
The Effect of PCC Strength and Other Parameters on the Performance of PCC Pavements

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INTRODUCTION

Many Portland cement concrete (PCC) pavements on the Interstate Highway System have met or exceeded their original design lives. Others have failed prematurely, often for unknown reasons, even though the PCC used may have met all quality control specifications in place during construction. State Highway Agencies must increasingly consider either rehabilitation or removal and replacement of these older PCC pavements. A thorough understanding of the factors affecting deterioration rates will allow highway engineers to better manage rehabilitation projects and build more durable and predictable new pavements in the future.

In concrete applications other than pavements (e.g., bridges, columns for high rise buildings, off shore structures, etc.), there is a trend toward using higher strength PCC. Design compressive strengths of 55 MPa to 75 MPa (8,000 to 11,000 psi) or higher have been specified. The advantages of using higher strength concrete in structural applications are well understood. The weight-strength-cost trade-off has favored the use of higher strength mixes. This trend toward use of higher strength PCC has not been observed in pavements due to the lack of hard evidence of improved cost/benefit ratio for higher strength mixes.

Pavements often exist in harsh environments and are subjected to millions of repeated wheel loads. The geometry of a pavement, a thin plate resting on the earth, results in much greater concrete exposure to temperature and moisture variations than that typically seen by mass structural concrete. The result is that many material properties and characteristics influence long term performance and life cycle costs of the total pavement system. Increased strength is assumed to change initial cost, maintenance outlays, and design life. Pavements can fail, not because of structural or load related factors but, because of PCC deterioration caused by the physical forces of nature and chemical reactions.

The main objective of this paper is to present some preliminary findings from an on-going Federal Highway Administration (FHWA) project studying the effects of increasing strength and resulting associated properties (i.e., elastic modulus, w/c ratio, permeability,...) on pavement performance. In many current paving specifications, quality is defined and controlled by aggregate gradation, flexural strength/compressive strength, and air content thresholds. It is likely that PCC properties other than strength and air content may prove to be good indicators of expected long-term performance of concrete pavements. The overall project objectives are to:

1. Determine the properties of Portland cement concrete (PCC) of higher strength found in certain in-service pavements which resulted in exceptional long-term performance; in particular freedom from distress near joints and free edges.
2. Identify test methods to measure (quantify) these properties. Also, determine the material characteristics of the concrete constituents, and their proportions, which are responsible for the levels of these properties found in the concrete.
3. Develop revised mix design procedures, including any additional tests, and prototype mix designs which will result in the production of concrete for use in pavements that would possess these properties while still meeting current construction requirements and economic considerations.

This paper summarizes findings from the first phase of this on-going project, which consisted of a detailed literature review and some preliminary analyses of the Long-Term Pavement Performance (LTPP) data. The project team is in the process of conducting Task B which is a detailed field investigation on up to 12 pavement sections in different climates with differing levels of distress. Task C will consist of detailed laboratory studies on the PCC properties which are shown to have high influence on the long term performance.

WHAT IS NORMAL STRENGTH AND HIGH STRENGTH FOR PCC PAVEMENTS?

The on-going FHWA-LTPP study, originally established by Strategic Highway Research Program (SHRP), contains comprehensive data on pavement performance including environmental factors, material characteristics, PCC properties and construction and maintenance information for each test section. The answer to what is normal and higher strength for PCC pavement is contained within these data. Table 1 shows some basic statistics from cores for some of the key PCC properties within the LTPP GPS3(JPCP), GPS4(JRCP), and GPS5(CRCP) data. Each data point used in the following analyses represents the average of the two or three core tests for each parameter per GPS site. The average PCC at the GPS sites was 13.5± years old with an elastic modulus of 3.12E+4 MPa (4.57E+06 psi), split tensile strength of 4.38 MPa (643 psi), compressive strength of 51.71 MPa (7,584 psi), and unit weight of 23.1 KN/m³ (147 pcf). Pavements with strengths above these average levels are considered higher strength in this study. The average strength values found in this study are higher than the strengths typically specified on paving projects. This is because 28 day strengths are typically used and PCC continues to gain strength beyond 28 days.

HOW DO PCC TRENDS IN THE LTPP DATA FIT EXPECTED TRENDS?

There were some general regional trends observed for PCC properties and strength within the LTPP data. Hot regions virtually all use lower cement content, lower modulus mixes. Cool, wet no freeze environments generally had the highest strength mixes. Cold, heavy freeze regions generally had higher cement contents and higher air contents which seemed to generally result in higher elastic modulus for a given tensile strength.

The following discussions and figures use the parameters described below:

Age:	Approximate age of the core at testing, yrs
Compstr:	Average site core compressive strength, psi
Poissons:	Average site core Poissons ratio
Unitwt:	Average site core unit weight, pcf
EMOD:	Average site core elastic modulus, psi
SplitTensile:	Average site core split tensile strength, psi
Air:	Estimated air content, %
Cagg:	Estimated coarse agg. per unit volume, lbs
Fagg:	Estimated fine agg. per unit volume, lbs
CFRat:	Cagg/Fagg
Cement:	Estimated cement content per unit volume, lbs
Water:	Estimated water content per unit volume, lbs.
WCRatio:	water/cement
P200:	Subgrade % passing #200 sieve.
w%:	Subgrade moisture content, %.
DaysWet/yr:	Number of days with precipitation per year.
FrzThwCyc:	Number of freeze thaw cycles per year.
Days32-:	Number of days below 0 C° (32 F°) per year.
Days90+:	Number of days over 32.2 C° (90 F°) per year.
JtSpace:	Joint spacing, ft.
PCCThick:	Pavement slab thickness, in.
KESAL/yr:	Average number of kilo-ESAL per year.

For many of the GPS sites, 28 day compressive strength information is available in the historical data (Avg.=32.0 MPa (4,692psi), Min.=17.9 MPa (2,625psi), Max.=46.2 MPa (6,780psi), stdev.=5.75 MPa (844psi)). The 28 day compressive strength values for the entire database were related to the core strengths and ages at the time of testing by calculating the linear slope of the strength gain between the two points in time. Strength gain in reality is non linear with

respect to time. This calculated value is simply an index used for the following statistical analyses. The slope values, shown in figure 1, multiplied by their corresponding ages at the time of LTPP testing gives the total observed strength gain between 28 days and the time of the core break. Correlation of this resulting slope of strength gain to many other PCC parameters available in LTPP were determined for pavements less than 10 years old and greater than 10 years old separately. The former correlates more to factors affecting strength and strength gain in younger concrete, and the latter more to factors affecting long term strength gain and ultimate strength. Figure 1 shows correlation matrices resulting from this analysis. The correlation coefficients presented are the Pearson correlation coefficients (1). This is a value between one and negative one. Values near positive, or negative, one indicate a strong positive, or negative, correlation which means an increase in one parameter is related to an increase, or decrease, in the related parameter.

Over the period of thirty to ten years ago, trends toward using slightly less coarse aggregate, lower water cement ratio, lower water, and higher air content became more prevalent. This is consistent with the changes in mixes which occurred during the switch from formed to slip form pavers. The highest correlation to the slope of strength gain for this age group, other than compressive strength and elastic modulus, was with unit weight, air content, and cement content. The correlations seem to indicate that higher 28 day strength did not mean higher slope of strength gain but that ultimate strength was positively correlated to the 28 day strength. Cement content and 28 day compressive strength were the factors most correlated to in service compressive strength, and 28 day compressive strength was the parameter most correlated to in service split tensile strength.

For the zero to ten year old age group, the correlations indicate that mix proportion trends have reversed using less fine aggregate, lower air contents, but still lower water cement ratios. The factors which show highest correlation with age for this group are unit weight, fine aggregate content, and air content. The w/c ratio had highest (negative) correlation to air content revealing the general practice for freeze thaw protection of concrete.

For both age groups, aggregate proportions show higher correlation to split tensile strength values than compressive strength values. Water to cement ratios for this data set show higher correlation to mix water amounts than to mix cement amounts. These correlations are not strong, but they reflect in general the current understanding of concrete behavior and practice.

Conventionally, elastic modulus and split tensile strength have been estimated based on the square root of a compressive strength. These data indicate that compressive strength is the best single indicator of elastic modulus and split tensile strength. Unit weight and aggregate proportions show similar correlation to split tensile strength, indicating the importance of aggregate types and sizes on tensile strength. Linear regressions have been performed on the LTPP data predicting elastic moduli and split tensile strengths based only on the square root of the compressive strengths from the GPS sites. The slope of the best fit line for split tensile strength prediction from the LTPP data is 7.38, which is close to the current ACI recommendation of 7.4(2). The slope of the line for elastic modulus prediction is 52,800. This value is less than the commonly used 57,000. Adding mix parameters to the regressions improves the r-square values. This indicates that materials characteristics have a significant effect on these relationships. Figure 2 shows the data and regression results.

To expand on this concept, figure 3 is a plot of measured elastic moduli vs. split tensile strengths. As shown, there is a large variation of split tensile strength at a given elastic modulus. It is believed that a brittle mix is a mix with higher elastic modulus (stiffer) with lower split tensile strength. A common indicator of poor faulting and roughness performance within the GPS PCC pavements is this higher modulus-lower strength type PCC, perhaps indicating the effects of more brittle concrete behavior.

THE EFFECT OF CONCRETE STRENGTH AND OTHER PARAMETERS ON PCC PAVEMENT PERFORMANCE

This ongoing study is focused on the performance of PCC pavements at joints and cracks. Specifically it has been decided to focus on the role that strength plays in the development of spalling (joint and crack deterioration/loss of concrete), faulting of cracks and joints, and overall pavement roughness (International Roughness Index). The following discussions summarize some of the key issues related to these types of PCC distress and present new prediction models. These models were used for evaluation of observed trends in the LTPP data.

LTPP is one of the few studies to obtain the amount of information required to conduct modeling studies which include detailed PCC information. Even though there are only a few time sequence distress measurements available at the current time, studies have been conducted investigating modeling techniques and identifying preliminary trends, preparing for when there is enough time sequence distress data (1). For this study, it was decided to place emphasis on extracting PCC

performance trends from the LTPP data. One of the tools for doing this was to establish some preliminary models for distress prediction attempting to actually quantify relevant trends observed. The model forms presented in this paper were developed to investigate trends for non doweled JPCP.

There are few performance models in the literature where one can do sensitivity studies with respect to PCC properties and material characteristics. Probably the most understood distress mode is transverse cracking. Stress analysis of PCC slabs indicate that higher tensile strength will generally give more repetitions until crack initiation (longer fatigue life) at a given stress level. Lower elastic modulus would result in lower thermal stresses at a given gradient (2,3,4,5). Strength parameters, such as modulus of rupture, have been used directly or indirectly as a parameter in existing models for cracking and faulting (2,7,8,9,1,10,11). Some of these models used core compressive strengths along with conventional relations to estimate an elastic modulus and tensile strength which were in turn used as variables in the model. It is clear after reviewing the performance data from LTPP that variations from these conventional relations are significant and that these variations can affect performance.

Most of the LTPP data is only available in US customary units. All statistical analyses conducted, models, and figures presented below use US customary units with the exception of faulting which was measured in mm.. The models presented below are for faulting (total faulting, mm, per 152m (500 ft) section), roughness (International Roughness Index, IRI, in/mi), and spalling (length of transverse spalling per length of road)(12) of non doweled JPCP.

Faulting Behavior

Faulting is the development of an offset at the joints or cracks of the pavement system. Aggregate interlock at cracks and joints plays a significant role with respect to faulting behavior. Aggregate interlock is a function of the surface texture of the resulting crack, the strength of the resulting irregularities, and the crack or joint opening. Durability of aggregate interlock is likely directly related to the durability and strength of the concrete and aggregate used. Aggregate type, size, and gradations along with behavior of the transition zones likely have most significant effects on aggregate interlock. The following general comments on faulting are offered:

- Faulting is primarily controlled by the combination of environmental precipitation, subgrade P200 and moisture content, and the amount and type of overburden pressure placed on the subgrade. These factors along with PCC strength and traffic control the rate of appearance of faulting indicating its primary relation to pumping action, repeated loads and stiffness.
- Joint spacing, concrete shrinkage, and thermal properties control the magnitude of crack and joint openings which can have a significant role in the load transfer behavior.

Faulting Model:

Most previous faulting models have used model forms which predict that the faulting will progress to infinity (8,1). This is not believed possible for well draining non erodible subgrades. The model in reference (1) does not include precipitation or subgrade parameters which are among the highest correlation to faulting within the LTPP data. The goal here was to include strength and stiffness of the concrete in a model, to use a model form which allows the faulting development curve to flatten out over time, and to include PCC, subgrade, and overburden pressure parameters. The model developed to predict faulting is as follows:

$$\text{Faulting} = \text{MaxFIt}(2)e^{r_o(t-D)} [\text{MaxFIt} - 2 + 2e^{r_o(t-D)}]^{-1} - 2$$

Faulting = Faulting per 152m, mm =0, t<D

D = Delay Time for initiation, years

MaxFlt = Maximum long term faulting, mm/152m section

r_0 = Growth Rate Constant >0.000, =0 for $r_0 < 0$

2 = magnitude of initial Fault size, mm, small value for modeling

t = time in years =D for t<D, else = t

$$D = A(KESAL/yr)^B + C(P200*w\%/10)^D + E(EMOD/100000)^F + G(SplitTensile/10)^H$$

$$MaxFlt = I(SlabThick)^J + K(P200*DaysWet/Po)^L + M(SlabL)^N$$

$$r_0 = Q(KESAL/yr)^R + S(w\%)^T + U(Dayswet)^V + W(SplitTensile/10)^X + Y(EMOD/100000)^Z$$

A=	822.833778	I=	473.2804362	Q=	0.599555618
B=	-0.999249182	J=	-1.275662692	R=	0.49868089
C=	68.12915887	K=	2.62052E-08	S=	6.45599E-05
D=	-126.6873865	L=	5.422318242	T=	4.940230289
E=	5.51186E-06	M=	4.07901E-08	U=	0.00025109
F=	4.224342101	N=	7.529691239	V=	2.670986643
G=	-1.94574E-06	O=	-688433763.3	W=	9.99373E-05
H=	3.662896114	P=	8.226363682	X=	3.368717172
				Y=	0.000112882
				Z=	3.502179556

The model coefficients A through Z are determined within an optimization solver such that the prediction errors would be minimized.

Figure 4 shows the line of equality plots for the faulting model along with both measured and predicted faulting vs. time. Also shown are predictions from an earlier model presented in reference (1). The new model better predicts faulting primarily due to the inclusion of precipitation and subgrade parameters and the use of a different form. Figure 5 shows the sensitivity of the model to increasing strength. The strength increase is assumed to be in the context of increasing compressive strength as shown. The standard ACI relations are used to imply a split tensile strength and an elastic modulus used in the model. The resulting model predicts that for these climate and design conditions, increasing strength will cause faulting to begin at a later age but that the faulting will develop faster once it begins. This is intuitively correct from what is known about fatigue and brittleness in PCC. The higher strength postpones the initiation of faulting. Climate and subgrade primarily control the rest. This model is sensitive to precipitation effects, subgrade P200 and moisture contents, subgrade overburden pressure, along with traffic and joint spacing.

Spalling Behavior

Though this study does not focus on D-Cracking or ASR susceptible aggregate sources, they certainly deserve mention because they have been a considerable source of the most accelerated and severe spalling documented in the past(1,13,14,10,15). Avoiding aggregates known to cause these forms of distress will radically reduce spalling of edges and joints.

The coefficient of thermal expansion, regional temperature and moisture conditions, slab length, and shrinkage factors significantly affect the relative daily and seasonal movement of slab ends. The combination of horizontal movements with curling and warping actions cause joints to open up in winter, or early morning, and close during summer, or mid afternoon. Each time the joints or cracks open, debris can fall slightly deeper into the discontinuities only to be crushed upon the next closing of the joints causing high compressive stresses at slab ends. These crushing forces in turn generate more micro cracks and eventually more debris.

Joint sealants affect both the ability for incompressible debris and water to enter the system. This in turn affects the moisture distribution at discontinuities, and loss of support due to pumping action affecting the rate of spalling.

In heavy wet freeze environments, severe spalling requires virtually continuous patching efforts during winter such that user dissatisfaction and perhaps vehicle damage are kept to acceptable levels. Higher spalling quantities are also found in the various PCC performance databases for very hot, arid regions which have a large number of days above 32.2 C°(90

F°) such as California and Arizona. In most cases, very little spalling was noted in wet no freeze environments for almost any strength, traffic level, or age.

Tensile forces would be expected to build up over time along the edges and top of a concrete slab, as irreversible drying shrinkage occurs during prolonged dry periods. Concrete of lower permeability would likely be more susceptible to developing more non-linear moisture gradients at edges resulting in higher tensile stresses. The following general comments on spalling are offered:

- Permeability and shrinkage characteristics control the development of desiccation and moisture gradient stresses through the slab thickness and along slab edges.
- The LTPP data for spalling (from distress surveys and faulting surveys) shows strongest correlation to annual precipitation (-) and air content(-) indicating a freeze thaw-permeability-shrinkage effect.
- The spalling information contained in the faulting survey data shows that more days above 32.2 C° (90 F°) indicated more spalls and that compressive strength shows negative correlation to spalling perhaps indicating a relation to resistance to the in-compressible material effect.
- Traffic rates play a strong role in the rate of spalling indicating that repeated loads are a key factor.

Spalling Model:

Spalling was quantified by summing all of the lengths of spalls noted in the LTPP faulting surveys and then dividing this value by the length of the test section. What results is a spalling density with dimensionless units, L/L. The number 0.02 was arbitrarily selected as a small initial value for use in modeling. The model developed for predicting spalling is as follows:

$$\text{Spalls, L / L} = \left(\frac{0.02(\text{LaneWidth})}{\text{JtSpace}} \right)^{e^{r_0 \cdot 1.1}} - \left(\frac{0.02(\text{LaneWidth})}{\text{JtSpace}} \right)^{e^{r_0 \cdot 1.1}}$$

$$r_0 = \begin{cases} r, & r > 0 \\ 0, & r \leq 0 \end{cases}$$

$$r = A(\text{Poissonratio})^B + C(\text{P200})^D + E\left(\frac{\text{EMOD}}{1\text{E} + 06}\right)^F + G\left(\frac{\text{SPLITT}}{100}\right)^H$$

$$+ I(\text{PCCThick})^J + K(\text{KESAL} / \text{yr})^L + M(\text{JtSpace})^N + O(\text{DaysWet} / \text{yr})^P$$

$$+ Q(\text{Days90+} / \text{yr})^R + S(\text{FrzThwCyc})^T$$

A=	-17576.06543	F=	0.498748851	K=	1.054880741	P=	5.263053564
B=	1.605082343	G=	0.000431018	L=	1.247090816	Q=	-11498.64643
C=	9.519865569	H=	3.759893617	M=	5686.491698	R=	-0.306653055
D=	0.437918844	I=	-7.069812421	N=	0.158779599	S=	1.11273E-05
E=	-35.84278947	J=	0.039291571	O=	-8.97821E-07	T=	4.084664825

Unlike faulting and roughness, PCC strength did not show much correlation to spalling development for the LTPP sections. Figure 6 shows the prediction accuracy of the model. The model predicts no spalling for the climate conditions shown in figure 5. Figure 7 and 8 show the sensitivity of the model to increasing traffic volume and increasing freeze thaw cycles for a dryer climate. This data set did not have many representatives from the wet freeze environments and hence is not valid for these conditions. Few non doweled, non reinforced, sections exist in the wet freeze climate.

Pavement Roughness (IRI)

IRI is an index which represents a pavements ride quality (suspension stroke or movement per unit length of road) based on measured surface profiles taken along the traveled wheel paths(16). The IRI reflects the effects of all distress modes and foundation settlement combined on ride quality. The correlation coefficients for IRI resemble faulting rather than spalling correlations. This is likely because faulting significantly changes pavement profiles. Only severe spalling showed any correlation to IRI.

Analysis of the LTPP data indicates that high strength, lower w/c ratio, high modulus pavements are generally rougher. This may suggest that mix workability was less which affected roughness. Another possible explanation is that less relaxation of stresses and higher early temperature gradients occurred during curing, resulting in greater construction curling affecting roughness.

Roughness(IRI) Model:

IRI is typically reported in inches per mile (1m/km=63.36 in/mi). The model form which was developed for IRI prediction is as follows:

$$IRI(t) = e^{rot} \left[\frac{IRI_{max} \times IRI_0}{IRI_0(e^{rot} - 1) + IRI_{max}} \right]$$

$$IRI_0 = A(100 \times w\%)^B + C(P200/P_0)^D + E(JointSpace)^F + G(w\%)^H$$

$$IRI_{max} = W(PCCThick)^X + Y(100 \times w\%)^Z + AA(P200 \times w\%)^{BB} + CC(JointSpace)^{DD}$$

$$r_0 = \frac{1}{10000} [I(PCCThick)^J + K(\frac{SplitTensile}{10})^L + M(\frac{EMOD}{100000})^N + O(FZI)^P + Q(Days32-)^R + S(DaysWet)^T + U(KESAL / yr)^V]$$

A= -0.2480371	H= 0.0525586	O= -4.0215953	V= -0.3173752
B= 1.3336220	I= 4403.715739	P= 0.7614758	W= 7313.61265
C= -826.468303	J= -3.5134802	Q= 0.0175914	X= -2.4763410
D= 0.0170486	K= -0.0132394	R= 2.3338356	Y= 0.0001225
E= 2.1071304	L= 2.3856773	S= 0.0257081	Z= 3.2994989
F= 0.0080561	M= 0.4798878	T= 1.9506785	AA= 2.8769925
G= 808.915445	N= 1.9169444	U= -3834.32168	BB= 0.5286807
			CC= 0.0263319
			DD= 3.0122959

Figure 9 shows the prediction accuracy of the resulting model. It is apparent that as more time sequence data points per section become available, such as here with the IRI data, modeling better predicts behavioral trends. Figure 10 shows the effect of increasing strength for conditions similar to figure 5 for the faulting model. The model predicts that lower w/c ratio mixes will in general result in higher initial roughness but lower roughness at old age.

CONCLUSIONS

All of the trends found in the first phase of this project seem to indicate that there is a different optimum level of strength for various environments and placement conditions which, in the past, has provided the best combination of construct-ability and long term performance. Mild temperature, wet no freeze environments appear to provide closest to ideal conditions for PCC performance provided protection against pumping and related faulting is provided. It appears that in these cooler wet no freeze environments, which have good construction and curing conditions, higher strength generally

indicates superior performance for all distress types holding all else constant. However, in hot regions, there is a trend in the LTPP data toward lower cement content, lower elastic modulus, mixes which in most cases have performed well. In areas with consistently hot placement conditions, performance may be significantly affected by construct-ability of the mix used. Slower strength gain associated with lower cement content may have resulted in more forgiving mixes for these hot conditions. The LTPP data indicates that lower modulus with relatively higher strength results in improved faulting and roughness performance.

Three new models based on the LTPP GPS3 data were presented which predict distress for non doweled JPCP. These models are preliminary and were developed to help assess the effects of PCC strength and associated properties on the development of pavement distress. Strength was found to have a significant effect on faulting and roughness prediction but not much effect on spalling. The model forms along with a sensitivity study which can be used as a check when programming the models is provided.

Data modeling is one way to quantitatively separate out the interacting effects of climate, PCC properties, subgrade properties, and traffic levels. The more time sequence data available for modeling, the more realistic future predictive models will become. Additional data collection and modeling work in the future is required to validate the trends observed here. For this study, approximately twelve older pavement sections in various climates with varying distress will be studied in great detail and compared to the trends observed. This will be followed by controlled laboratory studies on the key PCC properties and materials characteristics which affect PCC pavement performance.

- Table 1. Average per GPS site statistics for PCC Properties.
- Figure 1. Statistical correlation matrices for various PCC parameters from the LTPP GPS sections.
- Figure 2. Regression results for general trends in the LTPP GPS PCC core data.
- Figure 3. Relation between Site average core elastic moduli and split tensile strengths. Arrows show a general trend towards performance.
- Figure 4. Plots showing the accuracy of prediction for the faulting model and a comparison to a previous LTPP based model.
- Figure 5. Sensitivity of the GPS3 (un doweled) faulting model to changes in PCC strength.
- Figure 6. Prediction accuracy of the spalling model.
- Figure 7. Sensitivity of the spalling model to changes in traffic volume.
- Figure 8. Sensitivity of the spalling model to changes from dry no freeze to dry freeze climate.
- Figure 9. Plots showing the accuracy of prediction for the IRI model.
- Figure 10. Sensitivity of the GPS3 (un doweled) IRI model to changes in PCC strength.

Statistic	Age, yr	Elastic Modulus, psi	Split Tensile Strength, psi	Compressive Strength, psi
Maximum	32.5	6.80E+06	1012	11445
Minimum	1.6	2.00E+06	417	4860
Average	13.5	4.57E+06	643	7584
Standard Deviation	6.7	8.67E+05	106	1205

Table 1. Average per GPS site statistics for PCC properties.

Cores 10-30 years old

	Age	Slope	Compstr	Poissons	Unitwt	EMOD	Split_Te	WCRat	Air	CFRat	Cagg	Fagg	Cement	Water	H_Compst
Compressive Strength	1.000														
Poissons ratio	-0.393	1.000													
Unit Weight	0.101	0.729	1.000												
Elastic Modulus	0.016	-0.068	0.016	1.000											
Split Tensile	0.209	0.250	0.209	-0.061	1.000										
w/c ratio	0.010	0.464	0.578	0.230	0.310	1.000									
Air content	0.047	-0.006	0.228	-0.139	0.379	0.149	1.000								
Fine agg content	0.117	-0.055	0.124	-0.052	-0.233	0.011	-0.028	1.000							
Coarse to Fine agg ratio	-0.156	0.246	0.129	0.202	-0.123	0.025	-0.292	0.206	1.000						
Coarse agg content	0.098	-0.032	-0.127	-0.123	0.227	-0.173	0.235	0.154	-0.360	1.000					
Fine agg content	0.143	-0.045	-0.139	-0.071	0.257	-0.164	0.197	0.046	-0.393	0.948	1.000				
Cement content	-0.088	0.005	0.056	0.009	-0.187	0.168	-0.204	-0.129	0.288	-0.950	-0.920	1.000			
Water content	0.059	0.127	0.221	0.193	0.230	0.086	0.094	0.153	0.491	-0.315	-0.302	0.212	1.000		
28 day strength	0.152	-0.007	0.220	0.013	-0.120	0.061	0.019	0.942	0.347	0.031	-0.064	-0.043	0.437	1.000	
	-0.069	-0.090	0.370	0.116	-0.043	0.266	0.306	0.226	0.161	-0.321	-0.365	0.214	0.244	0.309	1.000

Cores 0-10 years old

	Age	Slope	Compstr	Poissons	Unitwt	EMOD	Split_Te	WCRat	Air	CFRat	Cagg	Fagg	Cement	Water	H_Compst
Compressive Strength	1.000														
Poissons ratio	-0.616	1.000													
Unit Weight	0.026	0.382	1.000												
Elastic Modulus	-0.285	0.127	-0.108	1.000											
Split Tensile	0.356	-0.060	0.354	-0.165	1.000										
w/c ratio	0.260	0.109	0.294	-0.022	0.447	1.000									
Air content	-0.130	0.227	0.454	0.102	0.210	0.032	1.000								
Fine agg content	0.112	-0.338	-0.106	0.113	0.148	-0.353	0.222	1.000							
Coarse to Fine agg ratio	0.282	0.037	-0.031	-0.150	0.239	0.333	-0.057	-0.209	1.000						
Coarse agg content	-0.208	0.367	0.268	0.142	0.146	0.074	0.452	0.083	-0.169	1.000					
Fine agg content	-0.077	0.300	0.300	0.053	0.317	0.187	0.369	0.072	-0.034	0.942	1.000				
Cement content	0.299	-0.389	-0.254	-0.113	-0.114	-0.029	-0.442	-0.112	0.210	-0.975	-0.922	1.000			
Water content	-0.045	0.084	-0.083	0.064	-0.241	-0.097	0.027	-0.414	0.180	-0.217	-0.344	0.184	1.000		
28 day strength	0.097	-0.308	-0.159	0.145	-0.006	-0.445	0.283	0.748	-0.099	-0.063	-0.164	0.013	0.286	1.000	
	-0.265	-0.248	0.202	0.220	-0.119	-0.127	0.148	0.174	-0.490	-0.133	-0.208	0.105	-0.034	0.164	1.000

GPS 3, 4, and 5 Sites with 28 Day Strength Information

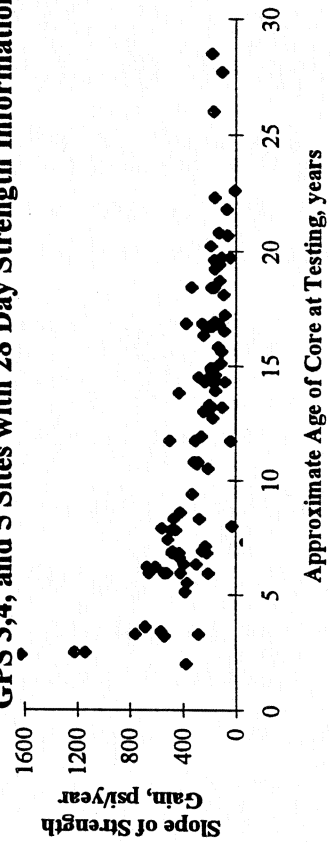


Figure 1. Statistical Correlation Matrices for various PCC parameters from the LTPP GPS sections.

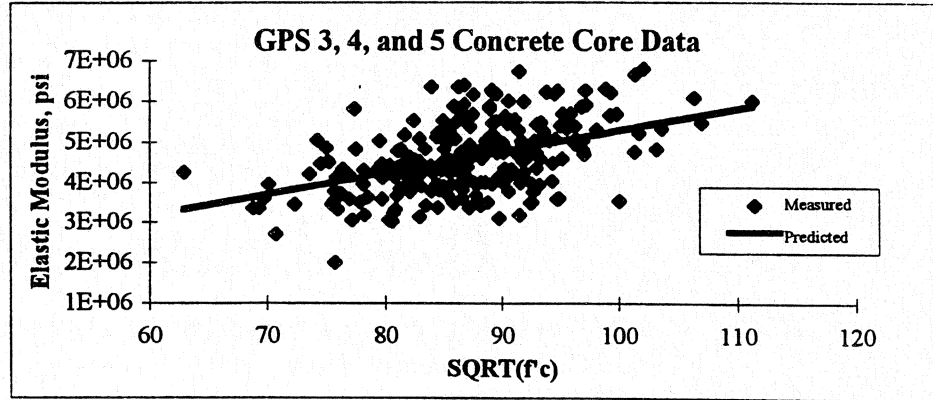
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.509968253
R Square	0.260067619
Adjusted R Square	0.256083556
Standard Error	746945.7496
Observations	252

ANOVA

	df	SS	MS	F	Significance F
Regression	1	4.92205E+13	4.92E+13	88.2201863	3.82083E-18
Residual	251	1.4004E+14	5.58E+11		
Total	252	1.8926E+14			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0							
SQRT(f _c)	52805.95496	538.5366343	98.05453	4.011E-202	51745.3282	53866.58173	51745.3282	53866.58173



Regression Statistics	
Multiple R	0.413151018
R Square	0.170693763
Adjusted R Square	0.1667097
Standard Error	97.1988529
Observations	252

ANOVA

	df	SS	MS	F	Significance F
Regression	1	488088.6663	488088.7	51.662622	7.58658E-12
Residual	251	2371351.868	9447.617		
Total	252	2859440.535			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0							
SQRT(f _c)	7.384304439	0.070078909	105.3713	8.787E-210	7.246286778	7.5223221	7.246286778	7.5223221

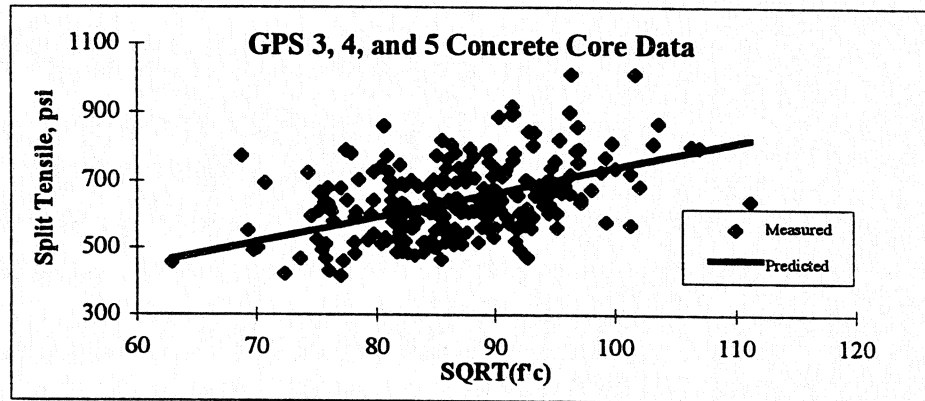


Figure 2. Regression results for general trends in the LTPP GPS PCC core data.

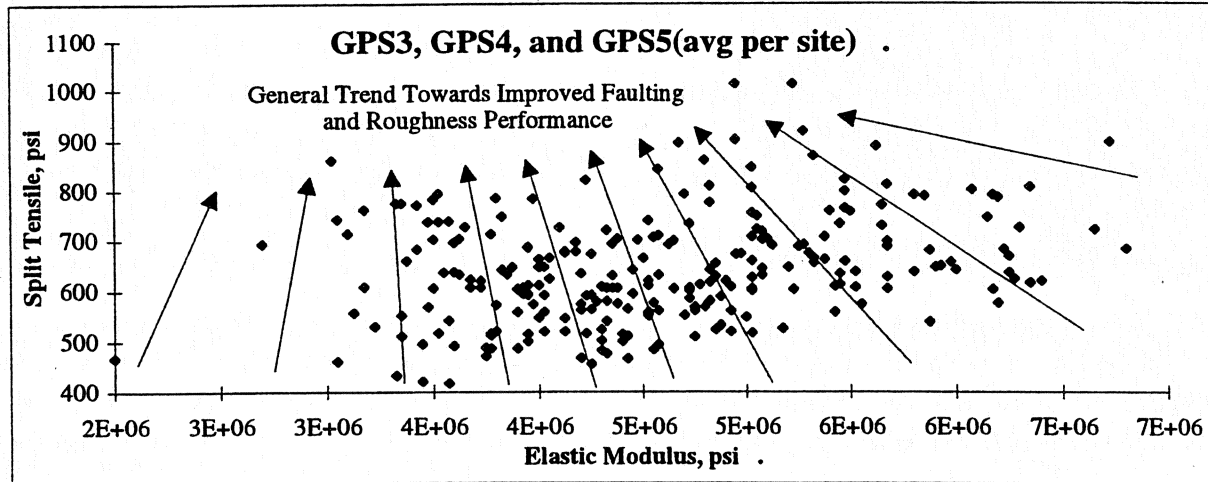


Figure 3. Relation between site average core elastic moduli and split tensile strengths. Arrows show a general trend towards improved performance.

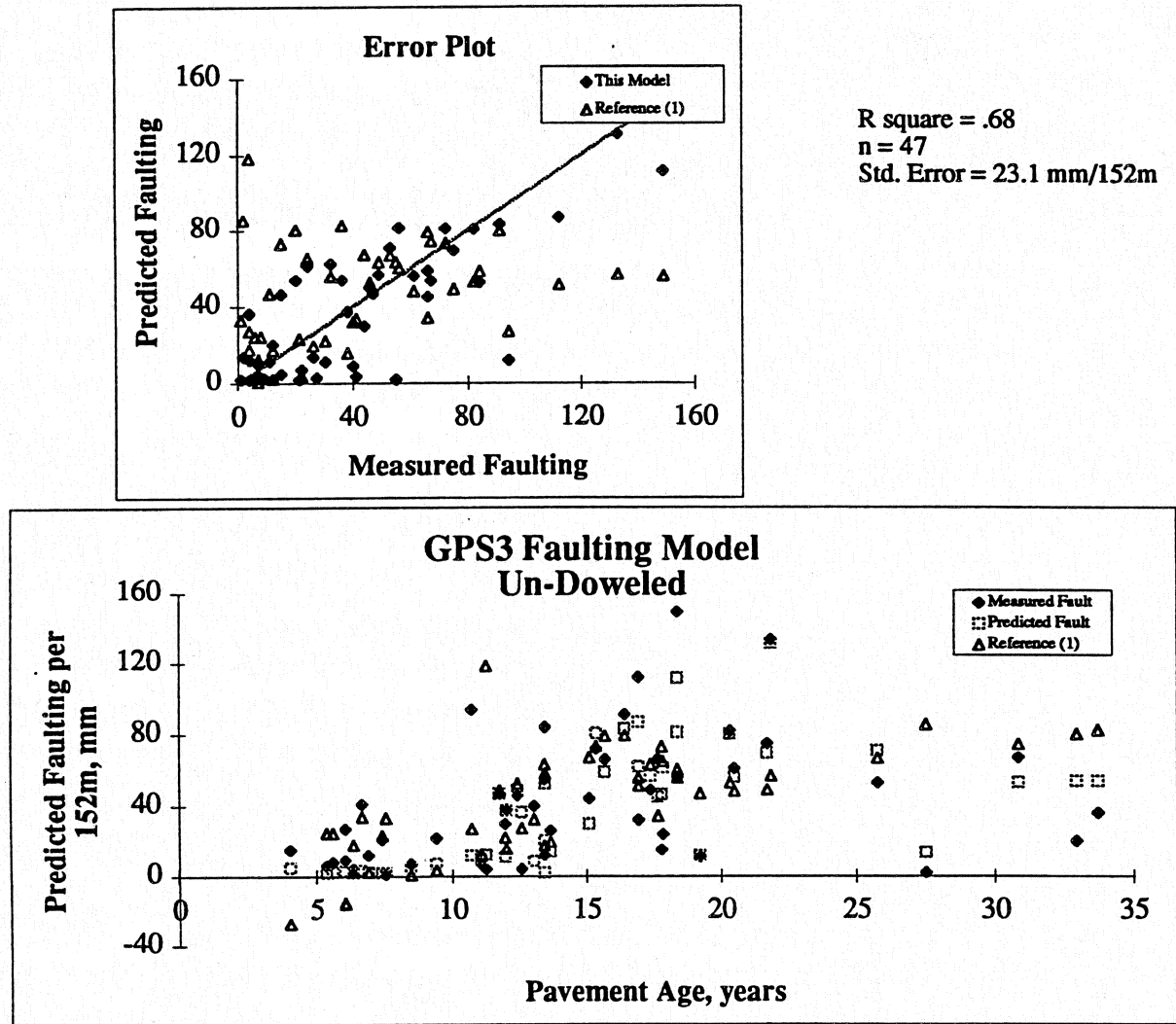


Figure 4. Plots showing the accuracy of prediction for the Faulting model and a comparison to a previous LTPP based model .

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5
PCC Thickness, in	9	9	9	9	9
Compressive Strength, psi	4000	6000	8000	10000	12000
Split Tensile, psi	468	573	662	740	811
E _{mod}	3604997	4415201	5098235	5700000	6244037
Overburden on Subgrade, psf	150	150	150	150	150
Subgrade P200	85	85	85	85	85
Subgrade w%	15	15	15	15	15
Days wet/year	120	120	120	120	120
Kesal rate	850	850	850	850	850
Slab Length, ft.	15	15	15	15	15
avgF _{lt} @25yr	4.7	6.4	7.1	6.3	1.7
Delay, years=	1.9	4.5	8.2	13.1	19.4
Max Fault, mm/152m =	280	280	280	280	280
Growth Rate constant=	0.2231	0.2977	0.3925	0.5060	0.6371

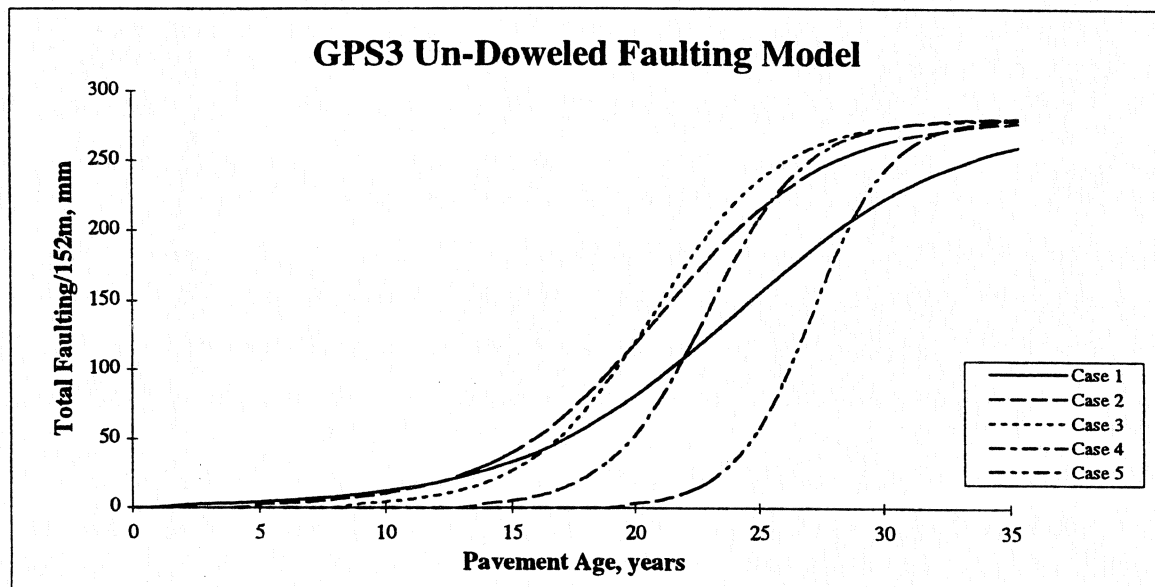


Figure 5. Sensitivity of the GPS3 (Un Doweled) Faulting model to changes in PCC strength.

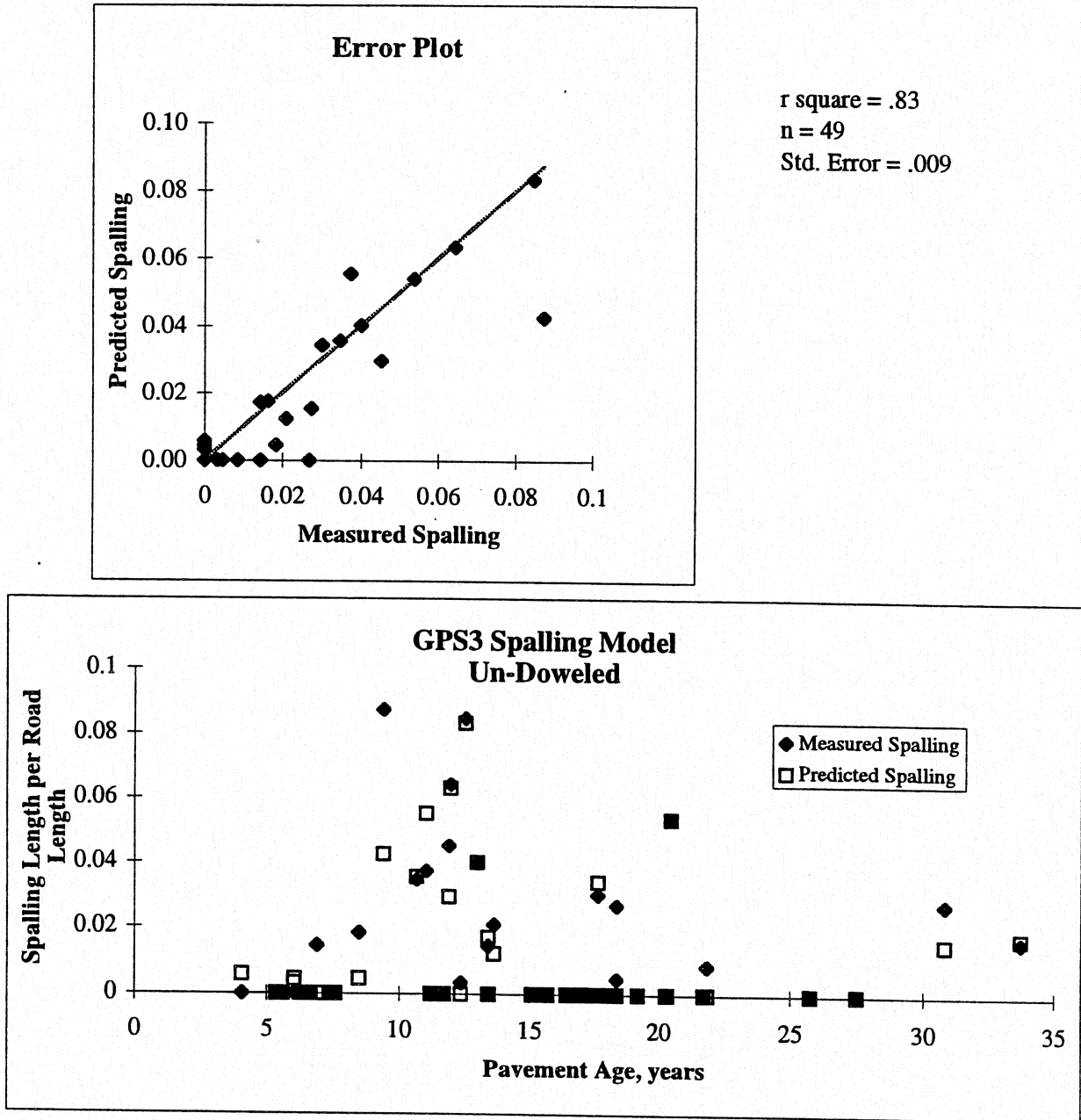


Figure 6. Prediction accuracy of the spalling model.

Parameter(Data Range)	Case 1	Case 2	Case 3	Case 4	Case 5
PCC Thickness, in(8 to 12)	10	10	10	10	10
Compressive Strength, psi(4730 to 10270)	7000	7000	7000	7000	7000
(1)Split Tensile, psi(416 to 1014)	617	617	617	617	617
(2)Elastic Modulus, psi(2.0e+6 to 6.7e+6)	4768962	4768962	4768962	4768962	4768962
Poissons Ratio(.11 to .26)	0.15	0.15	0.15	0.15	0.15
Subgrade P200(2 to 88)	36	36	36	36	36
Days 90+ degF per year(1 to 106)	35	35	35	35	35
Days wet/year(33 to 181)	65	65	65	65	65
Freeze Thaw Cycles/Yr(1 to 165)	75	75	75	75	75
Kesal rate(36 to 1616)	200	500	800	1100	1500
Slab Length, ft.(11.4 to 20)	15	15	15	15	15
avgSpall(ft)/joint@25yr	0.266	0.660	1.526	3.462	10.516
Growth Rate constant=	0.0217	0.0383	0.0579	0.0793	0.1102

(1). $7.4 \cdot \text{SQRT}(f'_c)$
(2). $57000 \cdot \text{SQRT}(f'_c)$

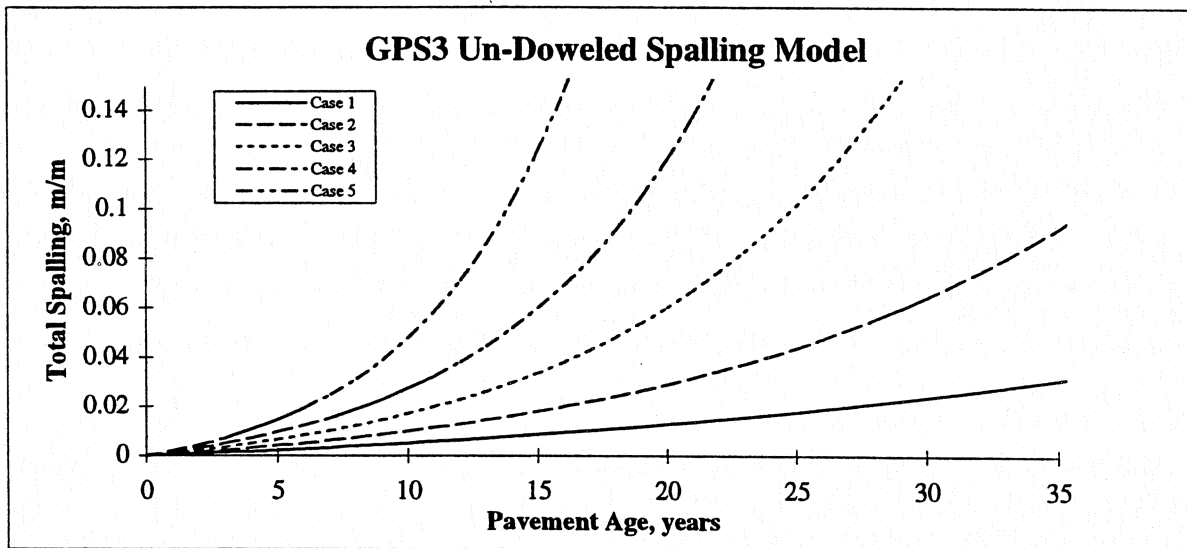


Figure 7. Sensitivity of the spalling model to changes in traffic volume.

Parameter(Data Range)	Case 1	Case 2	Case 3	Case 4	Case 5
PCC Thickness, in(8 to 12)	10	10	10	10	10
Compressive Strength, psi(4730 to 10270)	7000	7000	7000	7000	7000
(1)Split Tensile, psi(416 to 1014)	617	617	617	617	617
(2)Elastic Modulus, psi(2.0e+6 to 6.7e+6)	4768962	4768962	4768962	4768962	4768962
Poissons Ratio(.11 to .26)	0.15	0.15	0.15	0.15	0.15
Subgrade P200(2 to 88)	36	36	36	36	36
Days 90+ degF per year(1 to 106)	35	35	35	35	35
Days wet/year(33 to 181)	65	65	65	65	65
Freeze Thaw Cycles/Yr(1 to 165)	70	90	110	130	150
Kesal rate(36 to 1616)	350	350	350	350	350
Slab Length, ft.(11.4 to 20)	15	15	15	15	15
avgSpall(ft)/joint@25yr	0.397	0.567	1.048	2.681	10.636
Growth Rate constant=	0.0283	0.0352	0.0487	0.0725	0.1106

(1). $7.4 \cdot \text{SQRT}(f'c)$
(2). $57000 \cdot \text{SQRT}(f'c)$

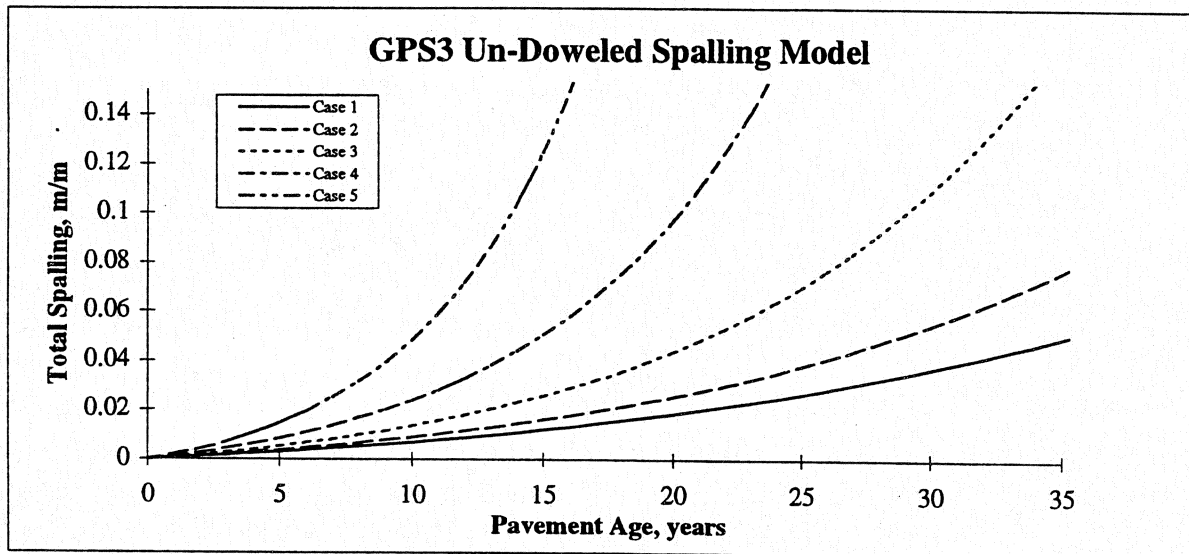


Figure 8. Sensitivity of the spalling model to changes from dry no freeze to dry freeze climate.

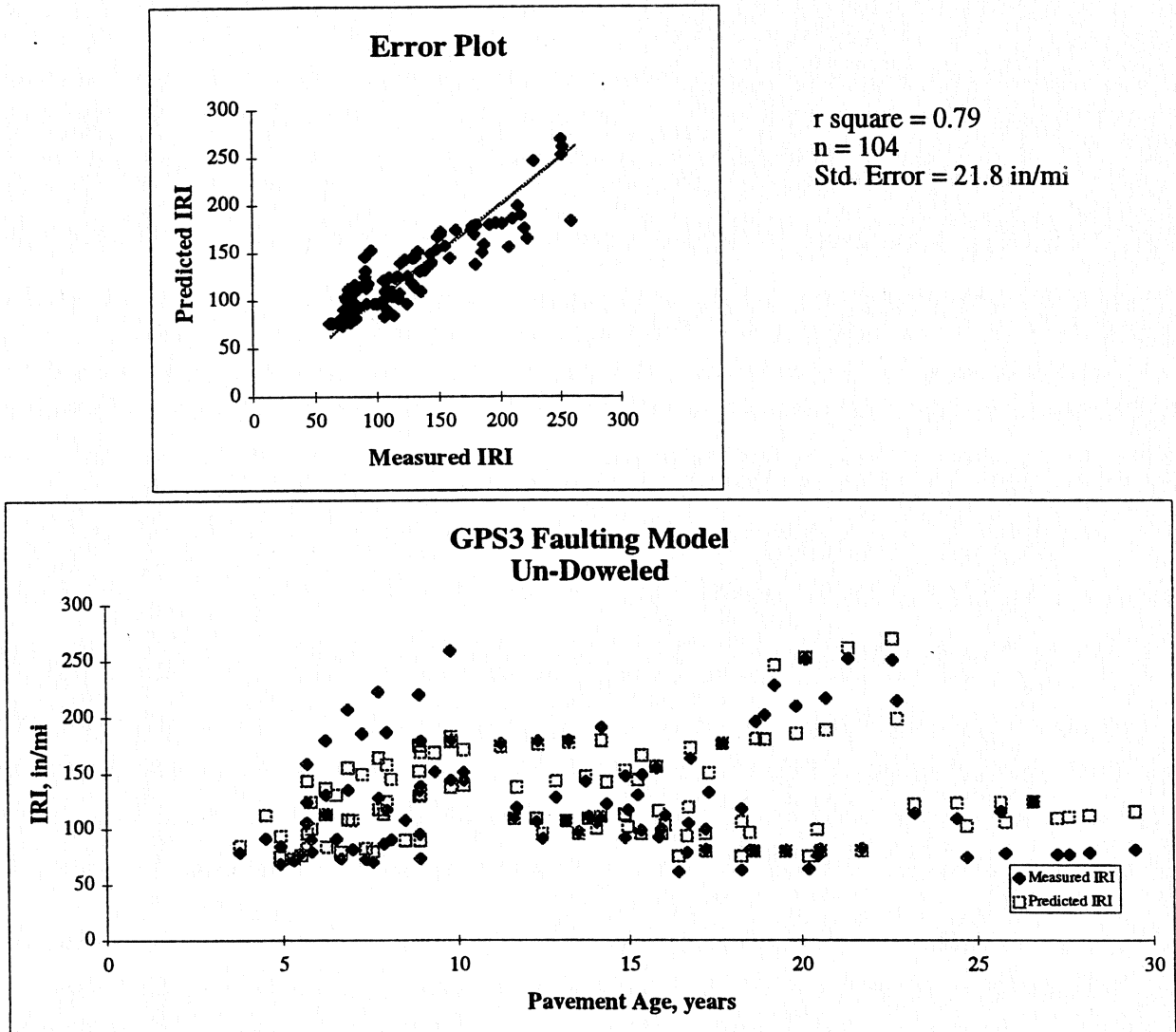


Figure 9. Plots showing the accuracy of prediction for the IRI model.

Parameter(Data Range)	Case 1	Case 2	Case 3	Case 4	Case 5
PCC Thickness, in(8 to 14)	9	9	9	9	9
Compressive Strength, psi	4000	6000	8000	10000	12000
(1)Split Tensile, psi(416 to 1014)	467	572	660	738	808
(2)Emod(2000000 to 6650000)	3604997	4415201	5098235	5700000	6244037
Conc w/c(0.27 to 0.57)	0.55	0.51	0.46	0.43	0.39
Overburden on Subgrade, psf(120 to 680)	150	150	150	150	150
Subgrade P200(3 to 88)	85	85	85	85	85
Subgrade w%(3 to 23)	15	15	15	15	15
Days wet/year(75 to 180)	120	120	120	120	120
FZI(1 to 1500)	550	550	550	550	550
Days 32-(8 to 160)	100	100	100	100	100
Kesal rate(30 to 1400)	850	850	850	850	850
Slab Length, ft.(11 to 20)	15	15	15	15	15
IRI@25yr	151	182	205	221	231
IRI(o), in/mile	64	69	75	79	83
Growth Rate constant=	0.0507	0.0648	0.0780	0.0906	0.1027
IRI(max)	317	302	287	280	271

(1). $7.4 \cdot \text{SQRT}(f'_c)$
(2). $57000 \cdot \text{SQRT}(f'_c)$

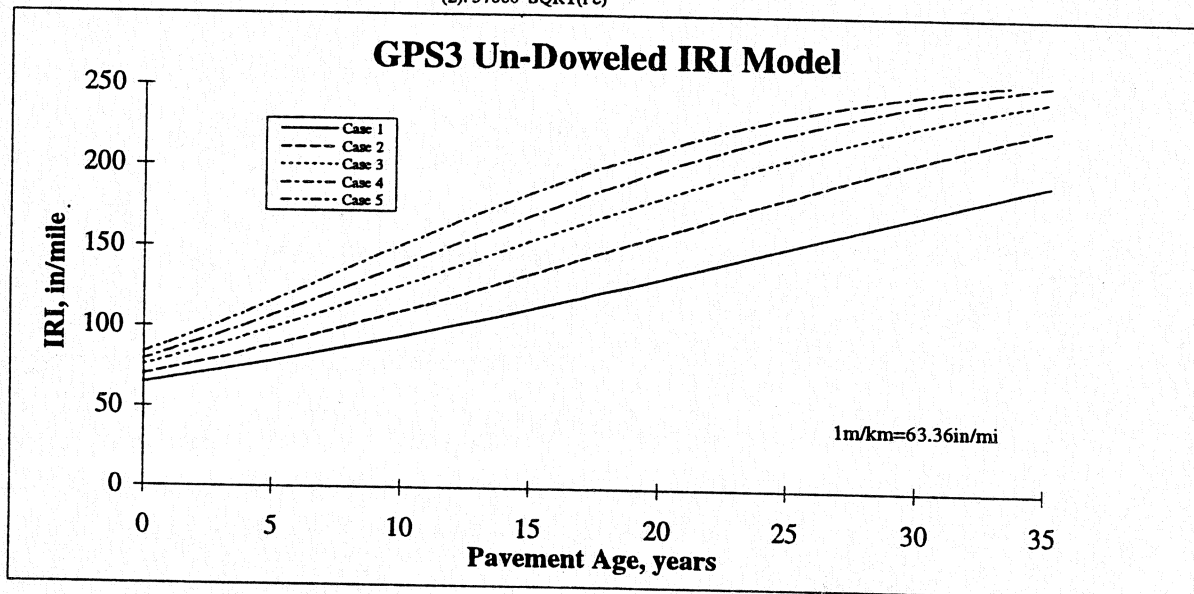


Figure 10. Sensitivity of the GPS3 (Un Doweled) IRI model to changes in PCC strength.

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