Evaluation of PCC Specification Changes Impact on Durability: 1992 to 1997 Core Study

Final Report
for
MLR-98-06

March 2005

Highway Division

Iowa Department
Of Transportation

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8. ABSTRACT

In 1990, early distress had shown up on US 20 in Hamilton/Webster counties, three years after paving. Since that time, over a dozen more projects, constructed between 1984 and 1994, have been found to exhibit similar early distress. Several changes to the concrete and Portland cement specifications occurred in 1994 and 1996. This study was undertaken to investigate in place concrete pavements before and after specification changes were implemented.

The objective of this research is to evaluate the impact of Portland cement and concrete specification changes made in 1994 and 1996 on PCC durability. Cores were obtained in 1998 and 2003 from projects constructed in 1992, before specification changes, and 1997 after specification changes.

The following is a brief summary of the conclusions:

1. The pavements in the study constructed under the new specifications are performing much better after 5 years of service than the pavements constructed under the old specifications.
2. According to ISU, micro-cracking is evident in all concrete that has been in service, due to thermal stresses and loading stresses. Also, the low vacuum SEM will desiccate the concrete enough to cause micro-cracking. The SEM should not be used as a tool to indicate micro-cracking.
3. Use of Type II cement (C_3A <8%) and a 3.0% SO_3 limit does not completely eliminate ettringite infilling in air voids, as indicated in the bottom of the 1997 cores.
4. In areas of high moisture (bottom of the core), infilling is present in most of the 1997 cores.
5. Low air content and high spacing factor in the top of 1992 cores apparently causes F/T cycling cracking and then increased moisture paths from cracking causes infilling.
6. Use of ground granulated blast furnace slag (GGBFS) and fly ash reduces ettringite infilling either by diluting the aluminate (C_3A) or lowering permeability, which slows ingress of moisture.
7. The specification changes that made the biggest impact on pavement durability are the limits on vibration and increase in air content in September 1994.
8. Investigations of cores from pavements placed in 2002 and 2003 indicate improved air contents and spacing factors. In-place air content and spacing factors should be monitored to determine if appropriate air void parameters are being met.

9. KEY WORDS

PCC Durability
Air Content
Spacing Factor

10. NO. OF PAGES

19

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DISCLAIMER

INTRODUCTION

In 1990, early distress had shown up on US 20 in Hamilton/Webster counties, three years after paving. Since that time, over a dozen more projects, constructed between 1984 and 1994, have been found to exhibit similar early distress. Several changes to the concrete and Portland cement specifications occurred in 1994 and 1996. The Materials CQI committee decided to look at cores from pavements constructed in 1992, before specification changes, and 1997, after specification changes, to evaluate if these changes have affected placement and performance of new pavements.

This study was undertaken to investigate in place concrete pavements before and after specification changes were implemented. The following specifications were implemented to try and eliminate early deterioration in concrete pavements:

September 1994 Specification Changes

- Increase in plastic air content to 7±1%
- Vibration limits 5000 to 8000 vpm
- Deleted supplemental vibration at baskets

October 1996 Specification Changes

- Maximum limit of 3.0% SO_3 in Portland Cements
- Maximum limit of 0.60% equivalent alkali
- Require Type II for Interstate & Primary paving

The original study began in 1998 to examine cores obtained from concrete pavements constructed in 1992 and 1997. Cores were analyzed with high pressure hardened air testing and a scanning electron microscope (SEM) investigation. A sampling of the original pavements would be cored again in 2003 to reexamine air content and spacing factors, degree of infilling in air voids, and micro-cracking in the paste.

OBJECTIVE

The objective of this research is to evaluate the impact of Portland cement and concrete specification changes made in 1994 and 1996 on PCC durability. The original study began in 1998 to examine cores obtained from concrete pavements constructed in 1992 and 1997. A sampling of the pavements were cored again in 2003 to determine if any changes, such as degree of infilling in air voids, and micro-cracking in the paste, have occurred five years later. The 2003 study concentrated mainly on the projects constructed in 1997.

PROJECT SITES

The projects selected were constructed in 1992 and 1997 and were full depth PCC on primary or secondary roads. The years of 1992 and 1997 were chosen to represent pre and post PCC and PC specifications changes.

In 1998, a total of 11 projects constructed in 1992 and 10 projects constructed in 1997 were selected based on a range of materials and contractors. Project summary sheets containing detailed information on the projects selected are listed in Tables 1 and 2 of the Appendix. Two cores were taken at mid-panel and at joint positions for each coring location. Coring locations identify material usage changes and/or mix changes within each project. 84 cores were obtained from 1992 projects and 76 cores were obtained from 1997 project, resulting in a total of 160 cores.

In 2003, a total of five projects constructed in 1992 and 10 projects constructed in 1997 were re-cored in 2003 selected to note any significant changes after five years. 20 cores were obtained from 1992 projects and 28 cores were obtained from 1997 projects, resulting in a total of 48 cores.

TESTING

The top and bottom of the cores were trimmed to remove the tining and sub-base. A 1/2" slice was sawed from the top and bottom of the cores. The slices were polished and saved for work in the scanning electron microscope (SEM). The remaining core portions were split into the top and bottom sections. High pressure hardened air testing was used to evaluate the total air content in the PCC at top and bottom of the cores. High pressure air testing was performed in accordance with Materials Laboratory Test Method 407-B.

The SEM investigation was performed at the MARL laboratory at Iowa State University using the Hitachi S-2460N low vacuum SEM. The SEM was used to evaluate the air void distribution as well as the total air content in the top and bottom of the cores. To perform air void analysis, a total of 20 images are collected and saved. An image analysis program was then used to determine air void size and distribution.

The SEM was also used to investigate any aggregate reactions, air void infilling, and micro cracking. X-RAY mapping was performed on selected samples using the x-ray detector in the SEM. The samples were scanned 40 times for the following elements: Alumina (Al), Sulfur (S), Magnesium (Mg), Silica (Si), Sodium (Na), and Potassium (K). Al and S were scanned to check for ettringite in the air voids. Si, Na, and K were scanned to check for alkali silica reactivity (ASR), and Mg for brucite.

Figure 1. High Pressure Air Test Unit

Figure 2. Hitachi S-2460N SEM

RESULTS

Hardened Air Testing

The results of the hardened air testing are in Table 3 of the Appendix. The high pressure air test measures bulk total air content only. After correcting for aggregate absorption, the results from the high pressure air testing indicate that all of the projects have adequate air content. The average air content for the 1992 projects was 6.0% for the top and 6.8% for the bottom. The average air content for the 1997 projects was slightly higher at 6.6% for the top and 7.5% for the bottom. Since the air content by image analysis provided more information, the high pressure air testing was only performed during the 1998 study.

Figure 3.
Air Content Statistics Summary-1998

High Pressure Air

	1992	1997
Average B	6.8	7.5
Average T	6.0	6.6
STDEV B	0.7	0.7
STDEV T	1.0	0.8
Maximum B	11.5	10.9
Maximum T	8.8	9.1
Minimum B	4.8	5.1
Minimum T	3.4	3.8

SEM Image Analysis Air Content

The results of the air void analysis testing by image analysis are in Table 4 and 5 of the Appendix. Results indicate low air contents and higher spacing factors in some of the cores obtained from 1992 projects. Research[1], using ASTM C666, has shown concrete with air content below 4.5% to be non durable in freezing and thawing. Air voids larger than 1 mm are not counted when determining air content by image analysis.

ASTM C 457 indicates the spacing factor should be in the range of 0.1 to 0.2 mm and specific surface in the range of 24 to 43 mm^{-1}. ASTM C457 also recommends a maximum spacing factor of 0.2 mm for moderate exposure to freezing and thawing and should be lower if exposed to severe freezing and thawing with deicing chemicals. Research[2] has shown deterioration in pavements with spacing factors above 0.24 mm, and pavements with spacing factors 0.2 mm or lower exhibited no deterioration.

The average air content for the 1997 projects were higher than the average air content for the 1992 projects. The average air content at the top of the 1997 projects averaged 1.5% higher than the 1992 projects. The average air content at the bottom of the 1997 projects averaged 2.0% higher than the 1992 projects.

The spacing factor was higher for the 1992 projects as compared to the 1997 projects. The specific surface was in the normal range for moderate freeze thaw exposure. There were no significant changes in spacing factors between the 1998 and 2003 studies.

Figure 4.

Air Content Statistics Summary-1998

Image Analysis - SEM

	1992	1997
Average B	5.3	7.6
Average T	4.4	5.8
STDEV B	1.0	1.2
STDEV T	0.9	1.3
Maximum B	7.8	10.6
Maximum T	8.4	11.8
Minimum B	2.4	4.8
Minimum T	1.6	3.0

Figure 5.

Air Spacing Factor Statistics Summary-1998

Image Analysis - SEM

	1992	1997
Ave. Spacing Factor B	0.17	0.11
Ave. Spacing Factor T	0.17	0.13
Ave. Diameter B	283	272
Ave Diameter T	262	257
Ave. Spec. Surf. B	25.2	30.5
Ave. Spec. Surf. T	28.9	29.7

Figure 6.
Air Content SEM Statistics Summary - 2003

Image Analysis - SEM

	1992	1997
Average B	4.4	6.2
Average T	3.9	5.5
STDEV B	0.8	0.7
STDEV T	0.8	0.6
Maximum B	7.2	9.4
Maximum T	6.6	8.1
Minimum B	2.3	4.1
Minimum T	1.9	3.3

Figure 7.

Spacing Factor Statistics Summary - 2003

Image Analysis - SEM

	1992	1997
Ave. Spacing Factor B	0.19	0.14
Ave. Spacing Factor T	0.17	0.13
Ave. Diameter B	280	264
Ave Diameter T	231	225
Ave. Spec. Surf. B	24.4	27.3
Ave. Spec. Surf. T	28.6	29.7

X-RAY Mapping

X-ray mapping was performed on selected images in 1998 and again in 2003. Infilling can be seen on images (Figures 8 and 9), but X-RAY mapping gives a better indication. (Figures 10 and 11) Elements were selected for detection based on their occurrence in certain materials that relate to a mode of deterioration such as ettringite, ASR, and brucite. Al and S were scanned due to their presence in ettringite. Si, Na, and K were scanned due to their presence in ASR gel. Mg was scanned due to presence in brucite.

Little or no ASR or brucite was detected in any of the projects selected. The main element detected was Al and S in the air voids. It was assumed that the presence of Al and S related to presence of ettringite. Projects were ranked on a scale of 1 to 10, according to their relative presence of ettringite in the air voids. A rating of 10 means the air voids are completely clean and a rating of 1 means the air voids are completely full of ettringite. The ranking of infilling by project can be found in Table 6 of the Appendix.

The 1992 projects had much more infilling than the 1997 projects in 1998 and in 2003. The top of the 1992 projects indicated more infilling when the air content was less than 4.5%. In the 2003 study, the 1997 projects indicated some minimal infilling in the bottom of the cores. At the location of higher moisture areas infilling is increased. In the top of the 1992 cores with low air, freeze thaw damage has occurred allowing an increase in moisture and thus increased infilling. The bottom of all pavements are in high moisture areas and thus indicate some infilling although it is much less than the top of the 1992 projects.

All of the SEM images and XRF scans are saved on a set of CD's in the Materials Office for further viewing.

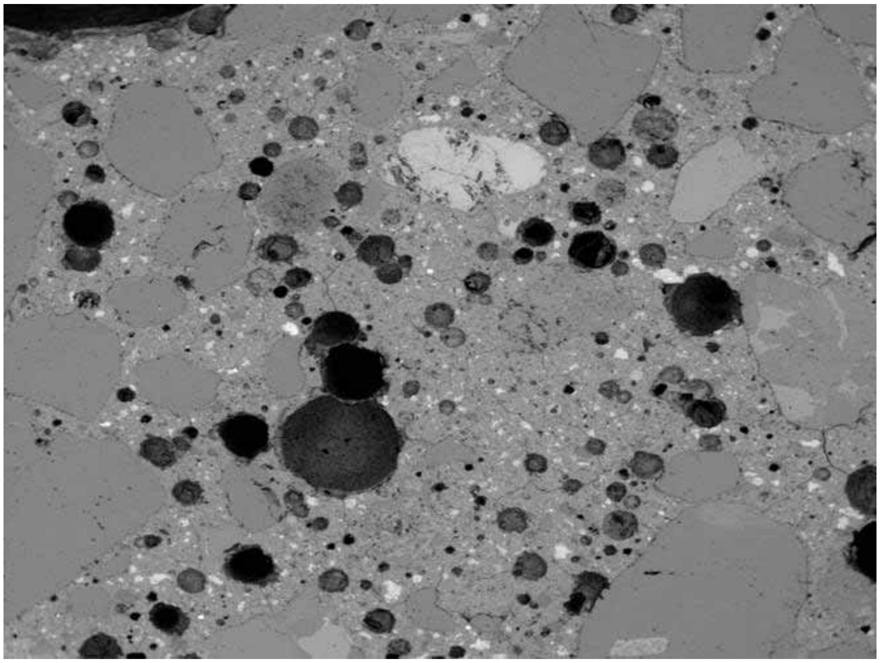

Figure 8. Image of Clean Air Void System

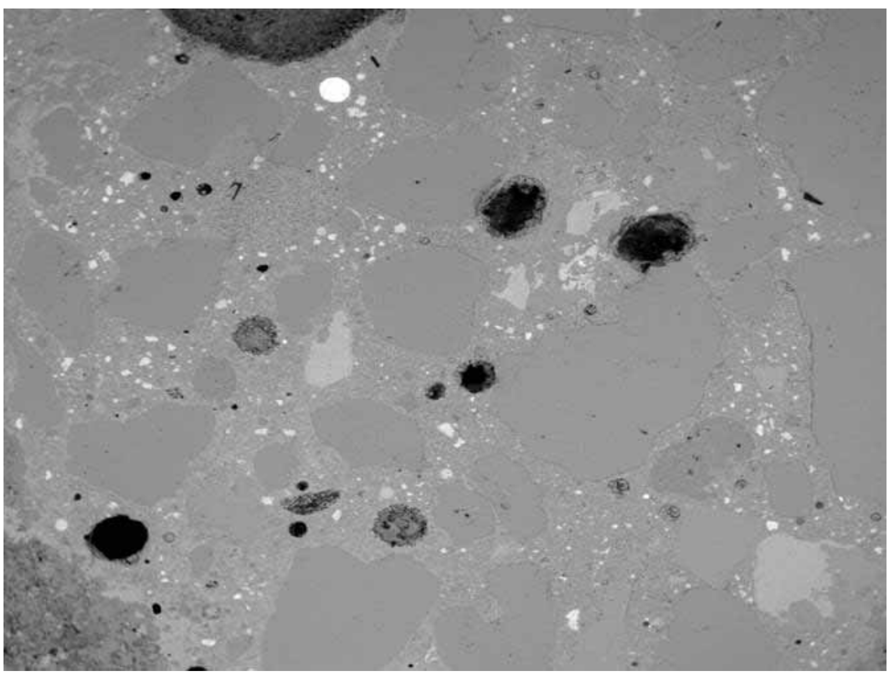

Figure 9. Image of Infilled Air Void System

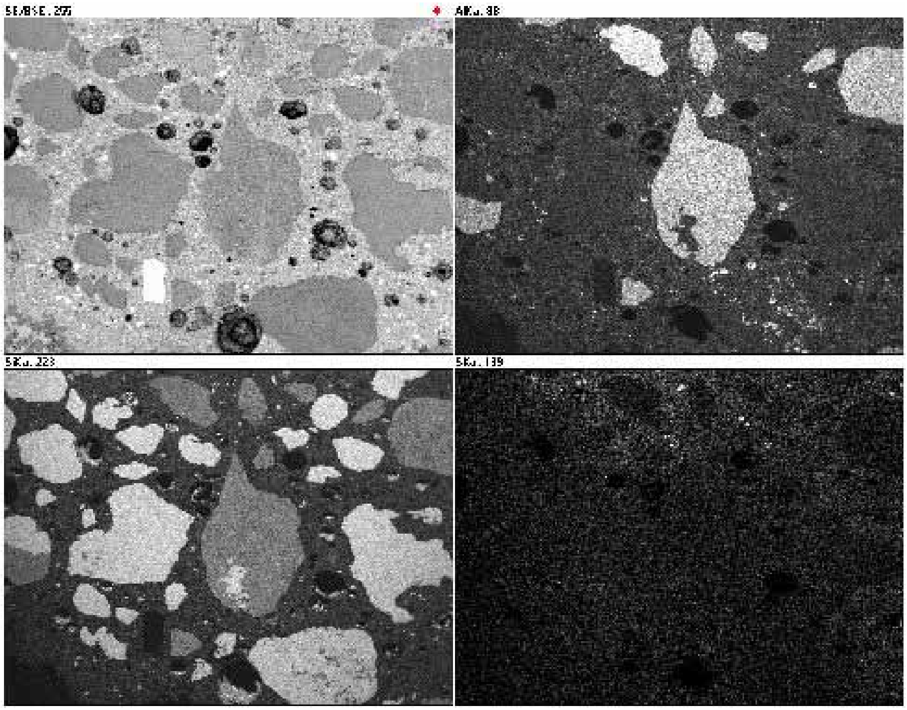

Figure 10. XRF Scan of Clean Air Void System (Note Sulfur (S) scan lower right - no highlighted areas)

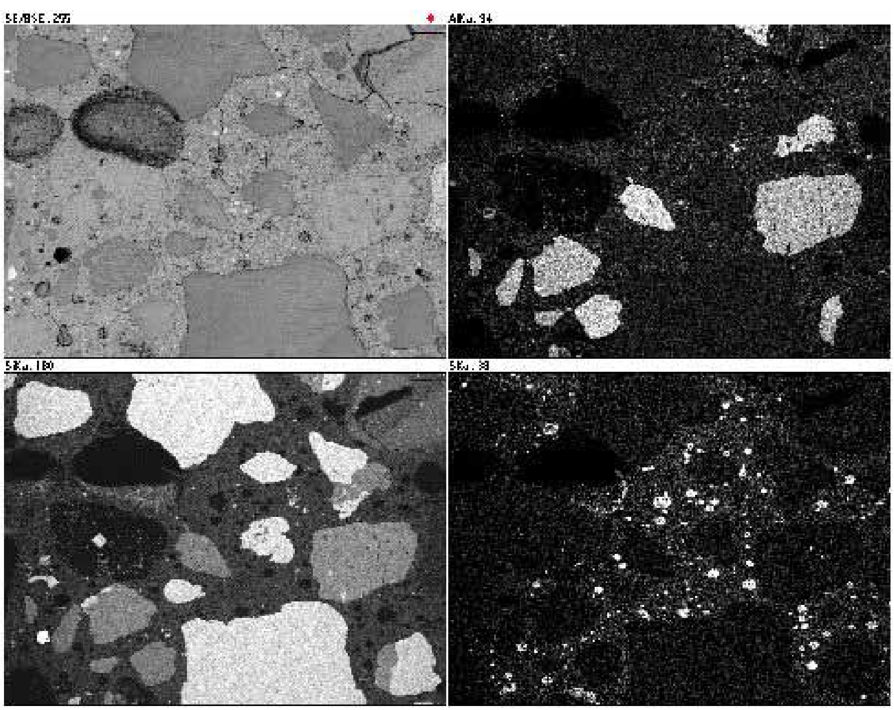

Figure 11. XRF Scan of Infilled Air Void System (Note Sulfur (S) scan lower right - highlighted areas)

Micro-cracking

During initial studies, it was assumed that micro-cracking in the paste may relate to early deterioration. After discussions with Scott Schlorholtz of the MARL laboratory at ISU, it was determined that even the low vacuum SEM was introducing micro-cracking in the concrete and should not be used in determining if micro-cracking is present.

SUMMARY

The following is a brief summary of the results:

- Air contents and spacing factors from 1998 and 2003 are within the variance of the test limits
- The average air for 1992 projects is 4.2% top & 4.9% bottom.
- The Average air for 1997 projects is 5.7% top & 6.9% bottom.
- The average spacing factor for 1992 is 0.17 top and 0.18 bottom
- The average spacing factor for 1997 is 0.13 top and 0.12 bottom
- Micro-cracking is evident in all cores
- When air contents in the top of the 1992 cores are low (<4.5%), an increase in infilling is indicated
- Infilling is evident in the bottom of 5 out of 7 of the 1997 cores
- No infilling is evident in the tops of the 1997 cores
- The 1997 Project O, incorporating GGBFS and fly ash, has minimal infilling in the bottom of the core compared to other 1997 projects

CONCLUSIONS AND RECOMMENDATIONS

1. The pavements in the study constructed under the new specifications are performing much better after 5 years of service than the pavements constructed under the old specifications.
2. According to ISU, micro-cracking is evident in all concrete that has been in service, due to thermal stresses and loading stresses. Also, the low vacuum SEM will desiccate the concrete enough to cause micro-cracking. The SEM should not be used as a tool to indicate micro-cracking.
3. Use of Type II cement (C_3A <8%) and a 3.0% SO_3 limit does not completely eliminate ettringite infilling in air voids, as indicated in the bottom of the 1997 cores.
4. In areas of high moisture (bottom of the core), ettringite infilling is present in most of the 1997 cores.
5. Low air content and high spacing factor in the top of 1992 cores apparently causes F/T cycling cracking and then increased moisture paths from cracking causes infilling.
6. Use of GGBFS and fly ash reduces ettringite infilling either by diluting the aluminate (C_3A) or lowering permeability, which slows ingress of moisture.

7. The specification changes that made the biggest impact on pavement durability are the limits on vibration and increase in air content in September 1994. To date, no pavement placed 1995 and later exhibits early deterioration.
8. Investigations of cores from pavements placed in 2002 and 2003 indicate improved air contents and spacing factors. (Figure 7-8 of the Appendix) In-place air content and spacing factors should be monitored to determine if appropriate air void parameters are being met.

ACKNOWLEDGEMENTS

The authors would like to thank the Warren Straszheim, Jerry Amenson, and Scott Schlorholtz of the MARL laboratory at Iowa State University for their efforts with the SEM and image analysis work. Also, the Cement and Concrete laboratory for their work on the high pressure air testing.

REFERENCES

1. Schlorholtz, S., Image Analysis for Evaluating Air Void Parameters of Concrete, HR-396, Iowa State University, Ames, Iowa,1998
2. Schlorholtz, S., Determine Initial Cause for Current Premature Portland Cement Concrete Deterioration, Final Report TR-406, Iowa State University, Ames, Iowa, 2000.

APPENDIX

Table 1. List of 1992 Projects

ID	Year	Project Number	Roadway	County	Mile Post	Lane	Station	Contractor	Max./Min. Temperature	Mix Type	Cement	Fly Ash	Fine Aggregate	Coarse Aggregate	Water Reducer	Air Entraining Agent
A	92	IM-29-4(39)56--13-78	I-29	Pottawattamie/	57.70 to 76.50	NB	608+41 to 629+23	Irving F. Jensen	78/60	C-5WR-C	Louisville NE (I)	Council Bluffs #3 (C	Oreapolis (ANE514)	Weeping Water (ANE002)	WRDA-82	Dara-Vair R
				Harrison	(18.80)	NB	634+00 to 655+90		78/58	C-5WR-C	Louisville NE (I)	Council Bluffs #3 (C	Oreapolis (ANE514)	Weeping Water (ANE002)	WRDA-82	Dara-Vair R
						NB	655+90 to 682+08		80/59	C-5WR-C	Louisville NE (I)	Council Bluffs #3 (C	Oreapolis (ANE514)	Weeping Water (ANE002)	WRDA-82	Dara-Vair R
						NB	1089+71 to 1102+90		81/58	C-5WR-C	Louisville NE (I)	Port Neal #4 (C)	Oreapolis (ANE514)	Weeping Water (ANE002)	WRDA-82	Dara-Vair R
						NB	1109+88 to 1130+00		74/56	C-5WR-C	Louisville NE (I)	Port Neal #4 (C)	Oreapolis (ANE514)	Weeping Water (ANE002)	WRDA-82	Dara-Vair R
B	92	STP-2-2(26)--2C-73	SH-2	Page	33.27 to 40.73	FW	113+54 to 126+50	Irving F. Jensen	81/61	C-6WR-C	Louisville NE (I)	Nebraska City (C)	Shennandoah (A73504)	Weeping Water (ANE002)	WRDA-82	Dara-Vair R
					(7.46)	FW	134+57 to 146+00		84/61	C-6WR-C	Louisville NE (I)	Nebraska City (C)	Shennandoah (A73504)	Weeping Water (ANE002)	WRDA-82	Dara-Vair R
						FW	166+10 to 178+00		86/62	C-6WR-C	Louisville NE (I)	Nebraska City (C)	Shennandoah (A73504)	Weeping Water (ANE002)	WRDA-82	Dara-Vair R
						FW	278+25 to 319+02		78/60	C-6WR-C	Louisville NE (I)	North Omaha (C)	Shennandoah (A73504)	Weeping Water (ANE002)	WRDA-82	Dara-Vair R
C	92	IR-80-1(186)43--12-78	I-80	Pottawattamie/Cass	45.14 to 59.91	WB	2088+20 to 2061+19	Fred Carlson	71/57	C-5WR-C	Louisville NE (I)	North Omaha (C)	Oakland (A78504)	Weeping Water (ANE002)	Sika Plastocrete 161	Sika AER
					(14.77)*	WB	2061+19 to 2031+73		71/58	C-5WR-C	Louisville NE (I)	North Omaha (C)	Oakland (A78504)	Weeping Water (ANE002)	Sika Plastocrete 161	Sika AER
						WB	1935+33 to 1910+99		80/60	C-5WR	Louisville NE (I)	None	Oakland (A78504)	Weeping Water (ANE002)	Sika Plastocrete 161	Sika AER
						WB	539+21 to 519+63 **		75/45	C-5WR	Louisville NE (I)	None	Oakland (A78504)	Weeping Water (ANE002)	Sika Plastocrete 161	Sika AER
						WB	468+15 to 441+39 **		78/45	C-5WR-C	Louisville NE (I)	North Omaha (C)	Valley (A15508)	Weeping Water (ANE002)	Sika Plastocrete 161	Sika AER
						WB	393+48 to 363+21 **		75/60	C-5WR-C	Louisville NE (I)	North Omaha (C)	Valley (A15508)	Weeping Water (ANE002)	Sika Plastocrete 161	Sika AER
D	92	IR-35-5(56)133--12-40	I-35	Hamilton	134.01 to 140.19	SB	762+50 to 753+50	Irving F. Jensen	72/55	C-4WR-C	Mason City IA (LH I)	Council Bluffs #3 (C	Popejoy (A35512)	Alden (A42002)	WRDA-82	Dara-Vair R
					(6.18)	SB	716+37 to 711+11		75/48	C-4WR-C	Mason City IA (LH I)	Council Bluffs #3 (C	Popejoy (A35512)	Alden (A42002)	WRDA-82	Dara-Vair R
						SB	711+11 to 704+37		69/50	C-4WR-C	Mason City IA (LH I)	Council Bluffs #3 (C	Popejoy (A35512)	Alden (A42002)	WRDA-82	Dara-Vair R
						SB	431+00 to 422+04		68/58	C-4WR-C	Mason City IA (LH I)	Ottumwa (C)	Popejoy (A35512)	Alden (A42002)	WRDA-82	Dara-Vair R
E	92	IR-80-6(157)205--12-4	I-80	Iowa	204.80 to 209.65	WB	260+00 to 238+40	Fred Carlson	85/55	C-3WR-C	Buffalo IA (I)	Ottumwa (C)	Disterhoff (A48508)	Sully (A50002)	Sika Plastocrete 161	Sika AER
					(4.85)	WB	231+70 to 201+65		77/54	C-3WR-C	Buffalo IA (I)	Ottumwa (C)	Disterhoff (A48508)	Sully (A50002)	Sika Plastocrete 161	Sika AER
						WB	57+04 to 46+94		86/65	C-3WR-C	Buffalo IA (I)	Ottumwa (C)	Disterhoff (A48508)	Sully (A50002)	Sika Plastocrete 161	Sika AER
F	91	F-150-3(42)--20-10	SH-150	Buchanan	49.20 to 51.35	FW	528+30 to 525+47	Manatt's	70/55	C-3WR-C	Mason City IA (LH I)	Louisa (C)	Hoffman (A10510)	Hazleton (A10010)	Protex PDA25-DP	Protex AES
					(2.15)	FW	525+47 to 511+55		89/60	C-3WR-C	Mason City IA (LH I)	Louisa (C)	Hoffman (A10510)	Hazleton (A10010)	Protex PDA25-DP	Protex AES
						FW	511+55 to 502+45		65/50	C-3WR-C	Mason City IA (LH I)	Louisa (C)	Hoffman (A10510)	Hazleton (A10010)	Protex PDA25-DP	Protex AES
						FW	502+45 to 502+00		65/50	C-3WR	Mason City IA (LH I)	None	Hoffman (A10510)	Hazleton (A10010)	Protex PDA25-DP	Protex AES
						FW	502+00 to 500+85		65/50	C-3WR	Mason City IA (LH I)	None	Hoffman (A10510)	Hazleton (A10010)	Protex PDA25-DP	Protex AES
						FW	484+50 to 476+56		50/35	C-3WR	Mason City IA (LH I)	None	Hoffman (A10510)	Hazleton (A10010)	Protex PDA25-DP	Protex AES
	92					FW	528+64 to 536+91		47/38	C-3WR-C	Mason City IA (HN I)	Louisa (C)	Randalia (A33510)	Hazleton (A10010)	Prokrete N-3	Conchem AES
G	92	F-30-5(80)--20-85	US-30	Story	151.92 to 156.80	WB	1427+77 to 1447+50	Fred Carlson	66/36	C-3WR-C	Louisville NE (I)	Ottumwa (C)	Christensen (A85502)	Ames (A85006)	Sika Plastocrete 161	Sika AER
					(4.88)	WB	1454+70 to 1486+10		82/49	C-3WR-C	Louisville NE (I)	Ottumwa (C)	Christensen (A85502)	Ames (A85006)	Sika Plastocrete 161	Sika AER
						WB	1514+90 to 1548+35		90/60	C-3WR-C	Louisville NE (I)	Ottumwa (C)	Christensen (A85502)	Ames (A85006)	Sika Plastocrete 161	Sika AER
H	92	RP-163-1(50)--16-77	SH-163	Polk/Jasper	12.36 to 17.01	WB	208+89 to 189+72	Cedar Valley	84/56	C-4WR-C	Mason City IA (HN I)	Ottumwa (C)	Colfax (A50502)	Sully (A50002)	WRDA-82	Dara-Vair R
					(4.65)	WB	189+72 to 170+76		86/68	C-4WR-C	Mason City IA (HN I)	Ottumwa (C)	Colfax (A50502)	Sully (A50002)	WRDA-82	Dara-Vair R
						WB	142+64 to 122+95		82/68	C-4WR-C	Mason City IA (HN I)	Ottumwa (C)	Colfax (A50502)	Sully (A50002)	WRDA-82	Dara-Vair R
						EB	982+00 to 995+53 **		57/46	C-4WR	Mason City IA (HN I)	None	Colfax (A50502)	Sully (A50002)	WRDA-82	Dara-Vair R
						EB	995+53 to 13+00 **		54/47	C-4WR	Mason City IA (HN I)	None	Colfax (A50502)	Sully (A50002)	WRDA-82	Dara-Vair R
I	92	F-RP-151-3(79)--36-57	US-151	Linn	37.83 to 46.11	EB	5154+00 to 5172+21	Fred Carlson	85/60	C-3WR-C	Buffalo IA (I)	Louisa (C)	East Marion (A57508)	Bowser-Springville (A57008)	Sika Plastocrete 161	Sika AER
					(8.28)	EB	5172+21 to 5195+32		80/62	C-3WR-C	Buffalo IA (I)	Louisa (C)	East Marion (A57508)	Bowser-Springville (A57008)	Sika Plastocrete 161	Sika AER
						EB	5195+32 to 5234+72		62/39	C-3WR-C	Buffalo IA (I)	Louisa (C)	East Marion (A57508)	Bowser-Springville (A57008)	Sika Plastocrete 161	Sika AER
						WB	5127+27 to 5157+82		87/65	C-3WR-F	Buffalo IA (I)	M.L. Kapp (F)	East Marion (A57508)	Bowser-Springville (A57008)	Sika Plastocrete 161	Sika AER
J	92	RP-34-6(54)--16-59	US-34	Lucas/Monroe	149.72 to 154.89	FW	849+17 to 821+03	Fred Carlson	55/34	C-5WR-C	Hannibal MO (I)	Council Bluffs #3 (C	New Harvey (A63512)	Sully (A50002)	Sika Plastocrete 161	Sika AER
					(5.17)	FW	821+03 to 799+20		60/34	C-5WR-C	Hannibal MO (I)	Council Bluffs #3 (C	New Harvey (A63512)	Sully (A50002)	Sika Plastocrete 161	Sika AER
						FW	612+00 to 632+35		55/43	C-5WR-C	Hannibal MO (I)	Council Bluffs #3 (C	New Harvey (A63512)	Sully (A50002)	Sika Plastocrete 161	Sika AER
						FW	662+25 to 699+65		64/43	C-5WR-C	Hannibal MO (I)	Ottumwa (C)	New Harvey (A63512)	Sully (A50002)	Sika Plastocrete 161	Sika AER
K	92	F-RP-30-6(29)--36-06	US-30	Benton/Linn	237.41 to 243.85	WB	1313+40 to 1273+77	Flynn	70/60	C-3WR-C	Buffalo IA (I)	Louisa (C)	Aggregate Inc. (A57528)	Lee Crawford (A57022)	Protex PDA25-DP	Protex AES
					(6.32)											

Table 2. List of 1997 Projects

ID	Year	Project Number	Roadway	County	Mile Post	Lane	Station	Contractor	Max./Min. Temperature	Mix Type	Cement	Fly Ash	Fine Aggregate	Coarse Aggregate	Water Reducer	Air Entraining Agent
L	97	NHSN-71-7(46)--2R-11	US-71	Buena Vista	176.67 to 177.02	FW	455+70 to 464+75	Wicks Construction	85/58	C-4WR-C20	Mason City IA (LH I)	Port Neal #4 (C)	Leitz North (A81530)	Moore (A76004)	WRDA with Hycol	Daravair 1400
					(0.44)	FW	464+75 to 474+75		85/60	C-4WR-C20	Mason City IA (LH I)	Port Neal #4 (C)	Leitz North (A81530)	Moore (A76004)	WRDA with Hycol	Daravair 1400
M	97	NHS-61-8(96)--19-31	US-61	Dubuque	174.79 to 183.20	SB	9454+55 to 9470+57	Flynn	50/29	C-3WR	Buffalo IA (I/II)	None	McCabe (A31510)	Andrew (A49010)	Conchem 25DP	Conchem AES
					(8.41)											
						SB	5092+84 to 5115+00		50/31	C-3WR-C20	Buffalo IA (I/II)	Pleasant Prarie (C)	McCabe (A31510)	Andrew (A49010)	Conchem 25DP	Conchem AES
						SB	5186+55 to 5196+06		62/41	C-3WR-C20	Buffalo IA (I/II)	Pleasant Prarie (C)	McCabe (A31510)	Andrew (A49010)	Conchem 25DP	Conchem AES
						SB	5196+83 to 5206+25		62/41	C-3WR-C20	Buffalo IA (I/II)	Pleasant Prarie (C)	McCabe (A31510)	Andrew (A49010)	Conchem 25DP	Conchem AES
						NB	5265+50 to 5293+75		83/62	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	McCabe (A31510)	Andrew (A49010)	Conchem 25DP	Conchem AES
						NB	5247+75 to 5260+55		83/71	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	McCabe (A31510)	Andrew (A49010)	Conchem 25DP	Conchem AES
						NB	5212+25 to 5238+15		85/71	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	McCabe (A31510)	Andrew (A49010)	Conchem 25DP	Conchem AES
N	97	IM-80-6(175)220--13-48	I-80	Iowa	215.12 to 221.35	WB	632+62 to 642+65	Manatt's	70/46	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	Disterhoff (A48508)	Conklin (A52004)	Conchem 25DP *	Conchem AES
					(6.23)	WB	647+10 to 664+90		82/54	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	Disterhoff (A48508)	Conklin (A52004)	Conchem 25DP *	Conchem AES
						WB	1024+49 to 1007+10		75/52	C-3-C20	Buffalo IA (I/II)	Louisa (C)	Disterhoff (A48508)	Conklin (A52004)	None	Conchem AES
						EB	680+49 to 702+75		86/59	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	Disterhoff (A48508)	Conklin (A52004)	Daratard 17	Conchem AES
						EB	628+18 to 676+04		90/63	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	Disterhoff (A48508)	Conklin (A52004)	Daratard 17	Conchem AES
O	97	NHS-151-3(97)--19-57	US-151	Linn	33.48 to 36.68	SB	284+26 to 297+07	Allied Construction	91/67	C-3WR-C10	Mason City IA (HN IS)	Louisa (C)	Ivanhoe (A57520)	Bowser-Springville (A57008)	Sika Plastocrete 161	Daravair 1000
					(3.20)	NB	243+61 to 277+26		77/53	C-3WR-C10	Mason City IA (HN IS)	Louisa (C)	Ivanhoe (A57520)	Bowser-Springville (A57008)	Sika Plastocrete 161	Daravair 1000
						NB	302+41 to 319+01		83/59	C-3WR-C10	Mason City IA (HN IS)	Louisa (C)	Ivanhoe (A57520)	Bowser-Springville (A57008)	Sika Plastocrete 161	Daravair 1000
P	97	NHS-163-4(22)--2R-62	SH-163	Mahaska	44.99 to 54.78	EB	1001+40 to 1040+45	Fred Carlson	82/56	C-3WR-C20	Louisville NE (I/II)	Council Bluffs #3 (C)	New Harvey (A63512)	Sully (A50002)	Sika Plastocrete 161	Sika AEA-15
					(9.79)											
						WB	1214+48 to 1187+56		75/56	C-3WR-C20	Louisville NE (I/II)	Ottumwa (C)	New Harvey (A63512)	Sully (A50002)	Sika Plastocrete 161	Sika AEA-15
Q	97	NHS-137-3(19)--19-62	SH-137	Mahaska	55.87 to 60.11	SB	1328+50 to 1324+30	Manatt's	46/23	C-3-C20	Mason City IA (HN I/II)	Louisa (C)	New Harvey (A63512)	Sully (A50002)	None	Conchem Air
					(4.24)	SB	1323+08 to 1316+50		46/23	C-3-C20	Mason City IA (HN I/II)	Louisa (C)	New Harvey (A63512)	Sully (A50002)	None	Conchem Air
						NB	1223+50 to 1243+53		90/70	C-3WR-C20	Mason City IA (HN I/II)	Louisa (C)	New Harvey (A63512)	Sully (A50002)	Conchem 25DP **	Conchem Air
						NB	1264+25 to 1281+00		87/68	C-3WR-C20	Mason City IA (HN I/II)	Louisa (C)	New Harvey (A63512)	Sully (A50002)	Conchem 25DP **	Conchem Air
R	97	NHS-500-1(96)--19-77	US-65	Polk	71.58 to 72.99	SB	673+55 to 686+50	Flynn	79/58	C-3WR	Buffalo IA (I/II)	None	Pleasant Hill (A77528)	Ames (A85006)	Conchem 25DP	Conchem AES
					(1.41)											
						SB	653+40 to 634+35		84/63	C-3WR-C20	Buffalo IA (I/II)	Colombia #2 (C)	Pleasant Hill (A77528)	Ames (A85006)	Conchem 25DP	Conchem AES
S	97	NHS-500-1(79)--19-77	US-65	Polk	72.74 to 74.11	SB ***	149+21 to 124+45	Cedar Valley	57/46	A-6-C20	Louisville NE (I/II)	Ottumwa (C)	Vandalia (A77522)	Durham (A63002)	None	Daravair 1400
					(1.37)											
						NB	132+50 to 148+49		81/52	C-3WR-C20	Louisville NE (I/II)	Council Bluffs #3 (C)	Vandalia (A77522)	Durham (A63002)	WRDA-82	Daravair 1400
						SB	148+54 to 129+14		72/56	C-3WR-C20	Louisville NE (I/II)	Council Bluffs #3 (C)	Vandalia (A77522)	Durham (A63002)	WRDA-82	Daravair 1400
T	97	IM-35-3(69)82--13-77	I-35	Polk	131.48 to 134.85	EB ***	888+00 to 927+50	Cedar Valley	63/34	C-3WR-C20	Buffalo IA (I/II)	Ottumwa (C)	Denny/Johnson (A77504)	Ames (A85006)	Daratard 17	Daravair 1400
					(3.37)											
						EB ****	846+17 to 868+00		52/41	C-3WR-C20	Buffalo IA (I/II)	Council Bluffs #3 (C)	Denny/Johnson (A77504)	Ames (A85006)	Daratard 17	Daravair 1400
U	97	IM-80-8(165)279--13-82	I-80	Scott	278.10 to 280.78	WB	12+73.15 to 18+28.55	McCarthy	86/62	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	Milan-Big Island (AIL504)	Milan (AIL010)	Daratard 17	Daravair 1000
					(2.68)	WB	18+28.55 to 23+94.46		85/57	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	Milan-Big Island (AIL504)	Milan (AIL010)	Daratard 17	Daravair 1000
						WB	43+25.5 to 35+80		88/64	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	Milan-Big Island (AIL504)	Linwood (A82008)	Daratard 17	Daravair 1000
						WB	29+31.7 to 23+94.46		78/55	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	Milan-Big Island (AIL504)	Linwood (A82008)	Daratard 17	Daravair 1000
V	97	STPN-5-4(40)--2J-91	SH-5	Warren	85.24 to 88.02	EB	273+05 to 300+59	Irving F. Jensen	57/42	QMC	Louisville NE (I/II)	Ottumwa (C)	Vandalia (A77522)	Durham (A63002)	WRDA-82	Daravair 1000
					(2.78)	EB	302+80 to 312+71		50/40	QMC	Louisville NE (I/II)	Ottumwa (C)	Vandalia (A77522)	Durham (A63002)	WRDA-82	Daravair 1000
W	97	NHS-218-3(49)--19-92	US-218	Washington	56.93 to 64.07	NB	701+28 to 743+72	Fred Carlson	90/80	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	Fredonia (A58504)	Conklin (A52004)	Sika Plastocrete 161	Sika AEA-15
					(6.90)	NB	787+26 to 830+22		79/51	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	Fredonia (A58504)	Conklin (A52004)	Sika Plastocrete 161	Sika AEA-15
						SB	667+93 to 707+80		101/70	C-3WR-C20	Buffalo IA (I/II)	Louisa (C)	Fredonia (A58504)	Conklin (A52004)	Sika Plastocrete 161	Sika AEA-15

Table 3. High Pressure Air Results 1998 Study

Summary Statistics of Hardened Air Contents - High Pressure Air Method
1998 INVESTIGATION

Location	Average	Standard Deviation	High	Low	Range
Bottom	7.3	1.3	11.5	4.8	6.7
Top	6.3	1.4	9.1	3.4	5.8

Project	Average	Standard Deviation	High	Low	Range
A Bot	7.2	0.5	7.9	6.6	1.2
A Top	6.8	0.9	8.1	6.2	1.9
B Bot	6.4	0.3	6.6	6.0	0.7
B Top	6.4	1.1	7.3	4.8	2.4
C Bot	7.8	1.1	9.5	6.6	2.9
C Top	6.4	1.8	8.8	3.8	5.0
D Bot	6.4	0.6	6.8	5.6	1.3
D Top	5.5	1.3	7.1	4.2	2.9
E Bot	5.4	0.6	5.9	5.0	0.9
E Top	5.6	0.3	5.8	5.3	0.4
F Bot	7.1	0.5	7.7	6.3	1.4
F Top	6.6	1.1	7.7	5.3	2.5
G Bot	7.6	0.8	8.2	7.1	1.1
G Top	7.6	0.3	7.8	7.4	0.4
H Bot	6.1	1.4	7.3	4.8	2.5
H Top	4.7	1.0	5.8	3.4	2.4
I Bot	9.1	1.7	11.5	7.5	4.0
I Top	5.6	2.0	8.3	3.7	4.6
J Bot	6.2	0.3	6.5	6.0	0.6
J Top	6.0	1.4	7.0	4.0	3.0
K Bot	5.9	0.1	6.0	5.8	0.2
K Top	4.8	0.0	4.8	4.8	0.0
L Bot	6.9	1.0	7.6	6.2	1.4
L Top	6.8	0.6	7.2	6.4	0.8
M Bot	8.5	1.3	9.7	6.6	3.1
M Top	6.5	1.6	8.1	4.0	4.0
N Bot	8.4	1.1	10.4	7.3	3.1
N Top	7.0	0.2	7.3	6.7	0.6
O Bot	8.2	0.5	8.6	7.8	0.8
O Top	8.6	0.7	9.1	8.1	1.0
P Bot	7.0	0.3	7.3	6.7	0.6
P Top	7.4	0.5	8.1	7.0	1.2
Q Bot	7.3	0.5	7.7	6.5	1.2
Q Top	6.2	0.9	7.4	5.4	2.0
R Bot	7.7	0.4	8.2	7.4	0.8
R Top	6.3	1.4	7.6	4.4	3.2
S Bot	9.2	1.3	10.9	7.9	3.0
S Top	7.9	1.1	9.0	6.6	2.4
U Bot	5.8	0.5	6.2	5.1	1.1
U Top	5.5	0.8	6.6	4.8	1.8
W Bot	6.1	0.4	6.3	5.8	0.5
W Top	3.9	0.2	4.1	3.8	0.2

Table 4. SEM Image Analysis Air Results 1998

Summary Statistics of Hardened Air Contents - SEM Image Analysis
1998 INVESTIGATION

Project	Average	Standard Deviation	High	Low	Range	Ave. Dia. (microns)	Spec. Surf. (mm^-1))	Spacing Factor (mm)
A Bot	6.7	0.7	7.3	5.8	1.5	292	20.8	0.15
A Top	5.4	0.8	6.2	4.3	1.9	292	20.7	0.17
B Bot	4.8	0.5	5.5	4.3	1.3	303	19.9	0.19
B Top	5.6	1.6	7.5	3.5	4.0	348	17.5	0.21
C Bot	6.4	1.3	7.8	4.5	3.3	286	21.5	0.15
C Top	4.8	2.0	8.4	3.1	5.2	262	26.9	0.16
D Bot	4.0	1.1	5.5	3.0	2.6	285	21.2	0.20
D Top	2.6	1.0	3.9	1.6	2.3	218	27.8	0.19
E Bot	3.6	0.4	3.8	3.3	0.5	240	25.2	0.17
E Top	4.0	0.3	4.2	3.8	0.4	273	22.0	0.18
F Bot	5.5	1.2	7.3	4.4	2.9	252	24.2	0.14
F Top	4.7	1.0	5.9	3.4	2.5	233	25.8	0.14
G Bot	6.3	1.7	7.6	5.1	2.4	271	22.3	0.14
G Top	5.7	0.3	5.9	5.5	0.4	261	23.0	0.14
H Bot	4.7	2.3	6.8	2.4	4.4	302	20.0	0.20
H Top	3.7	1.2	5.4	2.7	2.7	263	24.1	0.19
I Bot	5.8	0.6	6.5	5.2	1.3	313	19.2	0.17
I Top	4.1	0.9	5.3	3.2	2.2	269	22.4	0.18
J Bot	5.1	0.9	6.1	4.2	1.9	303	20.0	0.18
J Top	3.9	0.7	4.9	3.3	1.6	258	23.6	0.18
K Bot	5.9	0.5	6.2	5.5	0.8	265	22.6	0.14
K Top	4.4	0.0	4.4	4.4	0.0	208	28.9	0.13
L Bot	5.9	1.0	6.6	5.2	1.4	198	30.5	0.11
L Top	4.2	0.1	4.3	4.1	0.1	238	25.3	0.16
M Bot	8.3	1.6	10.5	6.6	3.9	320	18.9	0.13
M Top	6.0	2.3	8.2	3.2	5.0	267	22.7	0.15
N Bot	7.9	1.4	9.4	6.2	3.2	281	21.6	0.08
N Top	5.8	0.4	6.5	5.3	1.2	239	25.4	0.09
O Bot	6.9	0.1	7.0	6.8	0.1	233	26.1	0.11
O Top	6.8	0.6	7.3	6.4	0.9	245	24.5	0.12
P Bot	7.8	2.1	10.6	6.0	4.5	290	21.0	0.13
P Top	8.5	2.1	11.4	6.7	4.7	266	22.8	0.11
Q Bot	6.5	1.5	7.9	4.8	3.1	280	21.6	0.14
Q Top	4.6	1.2	5.9	3.2	2.8	300	20.1	0.19
R Bot	7.3	0.6	7.9	6.5	1.4	254	23.7	0.12
R Top	5.1	1.6	7.2	3.5	3.7	254	23.7	0.15
S Bot	9.0	1.2	10.2	7.8	2.4	300	20.1	0.07
S Top	7.4	3.1	11.8	5.1	6.6	313	19.2	0.08
U Bot	6.9	1.4	8.3	5.0	3.3	293	20.7	0.14
U Top	4.1	1.0	5.3	3.0	2.3	247	24.6	0.16
W Bot	9.1	0.8	9.7	8.5	1.1	277	21.7	0.11
W Top	5.4	0.1	5.5	5.3	0.2	205	29.7	0.11

Table 5. SEM Image Analysis Air Results 2003

Summary Statistics of Hardened Air Contents - SEM Image Analysis
2003 INVESTIGATION

Project	Average	Standard Deviation	High	Low	Range	Ave. Dia. (microns)	Spec. Surf. (mm^-1))	Spacing Factor (mm)
D Bot	3.7	0.8	4.5	2.6	1.9	271	22.5	0.191
D Top	3.2	0.5	3.8	2.7	1.1	214	28.5	0.166
E Bot	5.3	1.0	6.2	4.1	2.1	304	20.0	0.172
E Top	4.1	1.1	5.1	2.6	2.5	242	25.4	0.159
F Bot	5.7	1.0	7.2	4.3	2.9	248	24.4	0.134
F Top	5.6	0.6	6.6	4.7	1.9	211	28.6	0.115
H Bot	2.7	0.3	2.9	2.3	0.7	299	20.1	0.252
H Top	2.7	1.0	3.9	1.9	2.1	258	24.4	0.221
L Bot	6.1	1.2	7.3	4.7	2.5	256	23.6	0.135
L Top	5.8	1.0	6.5	4.3	2.2	210	29.7	0.113
M Bot	7.3	1.8	9.4	5.2	4.2	266	22.7	0.123
M Top	7.3	0.9	8.1	6.2	2.0	283	21.6	0.128
N Bot	6.9	0.6	7.6	6.2	1.4	316	19.0	0.154
N Top	4.4	0.9	5.5	3.3	2.2	235	26.0	0.151
O Bot	5.2	0.4	5.7	4.8	0.9	223	27.3	0.127
O Top	5.9	0.2	6.2	5.7	0.5	223	27.5	0.116
P Bot	6.2	0.3	6.5	5.9	0.6	256	23.6	0.130
P Top	4.8	0.7	5.5	4.0	1.5	180	29.0	0.132
Q Bot	4.6	0.4	5.0	4.1	0.9	274	22.1	0.172
Q Top	5.0	0.3	5.5	4.8	0.8	233	26.2	0.138
W Bot	7.2	0.4	7.8	6.8	1.0	257	23.5	0.118
W Top	5.3	0.5	5.9	4.6	1.3	211	28.6	0.119

Table 6. Air Void Infilling and Air Content Ranking

PROJECT RANKING

			1998 Investigation			2003 Investigation		
Project	Year	Mix	Air	Infilling	Total	Air	Infilling	Total
A	1992	C-5	7	5	12			
B	1992	C-6	5	3	8			
C	1992	C-5	8	8	16			
D	1992	C-4	2	1	3	3	1	4
E	1992	C-3	5	5	10	4	5	9
F	1992	C-3	10	3	13	9	3	12
G	1992	C-3	10	7	17			
H	1992	C-4	5	6	11	2	4	6
I	1992	C-3	7	5	12			
J	1992	C-5	6	6	12			
K	1992	C-3	9	8	17			
L	1997	C-4	8	10	18	9	8	17
M	1997	C-3	10	10	20	10	9	19
N	1997	C-3	10	10	20	9	9	18
O	1997	C-3	10	10	20	9	9	18
P	1997	C-3	10	9	19	9	8	17
Q	1997	C-3	9	9	18	7	8	15
R	1997	C-3	10	10	20			
S	1997	C-3	10	9	19			
U	1997	C-3	9	10	19			
W	1997	C-3	10	10	20	10	9	19

Table 7. Air Contents 1992 to 2003

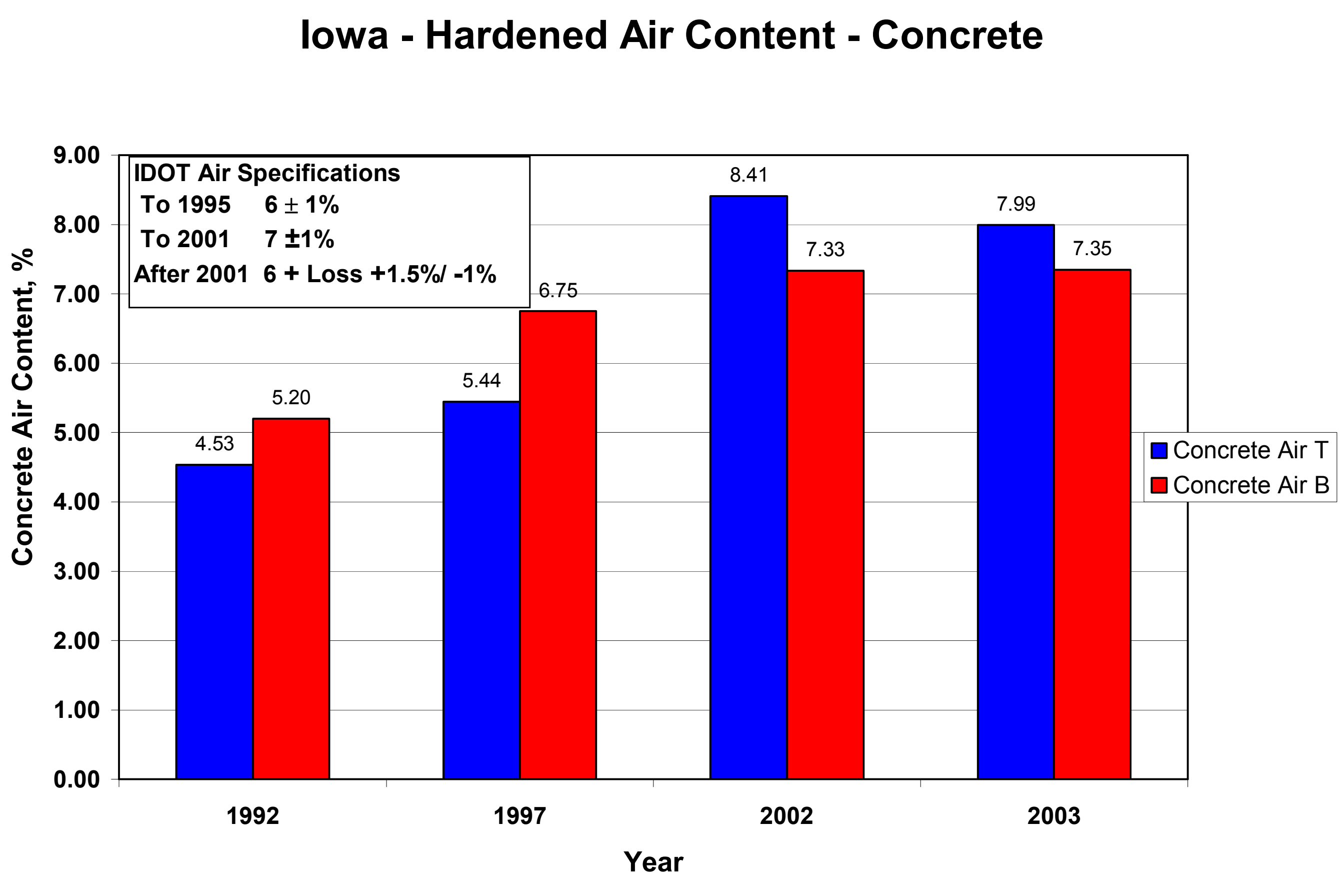

Table 8. Air Void Spacing Factors 1992 to 2003