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84-2

INFLUENCE OF DESIGN CHARACTERISTICS ON CONCRETE DURABILITY

MISSOURI HIGHWAY AND TRANSPORTATION DEPARTMENT

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16. Abstract

The primary objective was to investigate influence of cement factor, percent air, maximum coarse aggregate size, and percent of total aggregate as sand on the performance of concrete subjected to freeze-and-thaw cycling. An important secondary objective was to document air-void system characteristics of hardened concrete with these same design factors.

Data in this report includes durability and expansion of freeze-and-thaw beams, air-void system characteristics, flexural strength, and compressive strength in conjunction with concrete design factors and fresh concrete characteristics.

Resistance to freeze-and-thaw increased as maximum size of coarse aggregate decreased. Neither compressive strength nor flexural strength changed with maximum size of coarse aggregate.

Based on the results of this study, a desirable concrete pavement mix design using D-crack prone coarse aggregate of the materials tested would be: 1/2 maximum size coarse aggregate, 38 percent of aggregate as sand, 6.5 sacks of cement per cubic yard, 6.0±1.5 percent air by volume, and 2 1/2 inch maximum slump.

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INFLUENCE OF DESIGN CHARACTERISTICS ON CONCRETE DURABILITY

STUDY 84-2

Prepared By

MISSOURI HIGHWAY AND TRANSPORTATION DEPARTMENT

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The opinions, findings, and conclusions expressed in this publication are not necessarily those of the Federal Highway Administration.

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LIST OF ABBREVIATIONS

Abbreviation	Name
ACI	American Concrete Institute
Aggr.	Aggregate
ANOVA	Analysis of Variance
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
Bbls	Bubbles
BF	Bethany Falls
BUR	Burlington
CA	Coarse Aggregate
CF	Cement Factor
Compr	Compressive
Conc	Concrete
Cu Yd	Cubic Yard
Cy	Cycle(s)
DF	Durability Factor
Flex	Flexure or Flexural
Frm	Formation
Grd or Grad	Gradation
In	Inch(es)
Max	Maximum
Mod	Modulus
PCCP	Portland Cement Concrete Pavement
psi	Pounds Per Square Inch
Sk	Sack(s)

INTRODUCTION

Concrete pavement durability characteristics have been the subject of many studies by this and various agencies. Currently, D-Cracking in the northern and western portion of the state is the primary distress resulting in reduced durability of concrete pavements. After eliminating gravel as a source of coarse aggregate for PCCP, D-cracking is generally associated with the use of marginal limestone coarse aggregates in concrete subjected to freeze-and-thaw cycling.

In 1967, various steps were taken to alleviate the problem of D-cracking in PCCP with limestone coarse aggregate. Major emphasis was to increase the quality of coarse aggregate and reduce the maximum size from two inches to one inch. Sand content was also increased from about 39 percent to 45 percent of total aggregate. These restrictions have been beneficial but have not eliminated the increased maintenance and shortened service life generally associated with D-cracking.

In 1983, maximum size of coarse aggregate was reduced to 3/4" and sand content was increased to 50 percent of total aggregate. In conjunction with these latest changes, a field experiment with six test sections on two adjacent projects was established on Route I-435, Clay County. Burlington Limestone, an aggregate with no known history of D-cracking (1 1/2" maximum size) was used in one section while Bethany Falls Limestone, an aggregate with a known history of moderate to serious D-cracking (1", 3/4", or 1/2" maximum size) was used in the remaining five sections.

Information from the various test sections was reported in MCHRP 84-1 "Evaluation of Air-Void System in PCCP With Different Nominal Sizes of Coarse Aggregate".

This laboratory study was an extension of the field study and utilized coarse aggregate and cement from the same sources obtained while paving was in progress. A factorial experiment was established to independently evaluate four concrete design factors which are generally adjusted simultaneously in paving mixes. The factorial experiment included designs typical of those in the field experiment, and some which may not have been appropriate for paving concrete. Design factor ranges are shown in Table 1 with specific material and design combinations shown in Tables 2 through 5.

While related to the earlier studies, direct correlations have not been made between characteristics of concrete prepared under laboratory and field conditions.

CONCLUSIONS

This laboratory study investigated the performance of concrete when using selected sizes of D-crack prone coarse aggregate with several combinations of cement factors, percent sand, and percent air in the fresh concrete. As might be expected, changing a concrete mix design factor often improved one hardened concrete characteristic at the expense of another equally important characteristic. The following conclusions are believed to be reasonable.

1. A PCCP mix design utilizing one-half inch maximum size coarse aggregate, 6.5 sacks of cement per cubic yard of concrete (with Class A sand), 38 percent of the total aggregate as sand, and 6 ± 1.5 percent air content was determined to have very good design characteristics. The mix design should provide acceptable compressive and flexural strength, air-void characteristics, and increased concrete durability of PCCP.

2. A PCCP mix design utilizing three-quarter inch maximum size coarse aggregate, 6.3 sacks of cement per cubic yard of concrete (with Class A sand), 38 percent of the total aggregate as sand, and 6 ± 1.5 percent air content was determined to have better characteristics than designs presently in use. The mix design should provide acceptable compressive and flexural strength, air-void characteristics, and increased concrete durability.

3. Resistance to freeze-and-thaw increased as maximum size of coarse aggregate decreased.

4. Compressive and flexural strengths were satisfactory regardless of maximum size of coarse aggregate used.

5. Compressive and flexural strengths increased as the cement factor increased and decreased with increased air content.

6. Maintaining a constant cement to mortar ratio and constant air to mortar ratio optimized strength, durability, and air-void system characteristics for mix designs with 38 percent of the total aggregate as sand. For mixes with higher sand content, air content had to be increased an additional 0.1% for each 1.0% increase in sand to retain acceptable air-void system characteristics.

7. Increasing amount of sand from 38 to 45 or 50 percent caused a small increase in compressive strength but a small decrease in flexural strength.

IMPLEMENTATION

Monitoring of PCCP sections with various mix designs will continue in an effort to correlate resistance to laboratory freeze-and-thaw cycling, air-void system characteristics, and strength with field performance.

Mix design guidelines are being revised to reflect the findings to date and will be reviewed as field performance data becomes available.

DISCUSSION

The primary objective of this study was to investigate performance of concrete utilizing selected sizes of coarse aggregate with several combinations of cement factor, percent sand, and percent air in the fresh concrete. It was designed as a continuation of the preliminary field and laboratory phase which was initiated in 1983 on two adjacent construction projects on Route I-435, Clay County. Maximum coarse aggregate sizes of 1 1/2" (Gradation B), 1" (Gradation D), 3/4" (Gradation C), and 1/2" (Special Gradation) were included in all phases of these studies.

Results of the earlier phase were published in a MCHRP Report 84-1 "Evaluation of Air-Void System in PCCP with Different Nominal Sizes of Coarse Aggregate".

This study was initiated to provide additional information about the individual influence of design variables and how they interact with one another. Cement factor, aggregate size, sand proportion, and air content were independent variables in a factorial design at 2, 3, 2, and 2 levels respectively. Compressive strength, flexural strength, initial dynamic modulus of elasticity, expansion per freeze-and-thaw cycle, freeze-and-thaw durability factor, and air-void system characteristics were determined for each combination of design factors.

Three gradations or maximum sizes of Bethany Falls Limestone coarse aggregate were the main focus of this study. One size of Burlington Limestone coarse aggregate was included since it had been part of the field phase of this series. Chert in the Burlington limestone coarse aggregate caused low

durability factors, but performance of pavement with Burlington Limestone coarse aggregate is satisfactory with the exception of popouts on the surface.

Concrete mix design factors, sources of material, and ranges in measured characteristics of fresh concrete are shown in Table 1. Average characteristics of fresh concrete for each mix design and average compressive and flexural strength are shown in Table 2. Coarse aggregate formation, gradation, and maximum size are also shown in this table. Matching data in Tables 3 through 5 can be identified by the set name in the first column of each table.

Dynamic modulus of elasticity, durability factor and expansion data for beams subjected to freeze-and-thaw cycling is shown in Table 3. Resistance of concrete to freeze-and-thaw cycling increased as maximum size of coarse aggregate decreased. This confirms the validity of specifying a reduced maximum size for a coarse aggregate which is susceptible to D-cracking.

Expansion of concrete has been proposed as being a more reliable indicator of susceptibility to D-cracking than durability factor. In this and other studies recently completed, both were apparently equally effective means of differentiating performance of various concretes which were subjected to freeze-and-thaw cycling. Neither method has been related with field performance of Missouri aggregates.

Average mix design air-void system characteristics determined by linear traverse methods are shown in Table 4 along with some characteristics of the fresh concrete.

Analyses of variance indicated each of the four variables assumed to be independent (concrete mix design factors) had a significant influence on most of the measured parameters (hardened concrete characteristics). They also indicated interaction (lack of total independence) between two or more of the mix design factors and therefore computed average influence of a factor was not true for all levels of the variable. Because of these interactions, this data needed to be analyzed by other methods.

Table 5 illustrates the evaluation of each mix design on a pass-fail basis against fixed values of five characteristics. As would have been expected, changing a concrete mix design factor often improved one hardened concrete characteristic at the expense of another equally important characteristic. A method for optimizing all concrete mix design factors simultaneously was desirable.

Those concretes with approximately the same cement factor per cubic yard of mortar and percent air in mortar as the reference concrete generally were the best overall performers for any given size of coarse aggregate. Percent mortar in the hardened concrete was one of the characteristics measured by linear traverse (ASTM C457) on three cylinders from each of the 26 combinations of mix design factors.

A series of multiple regressions indicated percent mortar in hardened concrete could be reliably predicted for any maximum size of coarse aggregate. The three sizes of coarse aggregate in the main study had regression coefficients which were very close except for intercept. An overall set of regression

constants were then computed which provided a reasonable prediction of percent mortar for any combination of coarse aggregate maximum size, percent sand, cement factor, and percent air used in these mix designs.

Strengths and air-void system characteristics for concrete with 6.1 sacks of cement per cubic yard, 5.5% air, and 38 to 40 percent of total aggregate as sand with gradation A paving stone have been proven in actual field use over many years. Therefore, it was selected as the reference cement factor per cubic yard of mortar and percent air in mortar. Theoretical cement factors and air contents were then computed for each of the mix designs used in this study. Differences between actual and theoretical values were then computed and used as a basis for comparing other measured characteristics.

With the exception of the average air-void spacing factor, most characteristics were within acceptable limits when deviations in cement factor per unit mortar and percent air in mortar were small.

Maintaining an acceptable spacing factor was found to require additional air in the mortar for concretes with higher percentages of the total aggregate as sand. About 0.1 percent more air in the fresh concrete was required for each additional percent sand in the total aggregate.

Theoretical cement factor and air content were computed for several mix designs meeting these requirements. Typical designs are shown in Table 6. All values in this table represent target values and usual tolerances would apply when included in

specifications. Differences in cement factor usually applied for other classes of sand would be assumed to be valid.

For economic reasons, mixes lower in percentage of sand (and consequently lower in cement factor from the maximum used in this study) have been selected. It is not possible to predict how much additional service life of pavement would be realized from the higher durability factor of the special gradation of coarse aggregate (1/2 inch maximum size) when compared to Gradation C (3/4 inch maximum size).

Comments below pertain to general observations of influence on particular characteristics by individual concrete mix design factors.

As was expected, increasing air content caused a reduction in both compressive and flexural strengths. Increasing amount of sand in the total aggregate from 38% to 45% or 50% caused a small increase in compressive strength but a small decrease in flexural strength. Increasing cement factor from 6.1 to 7.1 sacks per cubic yard caused a large increase in both compressive and flexural strengths.

Air-void system characteristics were degraded by either increasing percentage of total aggregate as sand or by decreasing maximum size of coarse aggregate. These changes were at least as great as had been expected. Increasing the cement factor generally caused a slight improvement in system air-void characteristics. Increasing the air content of fresh concrete improved air-void system characteristics.

Quantities of air agent per sack of cement to produce a given air content were found to decrease as size of coarse

aggregate decreased and percentage of sand increased. Therefore, quantity of air agent per sack of cement to produce the optimum air content for any given set of materials may be nearly constant regardless of coarse aggregate size or percentage of sand.

One concern some engineers expressed about raising the air content for PCCP mixes with smaller maximum size coarse aggregate was fear of very large strength reductions when both decreased aggregate size and higher air content was specified simultaneously. Compressive and flexural strength both showed very small changes with maximum size of coarse aggregate.

APPENDIX

Four batches of concrete were prepared for each of the 26 concrete mix designs. One batch of each mix design was prepared during each of four consecutive weeks. Batching order was randomized each week.

Air content and slump were measured on each batch of concrete to determine whether it was acceptable for molding of test specimens. Each unacceptable batch of concrete was immediately re-batched with appropriate adjustments in air agent and/or water cement ratio. One flexural strength beam, one slow freeze-and-thaw beam, one compressive strength cylinder, and one linear traverse cylinder were molded from each acceptable batch of concrete. (A delay in delivery of cylinder molds prevented molding of traverse cylinders during week three.)

All concrete was covered with polyethylene and cured in molds until one day old. Molds were stripped at one day. Beams were then stored in the moist room until seven days old. They were then stored in saturated lime-water at room temperature until 35 days old. At this time they were subjected to their first freeze cycle or tested for flexural strength. Cylinders were stored in the moist room from one day until 28 days old. Compressive strength cylinders were tested at this time. Linear traverse cylinders were stored in air at room temperature until they could be sawed and polished for microscopic examination.

Freeze-and-thaw beams were subjected to one freeze cycle in 0° air per week with intermediate storage in saturated lime-water at room temperature (generally about 70°F). Beams were placed in tanks of constantly flowing water at 40°F and allowed

to come to equilibrium before the freeze cycle and before testing after each freeze cycle. Testing otherwise generally met the requirements of ASTM C666 and included determination of fundamental dynamic frequency, weight, and length of each beam after each freeze-and-thaw cycle.

At the beginning of the study, linear traverse equipment included a binocular microscope with 72X maximum magnification. This microscope was later replaced with one having a higher range which was used at 100X magnification for most of the study. A few small air voids may have been missed when traversing with the old microscope, but no marked difference in measured air-void system characteristics was noted between samples examined before and after the change in microscopes.

All slabs were sawed with a diamond saw blade and hand-ground with progressively smaller grit on a speedlap machine. Polishing with #1000 grit was the final step prior to microscopic examination.

Table 1

MIX DESIGN FACTORS AND CHARACTERISTICS OF FRESH CONCRETE

	Design*	Minimum	Maximum
Cement Factor (Sk/cu yd)	6.1 7.1	5.98 6.96	6.16 7.19
Slump (Inches)	2.0	1.3	2.7
Air Content (Percent)	5.0 7.5	4.3 6.7	6.0 9.3

*Target values

All materials met the requirements of Missouri Standard Specifications for Highway Construction, 1981 :

Coarse aggregate: Section 1005.1 and gradation requirements for Gradations B, C, and D. Special gradation (1/2" maximum size) met the requirements of Section 1005.1 and gradation requirements of Size Number 8, AASHTO Designation M43-82(1986).

Fine aggregate: Section 1005.2 and Gradation requirements of Section 1005.2.4.1. Proportion ranged from 38 to 50 percent of total aggregate.

Coarse aggregate retained on the #4 sieve was vacuum saturated while all other aggregate was air dry at the time of batching.

Bethany Falls Limestone was produced by Missouri Rock Inc. of Missouri City, Missouri. Material from all gradations was blended prior to screening and vacuum saturating. Appropriate gradations were prepared by combining individual fractions at the time of batching.

Burlington Limestone was produced by Hilty Quarries of Lincoln, Missouri.

Fine aggregate was Class A Kansas River Sand produced by Builders Sand Company of Kansas City, Kansas.

Cement was Type I from Missouri Portland Cement Company of Sugar Creek, Missouri.

Air-entraining agent was Ad-Aire Extra Strength. Quantity was adjusted as needed to meet the desired range of air content.

Water was adjusted as needed to maintain constant slump.

Table 2

STRENGTH OF CYLINDERS AND BEAMS

Set	Coarse Aggr Frm	Coarse Aggr Grd	Coarse Aggr Max	CF	% Sand	% Air	Slump (In)	Age Strength* (psi) Compr	Age Strength* (psi) Flex
B635	BUR	B	1 1/2	6.10	38	5.4	1.9	5850	1040
B637				6.10	38	8.1	2.0	4680	896
C635	BF	C	3/4	6.12	38	5.0	1.9	5970	1075
C637				6.09	38	8.0	2.0	4820	914
C655				6.08	50	5.3	1.8	5580	1011
C657				6.07	50	8.2	2.0	4960	882
C735				7.10	38	5.4	2.1	6270	1038
C737				7.09	38	7.9	2.0	4770	968
C755				7.10	50	5.1	2.0	6760	1070
C757				7.09	50	7.8	2.2	5680	984
D635	BF	D	1	6.09	38	5.4	2.0	5460	1021
D637				6.10	38	7.6	2.0	4740	883
D645				6.11	45	5.0	2.0	6000	969
D647				6.08	45	8.1	2.0	5000	899
D735				7.10	38	5.3	2.0	6300	1012
D737				7.10	38	8.0	2.0	5110	944
D745				7.11	45	5.0	2.0	6430	1040
D747				7.10	45	7.8	2.1	5620	934
S635	BF	S	1/2	6.11	38	4.8	2.0	5960	1069
S637				6.08	38	8.1	2.0	4880	950
S655				6.08	50	5.2	1.8	5590	970
S657				6.06	50	8.0	2.0	5000	970
S735				7.10	38	5.2	2.0	6480	1087
S737				7.06	38	8.2	2.0	5180	1006
S755				7.10	50	5.0	1.9	6270	1054
S757				7.07	50	8.0	2.0	5730	961

*28 Day Compressive Strength
35 Day Flexural Strength

S = Special Gradation (1/2" Maximum)

NOTE: Set identification consists of coarse aggregate gradation letter plus units digit of design cement factor plus tens digit of percent sand plus units digit of design percent air. As an example, set B635 denotes the following:

B = Coarse aggregate gradation B
6 = Design cement factor of 6.1 sacks per cubic yard
3 = Design sand percentage of 38
5 = Design air content of 5.0 percent

Table 3

DURABILITY AND EXPANSION
of Freeze-and-Thaw Beams

Set	Coarse Aggr Frm	Coarse Aggr Grd	CF	% Sand	% Air	Initial Mod	DF	% Expansion Terminal	% Expansion Per 100 Cy
B635	BUR	B	6.10	38	5.4	6.2	26*	0.148	0.398
B637			6.10	38	8.1	5.6	32*	0.127	0.274
C635	BF	C	6.12	38	5.0	6.2	81	0.092	0.092
C637			6.09	38	8.0	5.5	91	0.047	0.047
C655			6.08	50	5.3	6.1	82	0.102	0.102
C657			6.07	50	8.2	5.6	88	0.058	0.058
C735			7.10	38	5.4	6.1	87	0.086	0.086
C737			7.09	38	7.9	5.6	94	0.052	0.052
C755			7.10	50	5.1	6.2	87	0.091	0.091
C757			7.09	50	7.8	5.8	91	0.068	0.068
D635	BF	D	6.09	38	5.4	6.2	66	0.120	0.127
D637			6.10	38	7.6	5.6	73	0.097	0.098
D645			6.11	45	5.0	6.2	64	0.130	0.150
D647			6.08	45	8.1	5.7	73	0.091	0.094
D735			7.10	38	5.3	6.3	61	0.138	0.159
D737			7.10	38	8.0	5.7	69	0.114	0.117
D745			7.11	45	5.0	6.3	67	0.142	0.155
D747			7.10	45	7.8	5.7	74	0.107	0.109
S635	BF	S	6.11	38	4.8	6.0	97	0.040	0.040
S637			6.08	38	8.1	5.4	96	0.027	0.027
S655			6.08	50	5.2	6.0	93	0.063	0.063
S657			6.06	50	8.0	5.6	97	0.028	0.028
S735			7.10	38	5.2	6.1	100	0.044	0.044
S737			7.06	38	8.2	5.5	100	0.027	0.027
S755			7.10	50	5.0	6.2	97	0.060	0.060
S757			7.07	50	8.0	5.7	100	0.030	0.030

S = Special Gradation (1/2" Maximum)

NOTE: Set identification consists of coarse aggregate gradation letter plus units digit of design cement factor plus tens digit of percent sand plus units digit of design percent air. See example in Table 2.

*Pavement performance when using Burlington Limestone is satisfactory. However, in the freezing and thawing test, some chert in the Burlington Limestone caused low durability.

Table 4

LINEAR TRAVERSE DATA

Set	CA Grad	CF	Slump (In)	Percent Air: Fresh Conc All Bbls	Percent Air: Hardened Conc All Bbls	Percent Air: Hardened Mortar All Bbls	Percent Air: Hardened Mortar Bbls (1)	Percent: Bbls (1)	Percent: Mortar	Spacing Factor
B635	B	6.09	2.1	5.4	4.23	7.60	3.13	41.2	55.5	0.0065
B637	B	6.09	2.0	8.2	6.74	11.60	6.26	54.0	58.0	0.0037
C635	C	6.11	2.1	5.0	4.28	7.54	2.74	36.3	56.7	0.0071
C637	C	6.08	2.2	8.2	7.12	12.20	5.80	46.9	58.0	0.0044
C655	C	6.06	1.6	5.4	4.62	7.18	1.57	21.9	64.6	0.0114
C657	C	6.04	2.1	8.6	6.87	10.47	4.23	40.3	65.6	0.0056
C735	C	7.09	2.3	5.4	4.3	7.46	3.17	42.5	57.7	0.0059
C737	C	7.09	2.0	7.8	6.40	10.67	5.23	49.1	60.3	0.0043
C755	C	7.07	2.1	5.4	4.67	7.42	1.80	24.7	63.3	0.0102
C757	C	7.08	2.0	7.8	5.9	8.80	3.60	41.2	67.9	0.0055
D635	D	6.08	2.2	5.4	3.92	7.19	3.30	45.9	54.6	0.0060
D637	D	6.10	2.2	7.6	6.30	10.94	5.72	52.3	57.6	0.0043
D645	D	6.09	2.0	5.2	4.50	7.52	2.52	33.3	59.8	0.0078
D647	D	6.08	1.9	8.1	6.68	10.78	4.78	44.5	61.8	0.0048
D735	D	7.08	2.1	5.4	4.23	7.44	3.25	43.9	56.8	0.0058
D737	D	7.08	2.2	8.2	6.19	10.52	5.42	51.6	58.8	0.0041
D745	D	7.10	2.1	5.2	4.36	7.21	2.30	32.4	60.6	0.0078
D747	D	7.08	2.0	7.8	5.73	9.18	4.52	49.2	62.5	0.0046
S635	S	6.11	2.0	4.9	4.53	7.8	2.39	30.0	58.1	0.0095
S637	S	6.06	2.2	8.4	6.48	11.14	5.24	47.2	58.2	0.0049
S655	S	6.09	1.6	5.0	4.9	7.46	1.44	19.6	65.9	0.0129
S657	S	6.05	1.9	8.3	7.35	10.99	3.75	33.9	66.9	0.0065
S735	S	7.10	2.0	5.2	4.60	7.73	2.61	33.8	59.5	0.0074
S737	S	7.05	2.1	8.3	6.58	10.79	5.56	51.4	61.0	0.0043
S755	S	7.08	1.9	5.2	4.7	6.84	1.45	20.9	68.3	0.0124
S757	S	7.05	2.0	8.3	6.52	9.61	3.99	48.1	67.6	0.0057

(1) Smaller than 0.0060 inch chord.

S = Special Gradation (1/2" Maximum)

NOTE: Set identification consists of coarse aggregate gradation letter plus units digit of design cement factor plus tens digit of percent sand plus units digit of design percent air. See example in Table 2.

Table 5

EVALUATION OF FIVE CHARACTERISTICS

Set	Strength Compr >5000 psi	Strength Flex >1000 psi	Spacing Factor <0.0065 inches	100 Cycle Expansion <0.065 percent	Durability Factor >90 for 100 Cycles	Number of Positive Ratings
B635	Yes	Yes	Yes	No	No	3
B637	No	No	Yes	No	No	1
C635	Yes	Yes	No	No	No	2
C637	No	No	Yes	Yes	Yes	3
C655	Yes	Yes	No	No	No	2
C657	No	No	Yes	Yes	No	2
C735	Yes	Yes	Yes	No	No	3
C737	No	No	Yes	Yes	Yes	3
C755	Yes	Yes	No	No	No	2
C757	Yes	No	Yes	No	Yes	3
D635	Yes	Yes	Yes	No	No	3
D637	No	No	Yes	No	No	1
D645	Yes	No	No	No	No	1
D647	No	No	Yes	No	No	1
D735	Yes	Yes	Yes	No	No	3
D737	Yes	No	Yes	No	No	2
D745	Yes	Yes	No	No	No	2
D747	Yes	No	Yes	No	No	2
S635	Yes	Yes	No	Yes	Yes	4
S637	No	No	Yes	Yes	Yes	3
S655	Yes	No	No	Yes	Yes	3
S657	No	No	Yes	Yes	Yes	3
S735	Yes	Yes	No	Yes	Yes	4
S737	Yes	Yes	Yes	Yes	Yes	5
S755	Yes	Yes	No	Yes	Yes	4
S757	Yes	No	Yes	Yes	Yes	4

S = Special Gradation (1/2" Maximum)

NOTE: Set identification consists of coarse aggregate gradation letter plus units digit of design cement factor plus tens digit of percent sand plus units digit of design percent air. See example in Table 2.

Table 6

EQUIVALENT CEMENT FACTOR AND AIR CONTENT
By Coarse Aggregate Size and Percent Sand

(Examples for Typical Combinations)

Coarse Aggregate Gradation	Percent of Aggregate As Sand	Cement Factor, Sacks	Air Content, Percent
B	38	6.1	5.5
C	38	6.3	6.0
	45	7.0	7.0
	50	7.5	8.0
D	38	6.1	5.5
	45	6.8	7.0
	50	7.3	8.0
S	38	6.5	6.0
	45	7.1	7.0
	50	7.6	8.0

S = Special Gradation (1/2" maximum)

PROPOSED DESIGN VALUES FOR USE IN AREAS WITH D-CRACKING

C (1)	38	6.3	6.0
S (2)	38	6.5	6.0

(1) This combination utilizes the currently specified size of coarse aggregate and should provide performance slightly better than the current design. This would probably have the lowest initial cost of any of the acceptable designs.

(2) This combination should provide performance better than combination (1), but initial cost will be higher because of additional aggregate crushing required and a small additional amount of cement. No specific increase in service life could be predicted from the use of this design. Use of this design may be warranted in locations where pavement repair operations trigger serious traffic related problems.