SCHOOL OF
CIVIL ENGINEERING
OKLAHOMA STATE UNIVERSITY

FREEZE-THAW DURABILITY OF CONCRETE MADE WITH MARGINAL AGGREGATE

By

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FINAL
REPORT

Report No. FHWA/OK 91(04)

JUNE, 1991

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.
FHWA/OK 91(04)

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
FREEZE-THAW DURABILITY OF CONCRETE MADE WITH MARGINAL AGGREGATE

5. REPORT DATE
June 1991

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
John P. Lloyd

8. PERFORMING ORGANIZATION REPORT
90-04

9. PERFORMING ORGANIZATION AND ADDRESS
School of Civil Engineering
Oklahoma State University
Stillwater, OK 74078-0327

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.
2137

12. SPONSORING AGENCY NAME AND ADDRESS
Oklahoma Department of Transportation
Research and Development Division
200 NE 21st Street
Oklahoma City, OK 73105

13. TYPE OF REPORT AND PERIOD COVERED
Final Report: Jan. 1986-June 1991

14. SPONSORING AGENCY CODE
Item 2137

15. SUPPLEMENTARY NOTES
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. ABSTRACT

Much of the crushed limestone aggregate produced in the Oklahoma region is susceptible to freeze-thaw action and can result in popouts and D-cracking in concrete. Four series of tests involving over 120 batches of concrete were conducted to establish if adjustment of certain mix parameters would mitigate the detrimental properties of the aggregate. Freeze-thaw tests were conducted in accordance with Procedure A of ASTM C 666.

The first series of tests demonstrated the importance of the maximum size of coarse aggregate on the durability of concrete. By reducing the maximum size from 1 in. to 1/2 in., durability factors were increased from approximately 40 to 80. The second series of tests revealed that if the water-to-cement ratio is reduced below the range normally used for pavement construction, durable concrete can be made with marginal aggregate.

The third and fourth series considered the addition of Class C fly ash or silica fume to the mix. In the case of Class C fly ash, concrete made with marginal aggregate from one source experienced no major influence from the presence of fly ash. The durability of the concrete increased with an increase of compressive strength regardless of the fly ash percentage. However, with concrete made with aggregate from another source, durability remained low regardless of strength. Silica fume did not appear to significantly alter the durability of concrete.

17. KEY WORDS Aggregate Size, Compressive Strength, Concrete Durability, Fly Ash, Freeze-Thaw Durability, Silica Fume

18. DISTRIBUTION STATEMENT
No Restrictions

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
None	None	50	

FREEZE-THAW DURABILITY OF CONCRETE MADE WITH MARGINAL AGGREGATE

Final Report

By

John P. Lloyd

Prepared as Part of an Investigation
Conducted by the
School of Civil Engineering
Oklahoma State University
Sponsored by the
Research Development Division
Oklahoma Department of Transportation
State of Oklahoma
and the Federal Highway Administration
June, 1991

EXECUTIVE SUMMARY

A multi-year program was conducted to determine if the adjustment of certain mix parameters would mitigate the influence of coarse aggregate susceptible to D-cracking. Four series of tests considered the influence of maximum size of coarse aggregate, water-to-cement ratio, presence of Class C fly ash, and addition of silica fume. Prisms were subjected to rapid freezing and thawing in water in accordance with Procedure A of ASTM C 666.

It was found that satisfactory durability was achieved if the maximum size of the marginal aggregate was reduced from 1 in. (size No. 57) to 1/2 in. (size No. 7). Less improvement in durability was achieved when the maximum size was 3/4 in. (size No. 67).

As the water-to-cement ratio was reduced from approximately 0.5 to 0.3, the improvement in the quality of the paste and the strength of the concrete led to major increases in the durability factor of mixes made with marginal aggregate. When 19 and 37 percent fly ash was incorporated in concrete made with W/(C+FA) from 0.5 to 0.3, the concrete made with one source of marginal aggregate exhibited higher durability—apparently because of improved strength; the presence of fly ash had little influence. However, for another source of marginal aggregate, the presence of fly ash was detrimental. As the strength increased with a decrease in W/(C+FA), the durability remained relatively unchanged and no benefit from increase in strength was apparent. Further research in this area is needed.

Silica fume was used at percentages of 0, 10, and 20 percent in mixes with a W/(C+SF) of 0.5. There was no significant change in durability based on the presence of silica fume. Because the hardened air void system was not measured, it is not known if silica fume and superplasticizers had produced a detrimental influence on the spacing factor of these concretes.

ACKNOWLEDGMENTS

The investigation reported herein was conducted as a project of Engineering Research at Oklahoma State University in the School of Civil Engineering under sponsorship of the Oklahoma Department of Transportation and the Federal Highway Administration.

The author would like to express his gratitude to all those who contributed to the success of this investigation. In particular, the major contributions of Mr. Bassam Elias Touma, Mr. Troy Travis, Ms. Rui Wang, and Mr. Jaganath Venkataramanan, who served as senior laboratory assistants, are acknowledged. In addition, the donation of the portland cement used in this study by Blue Circle Cement is appreciated.

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1. INTRODUCTION

1.1 General

Long lasting pavements can only be achieved through proper design, construction, and maintenance. The service life of concrete pavements is sometimes limited by inherent freeze-thaw durability of the concrete. Often concrete is viewed as a two-phase material—paste and aggregate. While durability of the paste phase can be achieved during the manufacturing process by use of air entrainment, limitations on the water-to-cement ratio and proper curing, durability of the aggregate phase is sometimes more difficult to control. Although the ideal approach is to manufacture concrete using aggregate which is highly resistant to freeze-thaw action, such aggregate is not readily available in many regions of the country including Oklahoma.

1.2 Purpose of the Present Investigation

This study was undertaken with the philosophy that diminishing supplies of high quality aggregate will increasingly necessitate the manufacture of concrete using marginal and substandard aggregate. Research was conducted to determine the influence of certain mix parameters on the durability of concrete made with marginal aggregate. It is anticipated that the results will aid in striking the best compromise between durability and cost when high quality aggregate is not available.

1.3 Scope of the Experimental Program

Coarse aggregate for most of this program was obtained from a single shipment from each of three quarries. One quarry had a history of producing excellent aggregate while the other two quarries usually produced substandard aggregate not meeting specifications of the Oklahoma Department of Transportation. Near the end of the project, when additional aggregate was needed, stone from a fourth quarry was utilized because one of the original quarries was closed.

Four major parameters were considered by this research: maximum size of coarse aggregate, compressive strength, presence of Class C fly ash, and use of condensed silica fume. Freeze-thaw tests were conducted in accordance with ASTM C 666, Resistance of Concrete to Rapid Freezing and Thawing, Procedure A, Rapid Freezing and Thawing in Water.

2. BACKGROUND

2.1 Mechanisms of Freeze-Thaw Damage

Much of the work to explain the mechanisms of frost damage has been conducted by Powers and Helmuth and others at the Portland Cement Association Laboratories. Powers [1] proposed that two mechanisms involving hydraulic pressure and osmotic pressure were responsible for frost damage. During the liquid to solid phase change, water expands approximately 9 percent. If concrete is highly saturated, this process will result in the formation of hydraulic pressures in the unfrozen water in capillaries and macropores. In nonair-entrained concrete, water is unable to diffuse through the capillaries to the exterior without a significant buildup in pressure; as a result, a significant volumetric expansion occurs during freezing. For properly air-entrained concrete, a closely spaced system of air voids prevents a buildup in pressure and no expansion occurs during the freezing process.

Water in capillaries contains soluble substances such as alkalis and chlorides. As water in capillaries freezes, the formation of ice crystals causes the salt concentration in unfrozen water to increase on concentration, resulting in local concentration gradients with nearby locations which are slightly warmer. These gradients will generate osmotic pressures.

Litvan [2] proposed that as water in capillaries freezes, the absorbed water in the gel pores will become supercooled and be at thermodynamic disequilibrium with the frozen water in the capillaries at a lower energy state. This disequilibrium would cause water in the gel pores to migrate to the capillary pores and increase the supply of water to fill the capillaries with ice and generate hydraulic pressures.

2.2 D-Cracking

Some coarse aggregate has low permeability and high strength. Such aggregate does not tend to become saturated and is resistant to frost action. Aggregates of intermediate or high permeability can lower the freeze-thaw durability of concrete. For aggregate which is highly permeable, water is able to move freely as ice begins to form; however, the surrounding paste may be unable to accommodate the water expelled from within the aggregate without development of hydraulic pressure and damage to the paste.

For aggregates of intermediate permeability, water is unable to diffuse freely as freezing of internal water proceeds. Hydraulic pressures are developed within the aggregate sufficient to fail the aggregate. For this type of damage, the maximum size of the aggregate particles is important. If the size is less than what is referred to as the "critical size," the buildup of internal pressure is limited by the presence of a free surface a short distance from the interior. The critical size is dependent on the rate of freezing and degree of saturation, but is usually in the range of 3/8 in. to 1/2 in.

D-cracking is a form of freeze-thaw damage named for the visual appearance of deterioration in pavement with longitudinal and transverse joints. In advanced stages of deterioration, cracks tend to form parallel to the joints with curving of the cracks near the intersection of transverse and longitudinal joints giving the boundary of the deterioration a "D" shape. D-cracking is generally caused by the presence of aggregate which has an internal void system characterized by a large percentage of the pores with a diameter less than 1 μm. Problem aggregates are normally of sedimentary origin and can be calcareous or siliceous. D-cracking is a gradual process requiring many freeze-thaw cycles and a source of water to maintain a high degree of saturation in the concrete.

In Iowa, Dubberke and Marks [3] have identified a chemical mechanism of D-cracking for pavements containing ferroan dolomite aggregate. They suggest that the iron substitution for magnesium in the dolomite crystal is associated with instability of the aggregate in the presence of de-icing salts.

2.3 Influence of Mix Parameters on D-Cracking

Beyond the exclusion of aggregate susceptible to D-cracking from concrete, there are a number of mix parameters which may influence the durability of concrete made with marginal aggregate. As discussed in the previous section, if the coarse aggregate is graded such that the maximum aggregate size is less than the critical size, the freeze-thaw durability will be improved. This has been a common approach when high quality aggregate is not available within a reasonable distance. However, concrete made with small size coarse aggregate will generally contain a larger percentage of paste and may be more expensive and exhibit greater drying shrinkage than a concrete made with a coarse aggregate of larger maximum size. In addition, reducing the maximum size of the coarse aggregate will be detrimental to aggregate interlock at contraction joints.

Recognizing the role that the degree of saturation plays in the D-cracking phenomenon, mix parameters which alter the permeability of the binding matrix have the potential of influencing the freeze-thaw durability of concrete. The primary parameter influencing the permeability of the paste is the water-to-cement ratio. Providing a high quality paste is a fundamental principle of producing frost-resistant concrete. For example, the Oklahoma Department of Transportation (ODOT) Standard Specifications stipulate a minimum cement content and maximum water-to-cement ratio for various classes of concrete. Most research in the area of D-cracking has concentrated on techniques to identify substandard aggregate or aggregate benefication. Efforts to improve concrete durability by using higher strength concrete have employed high quality aggregate. For example, numerous studies have considered high strength, low permeability concrete for bridge decks in an effort to minimize chloride penetration and to reduce the quantity of freezable water. In recent years, concrete strengths in excess of 10,000 psi have been employed in construction. Air entrainment is often difficult to accomplish with such mixes; however, if the high strength concrete is well cured, there will be virtually no capillaries and freezable water. For such concrete, the need for air entrainment is a matter of uncertainty. Whiting [4] found that 8,000 and 10,000 psi concrete exhibited severe scaling in the presence of de-icer, while similar concrete with a 6,000 psi strength gave satisfactory performance.

During the past 20 years, admixtures have received wide acceptance. The three which have received the most attention are Class C fly ash, silica fume, and high range water reducers (superplasticizers). Research studies pertaining to concrete durability and the use of these admixtures have generally focused on the direct influence of a specific admixture. For example, earlier work at Oklahoma State University [5] found that fly ash can be used to replace up to 50 percent of the cement on a weight basis with no detrimental influence on freeze-thaw performance. Johnson [6] found that mixes with up to 42 percent Class C fly ash or up to 15 percent silica fume can be durable when tested in accordance with Procedure A of ASTM C 666, but scaling performance when tested under C 672 may be unsatisfactory. Research by Kleiger and Gebler [7] also found that Class C fly ash was not detrimental to frost resistance but promoted scaling. Carrasquillo [8] also found that concrete made with Class C fly ash was as resistant to freeze-thaw action as concrete without fly ash.

A number of studies have looked at the influence of silica fume on the durability of concrete. Philleo [9] pointed out that freeze-thaw testing in accordance with C 666 involves a relatively immature concrete. After the 14-day curing period associated with the test method, concrete with silica fume concrete will still contain a large volume of freezable water in capillaries. If concrete were thoroughly cured and allowed a period of air drying freeze-thaw testing, improved durability will be exhibited.

Many applications involving concrete with silica fume have been in buildings where air entrainment is not necessary because of the lack of freeze-thaw action and undesirable because of the desire to maximize strength. The presence of silica fume and superplasticizers can influence the void system. For example, Malhotra et al. [10] reported that for mixes with W/(C+SF) of 0.30 and 0.35, those containing 10 or 20 percent silica fume exhibited unsatisfactory freeze-thaw performance even though the mixes contained at least 4 percent air. Examination of the hardened air void system revealed larger than normal spacing factors.

Bilodeau and Carette [11], using mixes with W/(C+SF) between 0.45 and 0.60 and 8 percent silica fume, reported excellent freeze-thaw performance and low spacing factors. A slight trend toward increased scaling in mixes with silica fume was observed.

3. EXPERIMENTAL PROGRAM

3.1 Introduction

Experimental work for this program was active from June 1986 to December 1989. During this period four series of tests were conducted. These series involved maximum size of coarse aggregate, compressive strength of concrete, presence of Class C fly ash, and use of condensed silica fume. This chapter presents experimental details common to the overall program, while following chapters present information specifically pertaining to each of the four series. Two series of tests which were originally proposed—tests involving nonair-entrained, steam cured concrete and roller compacted concrete—were deleted because of time and budget constraints.

3.2 Materials

3.2.1 Portland Cement

Two shipments of type I portland cement were acquired during the life of the project from a cement plant in Tulsa, Oklahoma. For the second shipment, the plant supplied the results of in-house, quality control tests performed on cement manufactured at approximately the same time as the cement supplied for this project; these data are provided in Table 1. After receipt in the laboratory, each shipment of cement was separated into three lots and double wrapped in plastic film to resist prehydration.

3.2.2 Fly Ash

Two shipments of Class C fly ash were obtained from a coal-fired generating plant at Oolagah, Oklahoma. The first shipment was used during 1987 and the first half of 1988; the second shipment was used for the remainder of the project. Results of laboratory analyses on samples of these shipments are given in Table 2.

3.2.3 Fine Aggregate

The fine aggregate was Arkansas River sand. Two shipments of fine aggregate were employed in this project. The first shipment, which was used for approximately 80 percent of the study, met ASTM C 33 gradation requirements, while the second shipment was slightly

TABLE 1. PROPERTIES OF PORTLAND CEMENT

Chemical Tests:

SiO_2	20.87	C_3S	56.3
Al_2O_3	4.76	C_2S	17.4
Fe_2O_3	2.65	C_3A	8.1
CaO	63.64	C_4AF	8.1
MgO	2.25		
SO_3	2.96		
Loss	1.56		
Na_2O	0.32		
K_2O	0.70		
Na_2O Equiv.	0.78		

Blaine Air Perm: 3814 cm^2/gm

Autoclave Expansion: 0.010%

Compressive Strength, psi:		Setting Time:	
1 day	1790	Initial	140 min.
3 day	3050	Final	215 min.
7 day	3950	Entrained Air	11.8%
28 day	4875		

TABLE 2. PROPERTIES OF CLASS C FLY ASH

	Shipment 1	Shipment 2	ASTM C 618 Requirements
Fineness (+325 Mesh)	13.20%	14.40%	34% max
Moisture Content	0.20%	0.16%	3% max
Specific Gravity	2.65	2.58	none
Loss on Ignition	0.36%	0.28%	6% max
Soundness	0.04%	0.03%	0.8% max
Water Req., % control	91.50%	94.60%	105% max
SiO_2	33.19%	34.68%	none
Al_2O_3	23.99%	24.11%	none
Fe_2O_3	6.36%	6.94%	none
Total	63.54%	65.73%	50% min
SO_3	2.03%	2.13%	5% max
CaO	27.25%	24.95%	none

deficient in fines. Results of sieve analyses and ASTM limits are shown in Figs. 1 and 2. To prevent segregation, the sand pile was maintained in a damp condition after delivery. The fine aggregate had a specific gravity of 2.64 and an absorption capacity of 0.50 percent.

3.2.4 Coarse Aggregate

Sources of coarse aggregate were selected primarily on the basis of the results of past freeze-thaw tests conducted by the Oklahoma Department of Transportation and proximity to Stillwater, Oklahoma. Stone from a quarry near Drumright, Oklahoma, was used in mixes requiring a durable aggregate. For the first three series of tests, quarries near Cedar Vale, Kansas, and Davis, Oklahoma, were sources of marginal aggregate. For the final series involving silica fume, it was necessary to replenish the supplies of substandard aggregate. A second shipment of aggregate from the Cedar Vale quarry plus stone from a quarry near Tulsa, Oklahoma, were used for this series. The Tulsa quarry was used because of the closure of the Davis quarry.

The first series of tests involved ASTM C 33 sizes No. 7, No. 67, and No. 57. To obtain the gradation for size No. 57, which is nominally between the 1-in. and No. 4 sieves, the aggregate was rough sieved and separated into three categories: material retained on 3/4-in., 1/2-in., and No. 8 sieves. Material passing the No. 8 sieve was not used. At the time of batching, the coarse aggregate was recombined so that 30, 45, and 25 percent was retained on the 3/4-in., 1/2-in., and No. 8 sieves. Figure 3 shows a typical gradation for size No. 57 aggregate which was obtained by performing a standard sieve analysis on the recombined material.

The size No. 57 gradation was intentionally graded toward the coarse size of the limits. Mixes with this material tended to be quite harsh and adjustments of mix proportions were difficult. For Series 2, 3, and 4, a size No. 57 gradation approximately midway between the limits was employed. This gradation (shown in Fig. 4) was achieved by separating the aggregate into five size categories and batching each size separately.

To acquire the needed quantities for size No. 7 material, which is nominally between 1/2-in. and No. 4 sieves, the coarse aggregates were processed through a laboratory-size,

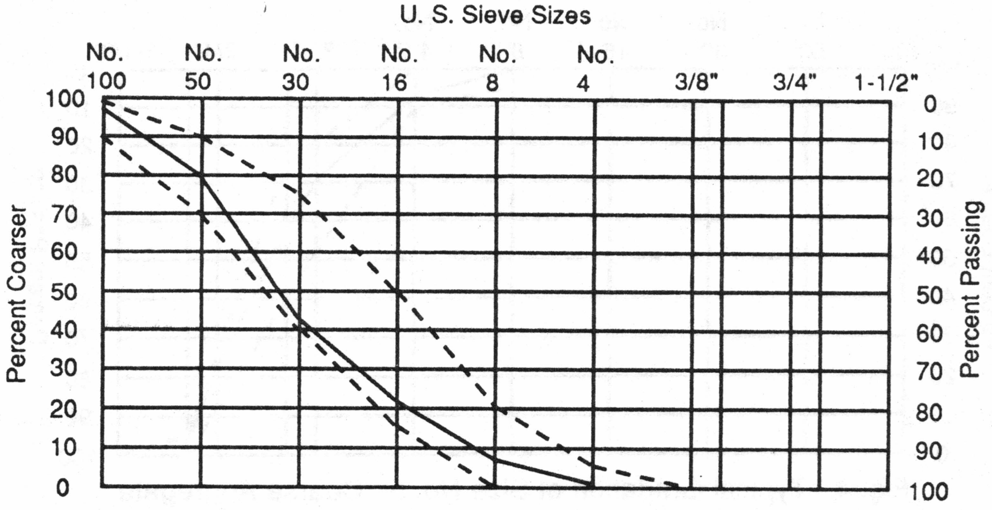

Fig. 1. Typical Gradation of Fine Aggregate Used in Batches 1-99

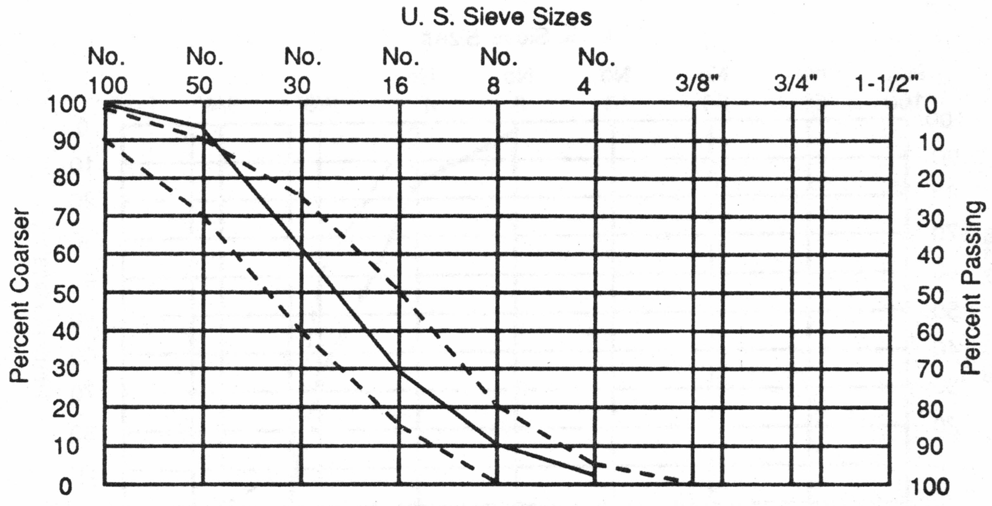

Fig. 2. Typical Gradation of Fine Aggregate Used in Batches 100-122

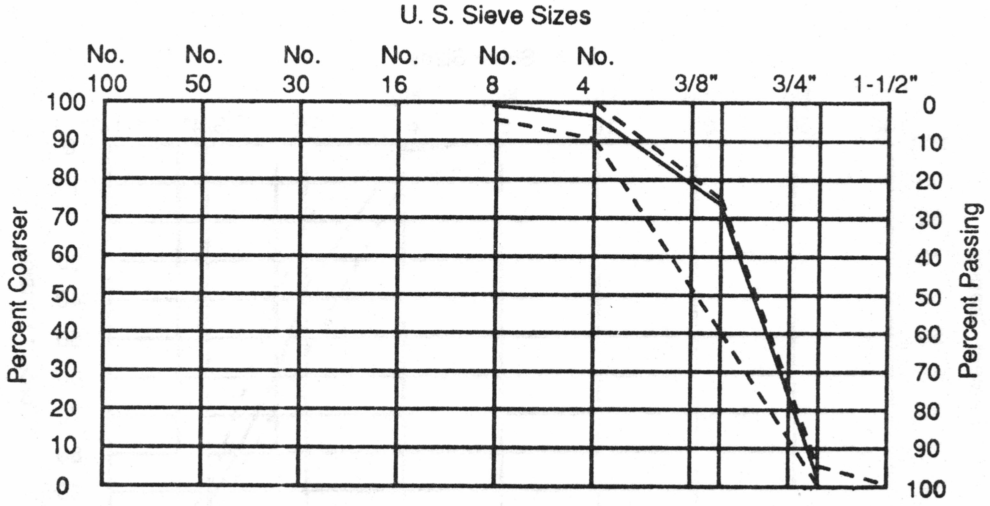

Fig. 3. Typical Gradation of Size No. 57 Coarse Aggregate Used in Series 1

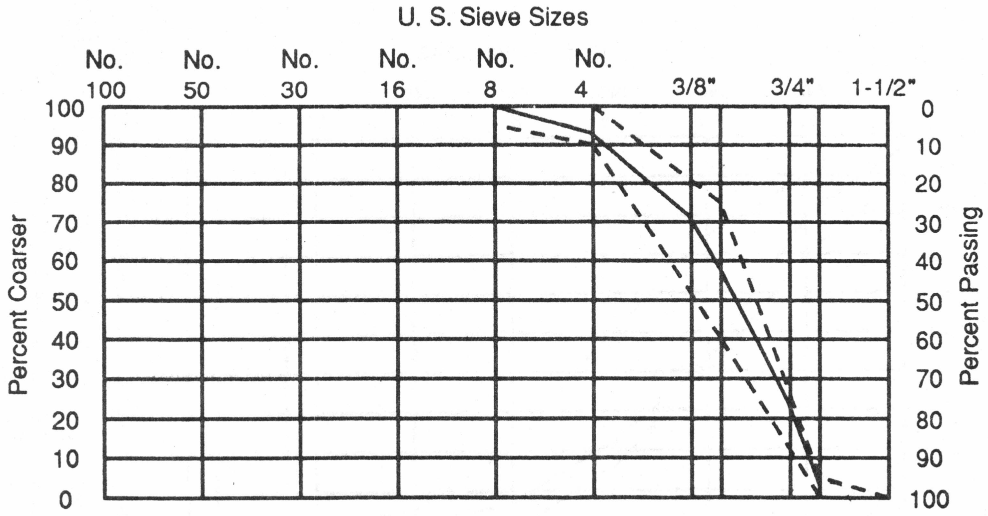

Fig. 4. Typical Gradation of Size No. 57 Coarse Aggregate Used in Series 2-4

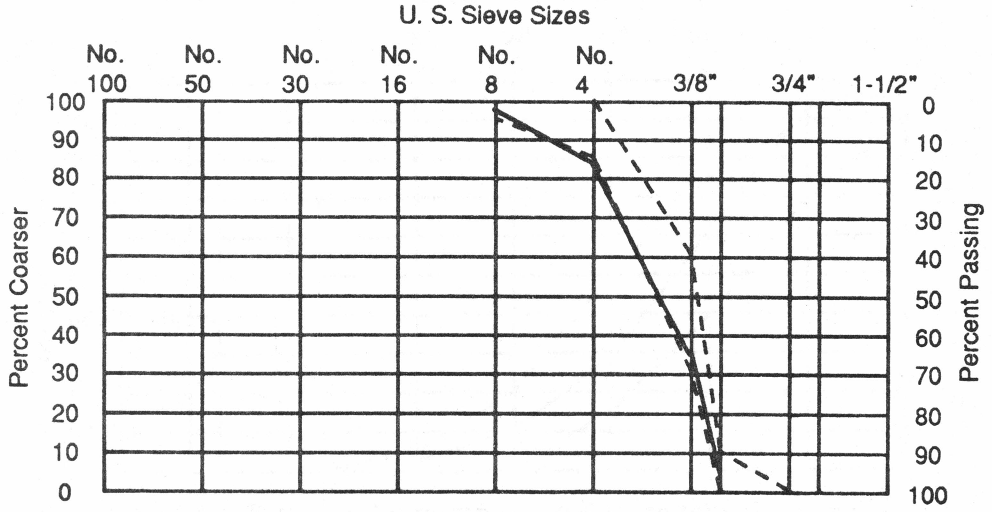

Fig. 5. Typical Gradation of Size No. 7 Coarse Aggregate

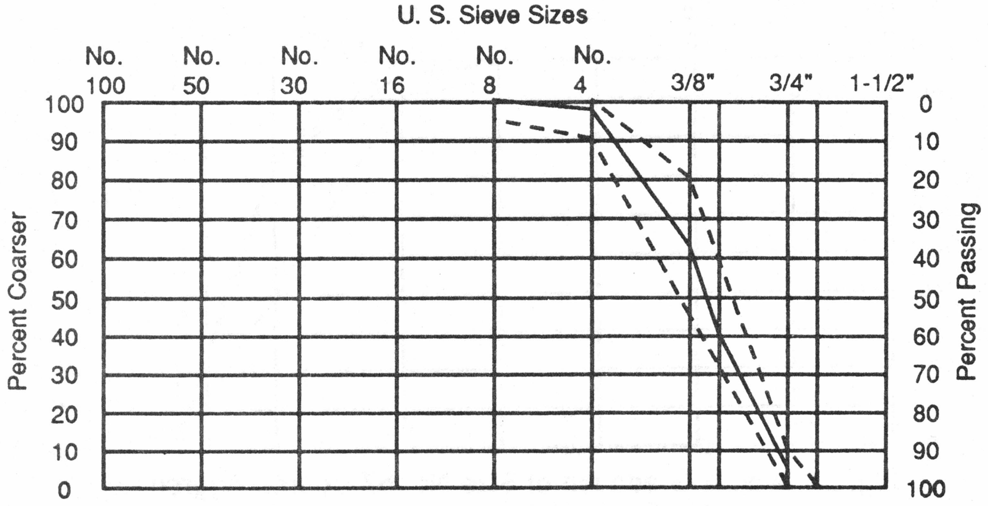

Fig. 6. Typical Gradation of Size No. 67 Coarse Aggregate

jaw-type rock crusher. By trial and error, the jaws were adjusted so that after the crushed stone was sieved and material retained on the 3/4-in. sieve and passing the No. 8 sieve was rejected, the gradation requirements of size No. 7 were approximately satisfied. A typical size No. 7 gradation is shown in Fig. 5; as can be seen the percent passing the No. 4 sieve is slightly high.

After initial tests revealed that mixes containing size No. 7 coarse aggregate from the Cedar Vale and Davis quarries were much more durable than similar mixes with size No. 57 aggregate, the test program was expanded to consider size No. 67 aggregate from these two quarries. To achieve the size No. 67 gradation, which is nominally No. 4 to 3/4 in., material was sieved into five size categories and batched separately. The gradation of size No. 67 aggregate is shown in Fig. 6. Physical properties of the coarse aggregate are presented in Table 3.

3.3 Mixing Operations

3.3.1 Preparation of Materials

Prior to batching, the as-stocked moisture content of the air-dry coarse aggregate was determined. Approximately 24 hrs prior to casting, the quantity of coarse aggregate needed for each batch was placed in water. Ample quantities of the fine aggregate, which had been kept moist since delivery, were thoroughly blended and covered with plastic and burlap to minimize the loss of moisture. A sample of the fine aggregate was then oven dried to establish the as-stocked moisture content and the appropriate batch weight of the sand.

3.3.2 Batching and Mixing of Concrete

In accordance with ASTM C 192, the mixing sequence consisted of a three-minute period of mixing followed by three minutes of rest and another two minutes of mixing. The concrete was discharged from the counter-current pan mixer (Fig. 7) and the slump, air content, and unit weight were measured. Although the concrete was batched and mixed in a laboratory supplied with both heating and air conditioning, substantial seasonal variation in air and tap water temperatures led to variations in the temperature of fresh concrete cast at different times of the year. In an effort to produce mixes with a slump between 1 and 3 in.

TABLE 3. PROPERTIES OF COARSE AGGREGATE[a]

	Source				
Properties	Drumright OK	Davis, OK	Cedar Vale,[b] KS	Cedar Vale,[c] KS	Tulsa, OK
Bulk Specific Gravity	2.80	2.58	2.46	2.45	2.55
Bulk Specific Gravity (SSD)	2.82	2.61	2.54	2.53	2.60
Absorption (%)	0.81	1.17	3.25	3.34	2.13
Unit Weight (Dry Rodded, pcf)	101.60	93.90	90.60	--[d]	--[d]
Percent Wear (%)	22.90	19.20	36.50	30.00	29.00

[a] Based on tests of size No. 57.

[b] First shipment.

[c] Second shipment.

[d] Not measured.

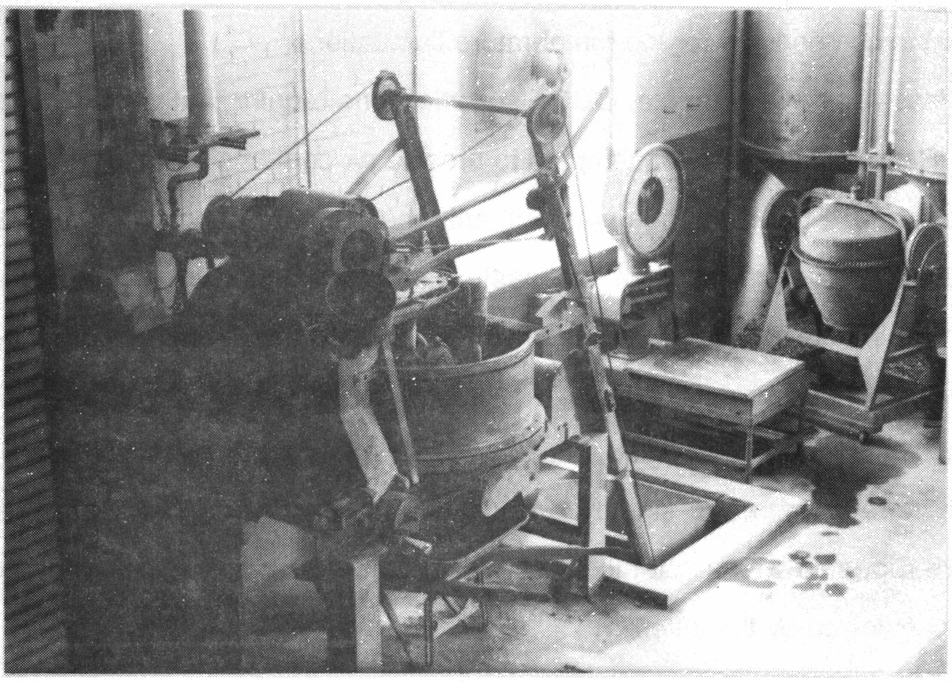

Fig. 7. Countercurrent Pan Mixer

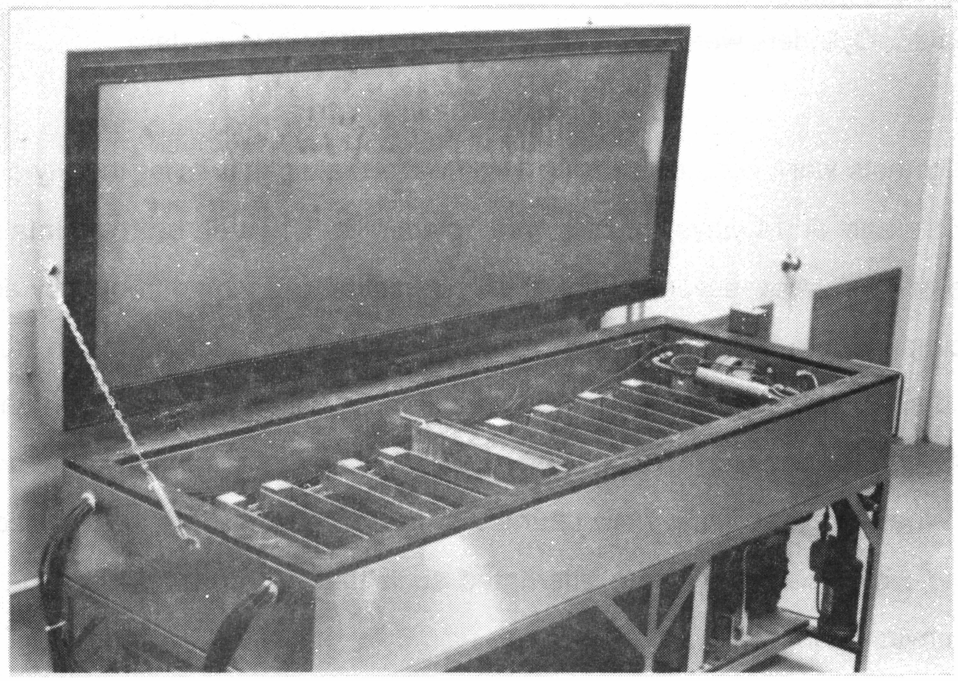

Fig. 8. Freeze-Thaw Cabinet

and an air content between 5 and 7 percent, minor adjustments in mix proportions were often required to compensate for the temperature fluctuations.

For a Class A paving concrete, ODOT specifications require that a mix contain 4 to 6 percent air. Research personnel attempted to provide air contents between 5 and 6 percent to ensure that freeze-thaw damage was primarily the result of poor quality aggregate and not associated with deterioration of the paste. As the quantity of cement and mineral admixtures was increased, it became more difficult to produce concrete with 5 percent air and mixes with less air were utilized.

The batches were numbered sequentially. A few mixes were used for freeze-thaw tests with one or more parameters slightly outside the target values. In some cases these batches were repeated with slight modifications; such batches are identified by the original batch number followed by the letter "M".

3.4 Test Specimens

Six 6- by 12-in. cylinders and three 3- by 4- by 16-in. prisms were cast from each batch. Immediately after casting, specimens were placed in a moist room maintained at a temperature of 73.4 ±3 F. After 24 hrs, specimens were demolded and placed in lime-saturated water. Cylinders were tested in compression at 14 and 28 days.

3.5 Freeze-Thaw Tests

Durability tests were conducted using two freeze-thaw cabinets of the style shown in Fig. 8. At an age of 14 days, prisms were placed in a water bath maintained at a temperature of 43 F. After several hours, the fundamental transverse frequency and weight of the specimens were measured. The specimens were then placed in the freeze-thaw cabinets and subjected to approximately six freeze-thaw cycles per day. The fundamental transverse frequency and weight of specimens were measured at intervals of approximately 30 cycles. When the specimens were returned to freeze-thaw testing, their positions—both between and within cabinets—were alternated such that all prisms were subjected to a similar test environment.

Although the fundamental transverse frequency was measured by vibrating the prism in both the 4- and 3-in. directions, data for the more rigid direction seemed more consistent and were used for data reduction.

As described in ASTM C 666, the relative dynamic modulus is defined as follows:

$$P_c = (n_i^2 / n^2) \times 100$$

where

P_c = relative dynamic modulus of elasticity after c cycles of freezing and thawing, percent;

n = fundamental transverse frequency at 0 cycles of freezing and thawing; and

n_i = fundamental transverse frequency after c cycles of freezing and thawing.

It is normal to summarize the results of the test in terms of the durability factor defined as follows:

$$DF = PN/M$$

where

DF = durability factor of the test specimen;

P = relative dynamic modulus of elasticity at N cycles, percent;

N = number of cycles at which P_c reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated; and

M = specified number of cycles at which the exposure is to be terminated.

In this program, M was selected to be 350 cycles to comply with ODOT testing procedures. The minimum P_c was selected as 50 percent; N was calculated by interpolation. Specimens were not removed from freeze-thaw testing prior to the application of 350 cycles unless it was necessary to stop the tests in order to prevent damage to the pans holding the specimens. It is important to note that the durability factor is computed by the ASTM definition. For example, if a prism reached a P_c of 50 percent at 175 cycles, but testing continued until P_c was 30 percent at 225 cycles, a durability factor of 25 percent (25 = 50 x 175/350) would be reported.

4. SERIES 1—INFLUENCE OF THE SIZE OF AGGREGATE ON THE DURABILITY OF CONCRETE

4.1 General

In this series of tests, mixes with a nominal strength of 4 ksi were prepared using three sizes of coarse aggregate. At the beginning of the test program, only sizes No. 57 (1 in. to No. 4) and No. 7 (1/2 in. to No. 4) were utilized. After tests involving marginal aggregate demonstrated that the concrete made with size No. 7 aggregate was more durable than concrete made with size No. 57 aggregate, the intermediate size No. 67 (3/4 in. to No. 4) was added to the test program.

As discussed in section 3, the aggregates were processed to obtain the desired size gradation (see Figs. 3, 5, 6). It can be seen that the size No. 57 was very coarsely graded with approximately 70 percent retained on a 1/2-in. sieve, while the size No. 7 was finely graded with approximately 70 percent passing the 3/8-in. sieve and more than 95 percent passing the 1/2-in. sieve. By selecting these gradations, it was believed that the influence of aggregate size would be easier to establish with a limited number of durability tests. However, from the standpoint of quality control, the gradation of the aggregates seemed to adversely influence the consistency of the mixes. Other factors which were detrimental to consistent slump and air content were laboratory temperatures which ranged from about 70 F to well over 100 F; a relatively stiff concrete; and the use of a countercurrent, pan-style, concrete mixer. Although the mixer was excellent for the low slump mixes used in this study, it did not seem to entrain air effectively or consistently. As observed in Tables 4, 5, and 6, laboratory personnel made minor adjustments to the mix proportions throughout Series 1 research in an attempt to maintain the desired strength, slump, and air content.

4.2 Experimental Results

Tables 4, 5, and 6 provide data on mix proportions, properties of fresh concrete, compressive strength, and durability data for concrete made with the three aggregates in this series of tests. Figure 9 presents the durability data in graphical form.

TABLE 4. MIX AND DURABILITY DATA — INFLUENCE OF SIZE FOR DRUMRIGHT AGGREGATE

Coarse Aggregate Size	57	57	57	7	7	7
Batch No.	1	7	11	4	10	12
<u>Mix Proportions</u>						
Water/Cement	0.48	0.48	0.43	0.47	0.47	0.43
Water (lb/yd^3)	260	260	231	266	271	246
Cement (lb/yd^3)	542	542	542	573	583	573
Coarse Aggregate (lb/yd^3)	1948	1948	1948	1621	1621	1621
Fine Aggregate (lb/yd^3)	1226	1226	1226	1472	1449	1471
Air Ent. Admix. (ml/yd^3)	271	266	260	287	280	269
<u>Properties of Fresh Concrete</u>						
Slump (in.)	2.75	3.25	2.75	1.25	1.25	2.75
Air Content (%)	6.00	6.20	6.30	6.00	6.20	7.00
Unit Weight (lb/ft^3)	148	147	147	145	145	144
<u>Compressive Strength</u>						
14 Days (ksi)	3.23*	3.04*	3.51*	3.77*	3.53*	4.09
28 Days (ksi)	3.99	3.88	3.87	4.65	4.61	4.29
<u>Durability Factor</u>						
Prism 1	98	100	90	103	72	94
Prism 2	76	98	96	114	104	93
Prism 3	97	91	94	95	95	96
Ave.	90	96	93	104	91	94

*Strength determined at 7 days.

TABLE 5. MIX AND DURABILITY DATA—INFLUENCE OF SIZE FOR DAVIS AGGREGATE

Coarse Aggregate Size Batch No.	57 2	57 8	57 8M	57 13	67 43	67 44	67 45	7 5	7 5M	7 14	7 15
Mix Proportions											
Water/Cement	0.48	0.48	0.47	0.48	0.48	0.48	0.48	0.45	0.48	0.45	0.45
Water (lb/yd^3)	249	256	255	255	269	269	271	259	255	260	259
Cement (lb/yd^3)	521	535	540	535	562	561	565	573	531	573	573
Coarse Aggregate (lb/yd^3)	1802	1800	1778	1803	1651	1649	1661	1503	1511	1493	1493
Fine Aggregate (lb/yd^3)	1272	1241	1266	1244	1309	1307	1316	1474	1468	1474	1474
Air Ent. Admix. (ml/yd^3)	261	265	243	214	213	191	182	287	228	269	246
Properties of Fresh Concrete											
Slump (in.)	1.75	3.00	2.25	1.75	2.75	2.75	2.50	2.75	1.50	2.75	2.50
Air Content (%)	5.40	6.30	6.40	5.20	6.60	6.70	6.00	5.80	6.60	7.10	7.00
Unit Weight (lb/ft^3)	145	141	142	144	141	140	141	142	140	137	139
Compressive Strength											
14 Days (ksi)	3.40*	2.81*	3.54*	3.74	4.76	4.80	4.66	3.89*	3.78	3.78	3.52
28 Days (ksi)	4.14	3.53	3.90	4.33	5.09	5.12	5.13	4.69	4.01	4.19	4.40
Durability Factor											
Prism 1	25	42	65	64	66	57	68	80	94	96	90
Prism 2	36	37	56	33	45	65	55	88	92	96	87
Prism 3	35	47	47	63	66	75	77	89	88	92	99
Ave.	32	42	56	53	59	66	67	85	91	95	92

*Strength determined at 7 days.

TABLE 6. MIX AND DURABILITY DATA—INFLUENCE OF SIZE FOR CEDAR VALE AGGREGATE

Coarse Aggregate Batch No.	57 3	57 9	57 16	67 46	67 47	67 48	7 6	7 6M	7 17	7 18
Mix Proportions										
Water/Cement	0.48	0.46	0.49	0.48	0.48	0.48	0.44	0.49	0.48	0.48
Water (lb/yd^3)	238	234	240	268	274	273	248	248	248	248
Cement (lb/yd^3)	500	510	490	560	572	570	552	510	521	521
Coarse Aggregate (lb/yd^3)	1712	1737	1720	1603	1637	1631	1452	1492	1492	1492
Fine Aggregate (lb/yd^3)	1315	1265	1304	1304	1332	1327	1494	1459	1437	1437
Air Ent. Admix. (ml/yd^3)	250	253	225	191	173	194	276	230	229	229
Properties of Fresh Concrete										
Slump (in.)	1.50	1.25	1.75	2.25	1.50	1.00	1.00	1.25	2.50	2.50
Air Content (%)	4.90	5.00	5.60	6.90	4.80	5.10	6.00	6.00	6.50	6.30
Unit Weight (lb/ft^3)	144	144	142	140	141	141	141	140	138	139
Compressive Strength										
14 Days (ksi)	3.97*	3.49*	4.07*	5.16	5.23	5.68	4.22*	4.00	3.59	3.73
28 Days (ksi)	4.76	4.87	4.29	5.67	5.82	5.88	5.26	4.37	3.81	4.01
Durability Factor										
Prism 1	36	41	36	56	44	34	70	80	80	81
Prism 2	36	48	34	45	44	39	73	84	85	80
Prism 3	50	40	42	57	33	40	84	83	74	84
Ave.	41	43	37	53	40	38	76	82	80	82

*Strength determined at 7 days.

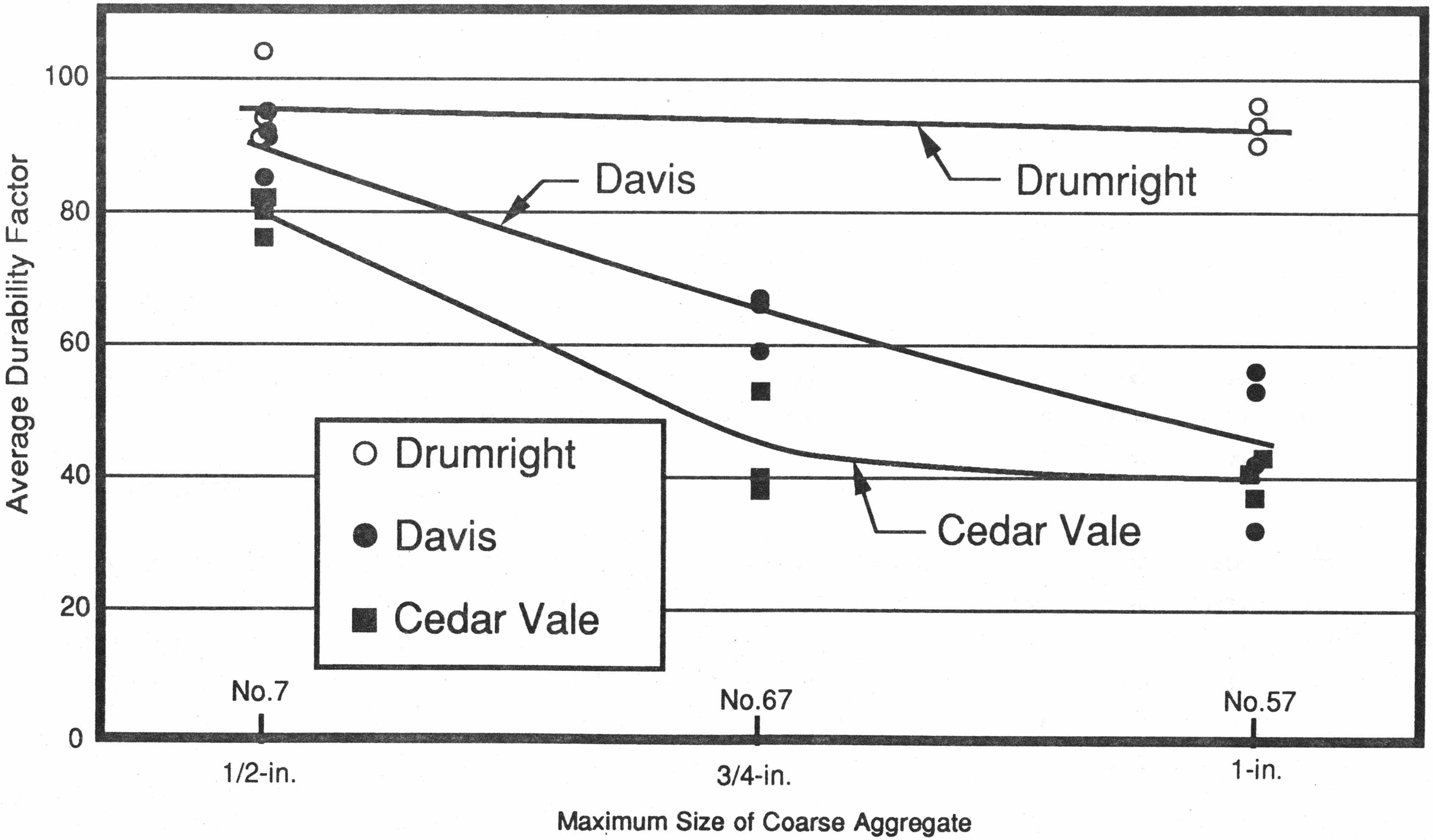

Fig. 9. Influence of Aggregate Size on the Durability Factor

Concrete made with coarse aggregate from Cedar Vale, Kansas, tended to have a higher strength than mixes containing aggregate from Drumright and Davis, Oklahoma. However, concrete mixed with Drumright coarse aggregate proved to be the most durable, while concrete mixed with Cedar Vale aggregate was the least durable. Specimens with size No. 57 aggregate from Cedar Vale exhibited severe deterioration, forcing their removal from the freeze-thaw cabinet prior to achieving 350 cycles.

Concrete made with size No. 57 Cedar Vale aggregate exhibited severe popout damage. As the size of the aggregate was reduced, the size of the popouts decreased but the total weight loss remained similar.

4.3 Discussion of Results

Throughout this program the weight loss of samples was monitored as they were subjected to freeze-thaw cycles. Because there was little correlation between durability factors and weight loss, this report will focus only on the durability factor data.

In Fig. 9, each data point is the average durability factor for the three prisms tested from each batch. As can be seen, concrete made with a high quality aggregate from Drumright was durable for both gradations studied. The figure also indicates that the performance of a marginal aggregate can be improved significantly if the maximum size is reduced from 1 to 1/2 in. The curves shown with data for Davis and Cedar Vale aggregates indicate that the inch reduction in maximum size from 3/4 to 1/2 in. was more significant than the reduction in size from 1 to 3/4 in. However, aggregate with a size No. 7 gradation was near the fine side of the limits, while size No. 67 was prepared to fall approximately midway between the gradation limits. For this reason, somewhat less dramatic improvement in durability than suggested here would occur if a coarser size No. 7 gradation had been utilized.

5. SERIES 2—INFLUENCE OF THE STRENGTH OF CONCRETE ON DURABILITY

5.1 General

During the first series of tests involving mixes with a strength of 4 ksi, it appeared that the coarse gradation of the size No. 57 aggregate resulted in a very harsh concrete which in turn caused problems with consistency in slump and air content. When the 6- and 8-ksi mixes of Series 2 were prepared, the gradation of the coarse aggregate was adjusted slightly to be near the center of the gradation limits.

The original proposal had assumed that the strength of concrete would depend primarily on mix proportions rather than the source of aggregate. However, after Series 1 tests were underway, it was apparent that the aggregate source had a significant influence on strength. It was believed that the basic intent of this series of tests was to investigate the influence of paste quality on durability. For this reason, as work on mixes involving 6- and 8-ksi concrete were undertaken, a new approach to mix design was initiated. An additional shipment of Drumright aggregate was obtained and used for trial mixes. Using the mix design procedures of the American Concrete Institute, the solid volume of coarse aggregate and water-to-cement ratio necessary to achieve the required strength were established. This mix design was then applied to the aggregates under study. Because the quality of paste and the quantity of coarse aggregate—on a solid volume basis—were controlled, strengths varied somewhat from the target values.

Many of the mixes in this series contained large quantities of cement and were prepared during a period where the air conditioning system in the laboratory did not function properly. To partially affect these factors, mix water was precooled with ice to approximately 40 F. It was found that 8-ksi concrete was relatively difficult to achieve, even with the aid of water-reducing types of admixtures. The use of size No. 57 aggregate in these mixes was probably detrimental to strength. Normally the maximum size of coarse aggregate is reduced when high strength is desired. It is also believed that none of the aggregates was inherently strong and well suited for the production of high strength concrete.

At the beginning of this series, the graduate laboratory assistant in charge of experimental work mistakenly cast six batches using size No. 7 rather than size No. 57 aggregate. Because of the limited value of these data, they are not shown in figures and are provided in a separate table of "miscellaneous" mixes.

5.2 Experimental Results

Tables 7, 8, and 9 provide data on mix preparation, properties of fresh and hardened concrete, and durability. Those Series 1 batches involving size No. 57 aggregate are also included in Series 2; data for these ten batches are repeated in these tables. Data for six mixes inadvertently made with size No. 7 aggregate are provided in Table 10.

The influence of compressive strength on the durability factor is presented in graphical form in Fig. 10. As might be expected, concrete made with the high quality Drumright aggregate yielded high durability factors regardless of the compressive strength. For concrete manufactured with aggregate from Davis, Oklahoma, the durability factor appeared to increase linearly with compressive strength. For concrete made with aggregate from Cedar Vale, Kansas, the durability factor increased significantly as the strength was increased to 6 ksi, but was essentially constant for higher strengths.

5.3 Discussion of Results

Results clearly demonstrate that the compressive strength of concrete has a major influence on the durability factors obtained from concrete made with marginal aggregate. This trend is probably partly related to the greater impermeability of high strength concrete which restricts the movement of water into aggregate. In addition, concrete with a high strength may have a greater ability to resist the expansive action associated with the freezing of internal water.

Another explanation for the results is suggested by the physical principles behind determination of the sonic modulus of elasticity and subjective observations. In some cases concrete prisms seemed to exhibit greater deterioration from a visual standpoint than was indicated by relative dynamic modulus measurements. In many cases the freeze-thaw damage to prisms was in the form of major transverse cracks. If a crack is stable and does

TABLE 7. MIX AND DURABILITY DATA—INFLUENCE OF STRENGTH FOR SIZE NO. 57 DRUMRIGHT AGGREGATE

Batch No.	1	7	11	19	39	31	34	35	36
Mix Proportions									
Water/Cement	0.48	0.48	0.43	0.35	0.36	0.36	0.28	0.28	0.28
Water (lb/^{yd})	260	260	231	275	280	280	264	267	251
Cement (lb/yd^3)	542	542	542	772	772	772	941	949	922
Coarse Aggregate (lb/yd^3)	1948	1948	1948	1747	1922	1922	2053	2072	2014
Fine Aggregate (lb/yd^3)	1226	1226	1226	1210	1027	1027	797	804	781
Air Ent. Admix. (ml/yd^3)	271	266	260	463	463	471	898	906	881
Superplasticizer (oz/yd^3)	0	0	0	0	0	0	3.1	3.8	4.2
Properties of Fresh Concrete	2.75	3.25	2.75	1.25	1.75	2.25	2.00	1.50	3.00
Slump (in.)	6.00	6.20	6.30	5.00	4.90	5.00	5.50	4.60	7.50
Unit Weight (lb/ft^3)	148	147	147	150	151	151	152	153	154
Compressive Strength									
14 Days (ksi)	3.23*	3.04*	3.51*	5.52	5.60	5.02	7.49	7.67	7.01
28 Days (ksi)	3.99	3.88	3.87	5.94	5.81	5.68	7.64	8.11	7.30
Durability Factor									
Prism 1	98	100	90	90	99	103	89	88	63
Prism 2	76	98	96	90	100	102	96	84	108
Prism 3	97	91	94	87	102	100	98	96	94
Ave.	90	96	93	89	100	102	94	89	88

*Strength determined at 7 days.

TABLE 8. MIX AND DURABILITY DATA—INFLUENCE OF STRENGTH FOR SIZE NO. 57 DAVIS AGGREGATE

Batch No.	2	8	8M	13	20	24	29	37	38	39
Mix Proportions										
Water/Cement	0.48	0.48	0.47	0.48	0.35	0.37	0.37	0.28	0.28	0.28
Water (lb/yd^3)	249	256	255	255	280	288	288	269	263	264
Cement (lb/yd^3)	521	535	540	535	790	780	780	959	939	942
Coarse Aggregate (lb/yd^3)	1802	1800	1778	1803	1536	1778	1778	1937	1914	1905
Fine Aggregate (lb/yd^3)	1272	1241	1266	1244	1237	999	999	778	783	767
Air Ent. Admix. (ml/yd^3)	261	265	243	214	474	468	476	913	752	694
Superplasticizer (oz/yd^3)	0	0	0	0	0	0	0	3.1	7.9	--[b]
Properties of Fresh Concrete										
Slump (in.)	1.75	3.00	2.25	1.75	1.25	2.75	1.50	2.00	2.75	6.00
Air Content (%)	5.40	6.30	6.40	5.20	4.90	5.00	4.90	4.40	5.60	6.10
Unit weight (lb/ft^3)	145	141	142	144	146	145	145	148	146	141
Compressive Strength										
14 Days (ksi)	3.40[a]	2.81[a]	3.54[a]	3.74	5.04	5.01	5.08	6.97	8.96	7.01
28 Days (ksi)	4.14	3.53	3.90	4.33	5.44	5.49	5.69	7.30	9.09	7.24
Durability Factor										
Prism 1	25	42	65	64	46	55	51	79	84	80
Prism 2	36	37	56	33	74	66	52	83	92	79
Prism 3	35	47	47	63	75	50	57	80	87	73
Ave.	32	42	56	53	65	57	53	81	88	77

[a] Strength determined at 7 days.

[b] Data not recorded; 4.2 oz/yd^3 was nominal value for mix.

TABLE 9. MIX AND DURABILITY DATA — INFLUENCE OF STRENGTH FOR SIZE NO. 57 CEDAR VALE AGGREGATE

Batch No.	3	9	16	21	25	32	40	41	42
Mix Proportions									
Water/Cement	0.48	0.46	0.49	0.36	0.36	0.37	0.28	0.28	0.28
Water (lb/yd^3)	238	234	240	275	278	280	265	268	266
Cement (lb/yd^3)	500	510	490	772	772	772	945	955	950
Coarse Aggregate (lb/yd^3)	1712	1737	1720	1689	1689	1535	1850	1870	1861
Fine Aggregate (lb//yd^3)	1315	1265	1304	1027	1033	1192	774	783	780
Air Ent. Admix. (ml/yd^3)	250	253	225	463	502	502	899	909	700
Superplasticizer (oz/yd^3)	0	0	0	0	0	0	4.0	3.4	3.8
Properties of Fresh Concrete									
Slump (in.)	1.50	1.25	1.75	1.25	1.75	1.75	2.50	2.00	3.00
Air Content (%)	4.90	5.00	5.60	4.60	4.90	5.00	5.90	4.80	5.30
Unit Weight (lb/ft^3)	144	144	142	145	143	143	143	145	143
Compressive Strength									
14 Days (ksi)	3.97*	3.49*	4.07*	5.96	5.51	5.68	7.75	7.94	8.22
28 Days (ksi)	4.76	4.87	4.29	6.49	6.11	6.00	7.83	8.54	8.34
Durability Factor									
Prism 1	36	41	36	76	87	71	97	96	84
Prism 2	36	48	34	89	91	91	91	105	90
Prism 3	50	40	42	84	86	90	90	93	87
Ave.	41	43	37	83	88	84	93	98	87

*Strength determined at 7 days.

TABLE 10. MIX AND DURABILITY DATA—MISCELLANEOUS MIXES CONTAINING SIZE NO. 7 AGGREGATE

Batch No. Quarry	22 Drumright	26 Drumright	27 Davis	33 Davis	23 Cedar Vale	28 Cedar Vale
Mix Proportions						
Water/Cement	0.37	0.37	0.37	0.37	0.37	0.37
Water (lb/yd^3)	287	287	287	288	285	285
Cement Aggregate (lb/yd^3)	770	770	775	770	760	760
Coarse Aggregate (lb/yd^3)	1654	1654	1494	1730	1640	1640
Fine Aggregate (lb/yd^3)	1252	1252	1240	1008	1027	1027
Air Ent. Admix. (ml/yd^3)	385	385	388	385	418	403
Properties of Fresh Concrete						
Slump (in.)	1.00	1.75	1.75	3.00	1.75	2.00
Air Content (%)	5.10	5.30	5.40	5.80	5.30	5.00
Unit Weight (lb/ft^3)	149	148	142	141	142	142
Compressive Strength						
14 Days (ksi)	6.08	5.36	5.18	5.01	5.57	5.75
28 Days (ksi)	6.36	6.07	5.87	5.60	6.01	6.24
Durability Factor						
Prism 1	90	96	93	95	88	87
Prism 2	85	95	93	88	92	86
Prism 3	90	98	95	89	86	90
Ave.	88	96	94	91	88	88

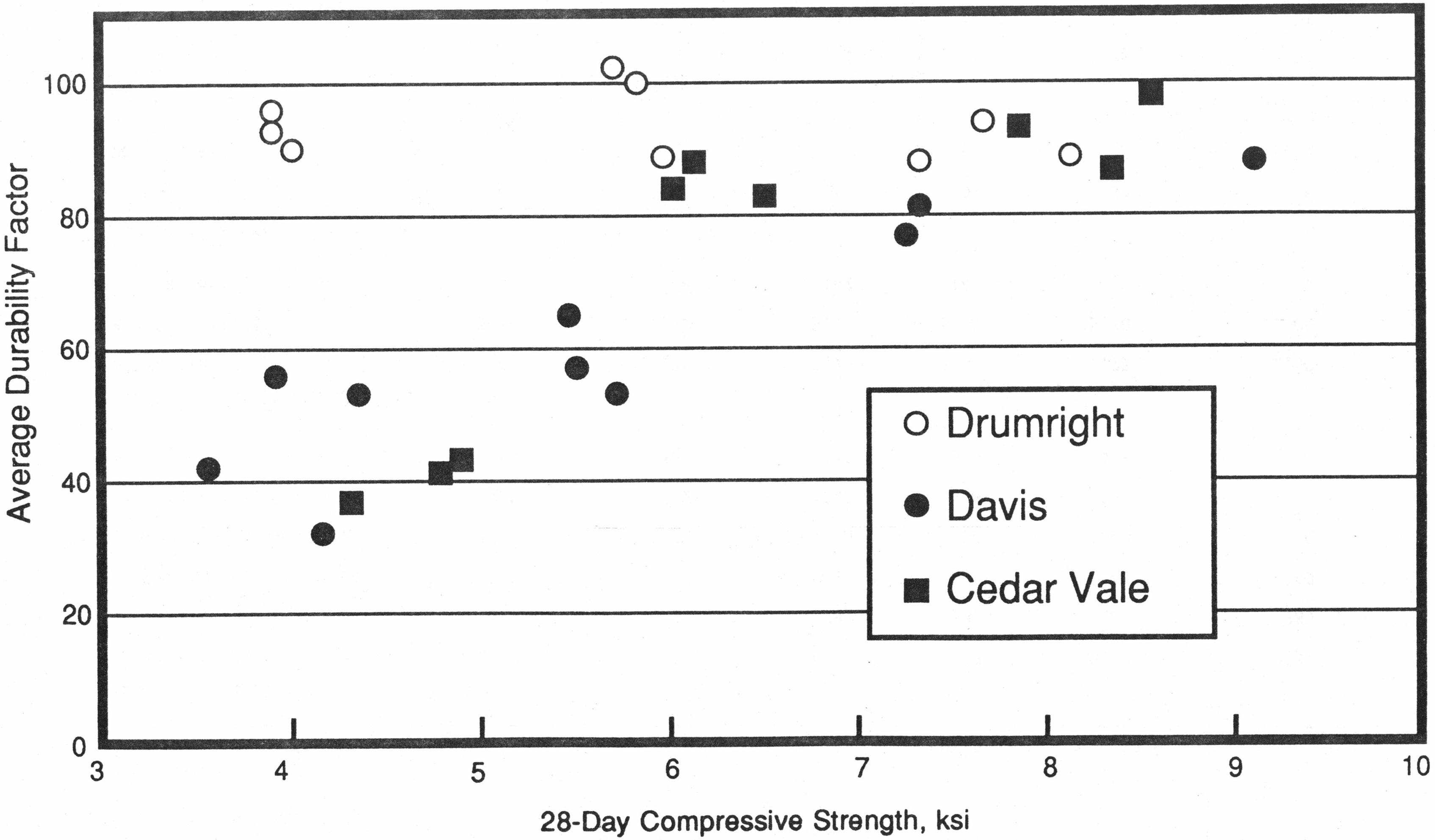

Fig. 10. Influence of Compressive Strength on the Durability Factor

not result in a complete failure of a prism, testing would have continued, provided the relative dynamic modulus did not fall below 50 percent. The influence of such cracks on the fundamental frequency will be related to the state of stress across the crack. If the crack surface is essentially free of stress, the effective moment of inertia and sonic modulus will be greatly reduced. However, if aggregate in the vicinity of the crack has expanded, there will be compressive stresses acting across the crack interface. Such stresses would increase the effective section modulus and therefore the sonic modulus of elasticity. It is probable that a higher strength of concrete would contribute to an increased ability to resist aggregate expansion at the crack interface and thereby lead to higher durability factors.

If the durability data in Tables 4, 5, and 6 for size No. 7 aggregate are compared to results in Table 10, it can be seen that there was no significant change in performance as the strength of concrete was increased from 4 to 6 ksi. Although this limited quantity of data was obtained by accident, it suggests that the benefits of reducing the maximum size of the coarse aggregate and increasing the strength of the concrete are not additive.

6. SERIES 3—INFLUENCE OF CLASS C FLY ASH ON DURABILITY

6.1 General

Class C fly ash has received wide acceptance during the past decade. Normally higher strength and more economical concrete can be manufactured using a Class C fly ash. Because of the ubiquitous nature of fly ash in concrete construction, this series of tests were performed to determine if the durability of concrete made with a marginal aggregate would be improved by the presence of fly ash.

The ODOT Standard Specifications for Highway Construction allow fly ash to be substituted for approximately 15 percent of the portland cement in the ratio of 1.35 lb of fly ash for each 1.0 lb of cement. For building construction, it is common practice to replace approximately 30 percent of the cement with fly ash on a pound-for-pound basis. Recognizing that the specific gravity of fly ash is approximately 2.60, this replacement strategy results in a volumetric increase of cementitious material of approximately 5 percent. Conversely, for the more restrictive ODOT specifications, the volume of cementitious materials increases by approximately 9 percent. It is anticipated that fly ash concrete manufactured to the ODOT specification will have significantly greater strength than a normal concrete.

It is quite common to express the fly ash as a percentage of the total cementitious weight—i.e., cement plus fly ash. In this study, 15 or 30 percent of the cement was replaced at a ratio of 1.35 lb of fly ash to 1.0 lb of cement. For these replacement levels, the mixes had an FA/(C+FA) of 0.19 or 0.37. The proposed target strengths of mixes were 4, 6, and 8 ksi.

6.2 Experimental Results

Tables 7, 8, and 9, which were presented earlier in section 5.3, provide data for zero percent fly ash. Tables 11, 13, and 15 supply results for mixes with 19 percent ash, while Tables 12, 14, and 16 contain information for mixes with 37 percent ash. These results are presented in graphical form for each of the three aggregates in Figs. 11, 12, and 13.

TABLE 11. MIX AND DURABILITY DATA—INFLUENCE OF 19.2% FLY ASH FOR DRUMRIGHT AGGREGATE

Batch No.	85	86	87	73	74	75	52	53	54
Mix Proportions									
Water/(Cement + Fly Ash)	0.47	0.50	0.48	0.39	0.40	0.39	0.30	0.30	0.30
Water (lb/yd^3)	249	259	252	260	257	253	314	312	311
Cement (lb/yd^3)	424	423	420	540	519	521	845	842	837
Fly Ash (lb/yd^3)	101	101	100	128	123	124	201	200	200
Coarse Aggregate (lb/yd^3)	1944	1936	1938	1937	1919	1925	1976	1966	1956
Fine Aggregate (lb/yd^3)	1268	1263	1273	1124	1149	1152	700	696	715
Air Ent. Admix. (ml/yd^3)	125	124	124	194	192	193	397	348	397
Properties of Fresh Concrete									
Slump (in.)	4.00	2.75	2.75	2.75	2.00	3.00	1.50	2.25	2.00
Air Content (%)	5.50	5.30	5.50	5.50	6.00	6.00	3.50	4.00	4.00
Unit Weight (lb/ft^3)	146.40	147.60	148.00	147.50	147.00	146.50	150.00	150.00	150.00
Compressive Strength									
14 Days (ksi)	4.48	5.04	4.75	5.31	5.55	5.49	6.72	6.81	6.42
28 Days (ksi)	5.12	5.65	5.49	6.20	6.16	6.09	7.30	7.85	7.47
Durability Factor									
Prism 1	97	67	79	95	90	93	93	102	98
Prism 2	89	87	88	90	94	90	91	90	98
Prism 3	97	88	81	91	94	85	92	79	96
Ave.	94	80	83	92	92	89	92	90	97

TABLE 12. MIX AND DURABILITY DATA—INFLUENCE OF 36.6% FLY ASH FOR DRUMRIGHT AGGREGATE

Batch No.	94	95	96	82	83	84	61	62	63
Mix Proportions									
Water/(Cement + Fly Ash)	0.48	0.48	0.48	0.40	0.39	0.38	0.29	0.29	0.29
Water (lb/yd^3)	231	230	228	252	245	243	279	279	269
Cement (lb/yd^3)	304	301	302	401	405	406	605	605	595
Fly Ash (lb/yd^3)	176	174	175	232	234	234	349	349	344
Coarse Aggregate (lb/yd^3)	1956	1937	1945	1930	1951	1955	1937	1937	1944
Fine Aggregate (lb/yd^3)	1370	1356	1362	1164	1170	1168	821	821	854
Air Ent. Admix. (ml/yd^3)	120	119	119	194	174	174	389	346	325
Properties of Fresh Concrete									
Slump (in.)	2.50	3.50	3.75	2.50	3.25	3.75	2.75	2.75	2.25
Air Content (%)	4.60	5.50	5.30	5.50	5.00	5.00	5.00	5.00	5.00
Unit Weight (lb/ft^3)	150.00	147.80	146.50	147.50	147.50	147.50	146.00	146.80	146.50
Compressive Strength									
14 Days (ksi)	4.07	2.83	3.49	5.12	5.12	4.95	6.84	6.61	6.65
28 Days (ksi)	4.72	4.43	4.36	5.92	6.15	5.77	7.53	7.53	7.34
Durability Factor									
Prism 1	61	93	86	109	78	84	95	94	95
Prism 2	83	92	95	87	69	67	98	85	86
Prism 3	64	96	91	84	51	69	92	92	87
Ave.	69	94	91	93	66	74	95	90	89

TABLE 13. MIX AND DURABILITY DATA—INFLUENCE OF 19.2% FLY ASH FOR DAVIS AGGREGATE

Batch No.	91	92	93	70	71	72	55	56	57
<u>Mix Proportions</u>									
Water/(Cement + Fly Ash)	0.49	0.50	0.48	0.40	0.40	0.40	0.29	0.29	0.28
Water (lb/yd^3)	243	249	240	283	280	277	299	293	284
Cement (lb/yd^3)	398	403	401	571	567	565	819	821	832
Fly Ash (lb/yd^3)	95	96	95	136	135	134	195	195	198
Coarse Aggregate (lb/yd^3)	1780	1800	1794	1799	1785	1779	1821	1826	1851
Fine Aggregate (lb/yd^3)	1313	1327	1323	1057	1049	1045	755	757	745
Air Ent. Admix. (ml/yd^3)	118	108	119	271	193	193	398	399	405
<u>Properties of Fresh Concrete</u>									
Slump (in.)	2.75	2.50	2.25	2.00	2.75	3.00	2.00	3.00	3.25
Air Content (%)	6.00	4.70	5.50	4.80	5.50	6.00	4.00	4.10	4.00
Unit Weight (lb/ft^3)	142.50	144.00	143.20	143.50	144.50	143.00	143.00	142.50	141.50
<u>Compressive Strength</u>									
14 Days (ksi)	4.50	4.88	4.52	5.76	5.58	5.31	5.75	5.62	5.88
28 Days (ksi)	4.89	5.17	4.98	6.15	5.95	5.83	6.23	6.14	6.57
<u>Durability Factor</u>									
Prism 1	62	78	68	69	53	72	78	44	69
Prism 2	61	69	56	58	68	64	73	71	66
Prism 3	52	76	58	72	73	69	74	81	64
Ave.	58	74	61	66	64	68	75	65	66

TABLE 14. MIX AND DURABILITY DATA—INFLUENCE OF 36.6% FLY ASH FOR DAVIS AGGREGATE

Batch No.	100	101	102	79	80	81	58	59	60
Mix Proportions									
Water/(Cement + Fly Ash)	0.48	0.48	0.48	0.39	0.38	0.38	0.29	0.30	0.29
Water (lb/yd^3)	208	215	205	256	246	245	325	318	308
Cement (lb/yd^3)	273	273	272	418	407	409	708	682	676
Fly Ash (lb/yd^3)	158	158	157	241	235	236	409	394	390
Coarse Aggregate (lb/yd^3)	1791	1789	1780	1803	1797	1806	1804	1790	1807
Fine Aggregate (lb/yd^3)	1429	1427	1420	1135	1160	1166	569	643	627
Air Ent. Admix. (ml/yd^3)	119	118	118	195	195	196	402	399	400
Properties of Fresh Concrete									
Slump (in.)	2.25	2.00	2.25	2.75	3.50	2.50	3.50	3.00	3.00
Air Content (%)	5.60	5.30	6.30	5.00	5.50	5.10	4.30	4.20	5.00
Unit Weight (lb/ft^3)	142.20	142.50	144.00	142.50	140.10	142.00	142.00	143.20	142.00
Compressive Strength									
14 Days (ksi)	3.81	3.99	4.01	4.94	4.45	4.74	5.83	6.22	5.80
28 Days (ksi)	4.56	4.32	4.54	5.58	5.37	5.54	6.47	6.85	7.00
Durability Factor									
Prism 1	64	55	50	67	87	87	86	76	75
Prism 2	70	59	57	49	71	82	81	88	66
Prism 3	70	58	61	66	49	84	92	70	62
Ave.	68	57	56	61	69	84	86	78	68

TABLE 15. MIX AND DURABILITY DATA—INFLUENCE OF 19.2 FLY ASH FOR CEDAR VALE AGGREGATE

Batch No.	88	89	90	67	68	69	49	50	51
<u>Mix Proportions</u>									
Water/(Cement + Fly Ash)	0.49	0.50	0.49	0.40	0.39	0.40	0.30	0.30	0.30
Water (lb/yd^3)	246	247	244	252	249	255	323	323	321
Cement (lb/yd^3)	406	399	403	516	517	515	871	871	866
Fly Ash (lb/yd^3)	97	95	96	123	123	122	207	207	206
Coarse Aggregate (lb/yd^3)	1748	1755	1734	1749	1753	1746	1771	1771	1760
Fine Aggregate (lb/yd^3)	1313	1342	1302	1186	1189	1184	658	658	654
Air Ent. Admix. (ml/yd^3)	124	125	123	195	195	194	274	274	348
<u>Properties of Fresh Concrete</u>									
Slump (in.)	2.50	1.25	3.25	1.75	3.25	2.75	2.50	2.50	1.75
Air Content (%)	5.20	4.50	6.00	5.00	5.00	5.00	3.50	3.50	4.10
Unit Weight (lb/ft^3)	141.50	143.00	141.00	142.00	140.50	140.50	142.50	142.50	142.50
<u>Compressive Strength</u>									
14 Days (ksi)	4.84	4.63	4.83	5.84	6.02	5.94	7.50	7.71	8.02
28 Days (ksi)	5.21	5.52	5.49	6.81	6.40	6.69	7.86	8.25	8.36
<u>Durability Factor</u>									
Prism 1	70	39	50	86	74	65	54	34	43
Prism 2	74	43	50	36	74	59	39	38	42
Prism 3	60	31	50	70	87	48	49	38	41
Ave.	68	38	50	64	79	57	48	37	42

TABLE 16. MIX AND DURABILITY DATA—INFLUENCE OF 36.6% FLY ASH FOR CEDAR VALE AGGREGATE

Batch No.	97	98	99	76	77	78	64	65	66
Mix Proportions									
Water/(Cement + Fly Ash)	0.50	0.48	0.48	0.39	0.40	0.40	0.30	0.30	0.30
Water (lb/yd^3)	241	245	234	255	255	254	317	316	316
Cement (lb/yd^3)	307	322	308	417	408	407	670	669	674
Fly Ash (lb/yd^3)	177	186	178	241	236	235	387	386	389
Coarse Aggregate(lb/yd^3)	1761	1848	1764	1754	1754	1754	1768	1764	1766
Fine Aggregate (lb/yd^3	1357	1424	1359	1137	1163	1168	655	654	642
Air Ent. Admix. (ml/yd^3)	120	126	120	199	199	199	437	491	437
Properties of Fresh Concrete									
Slump (in.)	3.25	3.00	2.75	2.75	2.25	3.25	2.25	3.00	2.75
Air Content (%)	4.20	--[a]	4.50	5.00	4.70	4.70	3.75	4.00	4.00
Unit Weight (lb/ft^3)	141.50	143.00	143.60	141.50	141.50	140.50	140.80	140.50	140.20
Compressive Strength									
14 Days (ksi)	4 12	4.35	4.45	5.96	6.12	5.84	7.39	6.84	7.78
28 Days (ksi)	4.84	4.69	5.26	6.74	7.01	6.43	8.08	7.33	7.16
Durability Factor									
Prism 1	90	58	74	40	38	53	60	54	44
Prism 2	76	50	64	45	31	45	72	51	57
Prism 3	69	41	52	38	53	48	52	62	50
Ave.	78	49	63	41	41	49	61	56	50

[a] Value was not recorded.

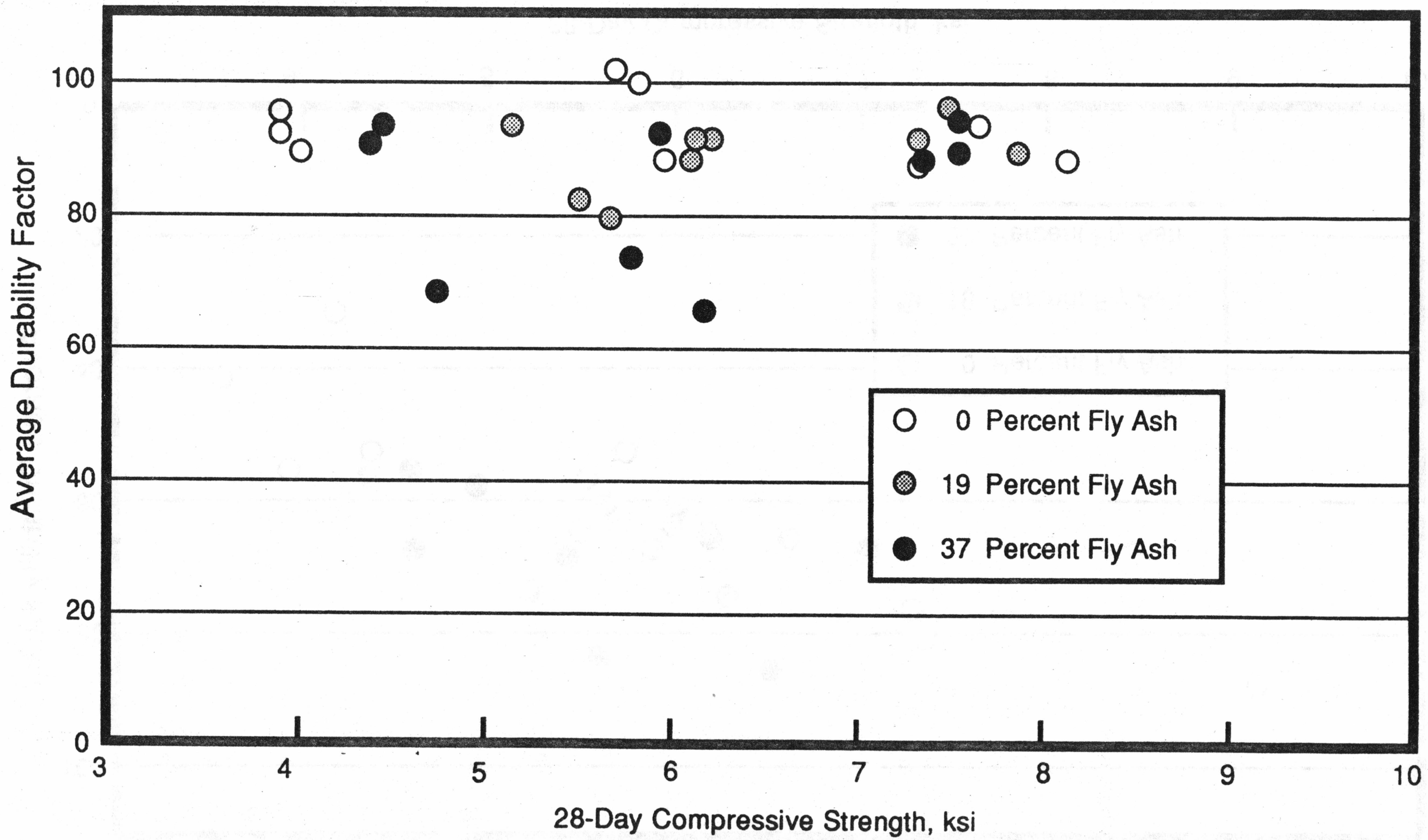

Fig. 11. Influence of Fly Ash on Durability of Concrete With Drumright Aggregate

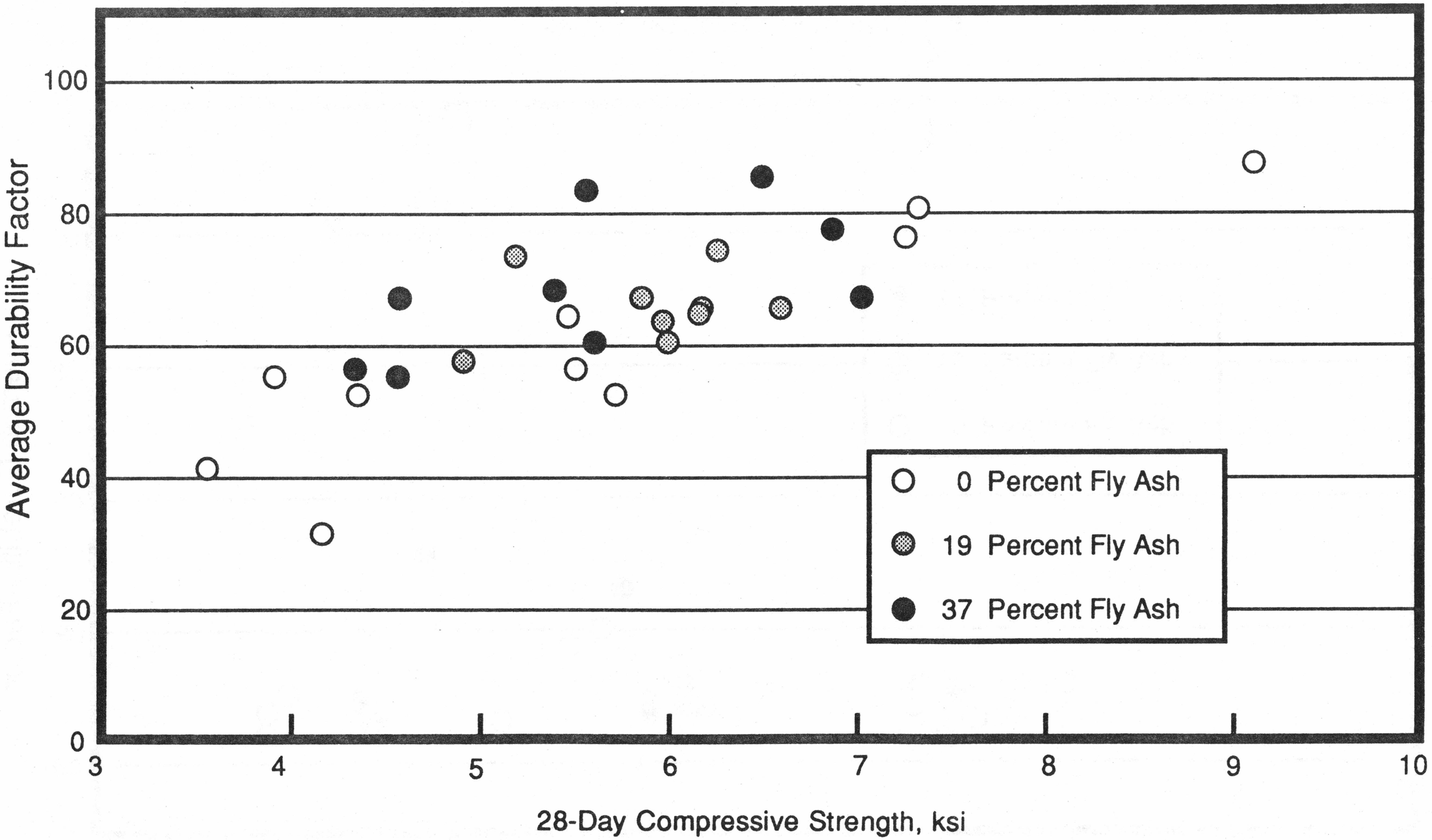

Fig. 12. Influence of Fly Ash on Durability of Concrete
With Davis Aggregate

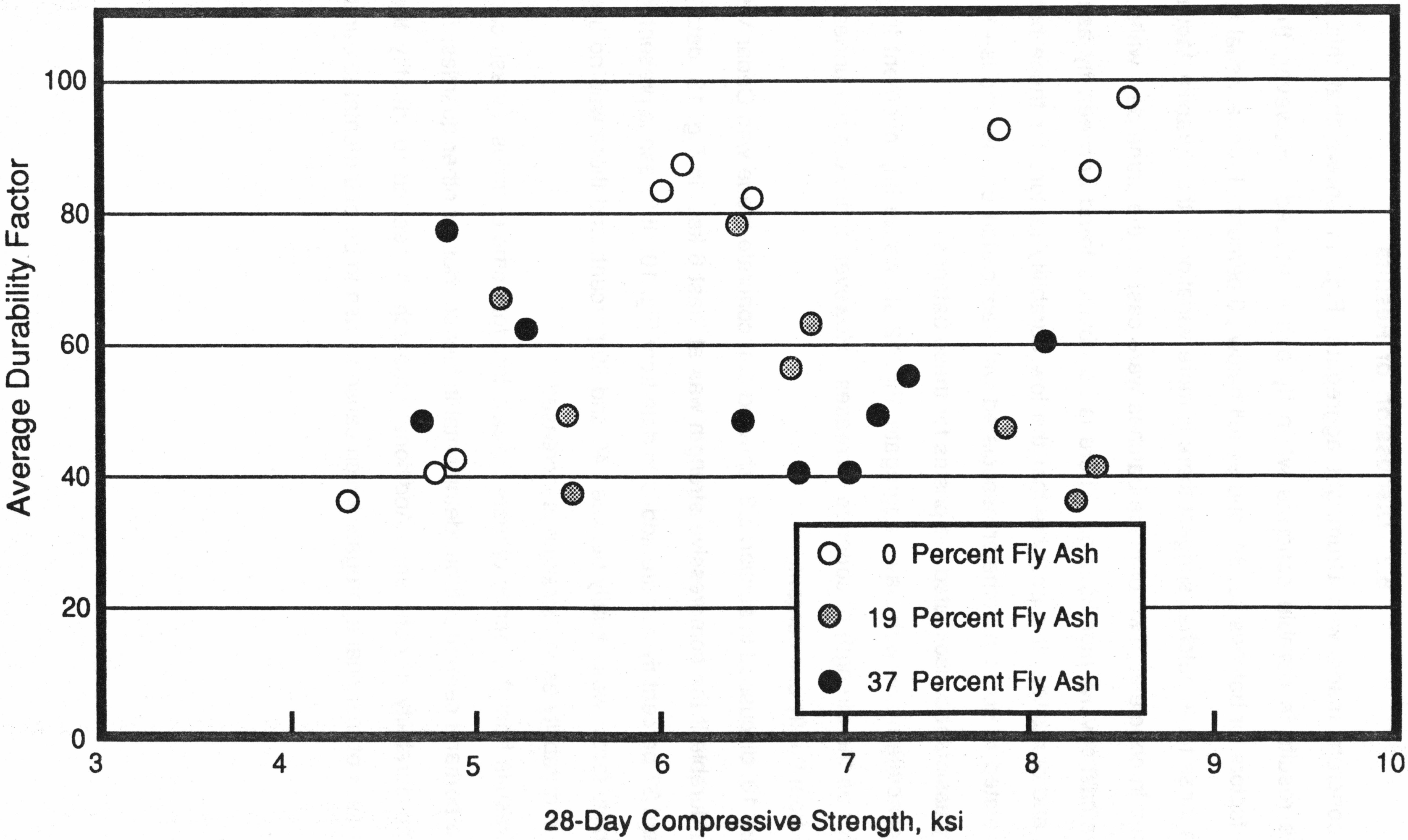

Fig. 13. Influence of Fly Ash on Durability of Concrete
With Cedar Vale Aggregate

6.3 Discussion of Results

For concrete made with Drumright aggregate, Fig. 11 shows that this source of aggregate results in durable concrete when fly ash is utilized. However, the average durability factors for batches 83, 84, and 94 fell below 80 percent. From a visual standpoint, data from these three batches suggest there is more variation in the durability factor when fly ash is used in concrete. Two of these batches were cast on the same day, while the other batch was cast several months later. There is no obvious trend between fly ash content, strength, and durability. It is possible that the low durability factors for these batches are actually related to some parameter associated with fabrication of specimens—e.g., which laboratory assistant consolidated the prisms for these batches.

For concrete made with Davis aggregate, Fig. 12 shows an improvement in the durability factor as the strength of concrete increases. However, there did not appear to be an influence from the fly ash content.

Figure 10, discussed in section 5.3, showed that concrete made with Cedar Vale aggregate was durable if the compressive strength was at least 6 ksi. In Fig. 13, data for mixes with 19 and 37 percent fly ash are added to data from Fig. 10. If fly ash is present in the mix, the durability factor was usually between 40 and 60 percent, and there was no trend for an increase in durability as the strength is increased.

The results from this series of tests indicate that for some quarries, fly ash can be used to replace portland cement without detrimental influence; but for other quarries, fly ash may reduce the durability of concrete. Additional research is needed to identify the specific characteristics of marginal aggregate which cause fly ash to be detrimental to durability.

7. SERIES 4—INFLUENCE OF SILICA FUME ON DURABILITY

7.1 General

These tests involved a new shipment of aggregate from Cedar Vale, Kansas, and aggregate from near Tulsa, Oklahoma. The quarry at Davis, Oklahoma, had closed since the beginning of the project and the Tulsa aggregate was substituted.

Silica fume is available in noncompacted and compacted dry forms and in a water slurry. The noncompacted dry form was used in these tests. The supplier of the silica fume indicated that the specific gravity is normally in the range of 2.1 to 2.2 and the specific surface is between 240,000 and 300,000 cm^2/gm.

7.2 Experimental Results

Tables 17 and 18 contain data on mix proportions, properties of the fresh concrete, compressive strength, and durability. For the aggregate from Tulsa, three batches of concrete were tested for each silica fume percentage. For the Cedar Vale aggregate, only two batches for each ash percentage were tested when experimental work was discontinued at the end of 1989.

Four prisms in batches 113 and 114 failed by the formation of a transverse crack somewhere between 323 and 358 cycles. For these prisms the durability factors were estimated as the relative dynamic modulus at 323 cycles multiplied by (323/350). The same approach was applied to the three prisms from batch 116, which failed shortly after 150 cycles. The influence of silica fume on the durability factor is shown in Fig. 14.

7.3 Discussion of Results

The proposed nominal strength of concrete for this series of tests was 4 ksi. In the first three series of tests, this strength was achieved with a water-to-cement ratio of approximately 0.5. Trial mixes with the new shipments of aggregate using water-to-cement ratio of 0.5 gave strengths slightly greater than 5 ksi. Rather than employ a high water-to-cement ratio, which would be unrealistic for pavement applications, the ratio was set at 0.50.

TABLE 17. MIX AND DURABILITY DATA—INFLUENCE OF SILICA FUME FOR CEDAR VALE AGGREGATE

Batch No.	115	116	117	118	119	120	121	122
Mix Proportions								
Water/(Cement + Silica Fume)	0.47	0.47	0.47	0.50	0.49	0.50	0.49	0.47
Silica Fume/(Cement + Silica Fume)	0.00	0.00	0.05	0.05	0.10	0.10	0.15	0.15
Water (lb/y^3)	243	222	224	222	287	295	316	309
Cement (lb/yd^3)	518	477	455	424	527	530	553	553
Silica Fume (lb/yd^3)	0	0	24	22	59	59	98	98
Coarse Aggregate (lb/yd^3)	1741	1751	1757	1715	1748	1760	1748	1751
Fine Aggregate (lb/yd^3)	1272	1371	1371	1384	1129	1137	985	986
Air Ent. Ad Mix (ml/yd^3)	119	103	125	122	217	218	596	597
Properties of Fresh Concrete								
Slump (in.)	3.50	2.25	3.00	2.75	2.25	2.00	3.00	3.00
Air Content (%)	6.00	5.50	5.10	6.70	5.00	4.00	5.20	5.50
Unit Weight (lb/ft^3)	138.00	143.00	141.00	140.00	140.00	143.00	132.00	130.50
Compressive Strength								
14 Days (ksi)	4.64	4.78	5.35	6.00	5.46	7.11	5.78	5.26
28 Days (ksi)	5.04	5.07	5.44	6.53	6.02	8.03	6.38	6.38
Durability Factor								
Prism 1	65	38[a]	68	63	66	67	65	73
Prism 2	63	34[a]	53	72	66	64	76	81
Prism 3	57	36[a]	63	62	65	61	65	76
Ave.	62	36	61	66	66	64	69	76

[a] Failed before P_c reached 50%. Estimated durability factor based on last P_c before failure.

TABLE 18. MIX AND DURABILITY DATA—INFLUENCE OF SILICA FUME FOR TULSA AGGREGATE

Batch No.	103	104	105	106	107	108	109	110	111	112	113	114
Mix Proportions												
Water/Cement + Silica Fume)	0.45	0.50	0.49	0.50	0.49	0.49	0.50	0.50	0.50	0.50	0.50	0.48
Silica Fume/(Cement+Silica Fume)	0.00	0.00	0.00	0.05	0.05	0.05	0.10	0.10	0.10	0.25	0.15	0.15
Water (lb/yd^3)	233	239	229	237	233	233	291	289	291	327	325	318
Cement (lb/yd^3)	520	479	470	453	447	452	524	521	524	556	557	560
Silica Fume (lb/yd^3)	0	0	0	24	24	24	58	58	58	98	98	99
Coarse Aggregate (lb/yd^3)	1794	1801	1766	1793	1770	1791	1785	1773	1785	1805	1808	1817
Fine Aggregate (lb/yd^3)	1278	1375	1348	1365	1347	1363	1124	1116	1124	991	993	998
Air Ent. Admix. (ml/yd^3)	119	103	107	108	123	119	324	321	324	513	601	714
Properties of Fresh Concrete												
Slump (in.)	2.25	1.75	2.00	1.75	1.75	2.25	2.75	2.50	3.25	3.25	2.50	3.00
Air Content (%)	6.20	4.20	6.50	4.80	6.10	5.10	5.10	5.80	5.10	4.00	4.00	4.00
Unit Weight (lb/ft^3)	143.00	143.00	141.00	144.50	142.80	142.00	138.40	139.40	136.60	135.20	134.50	133.00
Compressive Strength												
14 Days (ksi)	5.15	5.25	5.14	5.91	6.05	6.03	5.97	6.37	5.72	5.60	5.42	5.02
28 Days (ksi)	5.21	5.48	5.40	6.26	6.71	6.60	6.47	6.65	6.32	5.92	5.66	5.48
Durability Factor												
Prism 1	65	46	57	20	64	69	69	68	59	59	65[a]	64
Prism 2	58	51	35	42	79	64	72	69	72	64	69[a]	54
Prism 3	50	46	39	54	38	72	73	70	65	59	54[a]	66[a]
Ave.	58	48	44	39	60	69	71	69	65	60	63	61

[a] Failed before P_c reached 50%. Estimated durability factor based on last P_c before failure.

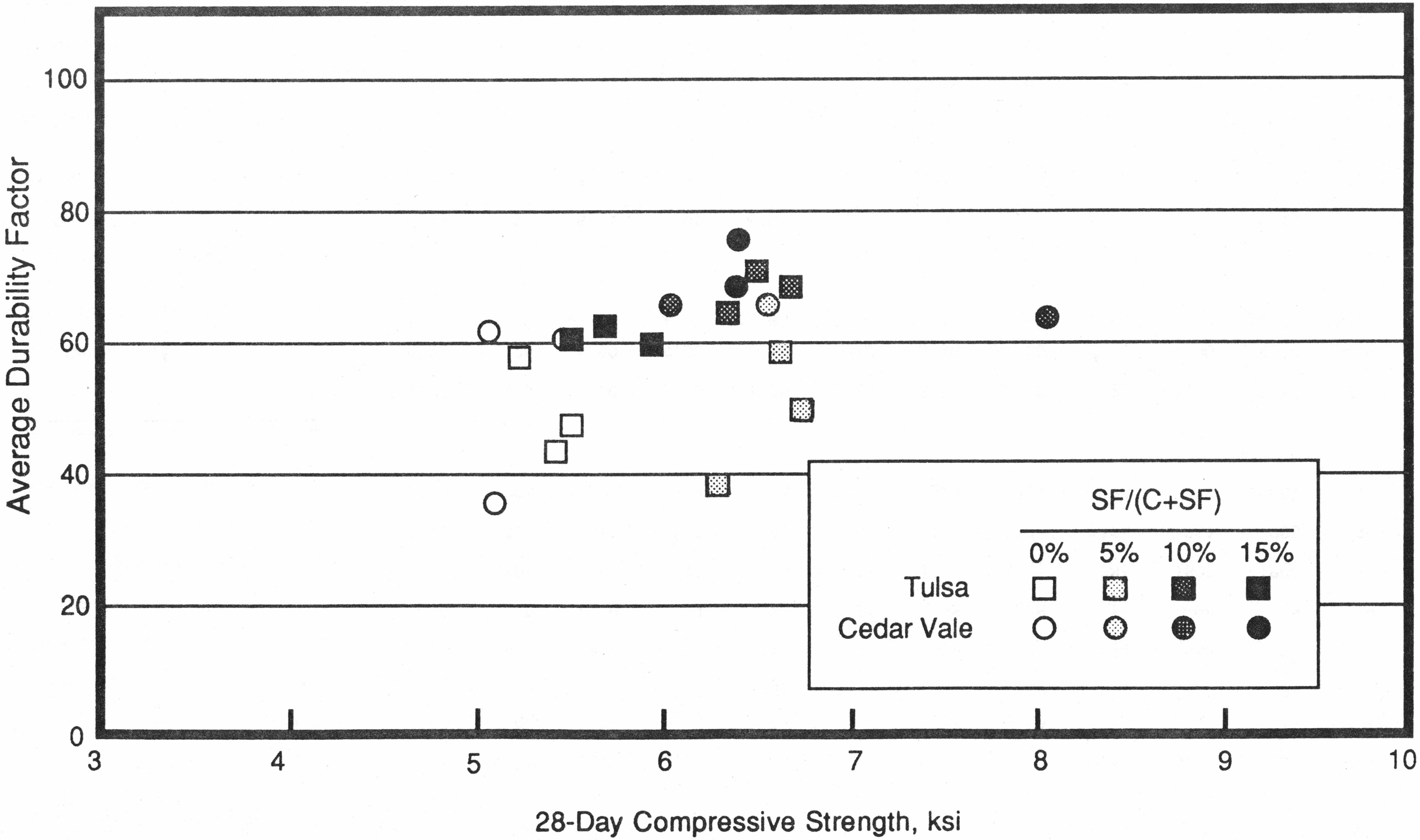

Fig. 14. Influence of Silica Fume on Durability of Concrete With Cedar Vale and Tulsa Aggregate

As the percentage of silica fume increased, the air entraining agent dosage and water demand increased markedly. The mixes with silica fume also contained a high range water-reducing admixture to partially offset the influence of the silica fume on the water demand. In retrospect it might have been advantageous to fix the total weight of cement and silica fume, and adjust the water reducer dosage to control slump.

Figure 14 suggests that silica fume is of questionable value in improving the durability of mixes made with marginal aggregate. Probably the minor increase in durability with silica fume percentage is largely attributable to the modest increase in strength associated with the presence of silica fume. In most cases silica fume is employed in mixes with extremely low water-to-cement ratios. It was assumed that such mixes are unlikely to be employed in pavements. Therefore, the role of silica fume on the durability of very strong mixes containing marginal aggregate was outside the scope of this study.

8. RECOMMENDATIONS

8.1 Identification of Substandard Aggregate

The use of Procedure A of ASTM C 666 to identify substandard aggregate has the advantage of providing a quantitative measure of quality—the durability factor. However, the rapid freezing and thawing method has many disadvantages. Because tests are labor intensive and require several weeks to conduct, the quality of stone produced by quarries cannot be checked at frequent intervals. The results obtained in this study show that for marginal aggregates the durability factor is strongly influenced by concrete strength and aggregate gradation. Unless testing procedures are tightly controlled, the repeatability and accuracy of the test will be questionable. Prior to mixing, aggregate should be dried, sieved into size fractions, recombined to a standard gradation, and soaked in water for 24 hrs. Mix proportions should be adjusted as necessary using trial mixes so that all batches contain the same solid volume of coarse aggregate and the same water-to-cement ratio.

It is suggested that additional tests be used to identify marginal aggregates—possibly to help select quarries which will be checked by normal freezing and thawing tests. For example, the Iowa Pore Index Test [12] appears to be a useful procedure to identify marginal aggregate or to detect changes in the quality of aggregate from a quarry over time. A prototype test procedure involving the freezing of saturated aggregate was recently developed at Oklahoma State University as a class project: acoustic emission instrumentation was used to detect cracking. Limited tests conducted on the aggregates used in the first three series of tests in this study indicated there was no cracking of the high quality aggregate during the freezing process, while cracking was detectable by the instrumentation for marginal aggregate. Undoubtedly a number of other tests have been developed to detect aggregate susceptible to D-cracking.

8.2 Producing Pavements Resistant to D-Cracking

Naturally, long lasting pavements entail correct design construction and maintenance. In ASTM C 666, it is pointed out that neither test method (A or B) is intended to provide a quantitative measure of the length of service that may be expected from a specific type of concrete. This is the most serious shortcoming of ASTM C 666. Tests of concrete made with aggregate from two sources can yield equal and low durability factors for different reasons. For example, the Cedar Vale material tested in this program contained chert particles which produced local popouts, while the Davis aggregate had a pore system which resulted in a more uniform deterioration. The stresses generated by the formation of a popout can cause severe damage or even total failure to a small test prism but less damage to a large pavement slab.

Implementation of research findings from studies such as this are risky without further laboratory and field investigations. For example, this program found durability factors were increased by reducing the maximum size of marginal aggregate and by increasing the strength of the paste. To what extent are such findings only a function of test parameters such as prism size, and to what degree will results be valid under field conditions? Freeze-thaw durability is only one criterion of performance. In a recently completed study [13], it was found that reducing the maximum size of aggregate or increasing the strength of concrete may be detrimental to joint life. With higher strength concrete, the fracture plane tends to pass through rather than around coarse aggregate, reducing aggregate interlock. If marginal aggregate is to be used in highway construction and if service life of pavements is an important consideration, further laboratory and field research is needed.

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