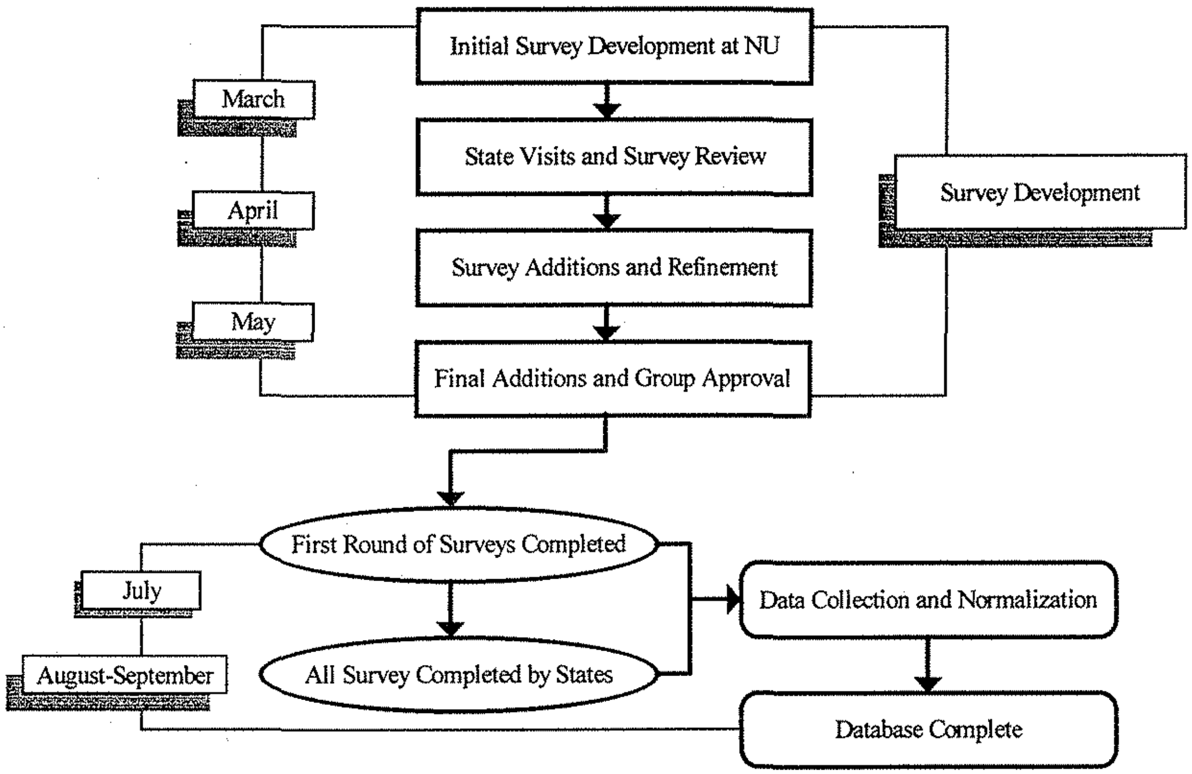

Figure 2.1: Timeline and organizational flow of survey development and data collection.

to the formulation of an extensive database for 54 pavements throughout the Midwest from which statistical analysis was performed.

III. Statistical Analysis: Procedure

a) Correlation

The basic premise of statistical analysis of trends is finding a correlation between a dependent variable and one or more independent variables. In its simplest form, a positive correlation between two variables means that as one variable is increased, the other tends to increase. When data are analyzed, it is possible to find the magnitude of the correlation, which represents the amount that the dependent variable changes with a given change in the independent variable. It also is possible to determine the statistical significance of the correlation and the amount of the variation in the data that is explained by this correlation.

If the data are affected by more than one independent variable, multiple correlation (also known as multiple regression) analysis determines the effects of these independent variables, and also the effects of any interactions among them. The result is an equation, known as a model, which describes the effects of the independent variables on the dependent variable (degree of deterioration in the present analysis). In simple single variable correlation it is the equation of a line, while in multiple correlation it is a response surface in multidimensional space, the axes of which represent the dependent variable and each of the independent variables that affect the results. The model equation can take the following form:

$$Y = AX_1 + BX_2 + CX_3 + \ldots$$

where Y is the dependent variable, X_1, X_2, and X_3 are independent variables, and A, B, and C are correlation coefficient. In a real world example, it would be possible to show that a student's grades could be a function of his ability, X_1, the amount of time he spends studying, X_2, and the percentage of classes he attends, X_3. It is left to the statistician to find the magnitudes of A, B, and C from the data.

b) Interactions

In some cases, two or more of the independent variables will have some sort of interaction in the system being studied. For example, X_2 might have a more pronounced effect at a high level of X_1 than at a low level of X_1. In order to account for this effect, it is possible to create new variables that are combinations of the original set of independent variables. These can then be added into the model when appropriate, creating and equation of the following form:

$$Y = AX_1 + BX_2 + I_{12}X_1{*}X_2 + CX_3 \ldots$$

where I_{12} represents the correlation coefficient of the interaction between X_1 and X_2. Since there is a virtually unlimited number of possible interactions, the present analysis will only include the interactions which have a reasonable likelihood of having a real effect on the system.

c) Building the Model

Every model is built on the framework of statistical information, and three of the key components of this information are described below:

Correlation Coefficient- The correlation coefficient reflects the magnitude and sign of the effect of a variable. A positive sign on a correlation coefficient predicts an increase in the dependent variable (i.e. deterioration) as the independent variable is increased.

T Value- The T value represents the relative certainty that a given independent variable has an effect on the dependent variable. Specifically, it is the magnitude of the correlation coefficient divided by the standard deviation of the variable to which it pertains. A T value of 2 corresponds to a 90% certainty that an increase in the independent variable will result in an increase in the dependent variable. It is important to note that the sign of the T value relates only to the sign of the effect, not the certainty involved with a given variable. Also, a variable with a T value of less than 2 is not considered to be significant.

R^2 Value (Model)- The R^2 value reflects the amount of the total variation of the data which is described by the model. An R^2 value of 1 would occur if all of the variation is explained by a given model. Any variation that is not explained could be a result of the effects of variables not included in the model, errors in the data, or any number of uncontrolled and uncontrollable effects (sometimes referred to as noise in the data).

R^2 Value (Individual Variables)- As a model is built, the analysis software also provides an R^2 value for each independent variable as it comes into the model. This number is a measure of the degree of confounding between that variable and the other variables already in the model. It is important to avoid the inclusion of variables with a high individual R^2 value.

There are several possible strategies for building the model. The strategy we have chosen is to add variables to the model one by one, beginning with the most significant one, using commercial software (Multiple Correlation, Harold S. Haller & Co., Cleveland, OH). After the data and variables are entered, any possible interactions are entered as additional independent variables. Then the computer evaluates each member of this extended set of variables to determine what its T value would be if it was brought into the model by itself. This approach makes it possible to evaluate the effects of each of a very large number of possible significant variables, and find the ones that are the most significant. After all variables have been evaluated, the variable with the highest T value is added to model, provided its presence in the model makes sense physically. At this point, the remaining variables are individually reevaluated to determine what their T values would be if they were included in the model. The variable with the highest T value is then added into the model, if it is physically plausible, and this process is repeated until all variables not in the model have T values lower than 2. There may be exceptions to this process under the following circumstances.

- Variables with high T values may have little physical relevance or the sign of their correlation is counter to the accepted understanding of the physical system.
- Variables to be included are highly confounded with other variables already in the model.
- Too many variables are included in the model to preserve a reasonable degree of freedom. In other words, it is important not to overdetermine the model.

It can be appreciated that the model building process is a detailed exercise involving meshing statistical data with physical principles. Much thought must be applied, and alternatives explored, before the "best" model can be obtained.

When the model has been completed, there still will be unexplained variation in the data, and perhaps a large number of variables left over, each of which might be responsible in part for that variation. However, their significance can not be determined on the basis of the data in hand. It goes without saying that additional data quite likely would result in refinement of the model and identification of other variables that are of importance.

d) Evaluating the Model

Since the building of a model involves a number of decisions based on judgment, it is important to be able to accurately evaluate a statistical model's validity. Alternative models can be evaluated by comparing their T and R^2 values. Since T values represent the certainty that a variable should be included, the model with the highest T values for included variables has a higher degree of certainty. Also, the model with the higher R^2 value explains a larger percentage of variation in the data. In evaluating a model, there are also a number of techniques including plotting fitted versus residuals and evaluating outliers which will reveal inappropriate skewing of a model. Most importantly, however, is a comparison of the model's predictions to predictions based on physical understanding. It is important that conclusions of the model be consistent with accepted views of the real world. This prevents the possible creation of a statistically valid result with no physical significance.

During each phase of the building of a model, each of the above evaluation criteria is considered. Whenever they indicate a misleading statistical result, every effort is made to revise the model in a positive way. The result is an iterative process, where each model developed is in many ways superior to the previous model. For this reason, models presented here are the result of multiple iterations of model building and evaluation.

e) Strengths and Weaknesses of Statistical Analysis

Statistical analysis provides a great deal of important information. It isolates the key variables which have the most significant effect on the system. It also reports the statistical certainty and relative weight of each of these variables. The major advantage of statistical analysis, however, is the ability to deal with large amounts of data containing large sets of variables. The traditional method of measuring the effect of one variable while holding all other constant is not possible in a complex system, such as concrete paving. And when working with historical data, when no experiments can be run, it is the only way to obtain useful information about plausible causes of observed effects. Because historical data are by their very nature incomplete, and often poorly distributed with respect to the independent variables, the model must of necessity be incomplete, and a greater or lesser degree of unexplained variation is to be expected. Because of these limitations, it may be helpful to keep in mind the following guidelines and caveats:

- Statistical results are only as good as data from which the model is derived.
- Variables reported in a model report a direct and quantifiable correlation with performance.
- No conclusions can be drawn concerning variables for which incomplete data exists.
- No conclusions can be drawn concerning significant variables for which the range of variation of that variable in the data is too small to reveal its significance.
- Two or more independent variables may be correlated with each other, in which case it is often not possible to determine which is causing the observed effect.

Despite these limitations, multiple correlation analysis provides the best estimate of the effects of the significant variables that can be determined, and reports the statistical significance of the results. The model can be used as a basis of further studies of historical data, or for planning experiments to test the predictions of the model.

IV. Results and Discussion

A large amount of data was collected from four different states participating in the study. This data was then compiled into a single database. However, it was necessary to exclude a number of variables from consideration. Variables were not included in the final analysis either because there was no significant site to site variation or because data for that variable was not complete for all states. Also, some sites had to be excluded because of incomplete data. Finally, sites from some states have not been included because they were not available or provided too late into the analysis process. In general, the inclusion of more sites results in having complete data for fewer variables. In order to balance this effect and build a model with an adequate number of sites, two models were created. It should be understood that the differences between these sites are a result of slight differences in available data. For that reason, they should be considered to be giving slightly different views of the same picture.

Model I contains a total of 37 sites, with 27 independent variables for each site. Model II contains a total of 43 sites, but has only 24 independent variables. Each model will be discussed in the context of its statistical validity and physical meaning.

a) Model I

Model I was constructed with data from 37 sites with complete information on 27 independent variables. Sites were included from Iowa (12 sites), Kansas (12 sites), and Nebraska (13 sites), and a list of the variables is included in table 4.1. Statistical Results are presented in table 4.2, with important variables listed in order of decreasing T value. These important variables will be discussed in further detail below.

Total Alkali * Total Sulfate

This variable represents the product of total alkali and total sulfate compositions in the cementitious materials. As this product increases, the resulting pavement damage has a strong tendency to increase. This tendency is reflected by the sign coefficient. The T value for this variable is 5.31. Since a T value of 2 or greater corresponds to at least a 90% certainty that the variable does in fact have an influence, this variable can be included in the model with an extremely high degree of confidence.

It is important to note that this variable reflects a fairly complex relationship. It indicates that an increase in either the total alkali or total sulfate levels alone correlates to an increase in damage. Furthermore, increasing both variables simultaneously will have an interactive effect greater than the sum of the effects of the independent variables. Physically, this suggests that there is a mechanistic relationship between sulfates and alkalis. The fact that alkalis significantly change sulfate solubility coupled with the synergistic effects of different deterioration mechanisms supports this possibility.

Paving Temperature

In this study paving temperature was treated as the maximum reported ambient temperature experienced during paving. This model shows that there is a high positive

Variable Number	Independent Variable
1	State
2	State Site Number
3	Age
4	Cement Type
5	C3S Content of Cement
6	C2S Content of Cement
7	C4AF Content of Cement
8	C3A Content of Cement
9	Cement Sulfate Content
10	Cement Alkali Content
11	Concrete Strength (7day)
12	Cement Content of Total Mix
13	Water Content of Total Mix
14	Coarse Aggregate Content of Total Mix
15	Fine Aggregate Content of Total Mix
16	Fly Ash Content of Total Mix
17	Total Alkali Content of Cementitious Materials
18	Tot Sulfate Content of Cementitious Materials
19	Average Reported Slump
20	Average Reported Air
21	Traffic
22	Slab Width
23	Slab Thickness
24	Slab Length
25	Permeability of Base Course
26	Minimum Paving Temperature
27	Maximum Paving Temperature
28	Degree of Pattern Cracking

Table 4.1: List of variables used in the creation of model I.

Variable	Coefficient	T	R squared
Alkali(tot) * Sulfate(tot)	8110	5.31	0.29
Paving Temperature	0.0607	3.87	0.11
Age	0.122	2.35	0.25
Base Course Perm.	-0.314	-2.19	0.17

Intercept= -6.01 RSQ= 0.5932

Table 4.2: Statistical information describing the results and validity of model I.

correlation between this temperature and pavement deterioration. A T value of 3.87 illustrates a high confidence that an increase in ambient, external temperature correlates to an increase in pavement deterioration. Since this result is not inconsistent with a number of physical mechanisms, including drying shrinkage and D.E.F., it is considered an important result.

Age

Model I also reveals a positive correlation between age and pavement deterioration. A T value of 2.35 indicates that older pavements have a higher tendency to exhibit deterioration. Although this is an intuitive result, its inclusion in the model is necessary to take account of variation due to age.

Base Course Permeability

Base course permeability, as evaluated on a discreet, qualitative scale, correlated fairly well with deterioration. In this case, pavements with impermeable pavements had an increased tendency to deteriorate, and this tendency had a T value of 2.19. Since an impermeable base course may result in more available external water, this result is considered to be statistically and physically reasonable.

Schematic Figures

A number of schematic figures have been included to illustrate model I. Figure 4.1 shows damage plotted versus total alkali and total sulfate at high levels of the remaining variables. It is important to note increased damage with respect to increases in total alkali and total sulfate. It is also important to note the synergistic effect of the two independent variables, as illustrated by curved lines separating regions of different damage levels. Figure 4.2 shows damage plotted versus paving temperature and total sulfate content, increasing with increases in both independent variables. In this case, the variables do not have a synergistic effect.

Figure 4.3 shows damage plotted versus total sulfate level for two different levels of total alkali and high constant values of the remaining variables. In this representation thick lines represent model predictions and thin lines represent the upper and lower bounds of the 95% confidence interval. The confidence interval represents the range into which the mean would fall 95% of the time if this experiment were repeated with the same

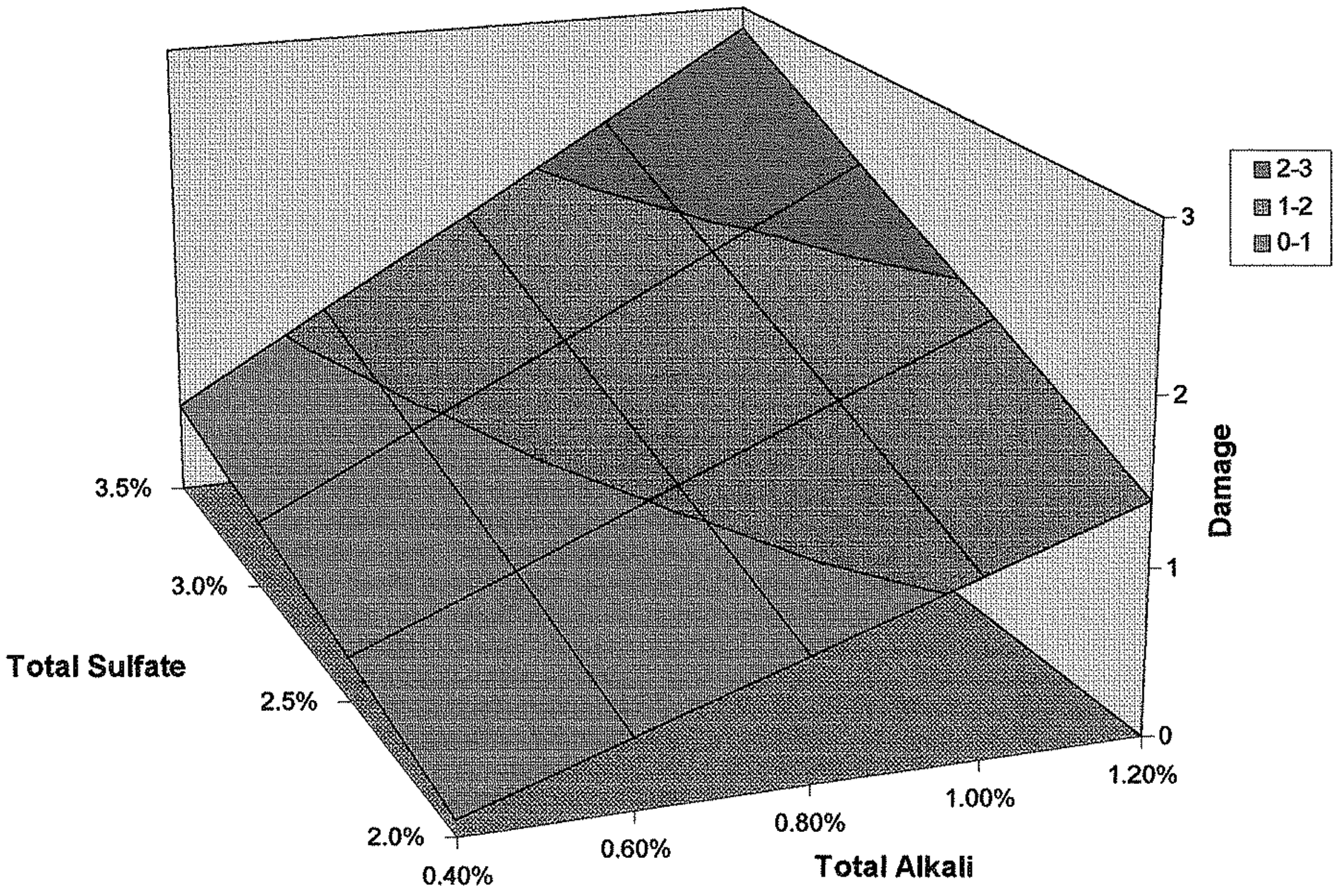

Figure 4.1: Schematic representation of damage vs. total sulfate and total alkali levels for model I with high levels of remaining variables.

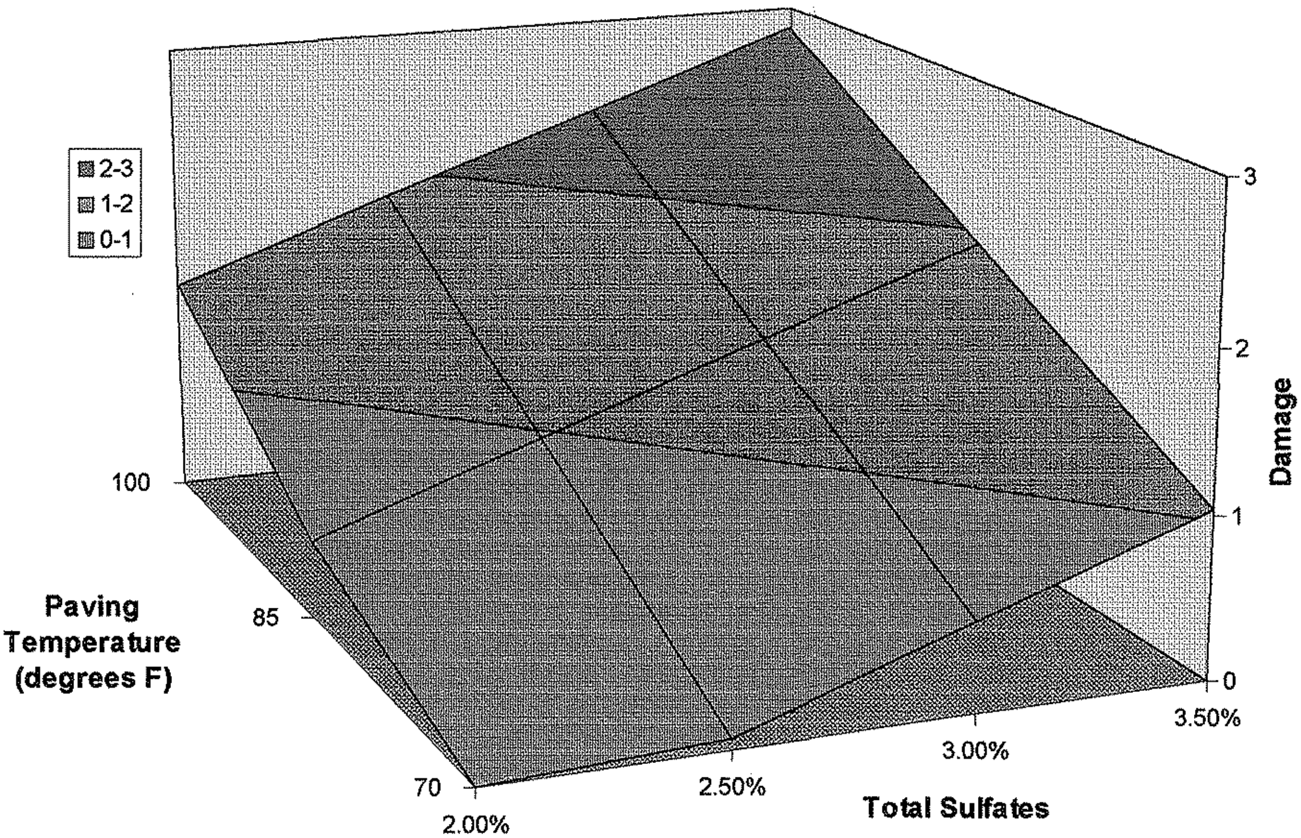

Figure 4.2: Schematic representation of damage vs. total sulfates and paving temperature for model I with high levels of remaining variables.

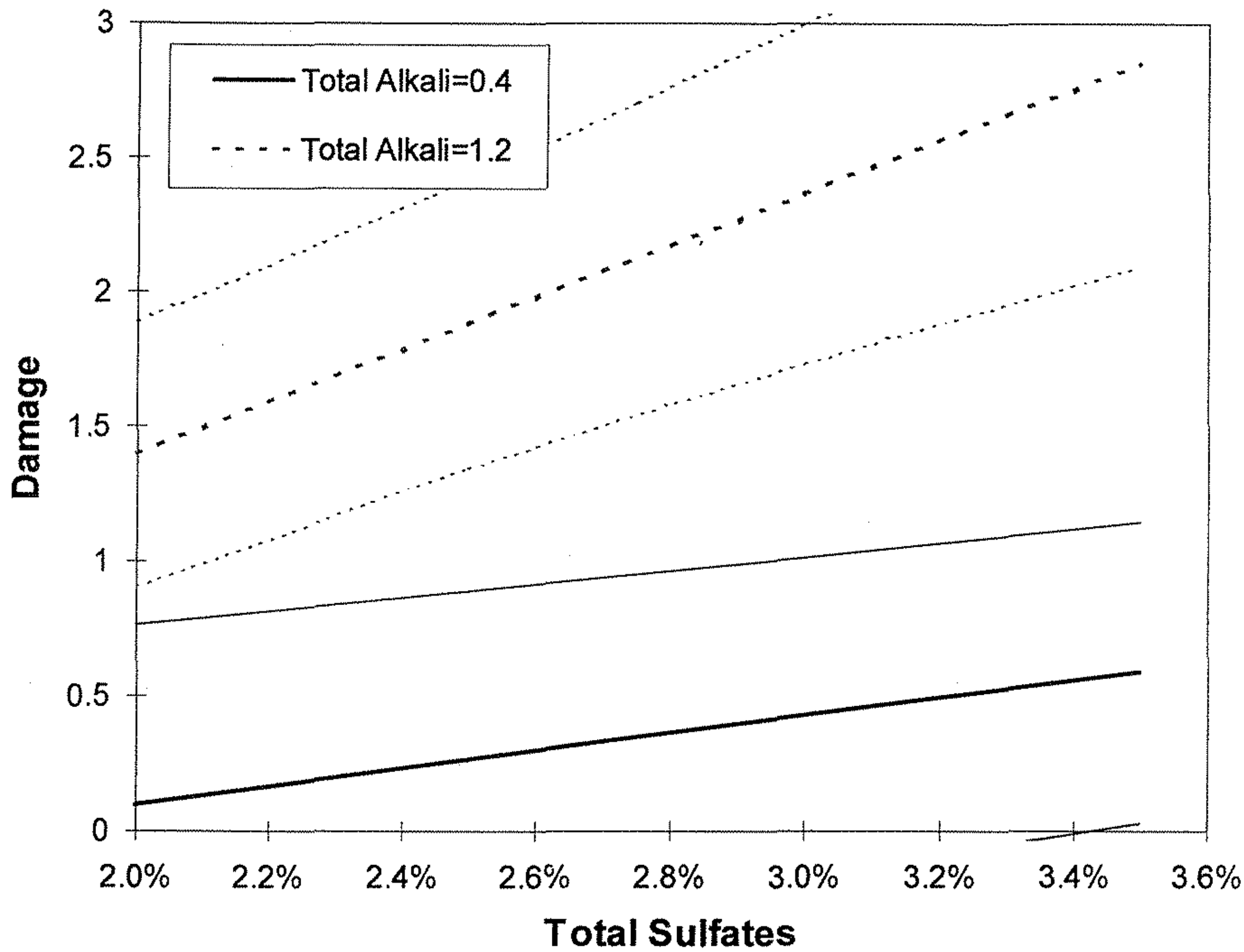

Figure 4.3: Damage plotted vs. total sulfate levels for two levels of alkalis as predicted by model I. 95% confidence intervals are plotted by lighter lines.

number of data points. More simply, it is a standard measure of the models ability to predict pavement deterioration. Clearly, the model illustrates a reasonable confidence in the correlation between sulfates and alkalis and damage. Figure 4.4 shows damage plotted versus age for permeable and impermeable base course. In this case 95% confidence intervals are much wider, reflecting lower T values and lower statistical confidence. Still, reasonable trends are illustrated.

Evaluation of the Model

The model has been evaluated in a number of ways, and two are illustrated below. The first is the evaluation of outliers. Table 4.3 shows outliers for Model I. This table lists the highest residuals, standardized residuals, and externally studentized residuals by row. If any row has a standardized residual or externally studentized residual above 3, or a residual that is more than 50% higher than the next highest residual, it is considered to be an outlier that would adversely affect the model . In this case there are no outliers. The second is an evaluation of the values fitted by the model and residuals for each data point. Figure 4.5 shows a plot of residuals versus fitted values for every data point. In an adequate model, there will be no overwhelming linear or quadratic trends. In this case, there is a distinct line of data points. These are a result of our limitations in evaluating a pavement's tendency to deteriorate. Since no pavement could have less than zero deterioration, a portion of the residual vs. fit plot is not available below this distinct line. Based on the even distribution of the remainder of the points, it has been concluded that our model fits a wide range of dispersed variables accurately.

Each model was also subjected to a number of other tests for validity, which will not be discussed in depth here. These have included the exclusion of data points with variables outside of a reasonable range and evaluation of other statistical descriptors. These have combined in an iterative process of statistical and physical evaluation to ensure the development of a model which accurately represents both the data and the system.

b) Model II

Model II was constructed with data from 43 sites and 23 independent variables. Sites were included from Iowa (12 sites), Kansas (12 sites), Minnesota (6 sites), and

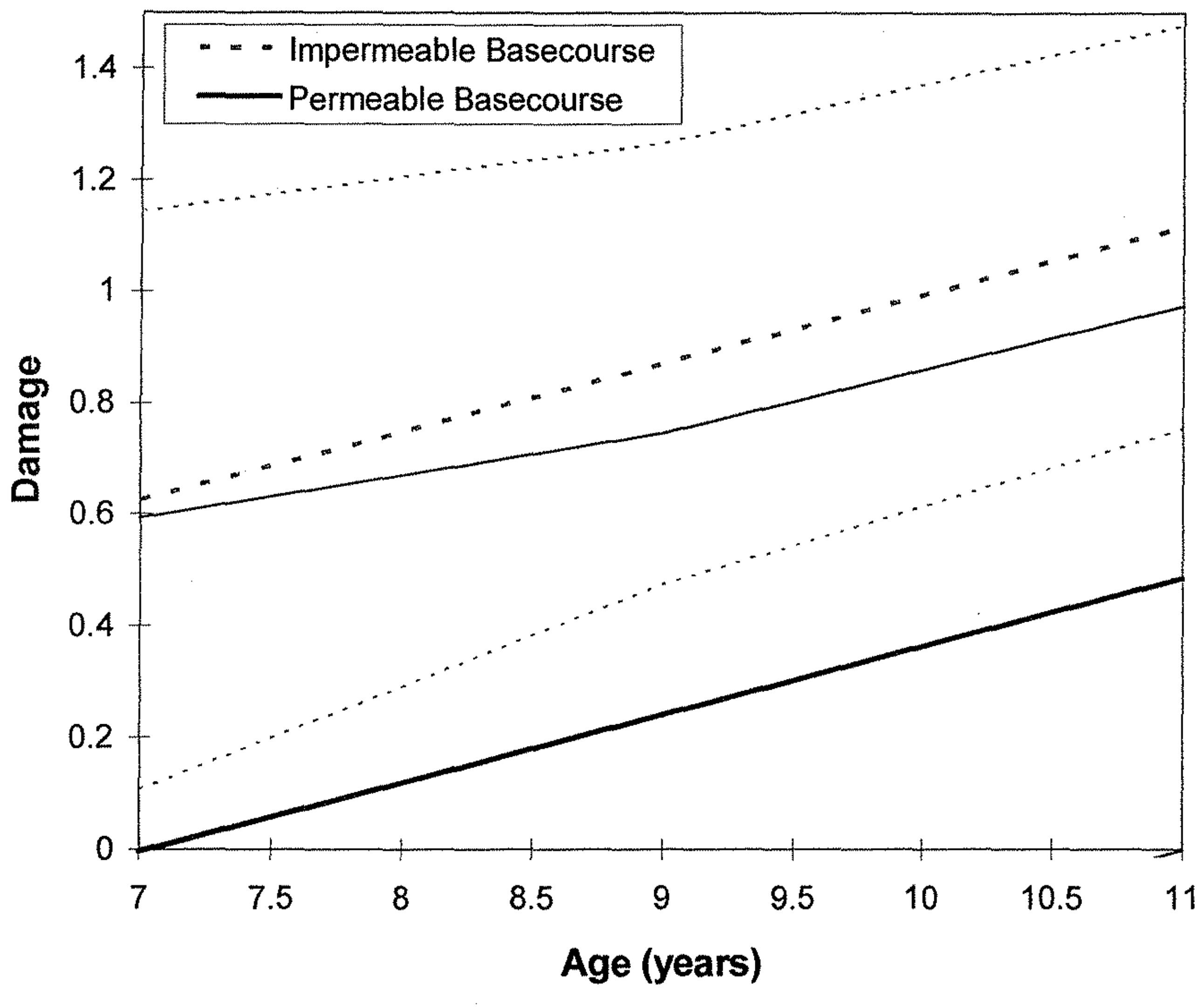

Figure4.4: Damage plotted vs. age for two levels of base course permeability as predicted by model I. 95% confidence intervals are plotted by lighter lines.

Row	Res.	Row	Std. Res.	Row	ES Res.
32	1.4257	32	2.0966	32	2.3
25	1.3468	25	1.9806	25	2.25
26	-1.1763	26	-1.7298	26	-1.8484
34	1.0508	34	1.5452	34	1.6545
8	0.8724	8	1.283	30	1.4712

Table 4.3: Partial outlier table for model I.

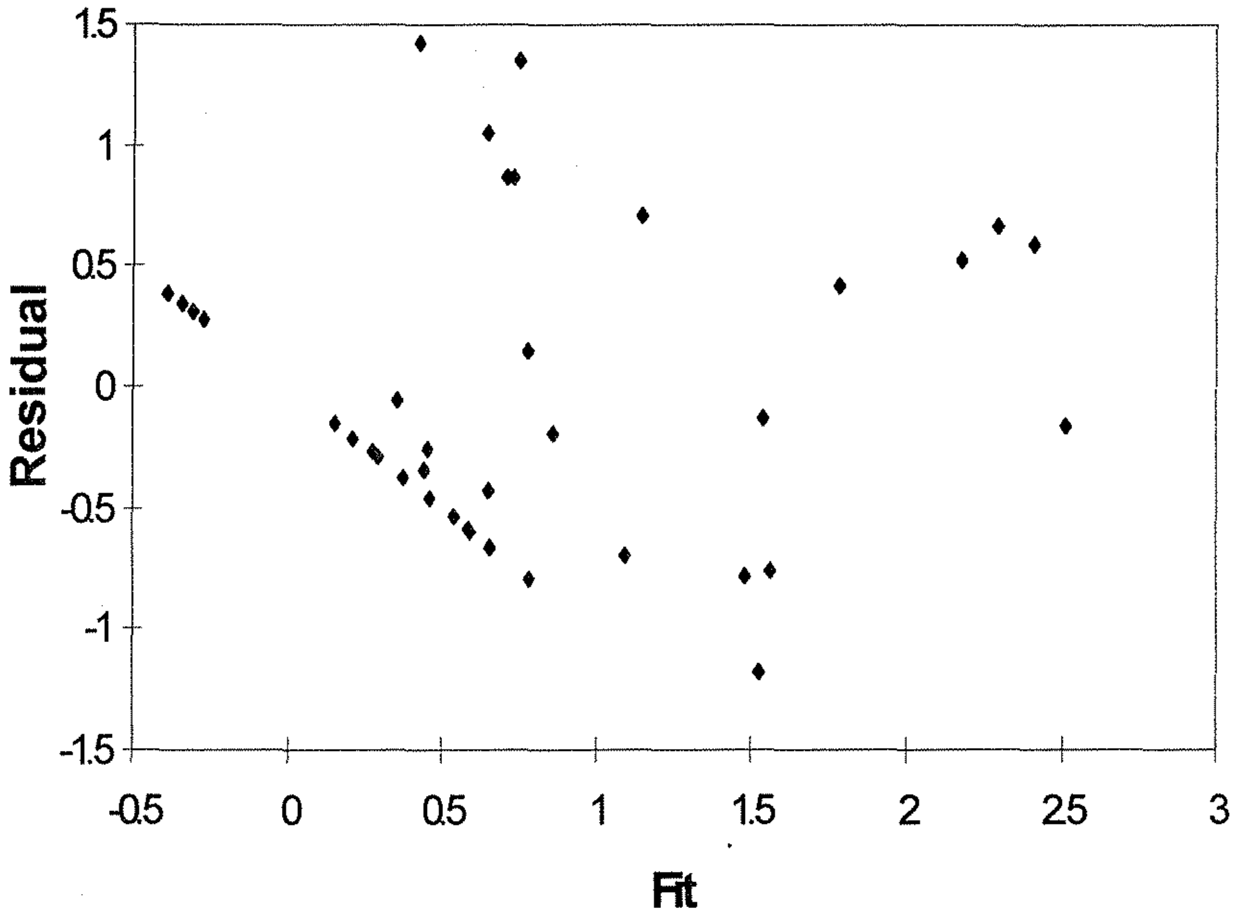

Figure 4.5: Residuals plotted vs. fitted values for model I.

Nebraska (13 sites). A list of the independent variables is included in table 4.4, and statistical results are presented in table 4.5, with important variables listed in order of decreasing T value. These important variables will be discussed in further detail below.

The major variables not included in model II are total alkali and sulfate contents for the cementitious materials and the maximum paving temperatures.

Fly Ash Content

In model II the fly ash content has the most significant correlation, with a T value of 5.44. A positive correlation indicates that mixes containing fly ash correlate highly with increased amounts of pavement damage. Since the presence of fly ash can dramatically affect the amount of sulfates and alkalis present in the cementitious materials and also significantly affect hydration mechanisms, this result is physically significant as well.

It is important to note that all fly ashes used in these pavements were class C fly ashes. Since the results of this study are limited to the scope of the variation within the reported sites, no conclusions can be made about different pozzolanic materials.

Alkali (Cement)

The equivalent alkali content of the cement was the next most significant variable in model II. The model predicts, with a T value of 4.3, that an increase in alkali content of the cement will increase the level of pavement deterioration.

Since complete data were not available on fly ash alkali content, alkali content of the cement has come into model II. This contrasts to the results of model I, which rely on the total composition of the cementitious materials.

Base Course Permeability

As was found in model I, base course permeability was a statistically significant variable with a T value of 2.68. As with model I, this predicts that pavements with impermeable base course will have a higher degree of deterioration.

Age

Finally, age has shown up as a statistically important variable with a T value of 2.21. As with model I, the inclusion of this intuitive result serves mainly to increase the accuracy of the model as a whole.

Variable Number	Independent Variable
1	State
2	State Site Number
3	Age
4	Cement Type
5	C3S Content of Cement
6	C2S Content of Cement
7	C4AF Content of Cement
8	C3A Content of Cement
9	Cement Sulfate Content
10	Cement Alkali Content
11	Concrete Strength (7day)
12	Cement Content of Total Mix
13	Water Content of Total Mix
14	Coarse Aggregate Content of Total Mix
15	Fine Aggregate Content of Total Mix
16	Fly Ash Content of Total Mix
17	Average Reported Slump
18	Average Reported Air
19	Traffic
20	Slab Width
21	Slab Thickness
22	Slab Length
23	Permeability of Base Course
24	Degree of Pattern Cracking

Table 4.4: List of variables used in the creation of model II.

Variable	Coefficient	T	R squared
Fly Ash	54.6	5.44	0.26
Alkali (Cement)	326	4.3	0.1
Base Course Perm.	-0.395	-2.68	0.22
Age	0.108	2.21	0.15

Intercept= -3.11 RSQ= 0.5841

Table 4.5: Statistical information describing the results and validity of model II.

Schematic Figures

Model II is illustrated with a number of schematic figures, chosen to represent a specific slice through the multidimensional design space. Figure 4.6 illustrates the additive effects of fly ash content of the entire mix and equivalent alkali content of the cement on deterioration. Clearly, increases in either variable will increase damage in an additive way. The same phenomenon is illustrated in figure 4.7, with a 2 dimensional plot of damage versus fly ash content at two different levels of equivalent alkali. The subsidiary 95% confidence interval lines illustrate the level of confidence with this model.

It is important to restate that these representations are intended to represent the trends present in a multi-variable model with simple figures. True predictions of damage cannot be made without considering the entire model.

Evaluation of the Model

An outlier table for model II is included in table 4.6. In this case, row 40, which represents a specific site in the data set, is a clear outlier. This indicates that this site is radically different from the remainder of the data, and should therefore be excluded. Figure 4.8 illustrates residual data plotted versus the fitted data, with the excluded row 40 clearly denoted. It is clear that the remainder of the data has a fairly even distribution, which supports the validity of model II.

c) Agreement of Models

Since both models deal with fairly similar data sets, it is important to reconcile the differences between models I and II. The most significant difference is the presence of fly ash and cement alkali values in model II, as opposed to the product of total sulfate and total alkali content in model I.. Since model II does not include data on total alkali and total sulfate content, variables have come into the model which have some similarity to these "missing variables". Cement alkali content combined with fly ash, which is a contributor of alkali and sulfates, are highly confounded with the excluded variable and therefore come into the model to replace it. Also, maximum paving temperature does not show up in model II because this variable is not available in this model. When this effect is taken into consideration, the models can be seen as largely similar.

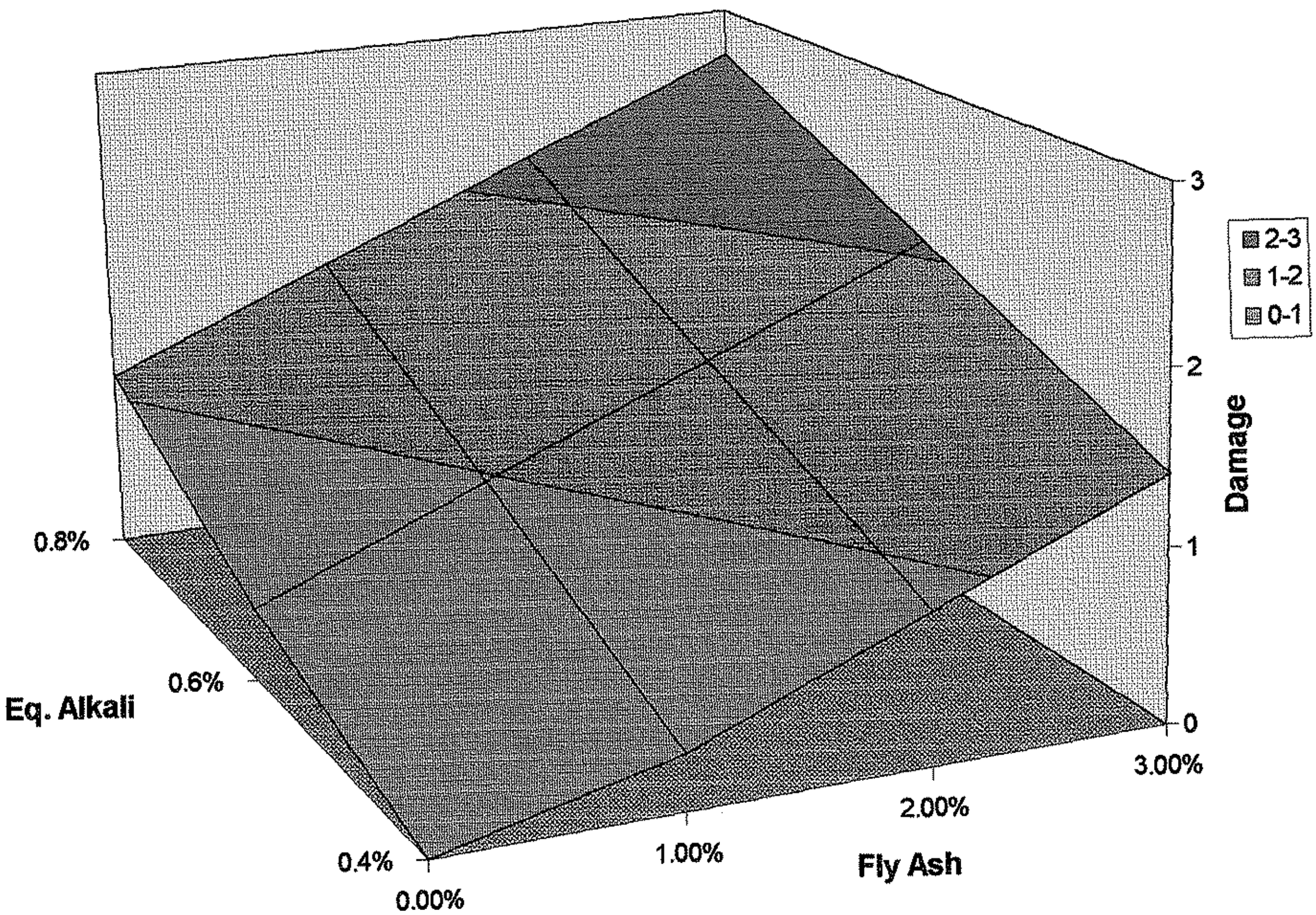

Figure 4.6: Schematic representation of damage vs. cement alkali and fly ash levels for model II with high levels of remaining variables.

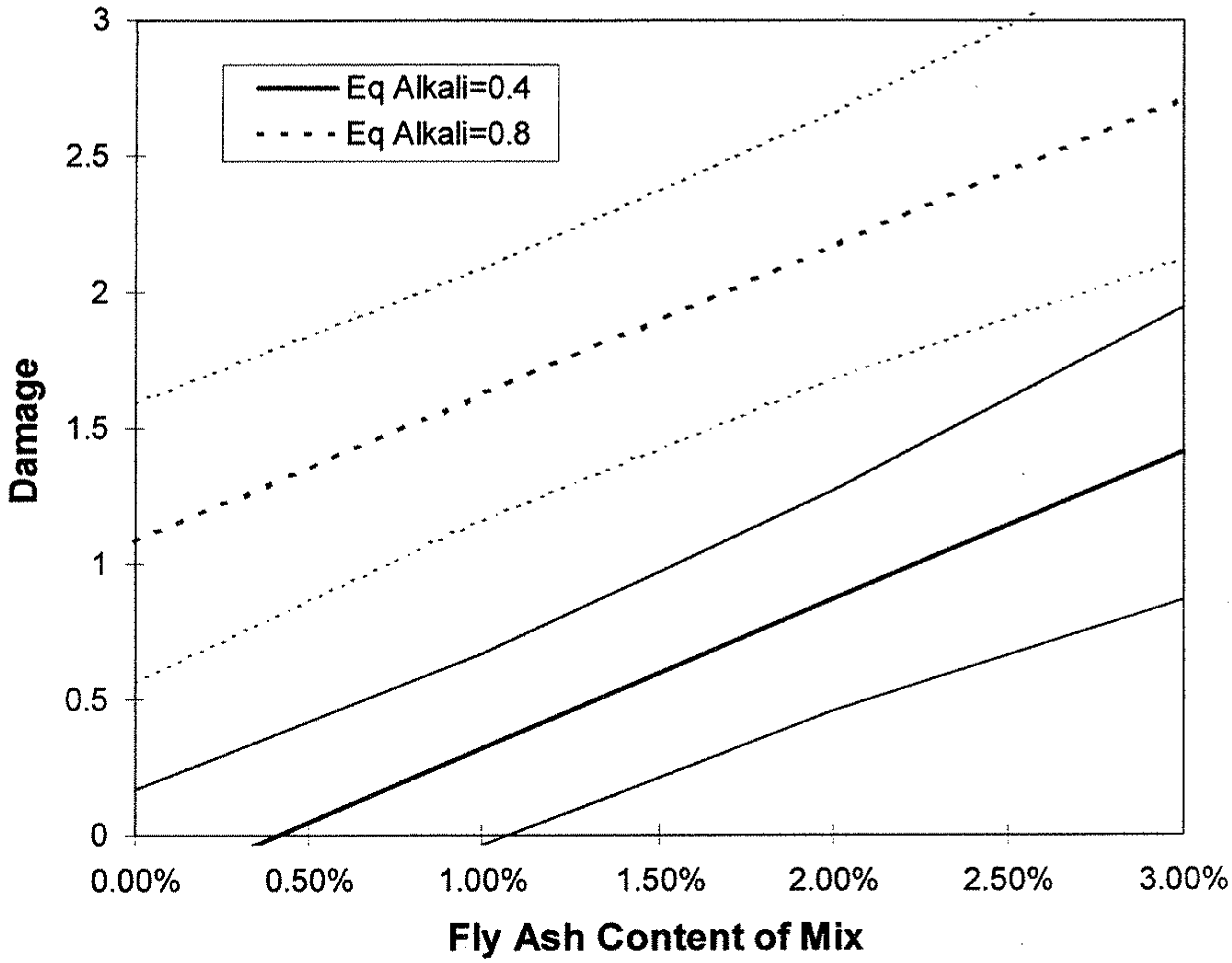

Figure4.7: Damage plotted vs. fly ash content for two levels of base course permeability as predicted by model II. 95% confidence intervals are plotted by lighter line.

Row	Res.	Row	Std. Res.	Row	ES Res.
40	-2.3858	40	-2.9378	40	-3.6961
30	1.5341	30	1.889	30	2.2085
25	1.4832	25	1.8263	25	2.0375
1	1.3465	1	1.658	1	1.7812
2	1.211	2	1.4912	2	1.5927

Table 4.6: Partial outlier table for model II.

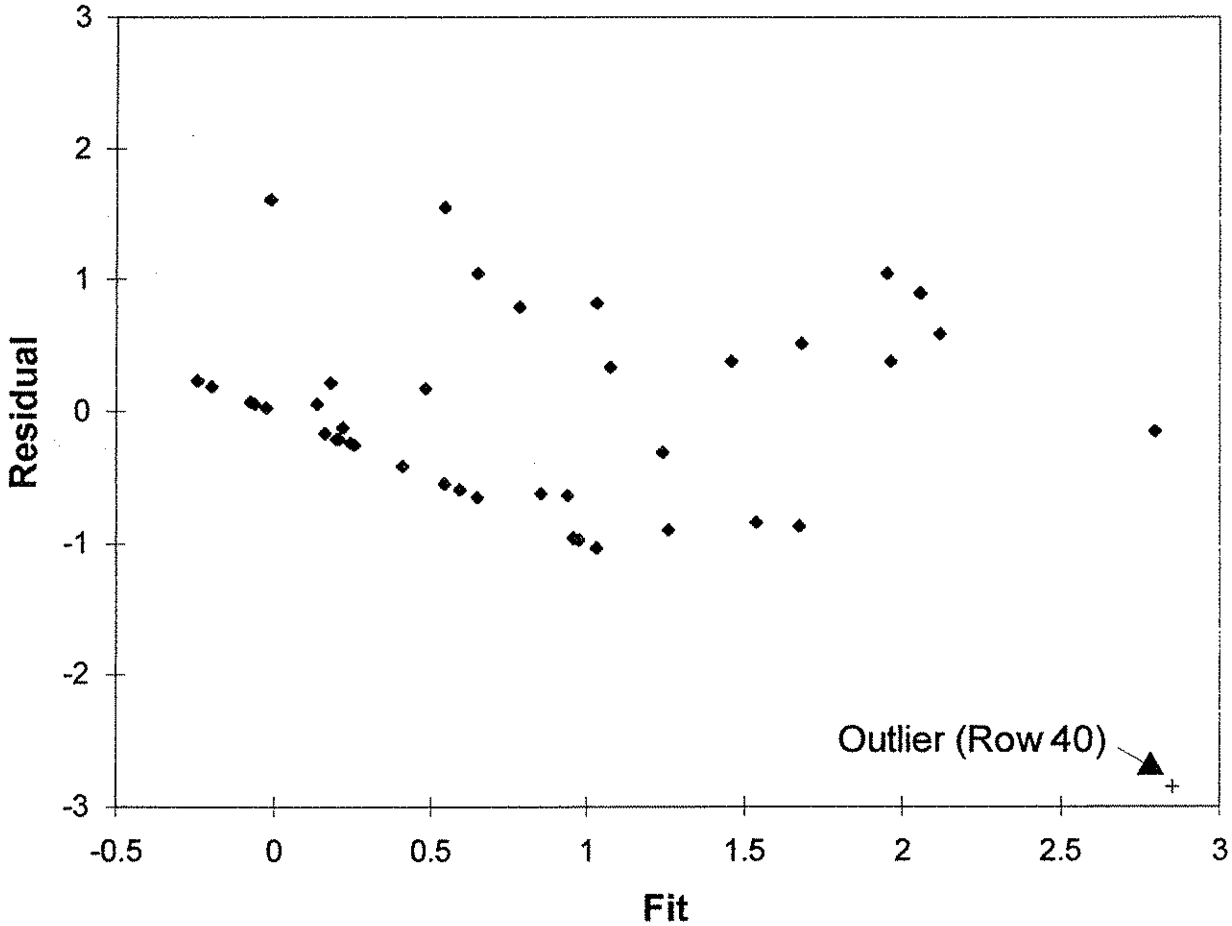

Figure 4.8: Residuals plotted vs. fitted values for model I.

In order to illustrate this effect, a hybrid model was created which included the sites used in model I but only the independent variables used in model II. The results of this model, model Ib, are shown with the results of model II in table 4.7. The comparable results illustrate the similarity between the two models.

d) Key Variables

Based on the models developed above, this work has identified a number of key which significantly correlate with pavement deterioration.

- Total alkali content of cementitious materials
- Total sulfur content of cementitious materials
- Class C fly ash content
- High paving temperature
- Use of impermeable base course

For the purposes of this work, it is important to note that these are not the only variables which affect cement durability, nor do they accurately represent behavior outside of the range of data collected. These results should serve as the basis for the design of experiments intended to provide conclusive evidence concerning deterioration mechanisms.

V. Summary and Conclusions

Statistical analysis of data from a wide range of paving sites has shown statistically relevant correlation with a number of variables, including alkali content, sulfate content, base course permeability, age, ambient temperature during paving, and the presence of class C fly ash. Although these results are by no means conclusive, they lead to the following recommendations and conclusions.

- Pavement deterioration is a result of a combination of multiple factors, and should not be blamed on a single ingredient or condition.
- Composition of total mix must be considered, not just individual components.
- The use of fly ash, especially class C, should be evaluated.

Model Ib

Variable	Coefficient	T	R squared
Fly Ash	41.8	3.3	0.49
Alkali (Cement)	383	4.21	0.14
Base Course Perm.	-0.472	-2.99	0.32
Age	0.0951	1.9	0.2
Paving Temperature	0.0327	1.88	0.28

Model II

Variable	Coefficient	T	R squared
Fly Ash	54.6	5.44	0.26
Alkali (Cement)	326	4.3	0.1
Base Course Perm.	-0.395	-2.68	0.22
Age	0.108	2.21	0.15

Table 4.7: Statistical information showing the similarities between results obtained for models I and II.

- It is important to consider the effects of base course permeability, paving temperature, and total sulfate and alkali contents of the mix.

Finally, the obstacles encountered in this study have shown the importance of good records. **One of the most important things an organization can do to ensure good concrete is to obtain and maintain good records regarding design, materials, and construction practices.** This will allow better control of the current system and easier identification and communication of problems encountered with this complex and changing material.

VI. Recommendations for Phase II.

There are two main avenues of research which could serve as logical and valuable extensions of Phase I of this project. These can be divided into further data collection and analysis and designed experiments. Both approaches are firmly grounded in the statistical analysis and design of experiments, and would represent a powerful application of resources to this complex problem.

a) Further Data Collection and Analysis

As has been discussed previously, the major drawback of the Phase I work is a direct result of the limitations of the data. The addition of more sites and more complete data on current sites would significantly increase the statistical certainty of results obtained in phase I. Since many of the pitfalls and limitations inherent in this type of data collection are now known, it would be possible to limit the questions to areas where complete data exists. This would greatly reduce the amount of unnecessary workload in data collection for additional sites, and increased statistical certainty would be a direct result of a limited amount of work.

b) Designed Experiments

The second recommendation for future work would involve the design of an experiment to test the models developed in Phase I. This experiment should involve the actual production and testing of materials. It should also utilize statistical design of experiments to minimize the number of tests needed to acquire the necessary information.

Statistical design of experiments would reduce an experimental matrix from hundreds or thousands of tests to mere dozens, allowing realistic management of the workload.

Acknowledgments

It is important to acknowledge the members of the Technical Advisory Group, who provided important advice and insight, and who were responsible for the collection of vast amounts of data. The T.A.G. including the following individuals: Karen Clowers, Steven Kosmatka, Vernon Marks, Nick Rabalais, Dave Rettner, Bob Schmiedlin, Jerry Voigt, and George Woolstrum. It is also important to recognize the work of all of the individuals on the state level who made contribution toward the success of this project.

Appendix A

Pooled Fund Study Proposal

Proposal For Pooled Fund Study on Premature Rigid Pavement Deterioration

Phase I

Abstract

Statistical analysis of pooled data is an ideal research strategy for studying "Premature Rigid Pavement Deterioration." A review of the literature provides a large number of potentially significant variables. The proposed research plan outlines key steps involved in developing a successful survey, relying in large part on communication with participating agencies. This research group is ideally suited for the investigation, having significant experience with statistical design and analysis, coupled with an in-depth understanding of the microstructure and mechanisms of cement-based materials.

Statement of Problem

Rigid pavement deterioration has recently become a significant problem in pavements 3 to 8 years old. Unfortunately, there is no clear understanding of the causes of this deterioration. The following proposal outlines the current scientific understanding of durability issues and proposes a plan for data collection and statistical analysis which will isolate key variables in this real-world problem. This analysis will provide valuable guidelines for future pavement construction.

Introduction

Durability is quite possibly the most important property of concrete, since it determines the performance of any structure over an entire lifetime. Concrete which is well-designed and carefully produced is an inherently durable material. However, deterioration can result from attack on any of its three principle constituents; cement paste, aggregate, and reinforcement. The attack can be from chemical effects, physical effects, or a combination of both [1-3]. Since permeability affects and is affected by many types of attack it will be discussed initially. In this study all of these effects will be considered with special attention to their role in middle-American states.

Permeability

Permeability and durability are intimately tied together. This relationship, although not direct, results from the correlation between permeability and various forms of attack. For example, permeability affects the rate of ingress of water containing destructive chemicals. It also controls the rate of movement of water during cycles of heating and freezing [1-2].

Permeability of concrete can depend on any number of factors. For example, a high water/cement ratio (w/c) will result in a greater amount of capillary porosity and a more permeable concrete. Furthermore, high w/c results in lower strength and a greater incidence of cracking, allowing easier ingress of water. The presence of aggregate also increases permeability. Regions at the paste/aggregate interface have a lower density and are more prone to cracking than the bulk paste. These regions serve as a permeable path through the material. Finally, pastes which are allowed to dry and are then rewetted show a much higher degree of permeability [4-5]. All of these factors increase vulnerability to chemical and physical attack, and thus, a decrease in durability. Additionally, various forms of attack (e.g. drying shrinkage) can increase permeability, making a concrete more vulnerable to yet other forms of attack.

Chemical Attack

There are a large number of sources of chemical attack on concrete. For example, leaching is important for concretes with high permeability and a large amount of calcium hydroxide [1, 6]. Crystallization of salts is important for intertidal regions with high salt contents and fluctuating water levels. Attack by acids is also serious, but only in areas near a source of acidic water, e.g. marshy areas [7]. Clearly, many sources of chemical attack are highly regional [8-10]. However, three major sources of chemical attack are fairly universal and extremely applicable to this study: sulfate attack, corrosion of reinforcement, and alkali-silica reactions.

Sulfate attack involves a complex process including a number of chemical reactions. The key reaction, sulfoaluminate corrosion, involves the formation of ettringite from monosulfoaluminate. This reaction is initiated when sulfate ions react with calcium hydroxide to provide the necessary precursors. This sequence of events causes a significant increase in volume and can eventually lead to cracking [11-14]. It is possible to prevent sulfate attack with different cement compositions, lower w/c, and additions of pozzolans and blast furnace slag [15].

Corrosion of reinforcement is a result of an electrochemical reaction at the surface of the metal. An oxidation-reduction reaction results in the formation of iron oxide. This is an expansive reaction and can lead to significant cracking. Normally, highly alkaline concrete creates a passive, protective layer surrounding the reinforcement. However, the formation of calcium carbonate from calcium hydroxide can lower the pH, allowing corrosion to occur. Chloride ions in solution also tend to destroy the passive layer, making reinforcement vulnerable to corrosion. It is possible to prevent this degradation through reduced permeability, protective coatings, and cathodic protection [1, 6].

Alkali-silica reactivity(ASR) is another important type of chemical attack. This is generally a reaction between the alkalis in cement and active silica in the aggregate. The alkali-silica reaction results in the formation of an alkali-silicate gel which attracts water by absorption or osmosis, leading to an increase in volume within the surrounding cement paste. The resulting expansion causes degradation which can be manifested in pop-outs, spalling, and map cracking of the concrete [6, 16]. Factors affecting ASR include the porosity and type of aggregate, water and alkali content of the paste, and permeability of the concrete. It is interesting to note that slag and fly-ash, although high in alkalis, help prevent degradation due to ASR. It has been hypothesized that a preferential reaction takes place resulting in a more dispersed and therefore innocuous product [17].

Physical Attack

Concrete is also prone to degradation from various types of physical attacks. Frost damage is the most common, as a result of repeated cycles of freezing and thawing. A number of theories exist to explain the degradation of the microstructure. These include expansion of water upon freezing, growth of ice lenses, and hydraulic pressure from movement of water through capillaries [18-21]. The damage due to freeze/thaw can often be eliminated through proper use of air entrainers.

Physical attack can also come from various types of dimensional instability. Plastic shrinkage, drying shrinkage, and uneven thermal expansion can all lead to cracking. Scaling, a spalling and pitting phenomenon, has also been attributed in part to thermal stresses induced on the application of deicing salts [1, 6]. Clearly, resistance to these forms of physical attack is important in determining concrete durability.

The Study of Durability

A reliable and valuable study of durability is significantly hindered by a combination of two factors. The first complication is the large number of variables which affect durability, as illustrated above. The second is the time-scale involved. Since most pavement deterioration occurs between three and ten years after construction, an ordered, controlled laboratory study is not feasible. Clearly, any successful study of durability will utilize an ordered statistical analysis of problems from field applications. Properly done, such a study can identify the relative effect of a large number of variables and allow accurate prediction of durability for a wide range of service conditions.

Multiple regression analysis is an ideal tool for treating experiments with two or more related variables. It is directly applicable to analysis of a set of "unplanned experiments" where observations and data already exist. And the advent of powerful statistical software packages has virtually eliminated tedious calculation steps. However, multiple regression must not be used as a "black box" for data analysis. It must be balanced by an understanding of basic physical principles and a knowledge of pitfalls such as insufficient experiments, outlying data, and confounding of variables.

Survey Development

Survey development involves a number of key components. The first is an extensive literature search in order to provide an extensive list of factors affecting durability. These factors will then be ordered based on severity of reported effects, reliability of the studies, and frequency of occurrence within the literature. Any practical and applicable study, however, is incomplete without a strong understanding of "real world" problems. For this reason, the participation of the Technical Advisory Group will be essential to the success of this project.

We intend to host a meeting between the researchers and the entire Technical Advisory Group during the initial stages of survey development. If possible, this meeting will take place in an easily accessible city (i.e. St. Louis, Chicago, Minneapolis/St. Paul). The purpose of this meeting will be two-fold. First, it will allow the researchers to utilize the expertise of the technical advisors. Secondly, it will ensure that the study fulfills the goals of the participating agencies by addressing the relevant questions.

For the two months following this meeting, the researchers will conduct follow-up visits with the participating agencies. The purpose will be to increase exposure to on-site variables and tailor the survey to the available field data. It is our assessment that such meetings are essential for maintaining the level of communication necessary for the proper evaluation and analysis of the pooled data.

Variables

From the review of the literature the following variables have been identified as potential parameters for analysis using statistical-response surface analysis.

Aggregate- reactivity, size distribution, amount
Additives- air entrainers, plasticizers, accelerators, retarders
Water/cement ratio
Cement- type and composition
Addition of blast furnace slag and pulverized fly ash
Finishing- type, amount, start time
Densification (Vibration effects)
Curing
Water Characteristics (i.e. ground water, mixing water)
Climate Profile of Geography

Conditions of Use (traffic profile)
Deicing Salts Used in the Region

Data Analysis

Traditionally, scientific experimentation has involved the study of the effect of one variable while all others were held constant. This is highly inefficient, and furthermore will not diclose any interactions among the variables. A full factorial experimental design eliminates these two problems. However, in systems where a large number of variables have an influence, full factorial experiments are not feasible, due to the number of experiments required. For example, studying 8 variables at 2 levels per variable would require 256 experiments. Fortunately, methods of experimental design and analysis (e.g. Taguchi analysis, latin squares, composite-response surface) allow for the variation of all design parameters simultaneously with fewer experiments [22-24]. Data can then be statistically analyzed to identify the effect and significance of each variable. For an examination of the durability of concrete where many variables have an effect, this type of design is superior.

Taguchi analysis, a widely used approach, relies on an ordered and complete set of data due to its mathematical basis of orthogonal arrays and reliance on analysis of variance operations [22-23]. Thus, every experiment will have a predetermined, multi-dimensional design space. This is a space in "n" dimensions which is bounded by the extreme values of the "n" variables. Taguchi analysis relies on a systematic coverage of this design space and is ideal for complete, predesigned experiments. However, for a pooled set of pre-existing data, as with this multi-state study, another approach must be taken. Unfortunately, other commonly used statistical techniques such as fractional factorials, latin squares, and composite-response surface take the same approach as the Taguchi method, and thus, are not appropriate for this study.

A more powerful approach involves multiple regression analysis. This type of analysis, available in Haller's Multiple Correlation software, will fit a response surface to any set of data. This is particularly useful for "historical" type studies. Every data point contributes to a better statistical accuracy of the surface, but no one point is critical. For this reason, it is possible to remove statistical outliers without destroying the model. This flexibility is the obvious benefit of multiple regression analysis for an "n" dimension design space. Since this study will involve both sound and deteriorated pavements, the relevant portion of the design space will be explored to determine the significance of the design parameters.

Due to the flexible nature of Multiple Correlation analysis, it is necessary to consider the validity of the fit of the response surface in order avoid erroneous conclusions. The nature of the residuals, T values of coefficients, and remaining degrees of freedom are important indicators of model accuracy. However, the most important indicator of validity is agreement with known physical principles. The researcher must possess an understanding of both the statistics involved and the physical fundamentals of the system (i.e. cement-based materials). If a model does not agree with physical understanding, then either the model, physical theories, or both must be adjusted. This necessary two-fold understanding is the strength of our research group.

We have found that Multiple Correlation analysis is often an iterative process, in which statistical analysis of data identifies a need for more data to improve on the model. Therefore, we have built into our research plan the possibility of a second survey after the initial statistical model has been developed. This survey would concentrate on those parameters identified as being most significant through analysis of the data developed in the first survey.

Final Report

The final report will include the summary of the literature review, data analysis, and the degree of premature rigid pavement deterioration reported by each state. Complete data and analyses will also be provided. Finally, we would like to propose a final presentation to either the Technical Advisory Group at their next meeting or at interested agencies. This presentation could coincide with the annual meeting of the American Ceramic Society in the spring of 1997.

Schedule of Tasks

Time	Task
Months 1-2	Literature Survey
Month 2	Research Group/ Technical Advisory Group Meeting
Month 2	Formulation of Draft Survey
Month 3	Researcher Follow-up at Individual Agencies
End of Month 3	Interim Report to Technical Advisory Group
Month 3-4	Submission of Final Survey to Technical Advisory Group
Month 5	Distribution of Final Survey to Agencies
Month 6-7	Collection of Surveys
End of Month 6	Interim Report to Technical Advisory Group
Month 8-9	Data Entry and Analysis
End of Month 9	Interim Report to Technical Advisory Group
Month 9-11	Possible Follow-Up Survey/Analysis
Month 12	Submission of Final Report to Technical Advisory Group
Month 12	Possible Oral Report to Technical Advisory Group or Agencies

Investigators

P.I.: Prof. Hamlin M. Jennings
Co-P.I.: Prof. D. Lynn Johnson

Budget: $75,000

Budget Justification

Secretarial-
This project involves a large amount of data processing, in particular, organizing and transferring data from various state departments and entering into computer programs.

Travel-
Extensive visits to participating state DOT's are necessary for conducting interviews and collecting data in order to develop an understanding of the pavement failures under investigation.

Computer Software and Services-
Use of several Pentium-based computers and purchase of appropriate software are necessary for analysis of data.

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Appendix B

Site Selection Protocol
Data Acquisition Survey
Reference Deterioration Levels

Premature Rigid Pavement Deterioration Pooled Study

Iowa - Kansas - Louisiana - Minnesota - Nebraska - Wisconsin - The American Concrete Paving Association - Portland Cement Association
Department of Materials Science and Engineering - Department of Civil Engineering - Northwestern University - Evanston, Illinois

Subject: Protocol for Site Selection
Date: May 20, 1996

- Pavements constructed during or after 1983 are appropriate for this study.

- It is important that deterioration is related primarily to materials and construction issues. This means that deterioration is a possible result of materials selection, composition, quality control, paving conditions, construction practices, or any variables that relate to the selection, processing, and treatment of the concrete as a material.

- If deterioration is directly attributable to issues of poor structural design (i.e. unreasonable stresses) these pavements should not be included in the study.

- Any given site should have a common cement and aggregate mix (mix design) and a common contractor for the entire site. For example, if a project uses two different cements at different times, that project should be split into two separate sites, each with one cement.

- Deteriorated Sites do not need to be "failed" sites. For example, a site with noticeable cracking could still give a good "ride" while exhibiting deterioration applicable to this study.

- Non-deteriorated sites should have similar age and project types as corresponding deteriorated pavements. However, they should be chosen to represent a distribution of variables including geography, cements used, and aggregate used.

- In general, all sites chosen should be from projects where sufficient data about materials, paving and performance are available.

- The sites chosen should include the following
    - At least 12 sites total
    - As many deteriorated sites as possible (ideally 6-8)
    - At least 4 non-deteriorated sites.

- If available, more than 12 sites may be included. These will serve to increase the validity of the statistical analysis.

Any questions should be directed to Gates Moss or Aaron Saak at (847) 491-7246 or Hamlin Jennings at (847) 491-4858.

Premature Rigid Pavement Deterioration Pooled Study

SITE DATA ACQUISITION FORM

State	Site Identification Number
IA KA LA NB WI MN	1 2 3 4 5 6 7 8 9 10 11 12

Note: **Please return the first completed form by June 21, 1996. The remaining forms should be completed and returned no later than August 1, 1996.** Send all forms to:
Attn. H. Jennings/Pooled Study Dept. of Civil Engineering Northwestern University
2145 Sheridan Road Evanston, IL 60208

This form is to be completed by personnel/engineers familiar with the given pavement and its history. All questions should be answered, with added comments pertaining to the accuracy of the data or any other additional information. Add pictures or drawings when necessary. Should any questions arise concerning this survey or information relevant to answering the questions, please contact Prof. Hamlin Jennings, Gates Moss, or Aaron Saak at (847) 491-7246 or (847) 491-4858.

Name of Individual(s) Completing Form:____________________

Title/Position:____________________ Phone:____________________

Address:____________________

____

I. PAVEMENT SITE AND CONSTRUCTION BACKGROUND

1. Road Number (example: northwestern section of US Route 50)____________________

2. Road Location:

   Beginning mile marker____________________

   Ending mile marker____________________

3. Nearest Towns/Urban Areas____________________

4. Dates of construction for this site.

   Beginning date (M/D/Y)____________________

   Ending date (M/D/Y)____________________

5. Principle paving contractor for the project:

Name____

Contact/Project Supervisor______________________________

Address____

____

Phone____________________ Fax____________________

6. List all subcontractors involved with the paving construction and their duties:

I. Subcontractor__________________________________

Duties_______________________________________

II. Subcontractor__________________________________

Duties_______________________________________

III. Subcontractor__________________________________

Duties_______________________________________

7. List any state Department of Transportation employees (including their positions) who were directly involved with this specific construction site (e.g. project engineers, inspectors, etc.). This is for possible contact purposes only.

____

____

____

8. Is this pavement still in use? Explain as necessary.________________________

____

____

9. Is this pavement an experimental test section (i.e. outside of normal state specifications)? If so, what is the reason it is considered experimental?

____

____

____

10. Has the pavement been repaired or resurfaced? If so, list dates and materials.______________________

___

___

11. Is this road up for service/repair? Explain as necessary.______________________

___

___

II. Composition of Construction Materials

Fill in the following table as accurately as possible. Provide units when relevant for all measurable data. If additional space is needed, please use the back of the page. Attach mill sheets if available.

		Cement
12.	Cement Type	
13.	Company/Mill Name	
14.	Plant Mill Location	
15.	Mill Production Date	
16.	Date Purchased	
17.	Cement Processing (i.e. Wet or Dry Processing)	
18.	Date Tested/Certified By State For Use In Paving	
19.	Frequency of Testing (i.e. how often has this type of cement been tested and certified)	
20.	Composition (%)	
	C_3S	
	C_2S	
	C_4AF	
	CSH_2	
	C_3A	
	Free Lime	
	Total Sulfur Content (%)	
	Other:____________	
21.	Specific Gravity	
22.	Equivalent Alkali Content (NaOH reference)	
23.	Blaine Fineness	
24.	Compressive Strength	
	Age When Tested	

Coarse Aggregates

Fill in the following table as accuracy as possible, providing units when relevant for all measurable data. If additional space is needed, use the back of the page. Two coarse aggregates should be used **only** if they were mixed in the batch.

		Coarse Aggregate A	Coarse Aggregate B
25.	Aggregate Source (Gravel Pit, Quarry, Other)		
	Type of Mine (Full-Faced, Bed, Ledge, etc.)		
	Ledge ID (if relevant)		
	Geographical Location		
	Date Mined		
	Date Tested/Approved		
26.	Geological Type (example: dolomite, argillaceous limestone, etc.)		
	Chemical Composition (percentage of each rock type i.e. % carbonate, % shale) (provide any available data)		
27.	Reactivity Test Method (Canadian Prism, ASTM number)		
	Reactivity Tests Results		
28.	Freeze-Thaw Test Method		
	Freeze-Thaw Test Results		
29.	Size Distribution/Gradation (attach table if available)		
30.	% Recycled Aggregate (i.e. crushed concrete)		
31.	Absorption Tests Results		
32.	% Reactive Silica		
33.	Additional Tests Results (i.e. magnesium sulfate, soundness, etc.)		

Fine Aggregates

Fill in the following table as accurately as possible, providing units when relevant for all measurable data. If additional space is needed, use the back of the page. Two fine aggregates should be used **only** if they were mixed in the batch.

		Fine Aggregate A	Fine Aggregate B
34.	Aggregate Source (Gravel Pit, Quarry, Other)		
	Type of Mine (Full Faced, Bed, Ledge, etc.)		
	Ledge ID (if relevant)		
	Geographical Location		
	Date Mined		
	Date Tested/Approved		
35.	Geological Type (example: dolomite, argillaceous limestone, etc.)		
	Chemical Composition (percentage of each rock type) (i.e. % carbonate, % shale, etc.) (provide any available data)		
36.	Reactivity Test Method (Canadian Prism, ASTM number)		
	Reactivity Tests Results		
37.	Freeze-Thaw Test Method		
	Freeze-Thaw Test Results		
38.	Size Distribution/Gradation (attach table if available)		
39.	% Recycled Aggregate (i.e. crushed concrete)		
40.	Absorption Tests Results		
41.	% Reactive Silica		
42.	Additional Tests Results (i.e. magnesium sulfate, soundness, etc.)		

Synthetic Admixtures

Fill in the following table as accurately as possible, providing units when relevant for all measurable data. If additional space is needed, use the comment section below and the back of the page if necessary.

		Synthetic Admixture 1	Synthetic Admixture 2
43.	Pasticizers/Water Reducers		
	Type and Commercial Name		
	Chemical Composition		
	Additional Data or Test Results		
44.	Accelerators		
	Type and Commercial Name		
45.	Retarders		
	Type and Commercial Name		
46.	Air Entraining Agents		
	Commercial Name		

Comments and Explanations: ______________________________

____

____

____

____

Mineral Admixtures

Fill in the following table, answering the questions as best as possible. Provide units when relevant for all measurable data. If additional space is needed, use the back of the page or the comment section below. **Attach available x-ray diffraction (XRD) and other characterization data.**

		Admixture 1	Admixture 2	Admixture 3
47.	Type (example: Class F or C Fly Ash, Blast Furnace Slag, Silica Fume)			
48.	Production Company/Mill Name			
49.	Plant/Mill Location			
50.	Production Date			
51.	Date Purchased			
52.	Date Tested/Certified By State For Use In Paving			
53.	Frequency of Mineral Admixture Testing (i.e. how often has this type of mineral admixture been tested and certified)			
54.	Chemical Composition (%)			
	SiO_2			
	Al_2O_3			
	Fe_2O_3			
	CaO			
	Free Lime			
	Total Sulfur Content (%)			
	Other:________________			
55.	Specific Gravity			
56.	Equivalent Alkali Content (NaOH reference)			
57.	Blaine Fineness			
58.	Loss on Ignition			

Water

59. What was the mix water source? ______________________________

60. What are the known impurities in the water? ______________________________

____

Final Mix Composition

61. Provide the amount of each ingredient in the final mix. When providing amounts, please provide units. When providing percentages, please indicate either a volume or weight percentage. If additional space is needed, use the back of this page.

Component	Type/Number	Amount/Percentage in Final Mix
Cement		
Water		
Coarse Aggregate	A	
	B	
Fine Aggregate	A	
	B	
Plasticizers	A	
	B	
Accelerators	A	
	B	
Retarders	A	
	B	
Air Entrainers	A	
	B	
Silica Fume	A	
	B	
Fly Ash	A	
	B	
Blast Furnace Slag	A	
	B	
Other: ________	A	

III. PROCESSING

62. Was the concrete batched or centrally mixed? (circle)
Batched Centrally Mixed Other: ______________________________

63. What was the distance between the mixing site and pavement? Explain if necessary. __________

____

____

64. What type of trucks were used for hauling? ______________________________

____

65. What type of equipment was used for mixing? ______________________________

____

66. How long was the concrete mixed? (in seconds): ______________________________

67. What was the specified/required slump, air, temperature, and water:cement ratio of the concrete?

Required Slump	Required Air	Required Temperature	Water:Cement Ratio

68. What were the recorded values for slump, air, and temperature?

Test	Maximum	Minimum	Average
Slump			
Air			
Temperature			

69. How often were the slump, air, and temperature tests performed? ______________________

____

70. Where were the slump, air, and temperature tests performed in relation to the pavement site?

____

____

71. What was the time between mixing and placement?

Number of Batches for Project	Maximum Time	Minimum Time	Average Time

72. How was the mixing monitored? (example: ammeter, etc.)____________________________

____

____

73. Was the mix reported to be workable or harsh? Explain if necessary. _____________________

____

____

Placement

74. Was the pavement slipformed or fixed-formed? (please circle) Slip Fix Other: ______

75. If the pavement was slipformed, was a spreader used ahead of the slipform paver to evenly distribute the concrete? Explain as necessary._________________________________

____

76. What equipment was used for placement/paving:

Type____

Brand____

Model____

77. What was the sequence of placement (e.g. both lanes at the same time, single, triple....)?_______

____

____

Consolidation

78. Was vibration used for consolidation? ______________________________

79. What type of vibrators were used (circle):

Hydraulic-Stinger   Electric-Stinger   Surface Pan   Roller Tamping

80. Complete the following table concerning the vibrator on the slipform paver. Please provide all information available concerning consolidation, with state procedures and practices explained.

Model	
Brand Name/Company	
Maximum Frequency	
Minimum Frequency	
Number of Vibrators (Stingers) (per lane width)	
Vibrator (Stinger) Spacing	
Vibrator (Stinger) Diameter	
Stinger Length	
Angel of Stinger With Respect to the Pavement	

Comments and Explanations: ______________________________

____

81. Did the pavement specifications contain a modern smoothness requirement (i.e. California Profilograph or Rainhart Profilograph but not a straight edge requirement)? Explain if necessary.

____

____

82. What was the profile requirement? (units of inches per mile) ______________

83. Was there a monetary incentive for the level of smoothness achieved? ______________

____

Finishing

84. What type of finishing was performed (circle): Straight-Edge Floating Texturing

85. How much time elapsed after placement before pavement finishing was started?

Maximum Time	Minimum Time	Average Time

86. What type of equipment was used for finishing (models, brand names, etc.)?________________

____

____

87. How much time elapsed after placement before the joints were sawed?

Maximum Time	Minimum Time	Average Time

88. Was the pavement diamond ground after paving? ______________________________

Curing

89. What types of curing compounds were used? ________________________________

Commercial Name____

Company____

90. How much curing compound was used and what was the application rate (example: 20 gallons/mile)? ____

____

91. When after placement was the curing compound applied?_________________________

92. What other types of curing methods were used? Explain if necessary. ____________________

____

____

93. How long was the pavement allowed to cure before it was opened to traffic? ______________

____

IV. STRUCTURAL AND GEOTECHNICAL ISSUES

Pavement Dimensions

94. What are the dimensions of the pavement? (provide units)

Width ________________________ Thickness ____________________

95. What was the slab length between saw cuts? ____________________________________

96. How many lanes were tied together? ____

Reinforcement Material

97. Were the joints reinforced (i.e. were load transfer joints used)? ______________________

98. If yes, provide the following:

dowel diameter ____

dowel spacing ____

99. Was reinforcing mesh used: Yes No Other: ______________________

100. If yes, list all types of reinforcing mesh used and any relevant specifications (example: welded wire fabrics, bar mats, etc.): ____

____

Joints

101. What was the orientation of the transverse contraction joints (skewed, non-skewed)?

____

____

102. What was the width of the saw cuts?____________________________________

103. What materials, if any, were used as joint sealants?____________________________

____

104. Were there longitudinal joints between each lane?_____________________________

105. Were the longitudinal joints tied?____

Base Course and Subgrade

106. What was the thickness of the base course?__________________________________

107. What types of materials were used for the base course?__________________________

108. Was the base course permeable/drainable?___________________________________

Test method____

Test results ____

109. Was the base course stabilized (i.e. with cement)?_____________________________

110. Were drainage ditches, including edge drains, used? Describe any irregularities.__________

____

111. What was the type of soil in the subgrade?___________________________________

____

____

112. Are there any indications that degradation could be related to the subgrade. Describe and elaborate:____

113. What is the grade/slope of the pavement? Describe if necessary.____________________

114. What type of material was used for the shoulder? ____________________________

115. Is there any correlation between pavement failure and grade?______________________

V. EXTERNAL EFFECTS

Weather

116. What was the logged weather during placement?

Temperature Maximum	Temperature Minimum	Precipitation	Wind Speed	Other

117. What is the average number of yearly freeze-thaw cycles in the project area (accounting for estimated thawing time)?____

118. Were any precautionary measures taken to account for the weather? Describe and elaborate.

____

____

____

Traffic

119. What is the traffic load for the highway (estimated single axil loads - ESAL's)?____________

____

____

120. What is the vehicle-type distribution? ____

____

____

121. What is the maximum weight allowable on the pavement? Provide any seasonal restrictions or limitations.____

____

____

122. Is there a weigh station on the road in the area under consideration (i.e. within the project area)?

____

Chemical Effects

123. What deicing salts were used on the pavement?

Deicing Salts	Type 1	Type 2
Commercial Name		
Source/Company		
Chemical Composition		

124. When were deicing salts first applied after construction?____________________

125. What is the frequency and amount of deicing salt use per year?____________________

126. Did this pavement have any contact with any chemicals?____________________

Adjacent Land Use

127. What type of land is adjacent to the pavement (example: agricultural, urban, industrial, etc.)

VI. PROPERTIES OF HARDENED CONCRETE

Please provide any data (beyond that specifically asked for below) from the testing of core samples of the concrete pavement after placement. This data should ideally cover a wide time span on the order of months or years.

128. Air content (percentage):________________________________

Test method (e.g. ASTM C 457): ________________________________

129. Compressive strength (MPa or psi):

Age	Test Method	Number of Tests	Maximum	Minimum	Average

130. Flexural strength (MPa or psi):

Age	Test Method	Number of Tests	Maximum	Minimum	Average

131. Permeability:________________________________

Test method: ________________________________

132. Provide any chemical analysis data for the hardened concrete, including chloride, sulfate, and alkali content.

VII. DAMAGE CHARACTERIZATION

Please provide characteristic photographs from deteriorated sites. These photographs can be in the form of negatives, prints, slides, or digital images.

Also, provide copies of any pavement management system information for this site.

133. How many photographs have been included for this site?______________________________

134. Are these photographs in the form of: (circle one)

Negatives Slides Prints Digital Images

135. When was distress first observed? This includes any noticeable deterioration.____________

____

136. Complete the following table:

Use SHRP P338 as a standard for evaluating the severity of each type of distress. For each site, provide the area fraction of the site which falls in each category (for example, None=30%, Slight=30%, Moderate=20%, Severe=30%.)

Use the additional photographs provided for the determination of pattern cracking severity.

Type of Deterioration	None	Slight	Moderate	Severe
Corner Breaks				
"D" Cracking				
Longitudinal Cracking				
Transverse Cracking				
Joint Spalling				
Scaling				
Popouts				
Pattern Cracking				

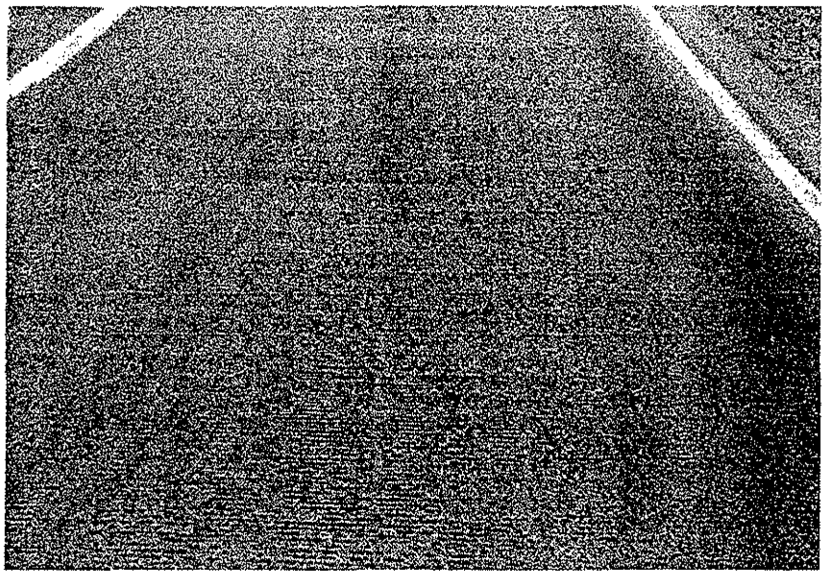
137. Are there any known or hypothesized reasons for failure? Provide any additional information which could support this claim?____

____

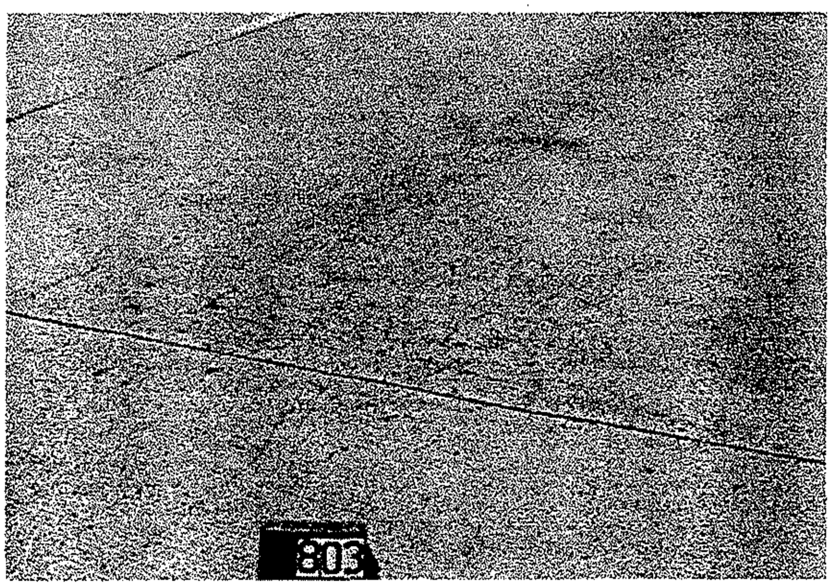
____

____

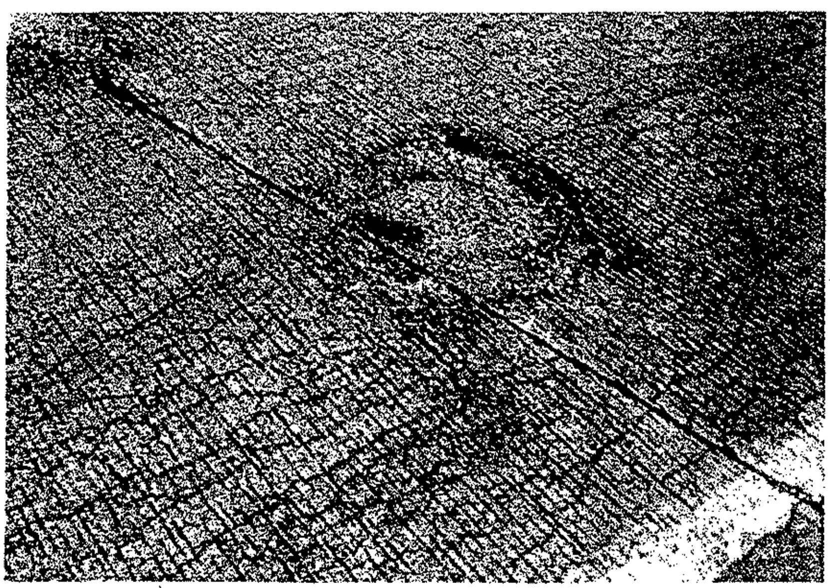
____



Low Severity
Pattern Cracking



Moderate Severity
Pattern Cracking



High Severity
Pattern Cracking

Appendix C

Site and Data Summaries
Geographic Location Summary

Range and Average for Variables included in Models

Variable	Min	Max	Average
Total Alkali	0.350%	1.177%	0.684%
Total Sulfate	0.790%	3.533%	2.561%
Cement Alkali Content	0.800%	0.250%	0.573%
Maximum Paving Temperature (degrees F)	107	74	89.72973
Fly Ash Content (in mix)	0.00%	2.40%	0.93%
Age (years)	7.847	16.8488	11.41938

Table C-1: Pavement sites and normalized deterioration values.

(note: Pavement deterioration was normalized on a scale of 0.00 to 3.00.
Sites with normalized deterioration of "-" were not used in the statistical analysis.)

Site Number	State	Road Number	Nearest Town	Beginning Mile Post	Normalized Deterioration
1	Iowa	US 20	Fort Dodge	124.87	3.00
2	Iowa	US 20	Fort Dodge	130.75	2.95
3	Iowa	US 20	Fort Dodge	130.2	0.00
4	Iowa	US 20	Fort Dodge	125.65	0.00
5	Iowa	I-80	De Soto	106.9	0.00
6	Iowa	I-80	De Soto	110.9	1.85
7	Iowa	I-80	De Soto	115.25	0.00
8	Iowa	I-80	Williamsburg	209.65	1.58
9	Iowa	I-35	Story City	121.46	1.42
10	Iowa	IA-175	Jewell	156.45	0.00
11	Iowa	US 218	Iowa City	90.08	0.67
12	Iowa	US 218	Riverside	73.25	0.93
13	Kansas	I-435	Kansas City	145+11	0.00
14	Kansas	US 50	Garden City	721+00	0.00
15	Kansas	I 70	Abliene/Chapman	2.3 mi E of K43	0.00
16	Kansas	US 36	Elwood	809+00	0.00
17	Kansas	I-435	Kansas City		0.00
18	Kansas	I 70	Kansas City	413	0.20
19	Kansas	US 54	Ft. Scott	52+00	0.00
20	Kansas	US 169	Olathe		0.10
21	Kansas	State Route 7	Olathe		0.00
22	Kansas	I-235	Wichita		0.00
23	Kansas	I-435	Kansas City		0.00
24	Kansas	US 36	Elwood		0.00
25	Nebraska	I-80	Parton	144	2.10
26	Nebraska	I-80	Sutherland	150.96	-
27	Nebraska	I-80	Sutherland	157.74	-
28	Nebraska	I-80	Elm Creek	256.65	0.35
29	Nebraska	I-80	Kearney	272.23	-
30	Nebraska	I-80		311.69	0.70
31	Nebraska	N-2		280.43	2.35
32	Nebraska	I-80	Giltner	324.6	2.70
33	Nebraska	N-2	Ansley	295.94	1.60
34	Nebraska	N-2	Litchfield	309.88	0.23
35	Nebraska	N-2		343.73	1.85
36	Nebraska	Hwy 2	Lincoln	459.7	-
37	Nebraska	N-2	Lincoln	462.57	0.40
38	Nebraska	Hwy 39	Genoa	20.68	-
39	Nebraska	US-81		19	1.70
40	Nebraska	N-81	Strang	22.02	-
41	Nebraska	US-81	York	64.13	-

Site Number	State	Road Number	Nearest Town	Beginning Mile Post	Normalized Deterioration
42	Nebraska	N-81		78.97	2.2
43	Nebraska	N-81	Shelby	95.52	0.3
44	Nebraska	Hwy-81		162.01	0.80
45	Minnesota	MN Hwy 15	New Ulm	60+00.077	2.65
46	Minnesota	MN Hwy 15	New Ulm	63.546	2.65
47	Minnesota	MN Hwy 15	New Ulm	60.077	0.00
48	Minnesota	MN Hwy 15	Lafayette	60.624	0.00
49	Minnesota	MN Hwy 65	Mora	65.209	0.00
50	Minnesota	MN Hwy 92	Mora	64.69	-
51	Minnesota	US Hwy 212	Glencoe	121.233	0.00
52	Wisconsin	US 53 N	Rice Lake	213m	-
53	Wisconsin	US 8	St. Croix Falls	5	-
54	Wisconsin	US 53	Sarona	226+0.00	-

Figure C-1. Map of site locations in Iowa, Kansas, Minnesota, Nebraska, and Wisconsin.

Key

X	deteriorated site
●	non-deteriorated site
Number	corresponds to site number in Table C-1

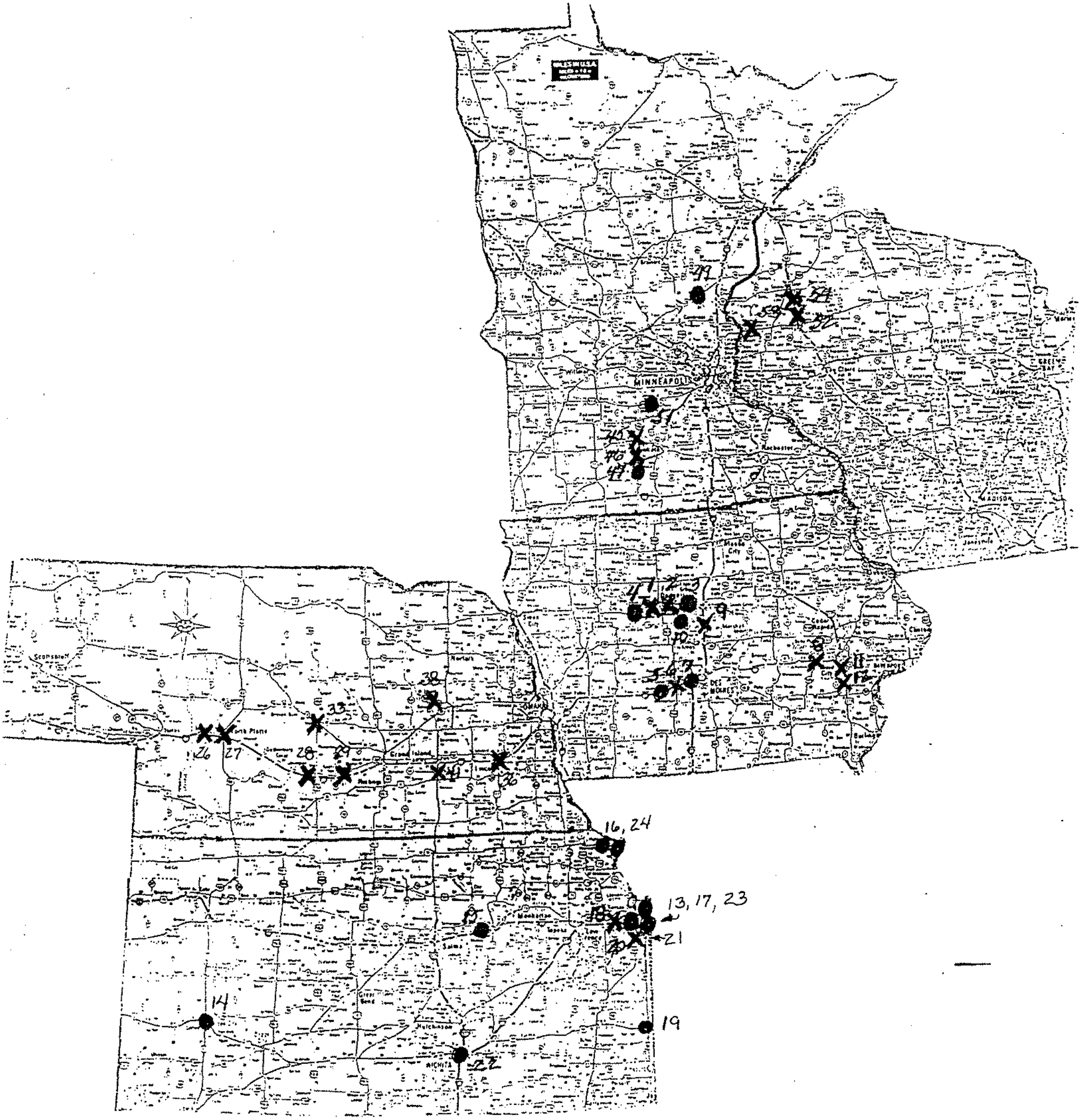


Table C-2: Percentage of each question answered from the data collection survey by state.

Note: This table was compiled based on the response to each question in the survey. If a question was left blank, it was assumed that the information was not available. In some cases, however, no response was an acceptable answer (e.g. Kansas with 0% mineral admixtures). THIS TABLE SHOULD IN NO WAY BE INTERPRETED AS THE DEGREE TO WHICH ANY STATE MAINTAINS HIGHWAY PAVEMENT RECORDS. The table is simply a rough estimate of how much data the research team was given in reference to each question in the data collection survey. It is also important to note how many pavement sites were supplied by each state since, on average, less information was available as the number of sites increased. FINALLY, THE ABILITY TO ANSWER A SURVEY QUESTION IN NO WAY REPRESENTS THE QUALITY OF THAT ANSWER. In select cases, questions pertaining to specific pavement sites were answered with state specifications or approximations. These responses are counted in the table, but obviously, the accuracy of such data in relation to the true conditions is questionable.

FDS

Number of pavement sites submitted by each state:

Iowa	12
Kansas	12
Nebraska	20
Minnesota	7
Wisconsin	3

Survey Question	Iowa %	Kansas %	Nebraska %	Minnesota %	Wisconsin %	Total %
1	100	100	100	100	100	100
2	100	100	100	100	100	100
3	100	100	100	100	100	100
4	100	100	100	100	67	93
5	100	100	100	100	100	100
6	100	42	0	86	0	45
7	100	100	100	100	33	87
8	100	100	100	100	100	100
9	100	100	100	100	100	100
10	100	100	100	100	67	93
11	100	100	100	100	67	93
12	100	100	95	100	100	99
13	100	100	95	100	100	99
14	100	92	95	57	100	89
15	0	42	40	86	0	33
16	0	25	15	0	33	15
17	100	0	0	71	0	34
18	0	83	55	86	100	65
19	0	83	10	71	33	40
20	100	100	5	57	0	52
21	25	100	35	57	0	43
22	100	100	70	71	0	68
23	25	92	30	86	0	46
24	100	100	70	86	67	84
25	100	100	70	86	67	84
26	100	100	100	71	100	94
27	0	75	100	100	0	55

Survey Question	Iowa %	Kansas %	Nebraska %	Minnesota %	Wisconsin %	Total %
28	100	100	0	71	0	54
29	100	100	100	0	0	60
30	-	-	-	14	-	-
31	100	92	95	71	100	92
32	67	25	90	29	100	62
33	100	67	0	29	100	59
34	100	100	100	100	100	100
35	0	100	95	57	0	50
36	0	42	0	100	0	28
37	0	100	0	0	0	20
38	100	100	90	14	67	74
39	100	100	80	57	100	87
40	0	100	75	57	100	66
41	0	25	0	100	0	25
42	8	100	0	0	100	42
43	75	100	60	0	0	47
44	-	-	-	-	-	-
45	-	-	-	-	-	-
46	100	92	100	86	0	75
47	100	100	85	71	67	85
48	100	-	85	71	67	81
49	100	-	85	71	33	72
50	0	-	45	0	0	11
51	0	-	20	14	0	9
52	33	-	70	0	67	43
53	100	-	0	0	33	33
54	83	-	70	0	33	47
55	83	-	70	43	67	66
56	83	-	70	0	33	47
57	0	-	65	0	67	33
58	83	-	70	0	67	55
59	100	83	40	0	100	65
60	100	25	0	71	67	53
61	100	100	30	86	33	70
62	100	92	100	100	100	98
63	83	33	45	14	0	35
64	100	75	0	100	0	55
65	100	8	85	71	0	53
66	100	100	100	0	100	80
67	-	-	-	-	-	-
68	100	-	85	86	33	76
69	100	100	100	71	100	74
70	100	100	90	100	100	98
71	100	25	100	29	0	51
72	100	0	15	29	0	29

Survey Question	Iowa %	Kansas %	Nebraska %	Minnesota %	Wisconsin %	Total %
73	58	8	5	14	0	17
74	100	100	100	100	100	100
75	100	8	100	100	67	75
76	92	8	20	0	0	24
77	92	75	100	100	67	87
78	100	100	100	100	100	100
79	83	33	100	0	0	43
80	58	0	0	0	0	12
81	100	92	100	100	100	98
82	92	8	70	71	100	68
83	100	83	100	71	0	71
84	100	100	100	100	100	100
85	100	100	0	100	0	60
86	0	100	25	86	0	42
87	100	100	100	86	100	97
88	100	75	95	86	0	71
89	100	100	100	86	100	97
90	100	100	100	71	67	88
91	100	100	100	100	0	80
92	42	100	65	71	0	56
93	100	92	95	86	0	74
94	100	100	100	100	67	93
95	100	100	100	100	67	93
96	100	100	100	100	67	93
97	100	100	100	86	67	90
98	100	100	0	71	0	54
99	100	83	100	86	67	87
100	0	25	0	0	0	5
101	100	100	100	100	100	100
102	100	92	100	86	0	75
103	100	100	100	86	100	97
104	100	100	100	100	100	100
105	100	100	100	100	100	100
106	100	100	85	86	0	74
107	100	100	95	86	67	89
108	100	92	100	86	33	82
109	100	83	100	86	100	94
110	100	92	95	100	0	77
111	100	100	90	86	0	75
112	100	83	90	86	0	72
113	100	100	100	100	0	80
114	100	92	95	100	67	91
115	100	83	5	86	0	55
116	100	100	100	14	0	63
117	100	100	100	86	0	77

Survey Question	Iowa %	Kansas %	Nebraska %	Minnesota %	Wisconsin %	Total %
118	100	0	20	71	0	38
119	100	58	20	86	0	53
120	92	83	100	100	0	75
121	100	75	100	100	0	75
122	100	92	100	100	0	78
123	100	100	100	86	0	77
124	100	100	100	100	0	80
125	100	8	0	71	0	36
126	100	67	100	0	0	53
127	100	100	100	100	0	80
128	100	0	0	57	0	31
129	100	100	85	100	33	84
130	100	50	0	29	0	36
131	0	0	0	0	0	0
132	8	0	0	0	0	2
133	-	-	-	-	-	-
134	-	-	-	-	-	-
135	92	42	55	71	0	52
136	-	-	-	-	-	-
137	-	-	-	-	-	-

Table C-3: Range of data values for questions from survey used in the statistical analysis. (note: Data from Wisconsin was not used in the statistical analysis.)

Key: "-" means no data available to properly compare.
A single number (e.g. "15") means there was no range of data given in the surveys

Survey Question	Units	Iowa Range	Kansas Range	Nebraska Range	Minnesota Range	Total Range (if applicable)
4	years	1980-1989	1983-1989	1982-1991	1985-1990	1980-1991
12	cement type	1	1 and 2	1 and 2	1	1 and 2
20	% C_3S	37.20 - 74.40	41.60 - 63.30	52.57	54.00	37.20 - 74.40
	% C_2S	0.40 - 40.00	7.30 - 32.70	23.99	18.10	0.40 - 40.00
	% C_4AF	5.10 - 9.90	7.80 - 15.63	10.95	7.00	5.10 - 15.63
	% C_3A	4.89 - 9.90	1.90 - 12.80	5.73	9.90 - 10.70	1.90 - 12.80
	% SO_3	2.21 - 3.50	1.19 - 2.95	2.20 - 3.00	2.20 - 3.10	1.19 - 3.50
22	% Alkali	0.35 - 0.80	0.35 - 0.54	0.43 - 0.60	0.29 - 0.80	0.29 - 0.80
61	% cement	12.00 - 15.00	15.80 - 16.95	-	15.05 - 17.88	12.00 - 17.88
	% water	6.00 - 7.00	5.66 - 7.77	-	6.39 - 10.17	5.66 - 10.17
	% coarse agg.	38.00 - 43.00	15.53 - 38.70	-	29.19 - 48.14	15.53 - 48.14
	% fine agg.	35.00 - 39.50	38.70 - 62.08	-	30.26 - 39.63	35.00 - 62.08
	% fly ash	0.00 - 2.40	0	-	0 - 3.14	0 - 3.14
68	avg. slump (in.)	1.45 - 2.30	1.00 - 1.90	0.50 - 2.88	1.34 - 2.06	0.50 - 2.88
	avg. % air	5.83 - 7.00	5.00 - 6.00	5.85 - 6.70	5.50 - 5.60	5.00 - 7.00
93	open to traffic (days)	7 - 10	14 - 120	7	7 - 30	7 - 120
94	width (ft.)	24 - 26	24 - 60	24 - 52	12 - 37.5	12 - 60
	thickness (ft.)	8 - 12	9 - 10	9 - 12	7 - 8	7 - 12
95	slab length (ft.)	20	15 - 40	12 - 19	15	12 - 40
108	base course perm.	yes or no	no	yes, slight, no	no	
116	min. paving T (F)	33 - 70	39 - 72	23 - 62	45	23 - 72
	max. paving T (F)	74 - 99	77 - 92	84 - 107	90	74 - 107

Appendix D

Output of Model Building

Appendix D: Output of Model Building

The following appendix includes the direct output from Multiple Correlation during the process of building Model I. It is important to note that these steps are not comprehensive, and they are not discussed in enough detail to be included in the main body of the report. They are included for illustrative purposes only. This process is similar to the one followed in the building of the other models cited in this report.

Variable Listing

This listing includes all of the independent variables considered during this model building exercise. Variables 1-27 are independent variables, 28 is the dependent variable, and variables 29-35 are a few of the combinations of variables included in this study.

Output 1

This output file provides information concerning each variable before any variables are included in the model. Below each variable is a number which represents the T value of that variable if it were to be brought into the model. Since there are no variables included in the model, the R^2 (RSQ) value is 0. At this point, variable 31 has the highest potential T value and will therefore be the first variable included in the model.

Output 2

This output file provides statistical information after variable 31 has been included in the model. The R^2 value is 0.31, representing the fact that 31% of the variation in the data is explained by this new model. This output now shows the T value of variable 31 to be 4.00. The output also indicates what the T values for the remaining variables would be if they were brought into the model. Based on this analysis, variable 27 would be the next included variable.

Output 3

This output provides statistical information after variable 27 has been added to the model. The R^2 has risen to 43.92%, and the prospective T values have been calculated for the remaining variables. At this point, variable 3 should be the next included variable.

Output 4

This output provides statistical information after variable 3 has been added to the model. The R^2 has risen to 51.69%, and the prospective T values have been calculated for the remaining variables. At this point, variable 25 should be the next included variable.

Output 5

This output provides statistical information after variable 25 has been added to the model. The R^2 has risen to 57.97%, and the prospective T values have been calculated for the remaining variables. At this point, none of the remaining variables could be included with a T value of greater than 2. Since there is no justification for the further inclusion of variables, this model will now be evaluated based on a number of criteria including its outliers and the distribution of its residuals.

Variable Listing

#	Var	Label
1:	Var 1	State
2:	Var 2	Site
3:	Var 3	Age
4:	Var 4	Type
5:	Var 5	C3S
6:	Var 6	C2S
7:	Var 7	C4AF
8:	Var 8	C3A
9:	Var 9	SO3
10:	Var 10	Eq Alkali
11:	Var 11	Strength (7day)
12:	Var 12	Cement
13:	Var 13	Water
14:	Var 14	Coarse
15:	Var 15	Fine
16:	Var 16	Fly Ash
17:	Var 17	Total Alkali
18:	Var 18	Total Sulfate
19:	Var 19	Average Slump
20:	Var 20	Average Air
21:	Var 21	Traffic
22:	Var 22	Width
23:	Var 23	Thickness
24:	Var 24	Slab Length
25:	Var 25	Permeability
26:	Var 26	Min T
27:	Var 27	Max T
28:	Var 28	Pattern Cracking
29:	V12 + V16	Cement + Fly Ash
30:	V17 * V29	Total Alkali in Mix
31:	V17 * V18	Tot Alk * Tot Sulf
32:	V17 * V13	Tot Alkali * Water
33:	V18 * V27	Tot Sulfate * Max T
34:	V8 * V27	C3A * Max T
35:	V3 * V25	Age * Permeability

Output 1

11/ 4/1997

Dependent Var. : 28 Pattern Cracking

Sy.x = 0.98895 RSQ = 0.0000 Deg Freedom = 36

VARIABLES IN THE EQUATION

Var	Coefficient	T	RSQ	LABEL

VARIABLES NOT IN THE EQUATION

VAR	3	4	5	6	7	8	9
T	-0.48	-2.74	-1.28	0.92	-2.41	1.25	2.00
RSQ	0.00	0.00	0.00	0.00	0.00	0.00	0.00

VAR	10	11	12	13	14	15	16
T	3.49	0.86	-2.85	-2.14	0.87	-0.61	3.19
RSQ	0.00	0.00	0.00	0.00	0.00	0.00	0.00

VAR	17	18	19	20	21	22	23
T	3.82	1.83	1.79	0.36	-3.52	-1.06	1.05
RSQ	0.00	0.00	0.00	0.00	0.00	0.00	0.00

VAR	24	25	26	27	29	30	31
T	-1.03	0.23	-1.10	2.97	-1.40	3.86	4.00
RSQ	0.00	0.00	0.00	0.00	0.00	0.00	0.00

VAR	32	33	34	35
T	3.60	3.41	1.34	0.36
RSQ	0.00	0.00	0.00	0.00

ROWS DELETED : None

Output 2

11/ 4/1997

Dependent Var. : 28 Pattern Cracking

Sy.x = 0.83076 RSQ = 0.3139 Deg Freedom = 35

VARIABLES IN THE EQUATION

Var	Coefficient	T	RSQ	LABEL
0	-4.16300928E-01			Intercept
31	6.28911106E+03	4.00	0.00	Tot Alk * Tot Sulf

VARIABLES NOT IN THE EQUATION

VAR	3	4	5	6	7	8	9
T	1.54	-0.64	-0.58	0.32	-0.73	0.94	-0.89
RSQ	0.23	0.39	0.06	0.04	0.27	0.02	0.53

VAR	10	11	12	13	14	15	16
T	1.16	-0.08	-0.63	-1.04	-1.18	1.35	0.98
RSQ	0.49	0.08	0.43	0.13	0.26	0.23	0.44

VAR	17	18	19	20	21	22	23
T	0.45	-0.80	0.15	0.38	-1.50	-0.16	-0.11
RSQ	0.85	0.46	0.24	0.00	0.39	0.08	0.11

VAR	24	25	26	27	29	30	32
T	-0.87	-1.24	-0.80	2.76	0.11	0.58	0.06
RSQ	0.01	0.13	0.02	0.03	0.19	0.84	0.85

VAR	33	34	35
T	0.82	1.06	-1.00
RSQ	0.57	0.02	0.12

ROWS DELETED : None

11/ 4/1997

Dependent Var. : 28 Pattern Cracking

Sy.x = 0.76207 RSQ = 0.4392 Deg Freedom = 34

VARIABLES IN THE EQUATION

Var	Coefficient	T	RSQ	LABEL
0	-4.45351936E+00			Intercept
27	4.65758302E-02	2.76	0.03	Max T
31	5.56083971E+03	3.79	0.03	Tot Alk * Tot Sulf

VARIABLES NOT IN THE EQUATION

VAR	3	4	5	6	7	8	9
T	2.30	-0.02	-0.18	-0.10	-0.48	0.36	0.06
RSQ	0.25	0.43	0.08	0.06	0.28	0.08	0.59

VAR	10	11	12	13	14	15	16
T	1.06	0.50	0.94	-0.54	-0.64	0.68	-0.52
RSQ	0.50	0.12	0.60	0.18	0.30	0.29	0.61

VAR	17	18	19	20	21	22	23
T	-1.52	0.51	-0.13	0.23	-0.84	-0.45	-0.91
RSQ	0.91	0.58	0.24	0.01	0.44	0.08	0.18

VAR	24	25	26	29	30	32	33
T	-0.20	-2.13	-0.62	0.99	-1.00	-1.98	0.57
RSQ	0.08	0.17	0.02	0.26	0.89	0.90	0.58

VAR	34	35
T	0.37	-1.98
RSQ	0.10	0.18

ROWS DELETED : None

Output 4

11/ 4/1997

Dependent Var. : 28 Pattern Cracking

Sy.x = 0.71795 RSQ = 0.5169 Deg Freedom = 33

VARIABLES IN THE EQUATION

Var	Coefficient	T	RSQ	LABEL
0	-6.73349354E+00			Intercept
3	1.26509285E-01	2.30	0.25	Age
27	5.31726426E-02	3.29	0.06	Max T
31	7.18189428E+03	4.63	0.23	Tot Alk * Tot Sulf

VARIABLES NOT IN THE EQUATION

VAR	4	5	6	7	8	9	10
T	-0.05	-0.47	0.29	-0.07	0.26	-0.29	0.92
RSQ	0.43	0.09	0.09	0.30	0.08	0.60	0.50

VAR	11	12	13	14	15	16	17
T	0.24	1.06	-0.46	-1.33	1.36	-0.48	-0.95
RSQ	0.13	0.60	0.18	0.35	0.34	0.61	0.92

VAR	18	19	20	21	22	23	24
T	0.06	0.09	0.53	-0.97	-0.58	-0.97	-0.28
RSQ	0.60	0.25	0.02	0.44	0.09	0.18	0.08

VAR	25	26	29	30	32	33	34
T	-2.19	-0.61	1.27	-0.40	-1.36	0.12	0.28
RSQ	0.17	0.02	0.27	0.90	0.91	0.60	0.10

VAR	35
T	-2.06
RSQ	0.18

ROWS DELETED : None

11/ 4/1997

Dependent Var. : 28 Pattern Cracking

Sy.x = 0.68000 RSQ = 0.5797 Deg Freedom = 32

VARIABLES IN THE EQUATION

Var	Coefficient	T	RSQ	LABEL
0	-7.65543413E+00			Intercept
3	1.22338168E-01	2.35	0.25	Age
25	-3.14916703E-01	-2.19	0.17	Permeability
27	6.07476468E-02	3.87	0.11	Max T
31	8.11047640E+03	5.31	0.29	Tot Alk * Tot Sulf

VARIABLES NOT IN THE EQUATION

VAR	4	5	6	7	8	9	10
T	-0.46	-0.01	-0.04	-0.46	-0.36	-1.27	1.11
RSQ	0.45	0.14	0.11	0.32	0.16	0.66	0.50

VAR	11	12	13	14	15	16	17
T	0.56	0.30	-1.34	-0.43	0.51	0.32	0.36
RSQ	0.15	0.65	0.27	0.48	0.46	0.66	0.95

VAR	18	19	20	21	22	23	24
T	-0.84	0.49	0.40	-1.77	-0.81	-0.11	-0.16
RSQ	0.66	0.28	0.03	0.49	0.09	0.33	0.09

VAR	26	29	30	32	33	34	35
T	-0.92	0.88	0.80	-0.72	-0.77	-0.34	0.25
RSQ	0.04	0.30	0.92	0.92	0.66	0.18	0.96

ROWS DELETED : None
