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FINAL REPORT

EVALUATION OF CONSOLIDATION PROBLEMS IN THICKER PORTLAND CEMENT CONCRETE PAVEMENTS

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Abstract

The purpose of this study is to investigate methods of reducing the size and total volume of the entrapped air voids in concrete slabs that are over nine inches thick. Laboratory and field tests were designed to investigate the effect of variations in vibration frequency and aggregate gradation on entrapped air content, strength and performance factors such as smoothness, faulting, adhesion failures, and spalling.

In 1993, a test section was constructed to compare the effects of increasing the proportion of coarse aggregate to fine aggregate and increasing vibration frequency. Annual surveys of joint sealant failures, spalling and joint faulting were performed from 1994 to 2001 on this test section. Samples from this project were cut, polished and analyzed to determine entrained and entrapped air content. In 1994, another test section was constructed to assess the effect of controlling the total gradation of concrete aggregate and increasing vibration frequency. A profilograph test was performed in 1996 to measure pavement smoothness on this project. Core samples were taken from both the wheel path and the wheel gap and nuclear density meters were used on both projects to measure the in-situ density of the pavements.

The following conclusions are supported by this investigation:

1. Increasing the proportion of coarse aggregate in the mix consistently reduced the amount of entrapped air in these pavements without significantly affecting other performance parameters.
2. Increasing the vibration frequency increased adhesion failures, spalling, faulting and entrapped air content of the standard 35% coarse-aggregate mix. Although increasing vibration frequency did improve the initial smoothness of the uniform-gradation mix, the markedly detrimental effects on the standard mix and the lack of significant performance improvements on the other mixes argues against further use of this technique on thicker portland cement concrete pavements without further study.
3. Relative density is not an accurate measure of percentage of entrapped air.
4. Using a more-uniformly-graded aggregate and a larger-sized coarse aggregate should result in better consolidation of thicker Portland Cement Concrete (PCC) pavements.

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EVALUATION OF CONSOLIDATION PROBLEMS IN THICKER PORTLAND CEMENT CONCRETE PAVEMENTS

Final Report

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DISCLAIMER

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ABSTRACT

The purpose of this study is to investigate methods of reducing the size and total volume of the entrapped air voids in concrete slabs that are over nine inches thick. Laboratory and field tests were designed to investigate the effect of variations in vibration frequency and aggregate gradation on entrapped air content, strength and performance factors such as smoothness, faulting, adhesion failures, and spalling.

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3. Relative density is not an accurate measure of percentage of entrapped air.
4. Using a more-uniformly-graded aggregate and a larger-sized coarse aggregate should result in better consolidation of thicker portland-cement concrete pavements.

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Introduction

The purpose of this study is to investigate methods of reducing the size and total volume of the entrapped air voids in concrete slabs that are over nine inches thick. Thickness cores taken from portland cement concrete pavement slabs have shown many entrapped air voids in the top few inches on some paving projects. The concrete meets density specifications but the large voids are likely to affect the long-term performance by making the concrete weaker and more permeable. Variations in vibration and aggregate gradation were investigated through laboratory and field tests. Their effect on void content, strength, and performance factors such as smoothness, faulting, adhesion failures, and spalling was investigated.

Background

Minimizing the amount of entrapped air in concrete is necessary to produce quality concrete with a longer pavement performance life, lower maintenance costs and fewer delays to the roadway users. Good quality concrete with low entrapped air content will have a higher strength and lower permeability than concrete with a considerable amount of entrapped air voids.

Consolidation can be defined as a purposeful action taken to reduce a freshly placed hydraulic cement concrete mixture to a smaller volume through the elimination of entrapped air voids, which are defined as voids over 1 mm in diameter. Consolidation improves all of the important properties of concrete. Permeability is reduced, strength is increased and resistance to abrasion, freezing and thawing, and to attack by aggressive fluids are also increased. Within reinforced concrete, bond to reinforcement is improved and penetration of deicing chemicals is retarded. Improper consolidation results in lower strength and durability, and leaves large, uncontrolled voids that can adversely affect performance and appearance.

On the other hand, entrained air voids less than one millimeter in diameter are intentionally introduced into concrete to enhance frost resistance. The voids relieve the hydraulic pressure developing in the channels of the paste during the freezing of the free water by providing compressible space for the increase in volume of the ice.

The total volume of all voids present, including entrapped air, entrained air, capillary pores, and gel pores, affects concrete strength. Concrete produced from a given mix decreases in strength as density decreases, and voids caused by entrained air will affect the strength in the same manner as voids of any other origin. Figure 1 shows that adding either entrained air or entrapped air to a mix without changing the proportions of other ingredients decreases the strength of the concrete proportionally.

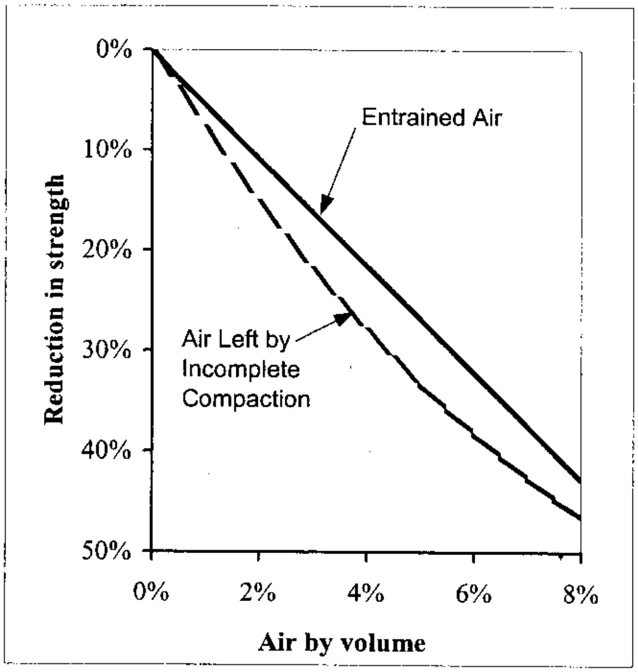

Figure 1. Effect of air content on strength of portland cement concrete. After Neville, 1981.

Consolidation is vital to the production of strong and durable concrete from an adequately designed mixture. Despite the importance of consolidation to concrete performance, a surprising number of specifications state merely that the concrete should be "adequately" consolidated, and some specifications include admonitions against heavy vibration. Although many of the factors influencing proper consolidation have been identified, the consolidation process remains qualitative and requires experience and judgment of the properties of the concrete mixture being compacted, the characteristics of the equipment, and their method of operation.

Vibration, either internal or external, is the most widely used method for consolidating concrete. When concrete is vibrated, the internal friction between the aggregate particles is temporarily eliminated and the concrete behaves like a liquid, settling in the forms under the action of gravity and allowing the large entrapped air voids to rise more easily to the surface. Internal friction is reestablished as soon as vibration stops. Vibrating the concrete eliminates little of the entrained air. Entrapped air accounts for essentially all of the air expelled in the vibration process (Whiting and Nagi, 1998).

Vibrators, both internal and external, are usually characterized by their frequency of vibration, expressed as vibrations per minute (vpm), and by amplitude of vibration, expressed as the deviation in inches from the point of rest. Failure to achieve at least 98% of the concrete's rodded unit weight during placement has been shown to result in extremely poor resistance to deicer penetration (Clear and Hay, 1973). Effective consolidation can therefore reduce reinforcement corrosion in a bridge deck or pavement. Kansas Department of Transportation standard specifications began requiring consolidation of concrete to 98% of the rodded unit weight in 1980. The finding of large and excessive voids throughout pavement cores prompted this change in the specifications.

Excessive vibration can lead to removal of intentionally entrained air in concrete, segregation of mixtures, and creation of excess bleed channels in relatively wet and high-slump concrete mixtures. Few studies have found negative effects from heavy vibration in low-slump mixtures commonly used with concrete slip-form pavers. More commonly, improvements occur in concrete quality such as increased bond strength and reduced permeability with no apparent reduction in freeze-thaw durability when heavy vibration is applied to stiff concrete pavement mixtures.

Project History

In 1990, research began on reduction of the size and volume of entrapped air voids in portland cement concrete pavement (PCCP) slabs greater than 230 mm (9 in) thick. A literature search was done to investigate good consolidation practices and problem areas. Many sources mentioned the vibrator frequency, spacing, amplitude, and speed of the paving machine, as possible sources of variation.

Earlier studies (Legge, 1982) had shown that increasing the frequency of vibration had the largest effect on the relative density of core samples. Changing the aggregate gradation from 70% sand-30% rock to 50% sand-50% rock also increased the relative density of cores appreciably, but the effect of increasing the frequency of vibration on the 50-50 mix was not investigated.

Although the ACI Manual of Concrete Practice mentioned controlling the vibrator angle, discussions with the ACI standards committee members and a local American Concrete Pavement Association (ACPA) official produced neither research nor contractor support for this practice. Cores taken from slabs constructed with a higher percentage of coarse aggregate and with coarse aggregates considerably larger than the KDOT maximum 19-mm (0.75 in) size were said to have no particular problems with excessive voids in the hardened concrete.

The literature search indicated that increasing the maximum aggregate size should improve strength and consolidation. However, because KDOT specifications limit the maximum aggregate size to control D-cracking, the durability of larger aggregate sizes had to be determined. The investigation began with freeze-thaw testing of beams made with seven different limestone aggregates in 1991 and 1992. This work has resulted in approval of some larger limestone aggregates (up to 25 mm) as class 2 aggregate. See Appendix A for a description of this testing and its results.

A field trial was initiated to use a mix with a higher proportion of coarse aggregate to fine aggregate on an active paving project. In 1993, a test section was constructed in the eastbound lanes of I-70 in Shawnee County, Kansas, to compare the effects of mix gradations and vibration frequency on core density. Four 152-m (500-ft) test sections of 266.7 mm (10.5 in) thick concrete were constructed. The coarse aggregate was increased from 35% to 50% of the aggregate weight for two sections. This mix design is referred to as "50-50 mix", and is an improved gradation according to the seeMIX analysis. Two more sections were constructed using a standard job mix concrete with 65% sand, 35% coarse aggregate (referred to as "standard mix"). The concrete mix information is listed in Table 1. The standard vibrator frequency of approximately 7400 vpm was used for one section of each mix, and the vibration frequency was increased about 8% on the other.

	50-50 Concrete Mix Design		"Standard" 65-35 Mix Design	
	kg/m^3 (lb/yd^3)	yield, m^3 (ft^3)	kg/m^3 (lb/yd^3)	yield, m^3 (ft^3)
Cement	281 (620)	0.089 (3.15)	281 (620)	0.089 (3.15)
Fine Aggregate	657 (1448)	0.25 (8.86)	854 (1883)	0.35 (12.40)
Coarse Aggregate	657 (1448)	0.25 (8.99)	460 (1014)	0.15 (5.40)
Water	126 (279)	0.13 (4.47)	126 (279)	0.13 (4.47)
Total Air, %	6.0 +/- 2.0	0.046 (1.62)	6.0 +/- 2.0	0.046 (1.62)
	Total	0.77 (27.10)	Total	0.77 (27.05)
W/C Ratio	0.45		0.45	
Slump mm (in)	25.4 (1.0)		25.4 (1.0)	
Unit Weight kg/m3 (pcf)	2242.6 (140.0)		2247.4 (140.3)	

Table 1. Typical concrete mix designs for 2.8 kg/mm^2 (4000psi) concrete at a constant water-cement ratio. All weights are saturated, surface dry.

In 1994, another test section in the southbound lanes of US 75 north of Topeka was added to assess the effect of controlling the total gradation of concrete aggregate and increasing vibration frequency. Recommendations from the seeMIX program, designed by the Shilstone Software Company, Inc., were used to design the mix used on this project. See Appendix B for more information on the design and capabilities of this program. Three aggregates, including an intermediate size of limestone chips chosen to fill the space usually occupied by entrapped air or mortar, were used. Although the same mix design was used throughout this project, the vibrator frequency was varied from 6000 vpm to 8000 vpm for four 305-m (1000-ft) long test sections.

Surveys of joint sealant failures, spalling and joint faulting were performed annually from 1994 to 2001 on the test section constructed on I-70 in 1992. A profilograph test was performed in 1996 to measure pavement smoothness on the US 75 project. Core samples were taken from both the wheel path and the wheel gap and nuclear density meters were used on both projects to measure the in-situ density of the pavements. In 2000, core samples from the I-70 project were polished and analyzed using image analysis to determine entrained and entrapped air content.

Results

Relative Density Measurements of I-70 Test Sections

Density was measured in the lab from core samples taken from the vibrator paths and the gap between the vibrator paths. Density was also measured in the field with a nuclear density meter placed on the fresh concrete behind the slip-form paver. These densities were compared to the rodded bucket density to obtain a relative density. The project specifications required at least 98% relative density. The densities obtained in the nuclear density tests easily met or surpassed this requirement with at least 99.4% relative density. However, the nuclear density meter readings are an average density of the entire slab, which may not reflect the density of the top portion of the slab. The densities measured from the core samples were lower than the nuclear density meter readings, but all sections met the minimum required 98% of rodded bucket density specification. The standard concrete cores averaged a 98.4% density; the 50-50-mix concrete averaged a 99.4% density. The path densities were only slightly higher than those of the gap. Although the core densities did not surpass the requirements with the same high margins as the nuclear-meter densities, the relative performance of the sections remained constant. In both tests the High Vibration/50-50 Mix section was the densest, and the Standard Vibration/50-50 Mix section least dense (see figure 2).

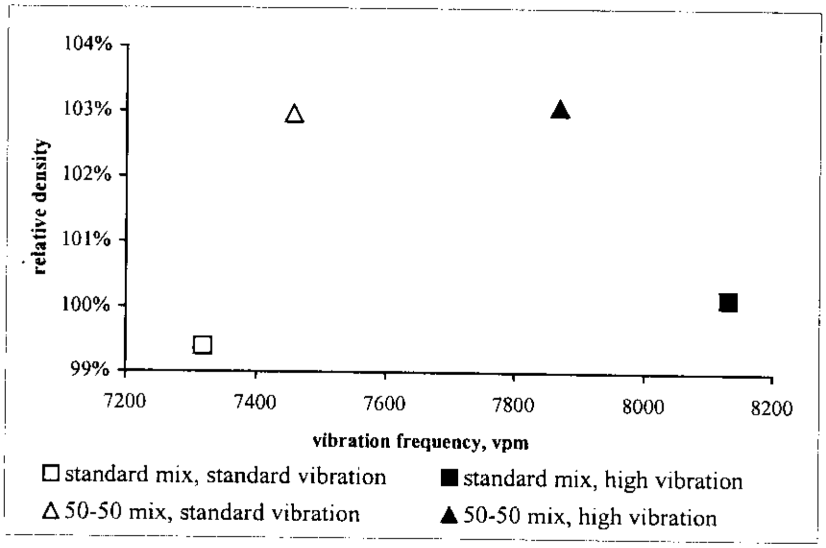

Figure 2. Relative densities of portland cement concrete versus vibration frequency and mix design as measured with in-situ moisture-density meter on I-70 test section, Shawnee County, Kansas.

The average unit weights of the core samples were quite uniform, varying less than 4 percent, from 2234.9 kg/cu m to 2309.8 kg/cu m (139.5 pcf - 144.2 pcf). Almost all of the variability in the unit weights was within one standard deviation of the average unit weight of all the samples and is considered negligible. Figure 3 shows the average unit weights of the core samples.

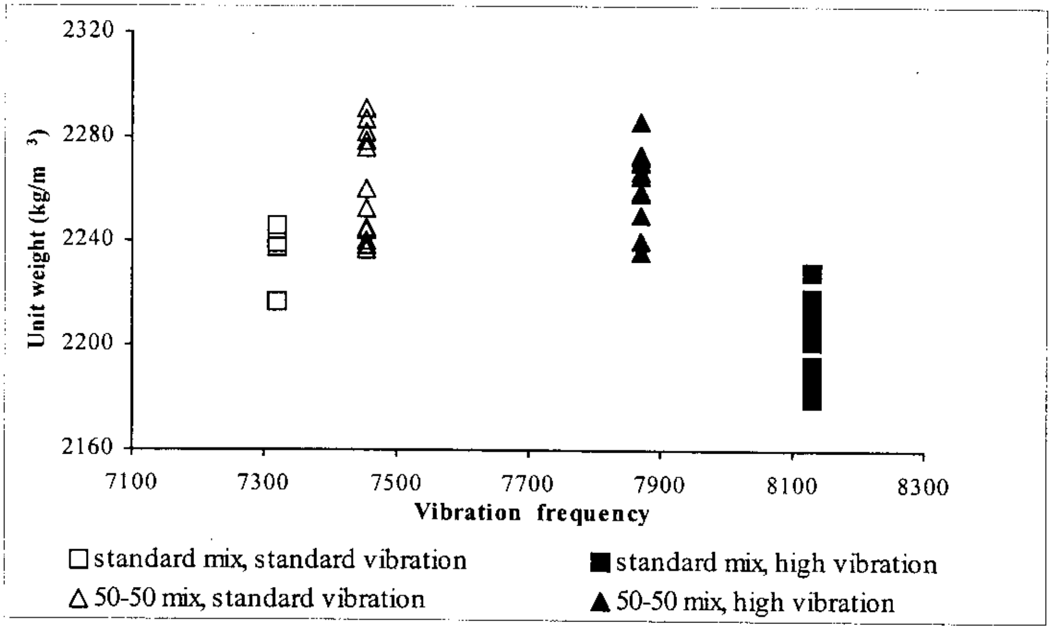

Figure 3. Unit weight of portland-cement concrete pavement core samples with respect to mix and vibration parameters, I-70, Shawnee County, Kansas.

Performance Survey of I-70 Test Sections

A survey of adhesion failure, spalling and faulting on the test sections collected data annually from 1994 to 2001, two to nine years after construction. The test sections were reground and resealed before the 1996 and the 2001 surveys. This operation eliminated pre-existing failures. Although the standard concrete-standard vibration section was the first and only section to develop adhesion failures in the initial surveys after resealing, overall it had the best adhesion performance of any section. Increasing the vibration frequency on the standard mix increased adhesion failures by nearly 300% on average over the life of the test. Increasing vibration frequency on the 50-50 mix did improve the adhesion performance.

The 50-50 mix sections performed better than the high vibration-standard mix section but not as well as the standard vibration-standard mix section. Increasing the vibration on the 50-50 mix did reduce the average annual adhesion failures by 62% (see table 2 and figure 4).

Sections with higher vibration frequency showed markedly different effects on the spalling performance of the two mixes, reducing spalling in the 50-50 mix section by 57% but increasing spalling in the standard-mix section by 64%. The high vibration-standard mix section had the worst overall performance and the high vibration-50-50 mix section had the best overall performance. The normally vibrated sections of the mixes had nearly identical spalling performance (see table 3 and figure 5).

Faulting was minimal and nearly equal on all sections at less than one millimeter per joint (see table 4 and figure 6).

	Average Adhesion Failures per Joint, mm			
	Standard Concrete Standard Vibration	Standard Concrete High Vibration	50-50 Concrete Standard Vibration	50-50 Concrete High Vibration
1994	94	210.8	96.5	78.7
1995	168.9	297.2	177.8	268
1996	1.3	0	0	0
1997	3.8	0	0.8	6.2
1998	9.7	47.4	11.4	27.7
1999	278.1	0.7	244.3	276.3
2000	609.6	2692	1219.2	665.8
2001	14	0	0	0

Table 2. Average length of adhesion failures per joint from portland cement concrete pavement test section constructed in 1992 on I-70 in Shawnee County, Kansas. Pavement was resealed just prior to the 1996 and 2001 surveys.

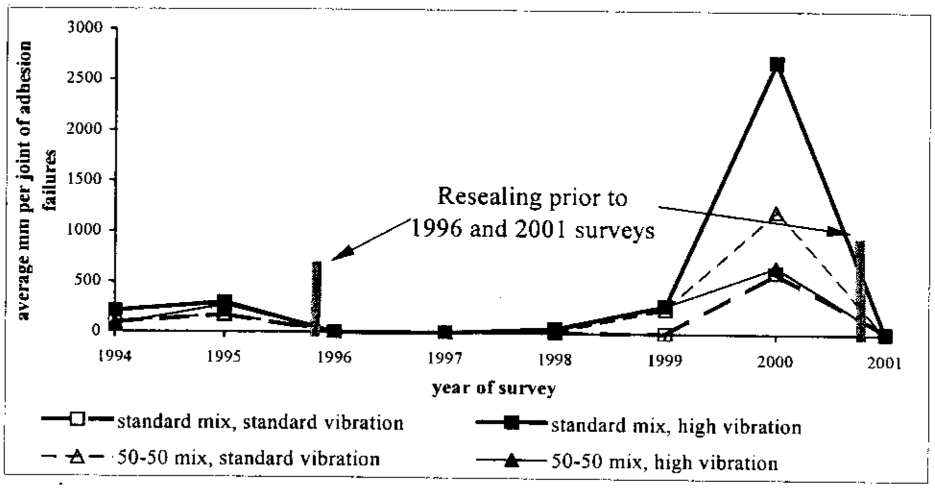

Figure 4. Effect of increasing vibration frequency and coarse-aggregate proportion on adhesion failures in portland-cement concrete pavement test section constructed in 1992 on I-70 in Shawnee County, Kansas. Pavement was resealed just prior to the 1996 and 2001 surveys

	Average Spalling per Joint, mm			
	Standard Concrete Standard Vibration	Standard Concrete High Vibration	50-50 Concrete Standard Vibration	50-50 Concrete High Vibration
1994	30.5	101.6	33	33
1995	68.6	88.1	74.4	50.8
1996	0	1.7	0	2.3
1997	6.4	0	6.7	0
1998	13.4	7.62	5.1	3.9
1999	29.2	19.5	36.6	9.2
2000	30.5	41.5	35.9	14.6
2001	1.3	9.3	13.4	6.9

Table 3. Average length of spalling per joint in mm from portland cement concrete pavement test section constructed in 1992 on I-70 in Shawnee County, Kansas. Pavement was resealed just prior to the 1996 and 2001 surveys.

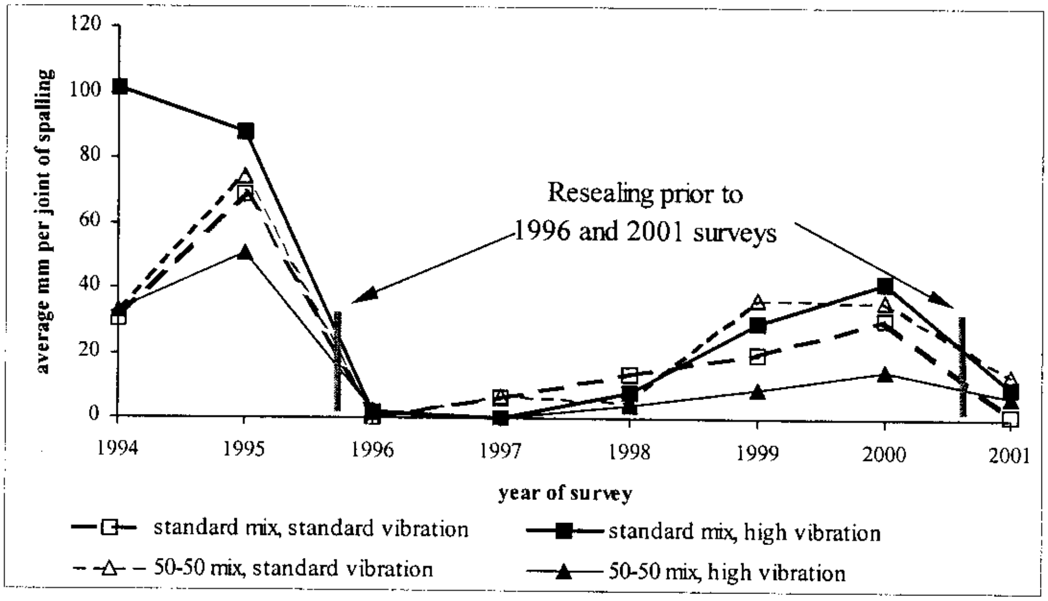

Figure 5. Effect of increasing vibration frequency and coarse-aggregate proportion on spalling of portland-cement concrete pavement test section constructed in 1992 on I-70 in Shawnee County, Kansas. Pavement was resealed just prior to the 1996 and 2001 surveys

Average Faulting per Joint, mm				
	Standard Concrete Standard Vibration	Standard Concrete High Vibration	50-50 Concrete Standard Vibration	50-50 Concrete High Vibration
1994	0.15	0.57	0.41	0.54
1995	0.35	0.73	0.38	0.7
1996	0.3	0.7	0.59	0.36
1997	0.5	0.8	0.32	0.55
1998	0.5	0.9	0.65	0.8
1999	0.95	0.22	0.8	0.9
2000	0.23	0.42	0.254	0.21
2001	0.35	0.44	0.22	0.33

Table 4. Average length of faulting per joint from portland cement concrete pavement test section constructed in 1992 on I-70 in Shawnee County, Kansas. Pavement was resealed just prior to the 1996 and 2001 surveys.

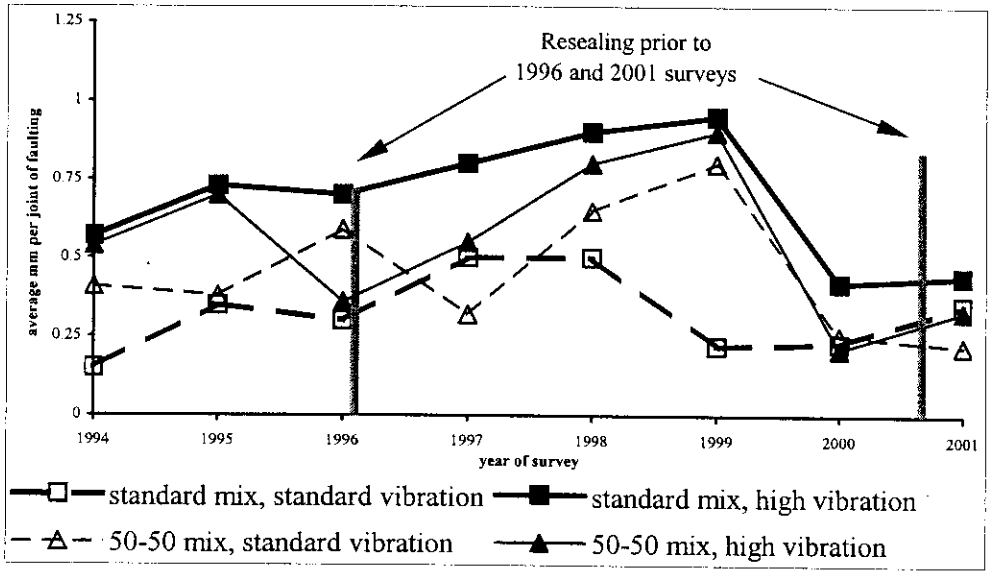

Figure 6. Effect of increasing vibration frequency and coarse-aggregate proportion on faulting of portland-cement concrete pavement test section constructed in 1992 on I-70 in Shawnee County, Kansas. Pavement was resealed just prior to the 1996 and 2001 surveys.

Air Void Analysis of I-70 Test Sections

Petrographic assessment of the air void system in the cores taken from the I-70 test sections revealed details of the air void system. Approximately two-thirds of the volume of air in the concrete was in large entrapped air voids for all cores.

The percentage of entrapped air had very little correlation with the relative density, either between mixes or between samples of the same mix (see figure 7). Although the percentage of entrapped air declined roughly as relative density increased, the correlation was weak. In the concrete made with the standard mix concrete, for example, the samples with the higher average relative density also had a higher average percentage of entrapped air.

Increasing the frequency of vibration from (approximately) 7400 to 8000 vpm did not reduce the entrapped air as much as increasing the proportion of coarse aggregate did. In fact, in the standard mix concrete, increasing the frequency of vibration actually increased the entrapped air by 13% (see figure 8). At standard vibration, changing from the standard mix to the 50-50 mix decreased the entrapped air by 21%. Increasing the vibration frequency on the 50-50 mix reduced the entrapped air by 15% (see figure 9).

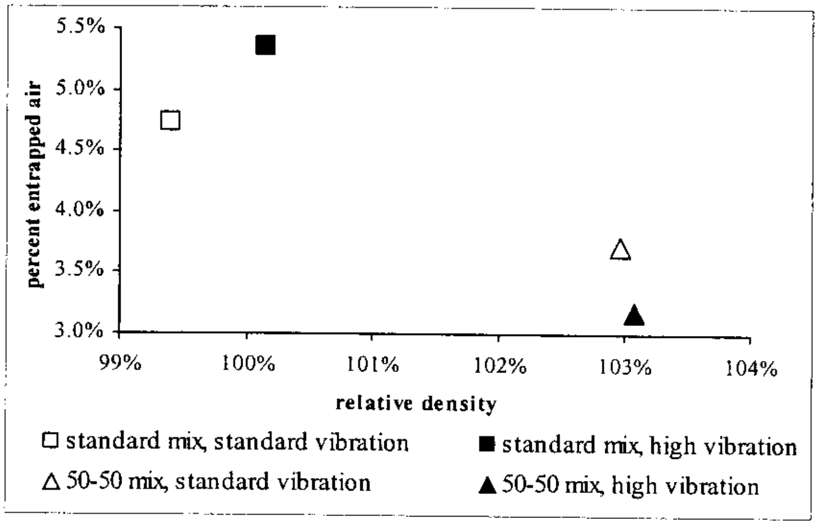

Figure 7. Percentage entrapped air versus percentage of rodded bucket density as measured with a nuclear moisture-density meter of portland cement concrete pavement in test sections on I-70, Shawnee County, Kansas.

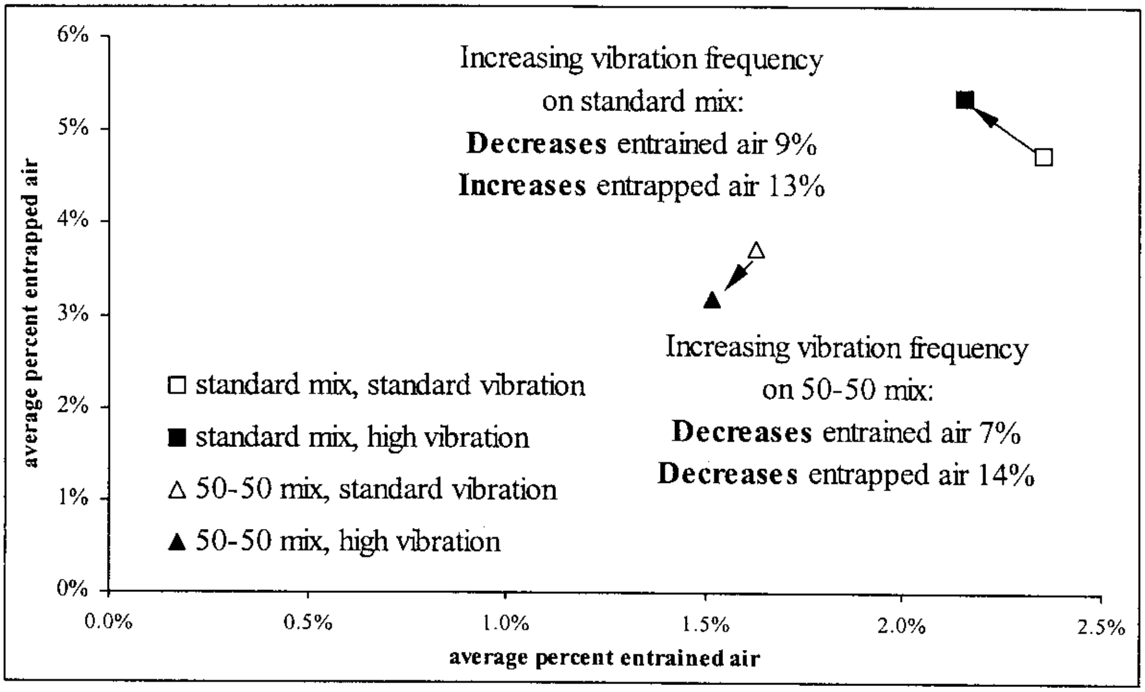

Figure 8. Effect of increasing vibration frequency on the air-void system of portland-cement concrete pavement made with varying coarse aggregate proportions. Test sections were constructed on I-70 in Shawnee County, Kansas.

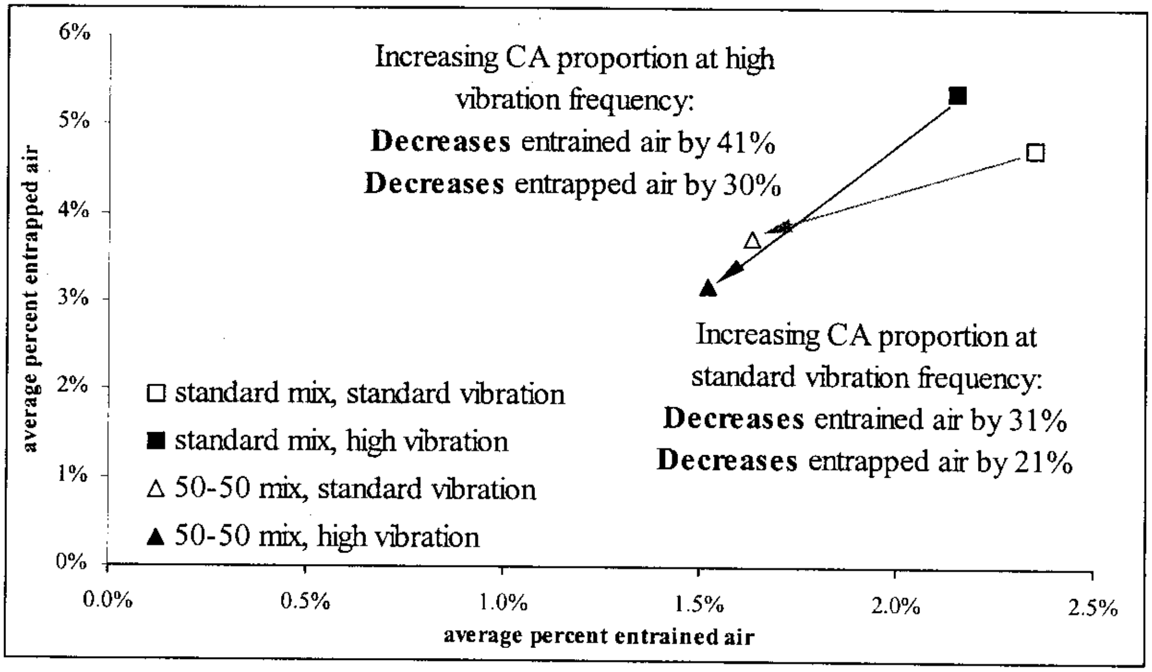

Figure 9. Effect of increasing coarse aggregate proportion on air void system of portland-cement concrete pavement vibrated at standard and high frequencies. Test sections were constructed on I-70 in Shawnee County, Kansas.

Relative Density Measurements of US-75 Test Sections

The US 75 project tested the effect of a range of vibrator frequencies on concrete made from a mix designed to have a more uniform aggregate gradation using recommendations from the seeMIX program. Test beams made in the lab from this mix had three-day strengths that exceeded the standard-mix average of 4.1 MPa (600 psi). Coarse aggregate distribution remained uniform at all vibrator frequencies.

Nuclear-density meter tests of the fresh concrete showed that all of the test sections passed the 98% of rodded bucket density requirement. Vibrator gap and vibrator path relative densities ranged from 100.3% to 101.9%, and the differences between the path and gap densities were negligible (see figure 10). The average unit weights of the cores on the US 75 project were also measured. The unit weights varied less than one percent, as expected for specimens of the same mix. The unit weights for this project are shown on figure 11.

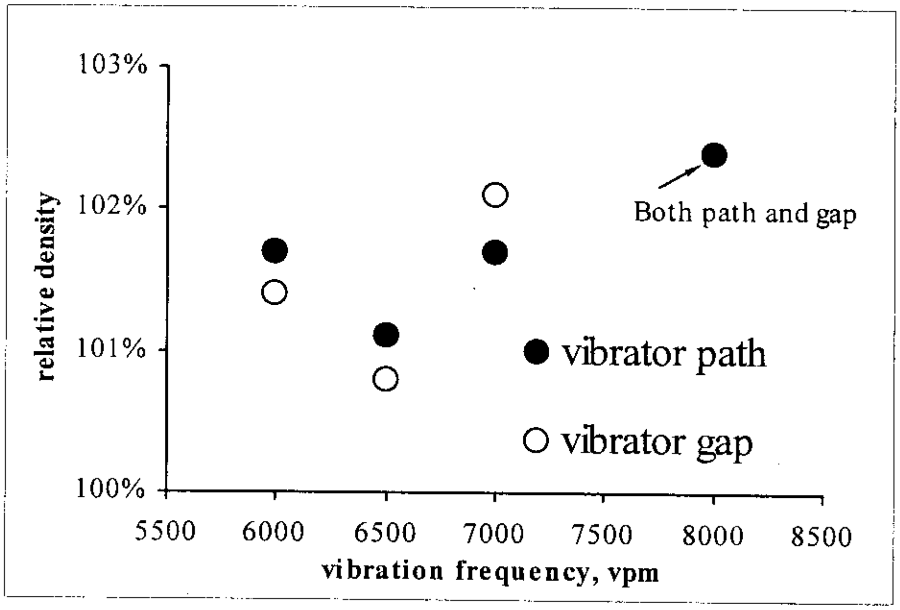

Figure 10. Effect of vibration path location on relative density of portland cement concrete pavements, from test section on US 75 in Shawnee County, Kansas

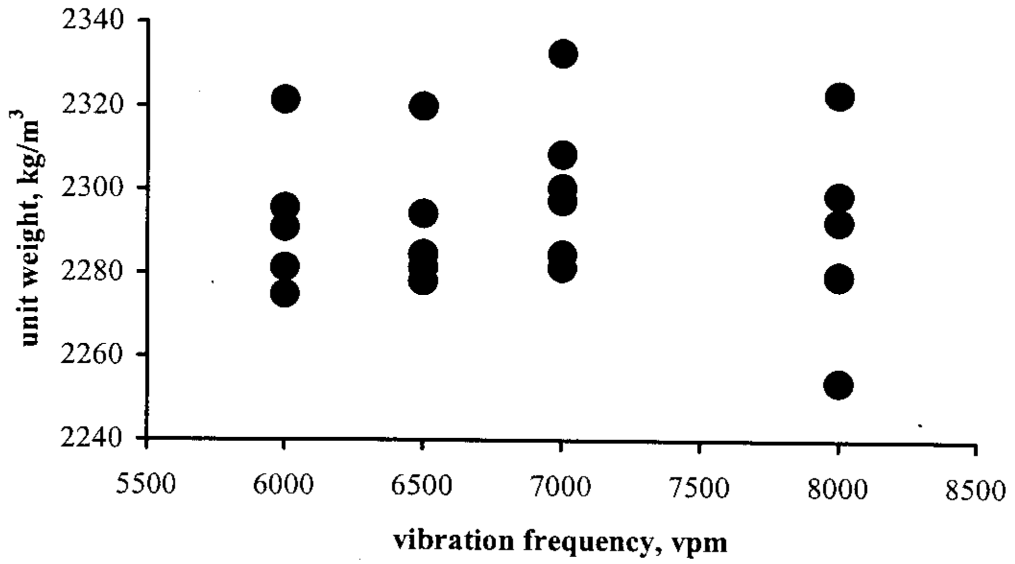

Figure 11. Effect of vibration frequency on unit weight of uniform-gradation mix portland cement concrete pavement. Test section on US-75, Shawnee County, Kansas.

Profilograph Smoothness of US-75 Test Sections

The profilograph measures the vertical variation in mm per km (in per mi). The greatest variation came from the lower vibration frequency sections. Variation decreased by approximately 20% as vibration frequency increased from 6000 to 8000 vpm, indicating that the higher the vibration, the smoother the pavement (see table 5 and figure 12).

Vibrator Frequency, vpm	Variation, mm/km	Variation, in/mi.
6000	383.5	24.3
6500	432.4	27.4
7000	336.2	21.3
8000	318.8	20.2

Table 5. Vertical variation per unit length as measured by profilograph on US-75 concrete pavement test section in Shawnee County, Kansas. All sections were constructed with the same uniform-gradation three-aggregate mix.

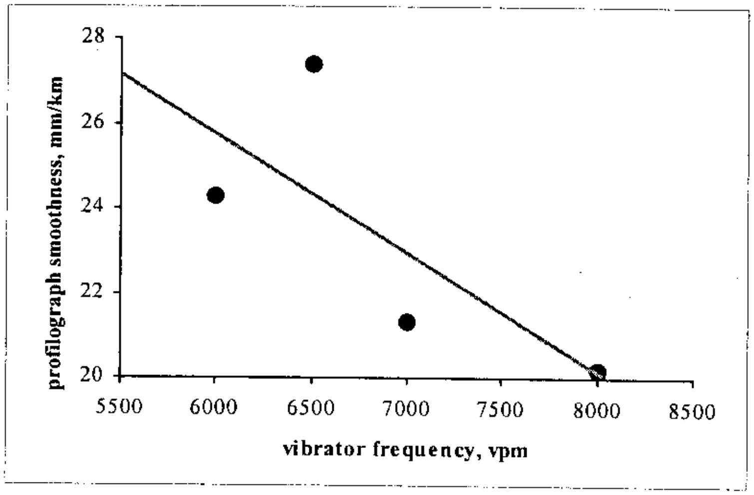

Figure 12. Profilograph smoothness, measured as vertical variation per unit length, with respect to vibration frequency on US-75 concrete pavement test section in Shawnee County, Kansas. All sections were constructed with the same uniform-gradation three-aggregate mix.

Discussion

Increasing the proportion of coarse aggregate in the concrete mixture used on the I-70 project reduced entrapped air and increased the average relative density at both standard and high frequency vibration. Increasing the coarse aggregate proportion increased adhesion failures, but by less than changing the vibration frequency. Increasing the coarse aggregate proportion improved spalling performance and had a negligible effect on faulting.

Although the US-75 study shows that increasing vibration frequency increases initial smoothness of portland-cement concrete pavements, the I-70 results suggest that this improvement may be short-lived. Pavements constructed with standard low-coarse aggregate mixes and high vibration frequencies had poorer performance as soon as two years after construction than those constructed from the same mix vibrated at the standard frequency. Most importantly, increasing vibration frequency on the standard mix actually increased the amount of entrapped air in the finished pavement. Increasing vibration frequency on the 50-50 mix decreased spalling, increased faulting and had a negligible effect on adhesion failures. Only the improvement in the spalling performance of the 50-50 mix under high vibration was as marked as the decline in performance in the standard mix under increased vibration frequency.

Increasing the proportion of coarse aggregate in the mix reduced the entrapped air and increased relative density in these pavements more, and more consistently, than did increasing vibration frequency (see figure 13). Thus, improving the total aggregate gradation in concrete mixes may reduce the entrapped air content even further.

These results are consistent with a previous analysis of concrete strength and mix design. Tests of cores taken from 16 projects constructed around Kansas in 1996 showed that concrete made from more uniformly-graded mixes had higher and less variable strengths those made from other types of mixes, as seen in Table 6.

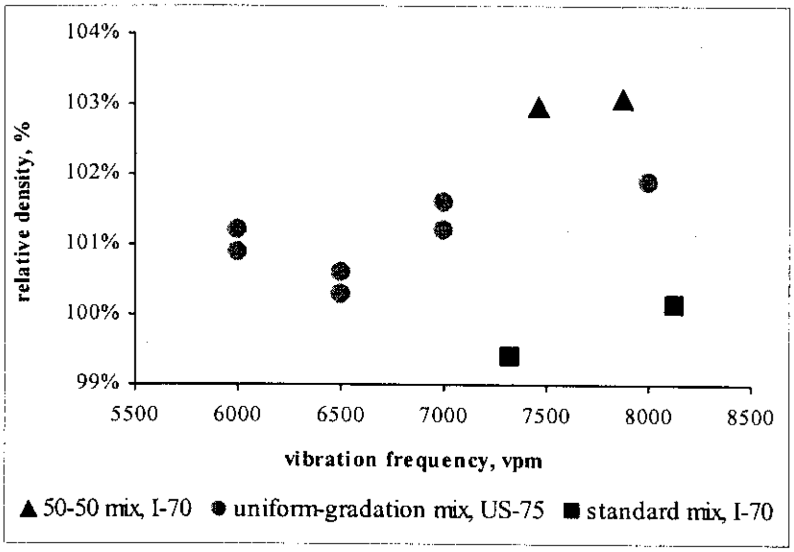

Figure 13. The effects of vibration frequency and mix design on relative densities of portland cement concrete pavements. Test sections are from US-75 and I-70 in Shawnee County, Kansas.

Mix type	Average core strength	Standard deviation	Number of Observations
Uniform-gradation mixes	5345 psi 36.85 MPa	302 psi 2.08 MPa	6
Standard mix, 50% FA-50% CA	4856 psi 33.48 MPa	742 psi 5.12 MPa	10
Standard mix, 65% FA-35% CA	4650 psi 32.06 MPa	629 psi 4.34 MPa	

Table 6. Average strength and variability of portland-cement concrete core samples from Kansas paving projects versus mix design type.

Likewise, a study of the air-void systems of portland-cement concrete pavements from six projects around the state of Kansas supports this conclusion. Image analysis techniques were used to measure the amount of entrapped and entrained air in 82 samples. A summary of the results is given in table 7 below. Entrapped air in the uniform-gradation mixes was 37% lower than in the standard two-aggregate mixes overall and even 16% lower than in the 50-50 mixes. The more uniformly graded mixes were also less variable than the standard two-aggregate mixes.

	Average percent entrapped air	Standard deviation	Number of Observations
Uniform-gradation mixes	3.80	1.80	35
All standard two-aggregate mixes	6.07	1.98	47
Standard mix, 50% FA-50% CA	4.53	1.44	11
Standard mix, 65% FA-35% CA	6.55	1.86	36

Table 7. Average entrapped air content and variability of portland-cement concrete from six Kansas Department of Transportation paving projects versus mix-design type.

Conclusions

The following conclusions are supported by this investigation:

Increasing the proportion of coarse aggregate in the mix from 35% to 50% consistently reduced the amount of entrapped air in these pavements without significantly affecting other performance parameters.

Increasing the vibration frequency increased adhesion failures, spalling, faulting and entrapped air content of the standard 35% coarse-aggregate mix. Although increasing vibration frequency did improve the initial smoothness of the uniform-gradation mix, the markedly detrimental effects on the standard mix and the lack of significant performance improvements on the other mixes argues against further use of this technique on thicker portland cement concrete pavements without further study.

Relative density is not an accurate measure of percentage of entrapped air.

Using a more-uniformly-graded aggregate and a larger-sized coarse aggregate should result in better consolidation of thicker portland-cement concrete pavements.

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Appendices

Appendix 1: Freeze-Thaw Testing of Coarse Aggregates and Results

Because the current KDOT specifications limit the maximum size of the coarse aggregate to 19 mm (0.75 in.), paired sets of freeze-thaw beams were made from seven different limestone aggregates to test the durability of the larger aggregates. The beams were made and tested by ASTM C 666 Procedure B, with the standard Kansas modification of the curing time to approximate Kansas' climatic conditions. The curing time modification calls for 67 days in the moist room, 21 days in a 21 °C (73 °F) 50% humidity room and a two-day soak before freeze-thaw testing begins. This curing time allows for nearly complete hydration of the cement and results in an unsaturated moisture condition of the surface of the concrete.

Six sets of beams were made with the standard 19-mm (0.75 in) maximum coarse aggregate, and six sets were made with a maximum coarse aggregate size of 25 mm (1 in). The seventh set of beams was made with a 50-50 fine aggregate to coarse aggregate proportion and a 65-35 proportion, both of which were later used on a monitored paving project. Freeze-thaw testing of the beams was marred by failure of the freezer unit that overheated twice and caused excessive drying and possible cracking of the specimens. A second set of test beams was later made. Aggregate with top size of 25 mm (1 in) and 19 mm (0.75 in) from 13 quarries was selected and used for comparative freeze-thaw testing.

The results of the first set of freeze-thaw beams tested show the deleterious effect of excessive heat and drying on the freeze-thaw durability of concrete. Expansion of all of the beams tested was greater than the original ledge sample results and some were outside specification limits. All except one aggregate had durability factors lower than the ledge sample results and less than the specification requirements. The expansions and durability factors for beams made with 19 mm (0.75 in) and 25 mm (1 in) rock differed little but the 19 mm (0.75 in) aggregate beams performed slightly better. Also, the 50-50 mix to the 65-35 mix showed that the sandier mix generally performed better.

A second set of test beams was later made for comparative tests with maximum aggregate sizes of 25 mm (1 in) and 19 mm (0.75 in). The data indicate that the better Class I 19-mm (0.75 in) maximum-size aggregates would be durable at the 25-mm (1 in) maximum size. These better aggregates have a maximum expansion of 0.015% and a minimum durability factor of 97 when tested at the 19 mm (0.75 in.) size. Conversely, non-durable 25-mm (1 in) aggregate show proportionally more deterioration than the 19 mm (0.75 in) as the expansion of the 19 mm (0.75 in) aggregate approaches 0.02%. Graphs of the durability factor relationships and the expansion relationship are displayed in Figure 1A and Figure 2A respectively.

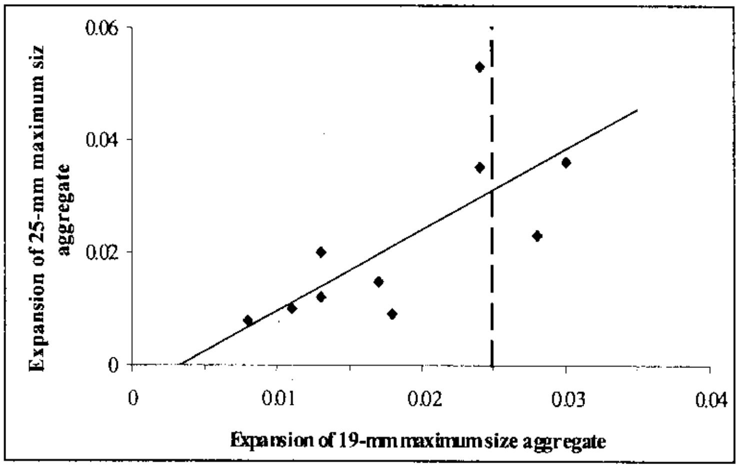

Figure 1A. Correlation of the durability factor of 25-mm coarse aggregate to the durability factor of 19-mm coarse aggregate.

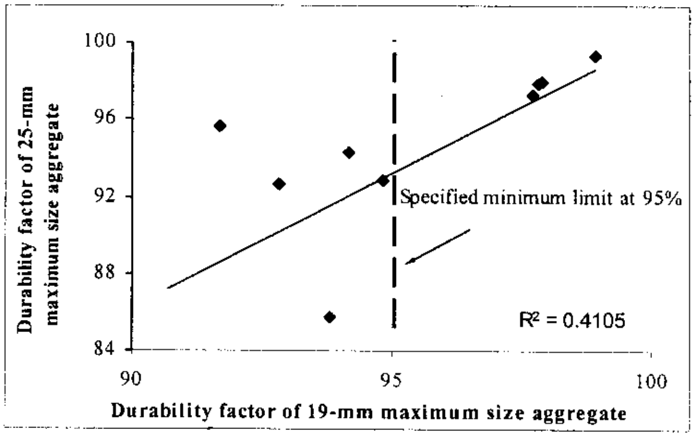

Figure 2A. Correlation of the expansion of 25-mm coarse aggregate to the durability factor of 19-mm coarse aggregate.

Appendix B: The seeMIX Program

The seeMIX program is based on the premise that traditional concrete mixes, designed as set proportions of variable stockpiled materials, must produce a variable product. The seeMIX mix designs help to reduce this variability by analyzing the total distribution and gradation of all materials blended together in a concrete mix and suggesting adjustments to mix proportions to compensate (Shilstone and Shilstone).

The seeMIX program can perform the following operations:

Calculate initial mixture proportions by ACI 211, manual entry, or other state-of-the-art methods.

Use input data to calculate the particle, air, and water distribution within the cubic yard of concrete as well as yield and material cost.

Display its findings in tables and on charts so that the user can "see" the pending mixture characteristics and interpret them to determine if they will meet the needs of engineering, construction, and batch costs.

Adjust the proportions accordance with the user's judgment of needs and provides guidance from documentation, "Interpreting Mix Submittals in the seeMIX Format," accompanying the program.

Print out submittal quality mix documentation that includes all data entered and charts produced. This documentation can be used for mix submittals or reviews.

Compensate for varying material characteristics by adjusting original weights of materials to produce a similar combined materials distribution.