TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.
FHWA/TX-87/35+367-1F

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
GUIDELINES FOR USE OF HIGH STRENGTH
CONCRETE IN TEXAS HIGHWAYS

5. Report Date
August 1986

6. Performing Organization Code

7. Author(s)
P. M. Carrasquillo and R. L. Carrasquillo

8. Performing Organization Report No.
Research Report 367-1F

9. Performing Organization Name and Address
Center for Transportation Research
The University of Texas at Austin
Austin, Texas 78712-1075

10. Work Unit No.

11. Contract or Grant No.
Research Study 3-5-85-367

12. Sponsoring Agency Name and Address
Texas State Department of Highways and Public Transportation; Transportation Planning Division
P. O. Box 5051
Austin, Texas 78763-5051

13. Type of Report and Period Covered
Final

14. Sponsoring Agency Code

15. Supplementary Notes
Study conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration. Research Study Title: "Guidelines for Use of High Strength Concrete in Texas Highways"

16. Abstract

Batching, mixing, transporting, placing, and quality control procedures for high strength concrete are not different in principle from those procedures used for conventional concrete. However, changes, refinement, and increased emphasis on some aspects of currently used concrete specifications are needed in order to ensure a successful concreting operation when dealing with high strength concrete.

This study investigated the applicability of currently used quality control procedures in the production of high strength concrete. In all, a total of over one thousand strength specimens were cast from twenty-nine different high strength concrete mixes. Factors investigated included type and size of test specimen, use of mineral and chemical admixtures, curing method, testing procedure, and typical strength gain characteristics of high strength concrete mixes with and without mineral admixture. In addition, a pilot study was conducted in which high strength concrete trial batches were conducted at a prestressing plant for a Texas Highway Department project.

Specifications need to be modified to allow for optimum use of materials for producing high strength concrete, including mineral and chemical admixtures. Mixing, transporting, and placing procedures must ensure uniform mixing and adequate compaction of the fresh concrete without any time delays. Special consideration must be given to field curing procedures, since the strength of high strength concrete is known to be affected more by improper curing practices than that of normal strength concrete.

17. Key Words
concrete, high strength, quality control procedures, strength specimens, mixes, admixtures, curing, testing

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	254	

Form DOT F 1700.7 (8-69)

GUIDELINES FOR USE OF HIGH STRENGTH CONCRETE IN TEXAS HIGHWAYS

by

P. M. Carrasquillo and R. L. Carrasquillo

Research Report No. 367-1F

Research Project 3-5-85-367

Conducted for

Texas

State Department of Highways and Public Transportation

In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

by

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

August 1986

PREFACE

This report summarizes a detailed study on the quality control procedures and specifications governing the production of high strength concrete in the field. Basic properties and behavior of high strength concrete are reviewed, particularly those that may differ from those of normal strength concrete, thus requiring special attention to quality control practices.

This research study, Project 3-5-85-367 entitled "Guidelines for Use of High Strength Concrete in Texas Highways," was conducted at the Phil M. Ferguson Structural Engineering Laboratory as part of the overall research program of the Center for Transportation Research, Bureau of Engineering Research, of The University of Texas at Austin. The work was sponsored jointly by the Texas State Department of Highways and Public Transportation and the Federal Highway Administration.

The overall study was directed by Dr. Ramon L. Carrasquillo, Associate Professor of Civil Engineering. The detailed work was carried out under the direct supervision of Peggy M. Carrasquillo, M.S., research engineer, Center for Transportation Research.

SUMMARY

Batching, mixing, transporting, placing, and quality control procedures for high strength concrete are not different in principle from those procedures used for conventional concrete. However, changes, refinement, and increased emphasis on some aspects of currently used concrete specifications are needed in order to ensure a successful concreting operation when dealing with high strength concrete.

This study investigated the applicability of currently used quality control procedures in the production of high strength concrete. In all, a total of over one thousand strength specimens were cast from twenty-nine different high strength concrete mixes. Factors investigated included type and size of test specimen, use of mineral and chemical admixtures, curing method, testing procedure, and typical strength gain characteristics of high strength concrete mixes with and without mineral admixture. In addition, a pilot study was conducted in which high strength concrete trial batches were conducted at a prestressing plant for a Texas Highway Department project.

Specifications need to be modified to allow for optimum use of materials for producing high strength concrete, including mineral and chemical admixtures. Mixing, transporting, and placing procedures must ensure uniform mixing and adequate compaction of the fresh concrete without any time delays. Special consideration must be given to field curing procedures, since the strength of high strength concrete is known to be affected more by improper curing practices than that of normal strength concrete.

IMPLEMENTATION

This report summarizes an experimental study aimed at developing sufficient data to provide guidelines in the development of quality control procedures to be used in the production of high strength concrete. The results of this study should be considered by the Texas State Department of Highways and Public Transportation in the development of specifications governing the production of high strength concrete in the field.

This report contains background information of interest to those responsible for deciding on specifications and code provisions. Included is a study of those factors affecting the strength of high strength concrete, mix proportioning guidelines, and basic properties of three different types of mineral admixture.

TABLE OF CONTENTS

Chapter Page

1. INTRODUCTION 1

1.1 General 1
1.2 Definitions 1
1.3 Uses for High Strength Concrete 1
1.4 Justification of Research 2
1.5 Objectives of Research 2
1.6 Research Plan 3
1.7 Report Format 3

2. BACKGROUND ON HIGH STRENGTH CONCRETE 5

2.1 Introduction 5
2.2 Fundamental Mechanisms of High Strength Concrete .. 5
  2.2.1 Portland cement paste 5
  2.2.2 Effect of chemical admixtures 7
    2.2.2.1 Water reducers and retarders 7
    2.2.2.2 High range water reducers 7
    2.2.2.3 Air entraining admixtures 7
  2.2.3 Effect of mineral admixtures 9
    2.2.3.1 Fly ash 11
    2.2.3.2 Slag 14
    2.2.3.3 Silica fume 14
  2.2.4 Coarse aggregate 16
  2.2.5 Summary 20
2.3 Mix Proportioning Guidelines for High Strength Concrete 20
  2.3.1 Required concrete strength 20
    2.3.1.1 Test age 20
    2.3.1.2 Laboratory versus field test results 20
  2.3.2 Water-to-binder ratio 20
  2.3.3 Cement 21
  2.3.4 Coarse aggregate content 21
  2.3.5 Fine aggregate 21
  2.3.6 Recommended slump of concrete 21
  2.3.7 Mineral admixtures 21
  2.3.8 Chemical admixtures 22

3. EXPERIMENTAL PROGRAM 23

3.1 Introduction 23
3.2 Mix Identification System 23
3.3 Material Properties 24
3.4 Batching Procedure 24
3.5 Corrected Mix Proportions 32

TABLE OF CONTENTS (continued)

Chapter Page

3.6 Test Procedures 32
    3.6.1 Slump 32
    3.6.2 Air content 32
    3.6.3 Unit weight 64
    3.6.4 Test specimens 64
3.7 Variables Studied 64
    3.7.1 Specimen size 64
    3.7.2 Mold material 64
    3.7.3 Curing conditions 64
    3.7.4 Addition of superplasticizer 67
    3.7.5 Capping method 67
    3.7.6 Consolidation 67
    3.7.7 Test age 67
    3.7.8 Field pilot study 67

4. EFFECT OF SPECIMEN SIZE 69

4.1 Introduction 69
4.2 Compressive Strength Tests 69
4.3 Flexural Strength Tests 81

5. EFFECT OF MOLD MATERIAL 83

5.1 Introduction 83
5.2 6-in. x 12-in. Cylinder Molds 83
5.3 4-in. x 8-in. Cylinder Molds 83

6. EFFECT OF CURING CONDITIONS 91

6.1 Introduction 91
6.2 Compressive Strength Tests 91
6.3 Flexural Strength Tests 91

7. EFFECT OF ADDITION OF SUPERPLASTICIZER 99

7.1 Introduction 99
7.2 Time of Addition 99
    7.2.1 Effect on compressive strength 99
    7.2.2 Effect on flexural strength 102
7.3 Redosing 102
    7.3.1 Effect on compressive strength 102
    7.3.2 Effect on flexural strength 102
7.4 Discussion 107

TABLE OF CONTENTS (continued)

Chapter Page

8. EFFECT OF CAPPING METHOD 111

8.1 Introduction 111
8.2 Type of Cap Used 111
8.2.1 Effect on 6-in. x 12-in. cylinder strength . 111
8.2.2 Effect on 4-in. x 8-in. cylinder strength .. 111
8.3 Age of Cap 115
8.4 Discussion 115

9. EFFECT OF CONSOLIDATION 121

9.1 Introduction 121
9.2 Effect on 6-in. x 12-in. Cylinder Strength 121
9.3 Effect on 4-in. x 8-in. Cylinder Strength 121

10. EFFECT OF TEST AGE 125

10.1 Introduction 125
10.2 Strength Gain Curves 125
10.3 Strength Gain: Percent of 28-day 125
10.4 Strength Gain: Percent of 56-day 138
10.5 Strength Gain: Percent of 91-day 138
10.6 Discussion 144

11. ADDITIONAL FINDINGS 149

11.1 Introduction 149
11.2 Effect of Coarse Aggregate Source 149
11.3 Third Point Loading Versus Center Point Loading ... 150
11.4 Seven-Day Flexural Strength Versus 28-Day Compressive Strength 154

12. RESULTS OF FIELD PILOT STUDY 161

12.1 Introduction 161
12.2 Material Properties 161
12.3 Trial Batch Information 161
12.4 Test Results 164

13. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY 169

13.1 Summary 169
13.2 Conclusions 169
13.3 Recommendations for Further Research 172

TABLE OF CONTENTS (continued)

Chapter Page

APPENDIX A STRENGTH VERSUS TIME CURVES 173

APPENDIX B PERCENTAGE STRENGTH GAIN CURVES, 28-DAY 185

APPENDIX C PERCENTAGE STRENGTH GAIN CURVES, 56-DAY 197

APPENDIX D PERCENTAGE STRENGTH GAIN CURVES, 91-DAY 209

APPENDIX E DOCUMENTS APPENDED TO SPECIFICATIONS FOR FIELD PILOT STUDY 215

REFERENCES 225

LIST OF TABLES

Table Page

3.1 Properties of coarse aggregates used in high strength concrete mixes 25

3.2 Properties of fly ash used in high strength concrete mixes .. 26

3.3 Properties of chemical and air entraining admixtures used in high strength concrete mixes 27

3.4 Materials used in each high strength concrete mix 28

3.5 History of mix number 01-107-00 34

3.6 History of mix number 02-095-00 35

3.7 History of mix number 03-096-00 36

3.8 History of mix number 04-100-00 37

3.9 History of mix number 05-089-00 38

3.10 History of mix number 06-097-00 39

3.11 History of mix number 07-098-00 40

3.12 History of mix number 08A-104-00 and 08B-104-00 41

3.13 History of mix number 09-106-00 42

3.14 History of mix number 10-094-00 43

3.15 History of mix number 11-093-27 44

3.16 History of mix number 12-093-38 45

3.17 History of mix number 13-100-00 46

3.18 History of mix number 14-110-28 47

3.19 History of mix number 15-112-38 48

3.20 History of mix number 16-107-00 49

3.21 History of mix number 17-100-00 50

3.22 History of mix number 18-111-35 51

3.23 History of mix number 19-103-00 52

LIST OF TABLES (continued)

Table Page

3.24 History of mix number 20-111-33 53

3.25 History of mix number 21-112-34 54

3.26 History of mix number 22-110-34 55

3.27 History of mix number 23-067-00 56

3.28 History of mix number 24-065-00 57

3.29 History of mix number 25-056-00 57

3.30 History of mix number 26-057-00 58

3.31 History of mix number 27-060-00 58

3.32 History of mix number 28-059-00 59

3.33 History of mix number 29-060-00 59

3.34 Corrected mix proportions per cubic yard for high strength concrete mixes 60

3.35 Design constants for high strength concrete mixes 61

4.1 Compressive strength results for 4-in. x 8-in. and 6-in. x 12-in. cylinders cast in steel molds 70

4.2 Compressive strength results for 4-in. x 8-in. and 6-in. x 12-in. cylinders cast in plastic molds 71

4.3 Correlation of 4-in. x 8-in. cylinder strength to 6-in. x 12-in. cylinder strength, when data are grouped according to concrete strength [13] 80

4.4 A. Test results of 4-in. x 4-in. x 14-in. and 6-in. x 6-in. x 20-in. beams, tested in third point loading 82

B. Test results of 4-in. x 4-in. x 14-in. and 6-in. x 6-in. x 20-in. beams, tested in center point loading 82

5.1 Comparison of strength of 6-in. x 12-in. cylinders cast in steel and plstic molds 84

LIST OF TABLES (continued)

Table Page

5.2 Twenty-eight day results of 6-in. x 12-in. cylinders cast in steel and plastic molds, from Peterman and Carrasquillo [20] 85

5.3 Comparison of strength of 4-in. x 8-in. cylinders cast in steel and plastic molds 87

5.4 Comparison of strength of 4-in. x 8-in. cylinders cast in steel and cardboard molds 87

6.1 Effect of curing conditions on compressive strength of 6-in. x 12-in. cylinders: fog room vs. curing compound 92

6.2 Effect of curing conditions on compressive strength of 6-in. x 12-in. cylinders: fog room vs. no curing 96

6.3 Effect of curing conditions on flexural strength of 6-in. x 6-in. x 20-in. beams 96

7.1 Effect of time of addition of superplasticizer on the compressive strength of high strength concrete 100

7.2 Effect of time of addition of superplasticizer on the flexural strength of high strength concrete 103

7.3 Effect of redosing with superplasticizer on the compressive strength of high strength concrete 105

7.4 Effect of redosing with superplasticizer on the flexural strength of high strength concrete 105

8.1 Effect of cap type on compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete 112

8.2 Effect of cap type on compressive strength of 4-in. x 8-in. cylinders cast from high strength concrete 114

8.3 Effect of cap age on compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete 116

9.1 Effect of consolidation on strength of 6-in. x 12-in. cylinders cast from high strength concrete 122

9.2 Effect of consolidation on strength of 4-in. x 8-in. cylinders cast from high strength concrete 123

LIST OF TABLES (continued)

Table | Page

10.1 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes having a water-to-cement ratio between 0.270 and 0.290 126

10.2 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes having a water-to-cement ratio between 0.290 and 0.300 127

10.3 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes having a water-to-cement ratio between 0.300 and 0.340 128

10.4 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes having a water-to-cement ratio between 0.340 and 0.550 129

10.5 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes containing less than 30 percent fly ash 130

10.6 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes containing more than 30 percent fly ash, and having a water-to-binder ratio between 0.250 and 0.270 131

10.7 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes containing more than 30 percent fly ash, and having a water-to-binder ratio between 0.270 and 0.340 132

10.8 Strength gain characteristics, based on 28-day strength, of high strength concrete mixes containing no fly ash, and having a water-to-cement ratio between 0.270 and 0.290 134

10.9 Strength gain characteristics, based on 28-day strength, of high strength concrete mixes containing no fly ash, and having a water-to-cement ratio between 0.290 and 0.300 135

10.10 Strength gain characteristics, based on 28-day strength, of high stength concrete mixes containing no fly ash, and having a water-to-cement ratio between 0.300 and 0.350 136

10.11 Strength gain characteristics, based on 28-day strength, of high strength concrete mixes containing less than 30 percent fly ash 136

LIST OF TABLES (continued)

Table Page

10.12 Strength gain characteristics, based on 28-day strength, of high strength concrete mixes containing more than 30 percent fly ash 137

10.13 Strength gain characteristics, based on 56-day strength, of high strength concrete mixes containing no fly ash, and having a water-to-cement ratio between 0.270 and 0.290 139

10.14 Strength gain characteristics, based on 56-day strength, of high strength concrete mixes containing no fly ash, and having a water-to-cement ratio between 0.290 and 0.300 140

10.15 Strength gain characteristics, based on 56-day strength, of high strength concrete mixes containing no fly ash, and having a water-to-cement ratio between 0.300 and 0.350 140

10.16 Strength gain characteristics, based on 56-day strength, of high strength concrete mixes containing less than 30 percent fly ash 141

10.17 Strength gain characteristics, based on 56-day strength, of high strength concrete mixes containing more than 30 percent fly ash 141

10.18 Strength gain characteristics, based on 91-day strength, of high strength concrete mixes containing no fly ash 142

10.19 Strength gain characteristics, based on 91-day strength, of high strength concrete mixes containing fly ash 143

10.20 Average strength gain characteristics for mixes with and without fly ash based on various test ages 145

11.1 Comparison of test results obtained from testing high strength flexural beam specimens in third point loading and center point loading; a) 6-in. x 6-in. x 20-in. beams; b) 4-in. x 4-in. x 14-in. beams 151

11.2 Flexural strength at seven days versus compressive strength at 28 days for high strength concrete mixes containing no fly ash 156

11.3 Flexural strength at seven days versus compressive strength at 28-days for high strength concrete mixes: a) mixes containing less than 30 percent fly ash; b) mixes containing more than 30 percent fly ash 157

LIST OF TABLES (continued)

Table Page

12.1 Properties of materials used in high strength concrete trial batches 162

12.2 Mix proportions per cubic yard and fresh concrete properties for high strength concrete trial batches 163

12.3 Curing received by each trial batch 167

12.4 Test results obtained from high strength concrete trial batches 167

E.1 High strength concrete mix design guidelines 223

LIST OF FIGURES

Figure Page

2.1 A model of the structure of mature hardened cement paste: (a) made with a high initial water/cement ratio; (b) paste made with a low initial water/cement ratio [21] 6

2.2 Strengths of concretes with and without HRWRs, and with different water-cement ratios [9] 8

2.3 Temperature-time curves at 22° C for pastes containing no chemical admixture [15] 10

2.4 Particle size distribution of typical materials [17] ... 12

2.5 Scanning electron micrographs of a: (a) low-calcium fly ash; (b) high-calcium fly ash; (c) broken plerosphere in a low-calcium fly ash [17] 15

2.6 Refinement of the pore system caused by the addition of silica fume to concrete [17] 17

2.7 Twenty-eight day compressive strength vs. w/c-ratio for concrete with different microsilica contents. Concretes with and without water reducing admixtures are not differentiated [23] 18

2.8 (a) Compressive strength and (b) modulus of elasticity of 7500 psi concrete for various types of coarse aggregate [2] 19

2.9 Compressive strength of 9000 psi concrete for various sizes and types of coarse aggregate [2] 19

3.1 (a) Measurement of chemical admixture dosage; (b) addition of chemical admixture to ready-mix truck 29

3.2 Addition of fly ash to ready-mix truck 30

3.3 Examination of concrete at ready-mix plant for proper consistency 31

3.4 Examination of concrete at laboratory for proper consistency after superplasticizer was added 33

3.5 Slump test 62

3.6 Air content test 63

LIST OF FIGURES (continued)

Figure Page

3.7 Unit weight test 65

3.8 Preparation of strength specimens 66

4.1 Comparison of test results obtained from 4-in. x 8-in. cylinders cast in steel molds to 6-in. x 12-in. cylinders cast in steel molds 72

4.2 Comparison of test results obained from 4-in. x 8-in. cylinders cast in plastic molds to 6-in. x 12-in. cylinders cast in plastic molds 73

4.3 Comparison of the 28-day compressive strength of high strength concrete specimens cast in 4-in. x 8-in. and 6-in. x 12-in. rigid steel molds [20] 74

4.4 4-in. x 8-in. versus 6-in. x 12-in. cylinder test results at 7 days [13] 75

4.5 4-in. x 8-in. versus 6-in. x 12-in. cylinder test results at 14 days [13] 76

4.6 4-in. x 8-in. versus 6-in. x 12-in. cylinder test results at 28 days [13] 77

4.7 4-in. x 8-in. versus 6-in. x 12-in. cylinder test results at 56 days [13] 78

4.8 Correlation of 4-in. x 8-in. cylinder strength to 6-in. x 12-in. cylinder strength [13] 79

5.1 Compressive strength of 6-in. x 12-in. cylinders cast in steel molds versus plastic molds 86

5.2 Compressive strength of 4-in. x 8-in. cylinders cast in steel molds versus plastic molds 88

5.3 Compressive strength of 4-in. x 8-in. cylinders cast in steel molds versus cardboard molds 89

5.4 Comparison of the 28-day compressive strength of high strength concrete specimens cast in 4-in. x 8-in. cardboard and rigid steel molds [20] 90

LIST OF FIGURES (continued)

Figure | Page

6.1 Effect of curing method on the compressive strength of 6-in. x 12-in. cylinders at early ages. Cylinders tested within 15 days of casting 94

6.2 Effect of curing method on the compressive strength of 6-in. x 12-in. cylinders at later ages. Cylinders tested between 28 and 91 days after casting 95

6.3 Effect of curing method on the flexural strength of 6-in. x 6-in. x 20-in. beams 98

7.1 Effect of early addition of superplasticizer on the compressive strength of 6-in. x 12-in. cylinders 101

7.2 Effect of early addition of superplasticizer on the flexural strength of 6-in. x 6-in. x 20-in. beams 104

7.3 Effect of redosing with superplasticizer on the compressive strength of 6-in. x 12-in. cylinders 106

7.4 Effect of redosing with superplasticizer on the flexural strength of 6-in. x 6-in. x 20-in. beams 108

7.5 Effect of repeated dosages of superplasticizer on slump, air content and compressive strength of concrete [11] .. 109

8.1 Compressive strength of 6-in. x 12-in. cylinders tested using aluminum and polyurethane caps versus cylinders capped with high strength sulfur mortar 113

8.2 6-in. x 12-in. cylinder tested using aluminum and polyurethane caps: (a) cylinder ready for testing; (b) failure of cylinder 117

8.2 6-in. x 12-in. cylinder tested using aluminum and polyurethane caps: (c) cone and sheared bottom 118

10.1 Strength versus time curve for Mix #16-107-00 133

10.2 Strength gain, based on 28-day compressive strength, of mixes containing no fly ash versus mixes containing fly ash 146

10.3 Strength gain, based on 56-day compressive strength, of mixes containing no fly ash versus mixes containing fly ash 147

LIST OF FIGURES (continued)

Figure | | Page
10.4 Strength gain, based on 91-day compressive strength, of mixes containing no fly ash versus mixes containing fly ash 148
11.1 Schematic representation of test set-up for (a) center point loading; (b) third-point loading 152
11.2 Schematic representation of beam to be tested 153
11.3 Beam tested in center point loading; failure occurs at midspan at 700 psi 153
11.4 Beam tested in third-point loading; failure occurs at cross section A at 650 psi 155
11.5 28-day compressive strength of 6-in. x 12-in. cylinders versus 7-day flexural strength of 6-in. x 6-in. x 20-in. beams 158
12.1 Addition of superplasticizer to central-mix drum 165
12.2 Placement of concrete into prestressed forms 165
12.3 Finishing of concrete 166
12.4 Strength specimens cured in prestressing bed 166
12.5 Compressive strength test results at release and 7 days for high strength concrete trial batches conducted at prestressing plant 168
A.1 Strength versus time curve for Mix #16-107-00 174
A.2 Strength versus time curve for Mix #09-106-00 174
A.3 Strength versus time curve for Mix #04-100-00 175
A.4 Strength versus time curve for Mix #08A & B-104-00 175
A.5 Strength versus time curve for Mix #13-100-00 176
A.6 Strength versus time curve for Mix #02-095-00 176
A.7 Strength versus time curve for Mix #01-107-00 177
A.8 Strength versus time curve for Mix #06-097-00 177

LIST OF FIGURES (continued)

Figure		Page
A.9	Strength versus time curve for Mix #19-103-00	178
A.10	Strength versus time curve for Mix #03-096-00	178
A.11	Strength versus time curve for Mix #05-089-00	179
A.12	Strength versus time curve for Mix #10-094-00	179
A.13	Strength versus time curve for Mix #07-098-00	180
A.14	Strength versus time curve for Mix #17-100-00	180
A.15	Strength versus time curve for Mix #14-110-28	181
A.16	Strength versus time curve for Mix #11-093-27	181
A.17	Strength versus time curve for Mix #15-112-38	182
A.18	Strength versus time curve for Mix #20-111-33	182
A.19	Strength versus time curve for Mix #21-112-34	183
A.20	Strength versus time curve for Mix #18-111-35	183
A.21	Strength versus time curve for Mix #12-093-38	184
B.1	Percent strength gain, 28-day, for Mix #16-107-00	186
B.2	Percent strength gain, 28-day, for Mix #09-106-00	186
B.3	Percent strength gain, 28-day, for Mix #04-100-00	187
B.4	Percent strength gain, 28-day, for Mix #08A & B-104-00 .	187
B.5	Percent strength gain, 28-day, for Mix #13-100-00	188
B.6	Percent strength gain, 28-day, for Mix #02-095-00	188
B.7	Percent strength gain, 28-day, for Mix #01-107-00	189
B.8	Percent strength gain, 28-day, for Mix #06-097-00	189
B.9	Percent strength gain, 28-day, for Mix #19-103-00	190
B.10	Percent strength gain, 28-day, for Mix #03-096-00	190

LIST OF FIGURES (continued)

Figure Page

B.11 Percent strength gain, 28-day, for Mix #05-089-00 191

B.12 Percent strength gain, 28-day, for Mix #10-094-00 191

B.13 Percent strength gain, 28-day, for Mix #07-098-00 192

B.14 Percent strength gain, 28-day, for Mix #17-100-00 192

B.15 Percent strength gain, 28-day, for Mix #14-110-28 193

B.16 Percent strength gain, 28-day, for Mix #11-093-27 193

B.17 Percent strength gain, 28-day, for Mix #15-112-38 194

B.18 Percent strength gain, 28-day, for Mix #20-111-33 194

B.19 Percent strength gain, 28-day, for Mix #18-111-35 195

B.20 Percent strength gain, 28-day, for Mix #12-093-38 195

C.1 Percent strength gain, 56-day, for Mix #16-107-00 198

C.2 Percent strength gain, 56-day, for Mix #09-106-00 198

C.3 Percent strength gain, 56-day, for Mix #04-100-00 199

C.4 Percent strength gain, 56-day, for Mix #08A & B-104-00 . 199

C.5 Percent strength gain, 56-day, for Mix #13-100-00 200

C.6 Percent strength gain, 56-day, for Mix #02-095-00 200

C.7 Percent strength gain, 56-day, for Mix #01-107-00 201

C.8 Percent strength gain, 56-day, for Mix #06-097-00 201

C.9 Percent strength gain, 56-day, for Mix #19-103-00 202

C.10 Percent strength gain, 56-day, for Mix #03-096-00 202

C.11 Percent strength gain, 56-day, for Mix #05-089-00 203

C.12 Percent strength gain, 56-day, for Mix #10-094-00 203

C.13 Percent strength gain, 56-day, for Mix #07-098-00 204

LIST OF FIGURES (continued)

Figure Page

C.14 Percent strength gain, 56-day, for Mix #17-100-00 204

C.15 Percent strength gain, 56-day, for Mix #14-110-28 205

C.16 Percent strength gain, 56-day, for Mix #11-093-27 205

C.17 Percent strength gain, 56-day, for Mix #15-112-38 206

C.18 Percent strength gain, 56-day, for Mix #20-111-33 206

C.19 Percent strength gain, 56-day, for Mix #21-112-34 207

C.20 Percent strength gain, 56-day, for Mix #18-111-35 207

C.21 Percent strength gain, 56-day, for Mix #12-093-38 208

D.1 Percent strength gain, 91-day, for Mix #16-107-00 210

D.2 Percent strength gain, 91-day, for Mix #13-100-00 210

D.3 Percent strength gain, 91-day, for Mix #19-103-00 211

D.4 Percent strength gain, 91-day, for Mix #10-094-00 211

D.5 Percent strength gain, 91-day, for Mix #17-100-00 212

D.6 Percent strength gain, 91-day, for Mix #14-110-28 212

D.7 Percent strength gain, 91-day, for Mix #11-093-27 213

D.8 Percent strength gain, 91-day, for Mix #21-112-34 213

D.9 Percent strength gain, 91-day, for Mix #18-111-35 214

D.10 Percent strength gain, 91-day, for Mix #12-093-38 214

E.1 Example of small trial mix design results 220

CHAPTER 1

INTRODUCTION

1.1 General

A brief overview of the research program presented herein will be given in this chapter. This will include a description of the topics which will be addressed and their importance to the production of high strength concrete. Fundamentals of the research program will be discussed, and basic terms defined.

1.2 Definitions

The meaning of the term "high strength concrete" depends on where in the United States the concrete is being produced. In general, the term "high strength concrete" is used to refer to any concrete having a specified compressive strength which is greater than that which is usually produced. For the purpose of this report, the term "high strength concrete" will refer to any concrete produced using conventional procedures and having a compressive strength of at least 6000 psi at 28 days, as measured by testing 6-in. x 12-in. cylinders.

Since mineral admixtures, including fly ash, slag and silica fume as described in Chapter 2, are often used in high strength concrete, the term "water-to-binder" ratio will be used in place of "water-to-cement" ratio. The "water-to-binder" ratio will be calculated by dividing the weight of water in the mix by the combined weight of cement plus mineral admixture.

1.3 Uses for High Strength Concrete

There are both technical and economical advantages in using high strength concrete in structures [20]. In highway bridge applications, the use of high strength concrete can result in: (1) greater compressive strength per unit cost, per unit weight, and per unit volume; (2) higher modulus of elasticity which helps reduce deflections; and (3) increased tensile strength [3]. The use of high strength concrete in tall buildings allows smaller column sizes to be used, which increases floor space, and, because of the increased modulus of elasticity of high strength concrete, deflections of tall, slender buildings can be reduced. The use of high strength concrete in bridge girders would allow for the use of longer spans, which in turn would decrease the number of piers required for support.

1.4 Justification of Research

There are obvious advantages in using high strength concrete. As a result of TSDHPT Research Project 3-5-82-315 on Production of High Strength Concrete [20], it has been shown that high strength concrete can be readily produced in Texas using commercially available materials and conventional production techniques. However, currently used concrete specifications and quality control procedures by the TSDHPT are not necessarily applicable to high strength concrete. Although the batching, mixing, transporting, placing, and control procedures for high strength concrete are not different in principle from those procedures used for conventional concrete, changes, refinements, and increased emphasis on some aspects of currently used concrete specifications may be needed in order to ensure a successful concreting operation.

Specifications need to be modified to allow for optimum use of the materials for producing concrete, including mineral and chemical admixtures. Mixing, transporting, and placing procedures must ensure uniform mixing and adequate compaction of the fresh concrete without any time delays. Special considerations must be given to field curing procedures, since the strength of high strength concrete is known to be affected more by improper curing practices than that of normal strength concrete. Of most importance is any needed revision to currently used quality control procedures.

In summary, current concrete specifications need to be revised to incorporate high strength concrete. The resulting specifications should be such that they (a) allow for optimum use of the materials and equipment available, and (b) consider available information on quality control procedures used in projects using high strength concrete.

1.5 Objectives of Research

The overall objectives of this study are as follows:

1. To make recommendations for revising current concrete specifications used by the TSDHPT to incorporate high strength concrete.

2. To use these specifications in highway applications in Texas using high strength concrete.

3. To conduct a field verification program by which these specifications are further refined based on information from the use of high strength concrete in highways in Texas.

1.6 Research Plan

A research program was conducted which allowed the study of various quality control procedures as applied to high strength concrete. This included type and size of test specimens, testing procedures, and testing ages. Also considered were the effects of various replacement rates for mineral admixtures, and addition rates and redosing for superplasticizing admixtures. Various curing methods were tested to determine their effect on concrete strength.

1.7 Report Format

This report is divided into thirteen chapters and five appendices. Chapter 2 presents background information on high strength concrete, and in Chapter 3 the experimental program is outlined. The results obtained from the research program are presented and discussed in Chapters 4 through 11, and Chapter 12 presents the results of a field pilot study. Summary, conclusions and recommendations for further study are presented in Chapter 13. Appendices A, B, C and D contain strength gain curves for each high strength concrete mix, and Appendix E contains the Addenda to the job specifications for the field pilot study, which governed the use of fly ash in the production of high strength concrete for use by the Texas Highway Department.

This study was conducted at the Phil M. Ferguson Structural Engineering Laboratory at The University of Texas Balcones Research Center.

CHAPTER 2

BACKGROUND ON HIGH STRENGTH CONCRETE

2.1 Introduction

The following is a review of information regarding high strength concrete. Topics covered include the characteristics of hydrated portland cement paste, the effects of mineral and chemical admixtures on the properties of the cement paste, and mix proportioning guidelines for high strength concrete.

2.2 Fundamental Mechanisms of High Strength Concrete

The load-bearing capacity of high strength concrete is determined by the strength of the coarse aggregate, the strength of the paste, and the strength of the paste-to-aggregate bond [18]. In the development of mix proportions for high strength concrete, the content of each component must be optimized to produce a mix having the strength, durability and workability required. Those factors found to affect the properties of high strength concrete will be examined in this section.

2.2.1 Portland cement paste. Properties of the paste which have been found to have a significant effect on its strength are the total porosity, pore size distribution, and presence of flaws within its structure [18]. As the total porosity of the paste increases, the strength decreases. Also, large pores are considered to be more detrimental to the strength of the paste than smaller pores [17]. It has been shown [18] that paste porosity decreases as the water-to-cement ratio is decreased, as seen in Fig. 2.1. However, Hester [9] found that lowering the water-to-cement ratio in some cases reduced the strength of the concrete. Hester attributed this to poor dispersion of the cement grains due to the low slump of the concrete, which would result in a larger pore size. Another possible explanation for these findings could be the difficulty encountered in compacting high strength concrete specimens having low slump.

Immediately surrounding the aggregates is a layer of paste known as the transition zone. The paste in the transition zone is less dense, thus weaker than the bulk paste [17]. Also, at the aggregate surface there occurs an increased amount of calcium hydroxide (C-H) crystals, which are a product of the hydration of portland cement, but contribute no cementitious properties [17]. When these crystals are oriented perpendicularly to the aggregate surface, they affect the paste-to-aggregate bond most detrimentally. It was found by Carles-Gilbergues et al. [17] that as the water-to-cement ratio was increased, both the thickness of the transition zone and the angle of orientation of the C-H crystals increased, thus weakening the paste-to-aggregate bond.

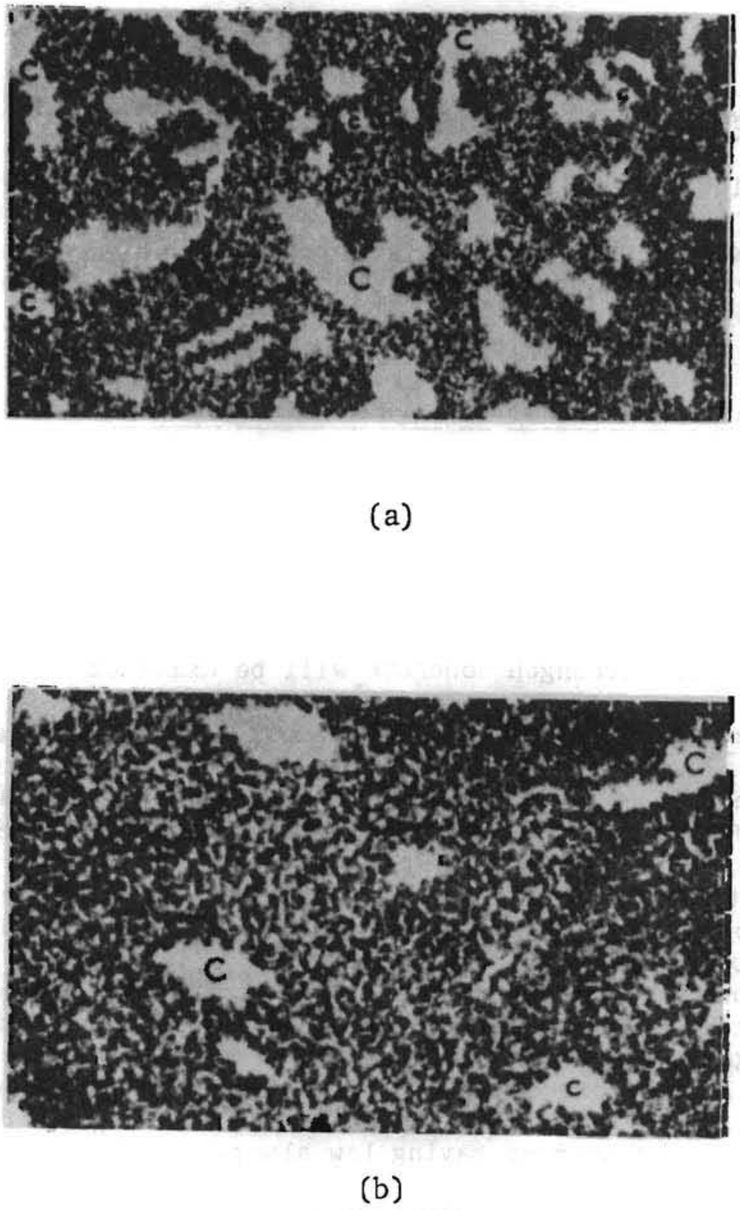


Fig. 2.1 A model of the structure of mature hardened cement paste: (a) made with a high initial water/cement ratio; (b) paste made with a low initial water/cement ratio [21].

In summary, it has been found that decreasing the water-to-cement ratio of concrete will increase its strength. This is a result of the increased paste strength due to a reduction in its total porosity and decreased pore size, as well as an increased paste-to-aggregate bond strength due to a decreased transition zone thickness and improved orientation of C-H crystals at the aggregate surface. However, one researcher [9] found that decreasing the water-to-cement ratio for a given mix beyond a certain point could cause a decrease in concrete strength, and attributed this to poor dispersion of the cement hydrates.

2.2.2 Effect of chemical admixtures. The use of chemical admixtures in the production of high strength concrete can significantly improve the quality of the concrete produced. In order to achieve the best results, the type and dosage rate of admixture should be optimized and tested under the expected field conditions.

2.2.2.1 Water reducers and retarders. The high cement content and desired low water-to-cement ratio of high strength concrete mixes makes the use of water reducers and retarders a necessity. Addition of a water-reducing admixture helps to decrease the otherwise high mixing water demand for proper workability of a cement-rich high strength concrete mix. The use of a retarding admixture will also reduce the mixing water requirement. But in addition, it will help prolong the plastic state of the concrete mix and reduce the temperature rise of the fresh concrete due to heat of hydration.

2.2.2.2 High range water reducers. The use of a high range water-reducing admixture (HRWR), often referred to as a superplasticizer, is considered to be very important in the production of high strength concrete [5, 9]. The addition of a high range water reducer to a high strength concrete mix allows for significant reduction in the mixing water, while producing very high slump concrete, if desired. It was shown by Hester [9] that the use of a high range water reducer in high strength concrete lessens the sensitivity of the concrete strength to low water-to-cement ratios, as shown in Fig. 2.2. He attributes this to the increased dispersion of hydration products achieved through the use of the admixture. Carrasquillo [5] suggests that high range water reducers can be used at dosage rates in excess of those recommended by the admixture manufacturer without affecting the mix detrimentally.

2.2.2.3 Air entraining admixtures. The occurence of entrained air in concrete is known to decrease its strength. For this reason, it is not desirable from the standpoint of strength considerations to use an air entraining admixture in high strength concrete. However, for durability considerations, it may be necessary to produce air-entrained high strength concrete. Due to the decreased porosity and higher strength inherent to high strength concrete, it may happen that high strength concrete is naturally more durable than normal strength

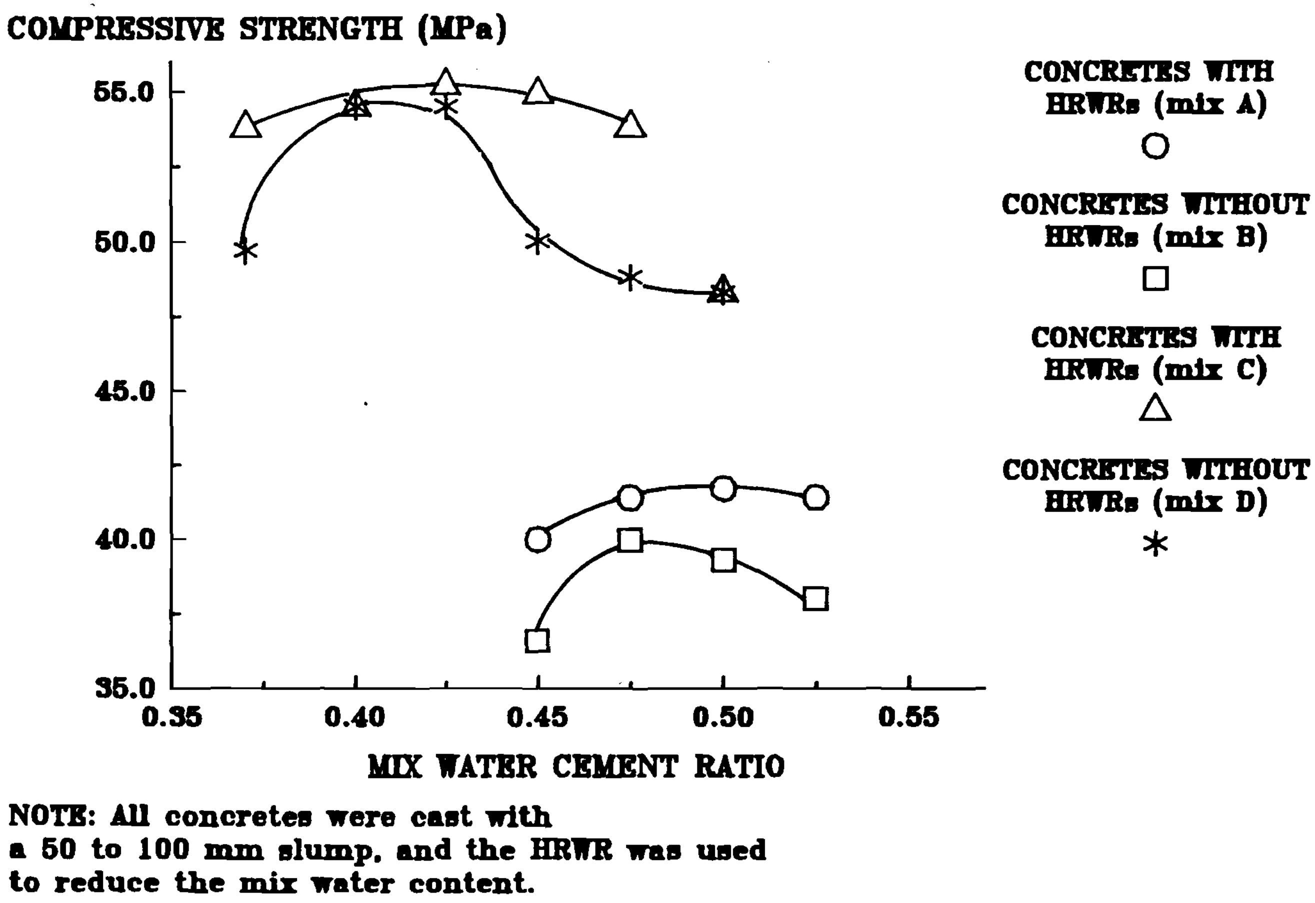


Fig. 2.2 Strengths of concretes with and without HRWRs, and with different water-cement ratios [9].

concrete. Research is needed to determine to what degree high strength concrete requires air entrainment to satisfy durability requirements.

2.2.3 Effect of mineral admixtures. Mineral admixtures, consisting mainly of fly ash, slags, and silica fume, are admixtures that, when added to concrete, exhibit pozzolanic, cementitious, or pozzolanic and cementitious properties [16]. Before studying the effect of mineral admixtures on the properties of concrete, it is important to understand the fundamental mechanisms of cementitious and pozzolanic reactions.

When portland cement comes into contact with water, it hydrates; that is, the chemical compounds within the portland cement react with water molecules and form hydration products. Two of the products formed in the hydration of portland cement are calcium silicate hydrate (C-S-H) and calcium hydroxide (C-H) [17, 22]. The C-S-H is highly cementitious, and comprises between 60 and 65 percent of the solids in a fully hydrated cement paste. The C-H, on the other hand, has no cementitious quality, and comprises approximately 20 percent of the hydration products. Also, being soluble and alkaline, the C-H is prone to attack by water or acids, thereby decreasing the durability of the concrete [17].

The pozzolanic reaction, unlike the cementitious reaction of portland cement, is the reaction of siliceous or siliceous and aluminous material with calcium hydroxide (C-H) in the presence of water to form C-S-H [17]. Thus, the reaction of a pozzolanic material requires the presence of moisture and an external source of C-H.

As stated earlier, C-H is a product of the hydration of portland cement, and contributes nothing to concrete strength. In fact, its occurrence at the aggregate surface decreases the strength of the paste-to-aggregate bond. When a pozzolanic material is added to portland cement concrete, the pozzolanic reaction does not begin until C-H is produced by the cementitious reaction. Then, the reaction with the pozzolan converts the harmful C-H crystals to the highly cementitious C-S-H. The strength of the paste is thus increased. However, since the pozzolanic reaction does not occur until C-H becomes available for reaction, it does not contribute to the concrete strength until later ages. On the other hand, since the cementitious and pozzolanic reactions occur at different times, the hydration temperature of concrete containing a given volume of portland cement and fly ash is generally lower than that of concrete containing the same volume of portland cement [15, 17], as shown in Fig. 2.3. The control of concrete temperature can be a useful tool in the placing and curing of concrete in Texas.

As stated earlier, mineral admixtures may exhibit pozzolanic, cementitious, or pozzolanic and cementitious properties. The effect on the properties of fresh and hardened concrete of each mineral admixture depends on its chemical composition and physical properties. Although

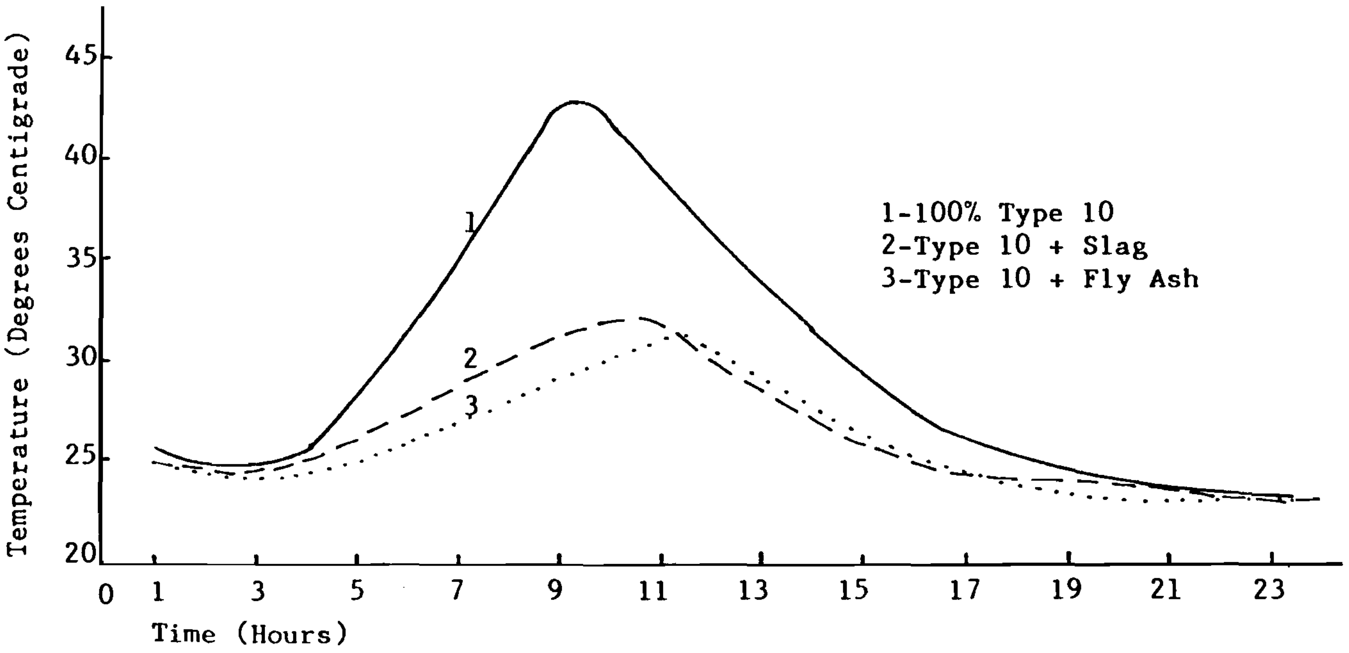


Fig. 2.3 Temperature-time curves at 22° C for pastes containing no chemical admixture [15].

the properties of a given mineral admixture type will vary according to its source, there are characteristics which generally apply to each type. The basic characteristics of each of three mineral admixture types will be described.

2.2.3.1 Fly ash. Fly ash is a by-product produced in coal-generated power plants. When the coal is burned, the impurities in the coal which don't burn and are suspended in the flue gases are called "fly ash." The fly ash, because of environmental concerns, is removed from the flue gases before they are discharged into the atmosphere [17]. Generally, fly ash consists of smooth, spherical particles with approximately the same particle size distribution as ASTM Type I portland cement, as shown in Fig. 2.4. However, due to its spherical nature, the water demand for most fly ashes is lower than for an equal volume of cement.

Fly ashes for use in concrete have been divided into two classifications. ASTM Specification C618 separates the fly ash according to its content of silicon dioxide plus aluminum oxide plus iron oxide. ASTM Class F fly ash must have a minimum of 70 percent of these oxides, whereas ASTM Class C fly ash must contain a minimum of only 50 percent. TSDHPT Specification D-9-8900 [27] also separates fly ashes according to their silicon dioxide plus aluminum oxide plus iron oxide content. That specification, however, requires that Type A fly ashes contain a minimum of 65 percent of these oxides, and Type B fly ashes a minimum of 50 percent. Comparing the TSDHPT and ASTM specifications, it can be seen that Texas Type A and Type B fly ashes are comparable to ASTM Class F and Class C fly ashes, respectively. Both of these specifications place further restrictions on the chemical and physical properties of fly ash. However, rather than examine the existing specifications governing fly ashes, the following discussion will examine various chemical and physical properties of each class of fly ash, and their effect on the properties of fresh and hardened concrete.

Type A fly ash is generally produced during the combustion of anthracite or bituminous coals. Having a specified content of silicon dioxide plus aluminum oxide plus iron oxide greater than 70 percent, these fly ashes generally contain less than five percent calcium oxide (CaO) [17]. Due to their low calcium oxide content, these fly ashes require an external source of calcium for their reaction, and thus are pozzolanic in nature. The pozzolanic reaction of these fly ashes begins after approximately two weeks [17]. After that, the contribution of the pozzolanic reaction to the concrete strength is noticeable. It was found by Diamond and Lopez-Flores [7] that the strength at 90 days of mortars containing 30 percent of low calcium fly ash by weight was equal to the strength of reference mortars containing no fly ash.

Type A fly ash generally consists of smooth, solid spheres. However, sometimes these fly ashes contain approximately five percent

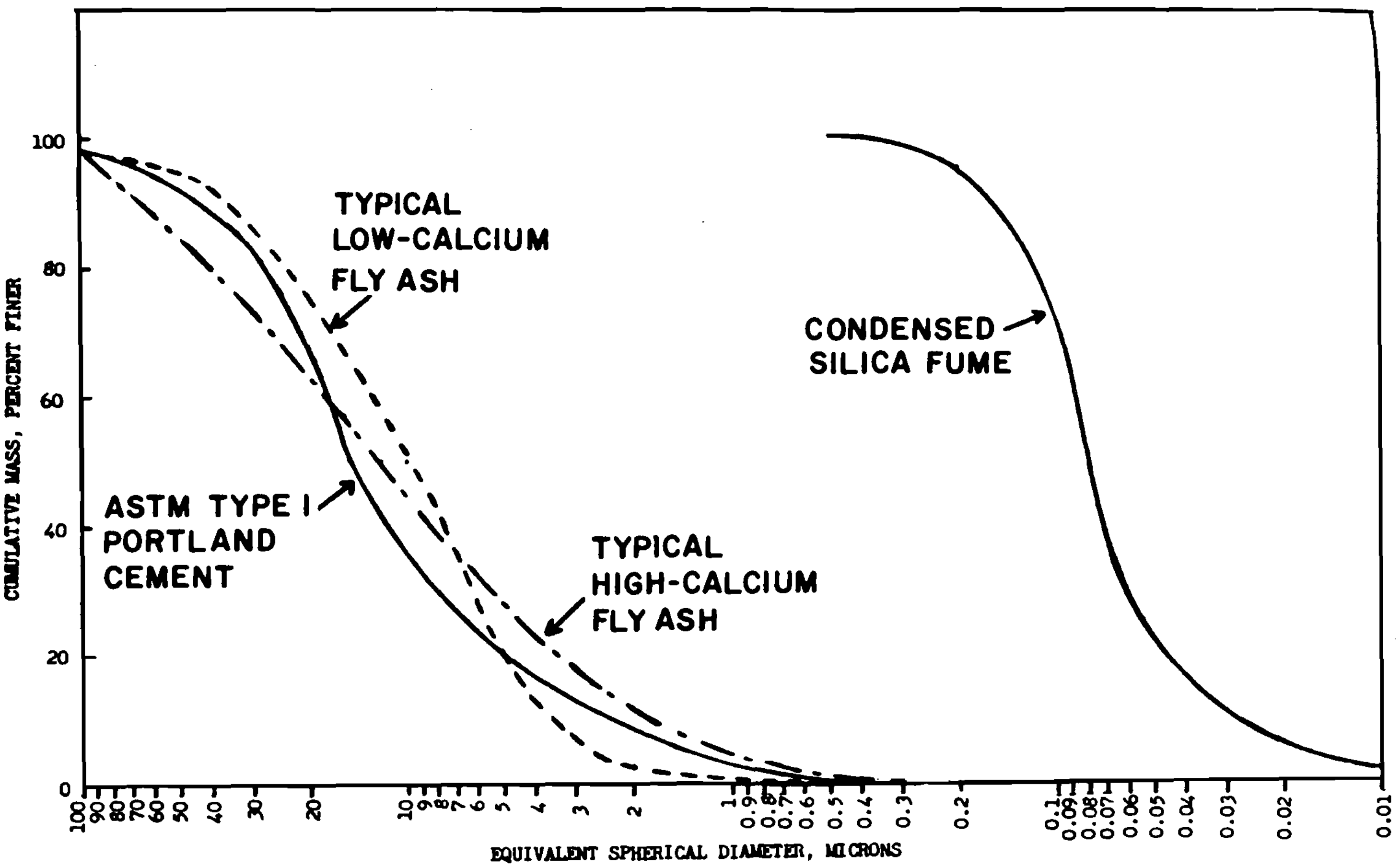


Fig. 2.4 Particle size distribution of typical materials [17].

by weight cenospheres or plerospheres [8, 14]. Cenospheres are hollow and empty, whereas plerospheres are hollow but contain smaller spheres inside. Type A fly ash also has a carbon content of two to ten percent [17], due to the incomplete combustion of the coal. A measure of its carbon content is indicated by the loss on ignition, or LOI, of a fly ash. The carbon particles are irregularly shaped and rough textured. Generally, concrete containing fly ash having a high LOI value will require a higher dosage rate of air entraining admixture to produce a given amount of entrained air, due to the adsorption of some of the air entraining admixture onto the carbon particles [17].

Type B fly ash is produced primarily from the combustion of lignite or subbituminous coals. Unlike Type A fly ash, Type B fly ash has a relatively high calcium oxide content, between 15 and 35 percent. Thus, Type B fly ashes exhibit cementitious behavior as well as pozzolanic [17]. Diamond and Lopez-Flores [7] found that mortars containing 30 percent by weight high calcium fly ash achieved equal strength with reference mortars at seven days. Also unlike Type A fly ash, Type B fly ash contains less than one percent carbon. Thus, using a Type B fly ash usually does not affect the required admixture dosage rate for air entraining admixtures.

Yuan and Cook [28] reported on a study of the strength, durability, and shrinkage of concrete containing a high calcium fly ash at replacement rates of 0, 20, 30 and 50 percent by weight of cement. They found that for all mixes, the compressive strength of concrete containing cement plus fly ash was equal to that of concrete containing an equal weight of cement at 28 days, and was higher than the reference concrete at 90 days by twelve to fifteen percent. In freeze-thaw durability tests on air entrained concrete, mixes containing 20 to 30 percent fly ash out-performed the reference concrete at 1200 cycles, while the concrete containing 50 percent fly ash did not. It was also found that the drying shrinkage of concrete was not affected by the use of fly ash, whereas fly ash contents of 20 to 30 percent resulted in increased creep and shrinkage of concrete.

An effect on the fresh concrete common to both types of fly ash is a possible decrease in the required dosage rate of water reducing or retarding admixtures. This can be attributed to the later time of reaction of the fly ash, thus not requiring the same dosage rate of these admixtures as an equal weight of cement. This effect is likely to be more prominent in Type A fly ashes, which are by nature more pozzolanic than Type B fly ashes.

In summary, there exist two types of fly ash: Type A, low calcium fly ash, and Type B, high calcium fly ash. Both types exhibit some degree of cementitious properties depending mainly on the calcium oxide content. Fly ashes having a high LOI value may require higher dosage rates of air entraining admixture due to adsorption of the admixture onto the carbon particles. Generally, the mixing water requirement for concrete containing fly ash is lower than for concrete having an equal volume of cement only. This is due, in part, to the spherical nature of the fly ash particles, as opposed to the angularity of the crushed cement particles which results from the grinding of the cement klinker, and to the later reaction time of the pozzolanic material. The later reaction time of fly ashes may also cause a reduction in the required dosage rates of water reducing or retarding admixtures. The appearances of low calcium and high calcium fly ashes, as well as a plerosphere, are shown in Fig. 2.5.

2.2.3.2 Slag. There are three main types of slag, two of which are currently being used as an admixture in concrete. These two are blast furnace slag and steel slag. Non-ferrous slag is not used as an admixture in concrete [17].

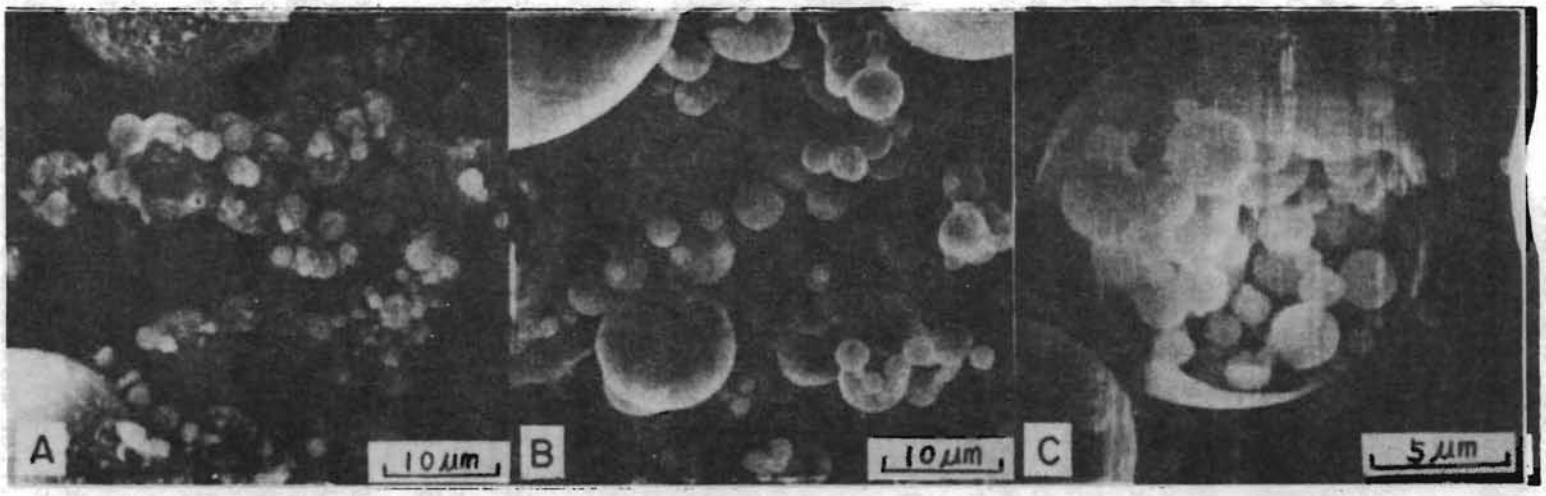
Blast furnace slag is a by-product of the production of pig iron. The type of blast furnace slag, granulated or pelletized, is determined by the method used for cooling the molten slag. If the liquid slag is quenched using water, granulated slag results; if quenched with air and water, pelletized slag results. Both of these products must be ground to a fineness of 400 to 600 m^2/kg to exhibit satisfactory pozzolanic or cementitious properties [17]. Generally, the water demand of this slag is higher than for an equal volume of cement, due to its coarse texture and higher fineness. However, concrete containing these slags can exhibit strength equal to the reference concrete at seven days [10].

Steel slag is produced in the conversion of pig iron to steel. The liquid slag is quenched with water and ground fine. Like granulated or pelletized blast furnace slag, steel slag will exhibit both pozzolanic and cementitious properties [17].

Non-ferrous slags are by-products of the production of metallic copper, nickel and lead. The slag produced from copper and nickel would exhibit pozzolanic properties. The slag formed in the production of lead, however, has a calcium oxide content of ten to twenty percent, and thus should exhibit cementitious and pozzolanic properties. These slags are not currently being used as an admixture in concrete [17].

2.2.3.3 Silica fume. Silica fume is produced in electric arc furnaces during the production of metallic silicon and ferrosilicon alloys. The particles of silica fume, being nearly pure silicon dioxide, are smooth and spherical like those of fly ash, but one hundred times finer [17]. Silica fume is highly pozzolanic, the reaction beginning as early as two days after mixing [24], and concrete containing silica fume can achieve equal strength with reference concrete at 14 days [25].

Silica fume has an extremely high water demand, due to its fineness, and requires the use of a water reducer [12, 17, 23]. To achieve adequate workability, the slump of silica fume mixes should be increased to offset the "stickiness" imparted to the mix by the ultra-



(a) (b) (c)

Fig. 2.5 Scanning electron micrographs of a: (a) low-calcium fly ash; (b) high-calcium fly ash; (c) broken plerosphere in a low-calcium fly ash [17].

fine particles. Also, the sand content of silica fume mixes should be reduced [12]. Since concrete containing silica fume generally bleeds very little, adequate curing should be maintained to avoid plastic shrinkage cracking [12].

The silica fume particles decrease the porosity of the paste by distributing the hydration products uniformly [18, 22, 23], as shown in Fig. 2.6. Radjy and Loeland [22] reported that the permeability of concrete incorporating silica fume was reduced by 10 to 1000 times that of typical concrete without silica fume.

Sellevold and Radjy [23] and Radjy and Loeland [22] reported that the use of silica fume in concrete can significantly enhance both the strength and durability of concrete. As shown in Fig. 2.7, the 28-day compressive strength of silica fume mixes is higher than that of the reference concrete in all cases, for a given water-to-cement ratio. The use of silica fume in concrete was also found to increase freeze-thaw resistance, decrease alkali-aggregate reactivity, increase sulfate resistance, and possibly increase resistance to corrosion.

In summary, there are three main types of mineral admixtures used in concrete: fly ash, slag, and silica fume. Type A fly ash exhibits pozzolanic properties, while Type B fly ash exhibits both cementitious and pozzolanic properties. Both slags used as mineral admixtures in concrete, blast furnace and steel slag, exhibit properties similar to Type B fly ash, except that generally the mixing water demand of the concrete is increased with the use of slag, and decreased with the use of fly ash. Silica fume is one hundred times finer than fly ash, and highly pozzolanic. Because of the fineness of silica fume, the use of water reducers is required to reduce the water demand of the mineral admixture.

2.2.4 Coarse aggregate. The coarse aggregate used in the production of high strength concrete must not only be stiff and have sufficient strength, but it must also provide a good surface for the paste-to-aggregate bond [5, 9, 18].

The compressive strength of a given rock type varies with its source, so it must be determined that coarse aggregate obtained from a particular source has adequate strength for use in high strength concrete. For instance, according to Mindess [18], the compressive strength of limestone can be from 13,000 to 39,000 psi, depending on the particular formation, and that of granite has similar limits.

According to Blick [2], the use of a river gravel produces lower strength and lower modulus of elasticity than the use of a crushed stone in high strength concrete, as shown in Fig. 2.8, due to the increased paste-to-aggregate bond of an angular aggregate. He also reported that the use of smaller maximum size aggregate allowed the production of higher concrete strengths as shown in Fig. 2.9. This is attributed to the increased surface area for bonding of the smaller

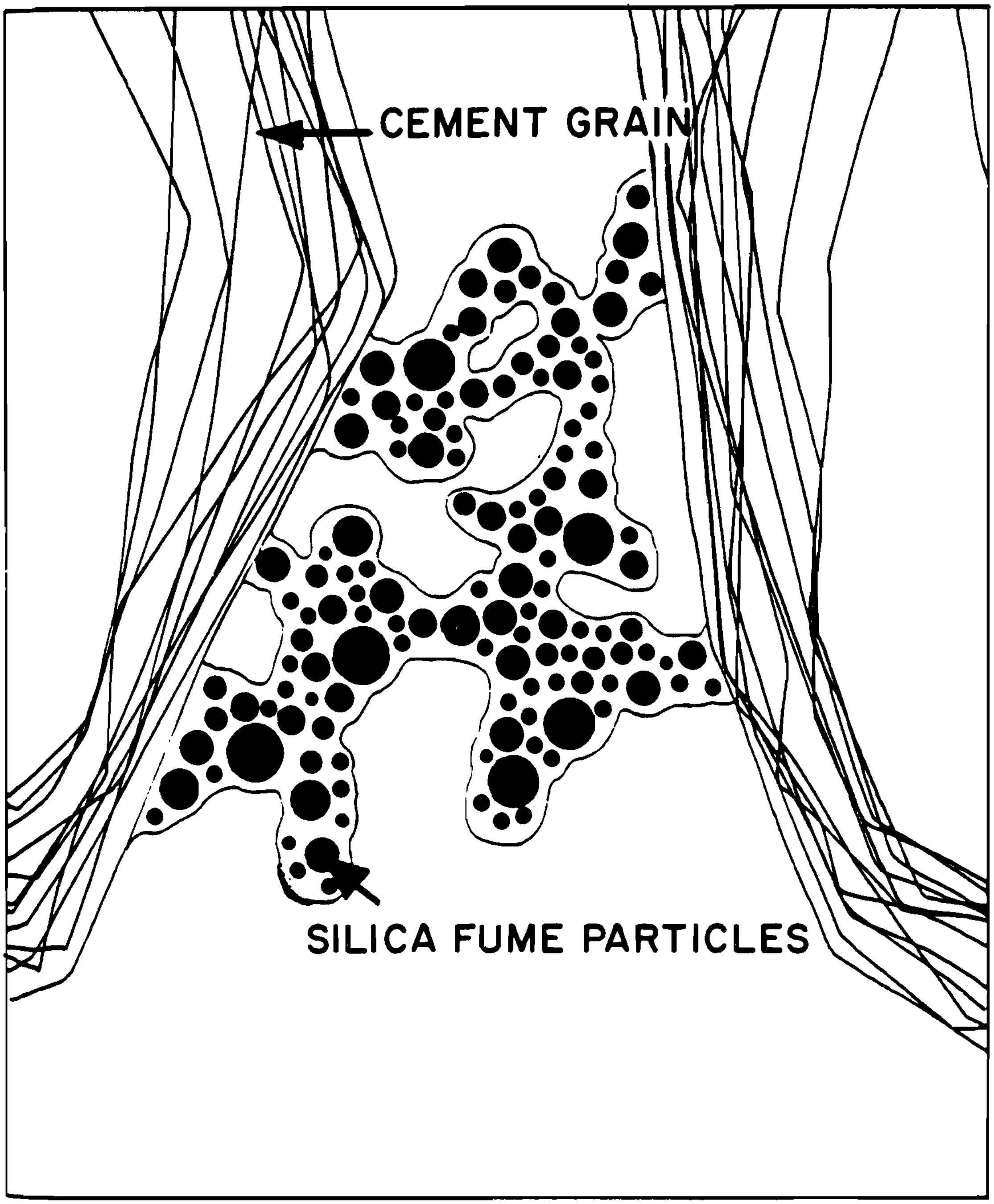


Fig. 2.6 Refinement of the pore system caused by the addition of silica fume to concrete [17].

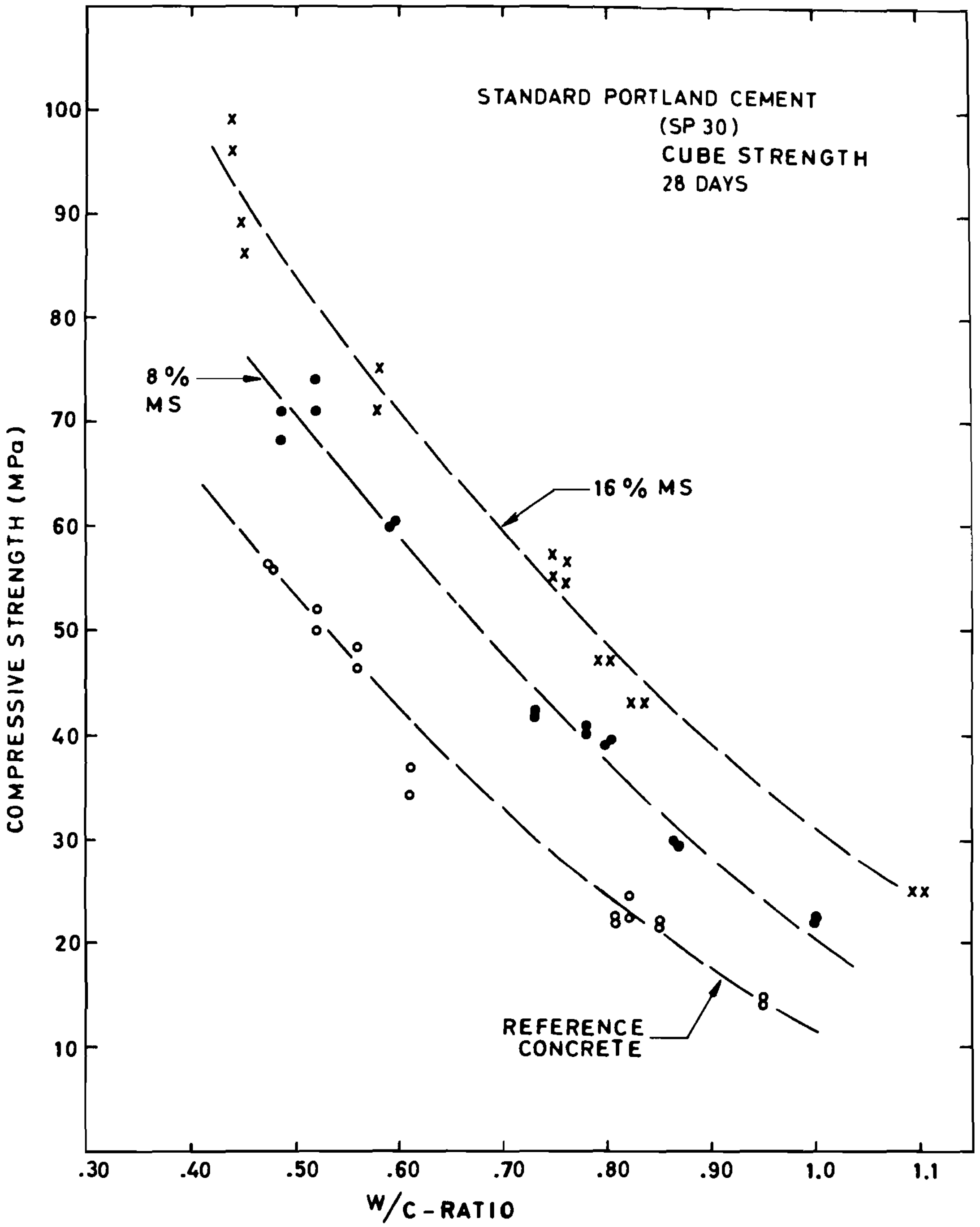
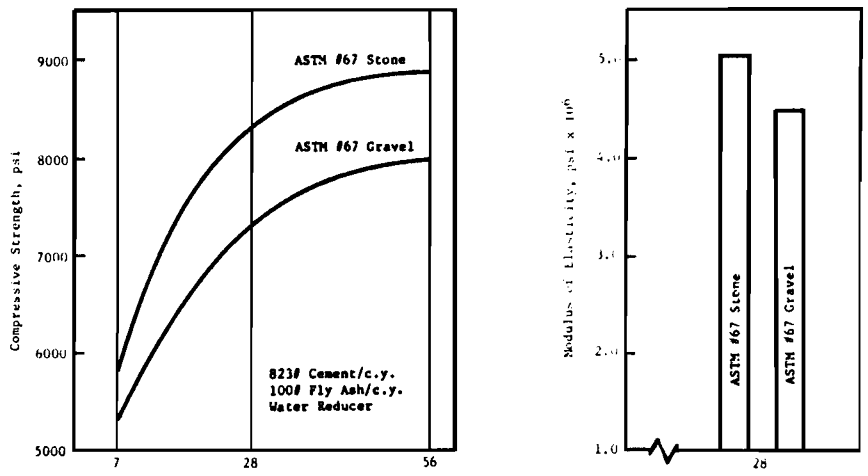


Fig. 2.7 Twenty-eight day compressive strength vs. w/c-ratio for concrete with different microsilica contents. Concretes with and without water reducing admixtures are not differentiated [23].



(a) (b)

Fig. 2.8 (a) Compressive strength and (b) modulus of elasticity of 7500 psi concrete for various types of coarse aggregate [2].

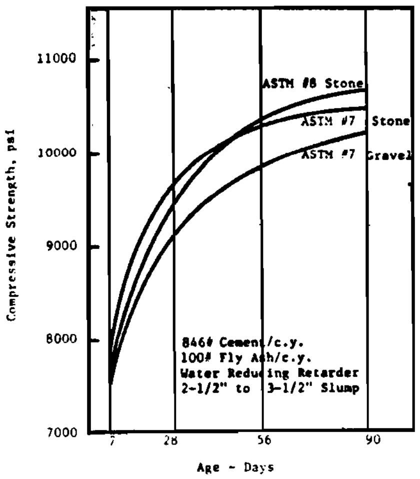


Fig. 2.9 Compressive strength of 9000 psi concrete for various sizes and types of coarse aggregate [2].

aggregates, as well as the decreased likelihood of having a weak plane, or fissure, within the smaller aggregate.

2.2.5 Summary. The strength of high strength concrete depends on the strength of the paste, the strength of the coarse aggregate, and the strength of the paste-to-aggregate bond. The strength of the paste can be increased by decreasing the water-to-binder ratio, and through the use of high range water reducers and/or mineral admixtures. The coarse aggregate used should provide good bonding with the paste, and have sufficient stiffness and strength to fully develop the strength of the paste.

2.3 Mix Proportioning Guidelines for High Strength Concrete

Although the exact proportions of a high strength concrete mix will depend on the chemical and physical properties of the mix constituents, there are basic guidelines which can be applied in the proportioning of the mix. These guidelines are outlined below.

2.3.1 Required concrete strength. The initial step in the proportioning of a high strength concrete mix is determining not only what concrete strength is desired, but at what age this strength should be achieved. Thus, consideration must be given to the age at which the concrete will be tested for strength, and whether the strength should be obtained from a laboratory trial mix or field trial batch.

2.3.1.1 Test age. High strength concrete generally has a high early strength, as well as significant strength gain at later ages, especially if mineral admixtures are used. Therefore, it is reasonable that, if construction loads do not require the design strength of the concrete by 28 days, a later testing age may be specified for acceptance of the concrete based on strength, such as 56 or 90 days.

2.3.1.2 Laboratory versus field test results. According to Cook [6], test results obtained from laboratory trial mixes are generally ten percent higher than those obtained in the field for identical mix proportions. Therefore, if laboratory trial mixes are to be used for strength evaluation, the strength achieved by these mixes should be ten percent higher than the average compressive strength desired in the field. It is recommended that field trial batches be run to determine the performance of the mix under actual field conditions.

2.3.2 Water-to-binder ratio. The production of high strength concrete requires the use of low water-to-binder ratios. The production of concrete having compressive strengths between 6,000 and 12,000 psi at 28 days will require water-to-binder ratios in the range from 0.52 to 0.25 by weight. Generally, for a given water-to-binder ratio, concrete made using superplasticizer will have a slightly higher compressive strength than that of concrete without superplasticizer.

2.3.3 Cement. The cement used in the production of high strength concrete should have good strength-producing properties. High strength concrete mixes, having cement contents of from seven to ten sacks per cubic yard, can develop high concrete temperatures due to hydration of the cement. The use of coarse-ground cement could help to control the concrete temperature rise due to heat of hydration. However, the use of coarse-ground cement may also result in incomplete hydration of the cement particles, thereby reducing the ultimate strength capacity of the concrete [9].

Trial mixes should be performed to determine the optimum cement content of a high strength concrete mix. This is the cement content in excess of which further addition of cement does not result in increased concrete strength, and usually corresponds to the point at which all aggregates are completely surrounded by cement particles [9].

2.3.4 Coarse aggregate content. High strength concrete mixes should contain a larger volume of coarse aggregate than do normal strength concrete mixes. This helps to reduce the water demand of the concrete, as well as increase the modulus of elasticity of the concrete. A stiffer aggregate will produce concrete with a higher elastic modulus.

2.3.5 Fine aggregate. Since high strength concrete has a high cement content, the gradation of the fine aggregate is not so important as in normal strength concrete. Basically, a sand should be used which minimizes the mixing water demand and provides good workability. Generally, sands having a fineness modulus between 2.6 and 3.2, and meeting ASTM C-33 requirements, perform well in high strength concrete mixes. High strength concrete mixes made with sand having a low fineness modulus may be too cohesive.

2.3.6 Recommended slump of concrete. It is recommended that the slump of high strength concrete to be made without the addition of a superplasticizer be between two to four inches. The minimum slump of high strength concrete containing superplasticizer before the addition of a superplasticizer is recommended to be one inch. Requiring a one-inch slump prior to the addition of the superplasticizer ensures that the mix contains enough water to provide adequate workability and finishing. It has been found [4] that high strength concrete mixes which do not have at least an initial slump of one inch are, even after addition of a superplasticizer, very cohesive and difficult to place or finish.

2.3.7 Mineral admixtures. The rates of addition of mineral admixtures are different for each type. Type A fly ash is generally used at replacement rates of 20 to 30 percent by volume of portland cement, and Type B fly ash at 25 to 40 percent by volume of portland cement. Slags are used at a replacement rate of 30 to 50 percent by volume of portland cement. Silica fume can be used at 10 to 50 percent by weight of portland cement [12].

2.3.8 Chemical admixtures. It is advantageous to use certain chemical admixtures, such as water reducers, retarders, and high range water reducers, in the production of high strength concrete. It may be possible to use these at rates higher than those recommended by the manufacturer without adversely affecting the properties of the concrete. The optimum dosage rate of any chemical admixture must be determined through field trial batches conducted under the expected job conditions.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Introduction

In all, over one thousand specimens for strength evaluation were cast from high strength concrete mixes having compressive strengths of 6,000 to 14,500 psi at 28 days. Of the twenty-nine concrete mixes batched, eight contained between 25 and 35 percent fly ash by weight of binder material (28 to 39 percent by volume). The following variables were studied:

a. specimen size;

b. mold material used in casting specimens;

c. curing conditions;

d. time of initial addition of superplasticizer;

e. redosing with superplasticizer;

f. type of capping material used;

g. age of cap at testing;

h. effect of consolidation;

i. test age;

j. 28-day compressive strength versus 7-day flexural strength;

k. effect of fly ash content.

In this chapter, details of each of the high strength mixes will be given. These will include the properties of the materials used, notation used in identifying mixes, batching procedures followed, corrected mix proportions, and methods used in preparing, curing and testing both fresh and hardened concrete properties. Results obtained from strength tests will be presented in later chapters, but the approach taken in studying each of the above variables will be described in this chapter.

3.2 Mix Identification System

Each of the twenty-nine high strength concrete mixes used will be identified by three sets of numbers. The first set will be a two-digit number, ranging from one to twenty-nine, and will correspond to the mix number. The second, a three-digit number, will denote the volume of cement plus fly ash, or binder, in the mix to a tenth of a "sack", or 0.485 cubic feet. The third, another two-digit number, will denote the volume of fly ash in the mix as a percentage of the total binder. For example, a mix designated as mix number 13-094-38 would be the thirteenth mix batched, and it would contain 9.4 "sacks" of cement plus fly ash, of which 38 percent by volume would be fly ash. For simplicity, in the text, mixes will be referred to by their first two digits (or mix number) only.

3.3 Material Properties

Twenty-nine different mixes were batched. These used five different types of coarse aggregate, fly ashes from three different sources, and two different brands of water reducing/retarding admixture. The properties of these materials are given in Tables 3.1 through 3.3. The components used in each mix are given in Table 3.4.

The fine aggregate used in all mixes was natural river sand having a bulk specific gravity and absorption capacity, both based on saturated surface dry conditions, of 2.62 and 1.0%, respectively. Cement conforming to ASTM C-150 specifications for Type I cement was used in all mixes.

3.4 Batching Procedure

Of the four types of chemical admixtures used, two had to be added by hand. One type of fly ash had to be added by hand.

Chemical admixtures Chem-B and Chem-C were added to the ready-mix truck by hand using a bucket or pitcher, as shown in Fig. 3.1. When Chem-B was added, it was added to the empty drum or after half of the mixing water had been added to the empty drum. If added to the empty drum, half of the mixing water was then added. In either case, the water and Chem-B were mixed before the other materials were batched. Chem-C was added to the drum by means of a hand-held bucket after the concrete had been examined for suitable properties.

Plastic garbage bags were used to load fly ash FA-A into the ready-mix truck, as shown in Fig. 3.2. The fly ash was added to the truck after the retarder, half of the fine aggregate, coarse aggregate, and water, and all of the cement were batched into the drum. After the fly ash was added, the remaining fine aggregate, coarse aggregate, and water were batched.

After the concrete was batched, it was mixed for five minutes at the ready-mix plant. At the end of that time, the concrete was examined for consistency, as shown in Fig. 3.3. If the concrete appeared to be too dry, water was added until the desired consistency

TABLE 3.1 Properties of coarse aggregates used in high strength concrete mixes.

COARSE AGGREGATE DESIGNATION	COARSE AGGREGATE PROPERTIES
CA-A (Source A)	Crushed limestone ASTM C33 No. 8, 3/8-in. to #8. BSG_{ssd} = 2.53 DRUW = 94 pcf AC_{ssd} = 3.0%
CA-B (Source C)	Crushed limestone ASTM C33 No. 57, 1-in. to #4. BSG_{ssd} = 2.79 DRUW = 99 pcf AC_{ssd} = 0.5%
CA-C (Source B)	Crushed limestone ASTM C33 No. 8, 3/8-in. to #8 BSG_{ssd} = 2.43 DRUW = 91 pcf AC_{ssd} = 4.5%
CA-D (Source C)	Crushed limestone ASTM C33 No. 8, 3/8-in. to #8 BSG_{ssd} = 2.79 DRUW = 100 pcf AC_{ssd} = 0.5%
CA-E (Source B)	Crushed limestone ASTM C33 No. 67, 3/4-in. to #4 BSG_{ssd} = 2.48 DRUW = 91 pcf AC_{ssd} = 3.0%

TABLE 3.2 Properties of fly ash used in high strength concrete mixes

FLY ASH DESIGNATION	FLY ASH PROPERTIES
FA-A	ASTM C618 Class C TSDHPT Type B BSG = 2.72
FA-B	ASTM C618 Class C TSDHPT Type B BSG = 2.64
FA-C	ASTM C618 Class C TSDHPT Type B BSG = 2.64

TABLE 3.3 Properties of chemical and air entraining admixtures used in high strength concrete mixes.

ADMIXTURE DESIGNATION	ADMIXTURE PROPERTIES
Chem-A	ASTM C494 Type A and D Water reducing and retarding admixture Lignin-based; calcium-free S.G. = 1.17-1.18 % solids = 42% Dosage rates: Water-reduction = 3 oz/cwt Retardation = 6 oz/cwt
Chem-B	ASTM C494 Type D Water reducing and retarding admixture Polymer-based S.G. = 1.24 % solids = 42% Dosage rates: 2-4 oz/cwt
Chem-C	ASTM C494 Type F High range water reducing admixture Naphthalene-based S.G. = 1.21 % solids = 42% Dosage rates: Flowing concrete = 6-12 oz/cwt High range water reduction = 12-16 oz/cwt
Chem-D	ASTM C260 Air entraining admixture Soponified natural wood resin S.G. = 1.01 % solids = 6-7% Dosage rates = 1/4-4 oz/cwt pH = 10.4-13.5

TABLE 3.4 Materials used in each high strength concrete mix.

MIX NO.	COARSE AGGREGATE					FLY ASH			CHEMICAL OR AIR ENTRAINING ADMIXTURE			
	A	B	C	D	E	A	B	C	A	B	C	D
01-107-00	X								X		X	
02-095-00	X									X	X	
03-096-00	X								X		X	
04-100-00	X								X		X	
05-089-00	X								X		X	
06-097-00	X								X		X	
07-098-00	X								X		X	
08-104-00 A & B	X								X		X	
09-106-00	X								X		X	
10-094-00	X								X		X	
11-093-27	X					X			X		X	
12-093-38	X					X			X		X	
13-100-00	X									X	X	
14-110-28	X					X				X	X	
15-112-38	X					X				X	X	
16-107-00	X									X	X	
17-100-00			X							X	X	
18-111-35			X				X			X	X	
19-103-00	X								X		X	
20-111-33		X						X		X	X	
21-112-34				X				X		X	X	
22-110-34				X				X		X	X	
23-067-00	X								X		X	
24-065-00	X								X			
25-056-00	X								X			
26-057-00	X								X			
27-060-00					X							X
28-059-00					X							
29-060-00	X								X			

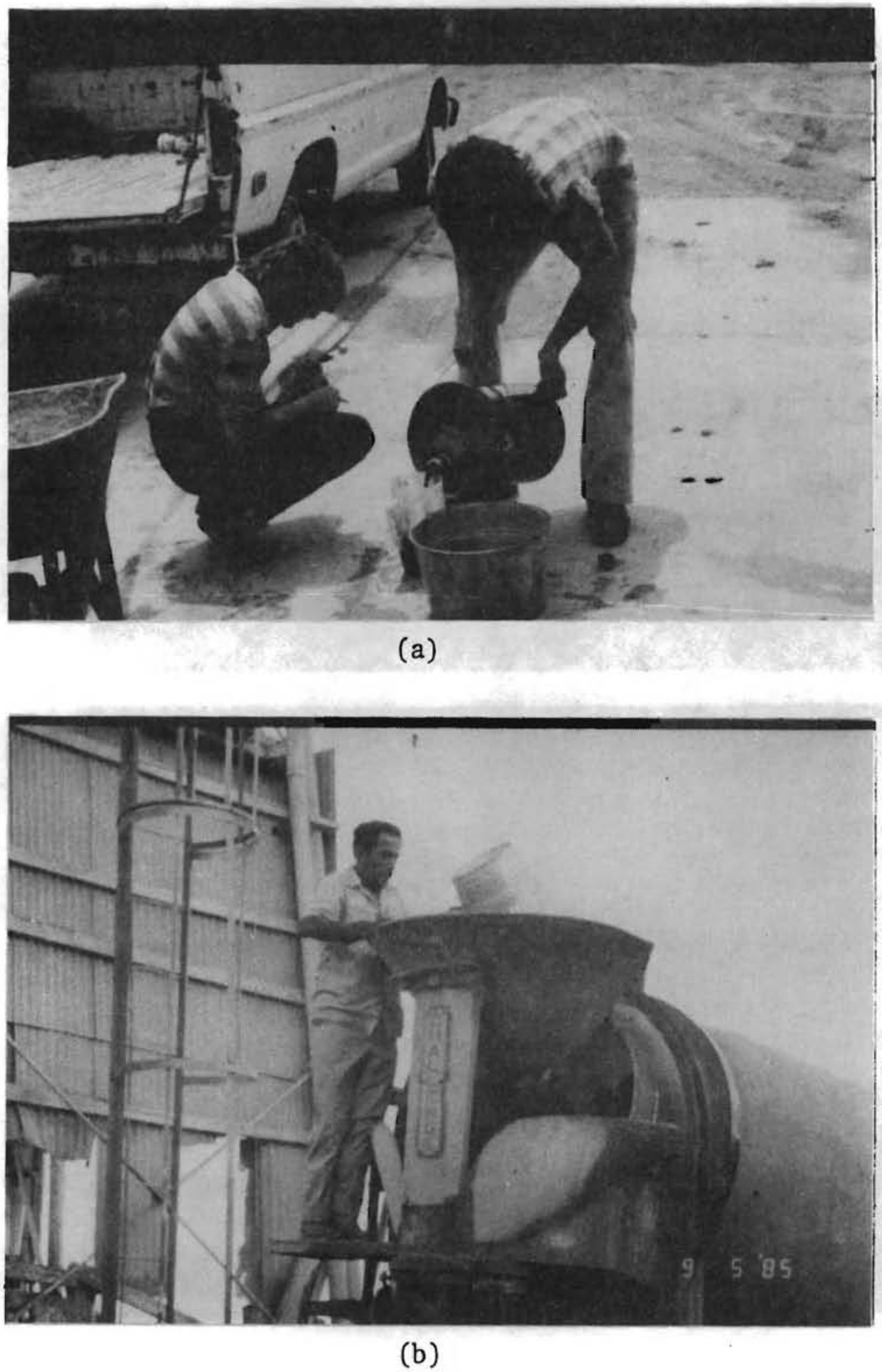
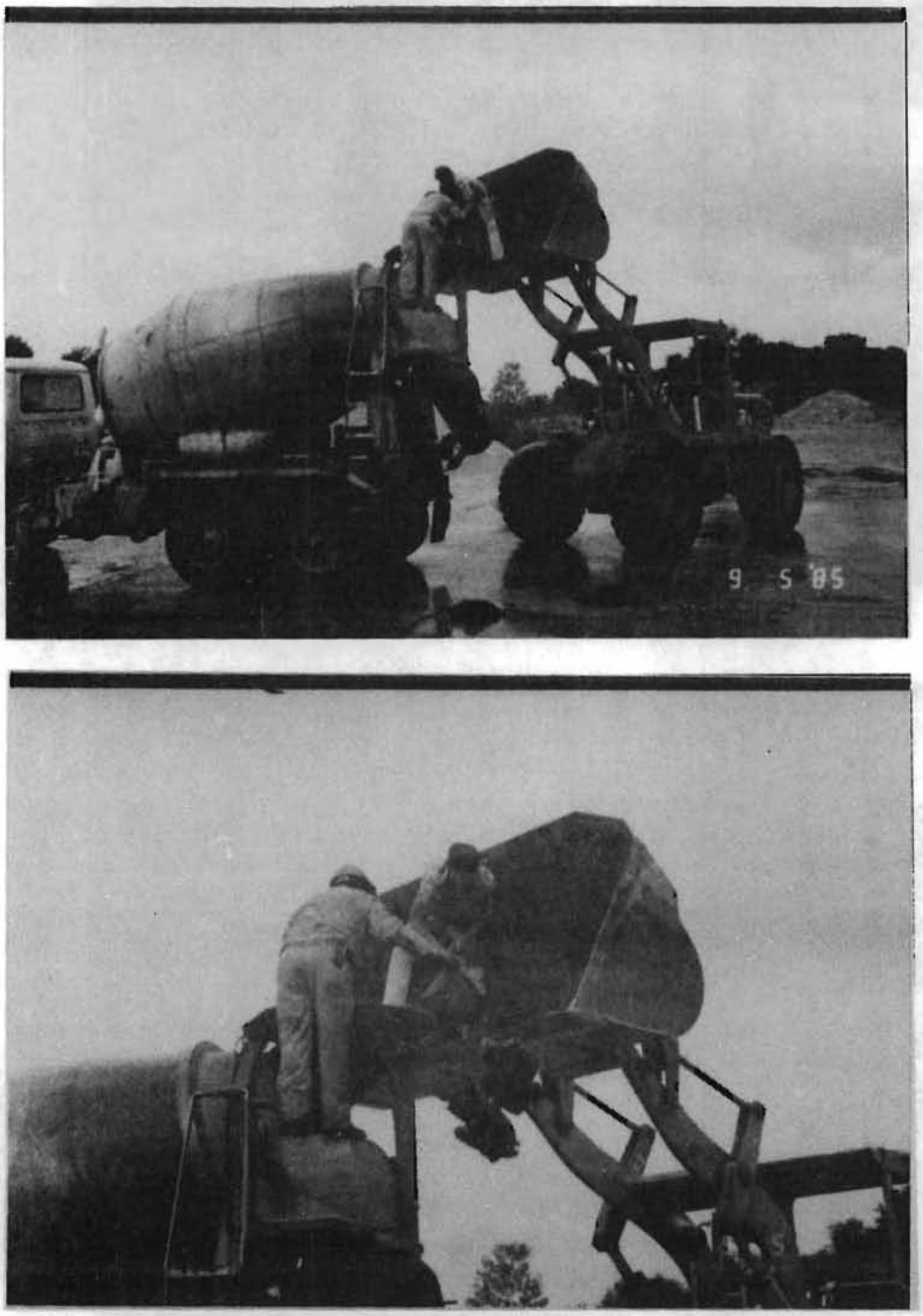


Fig. 3.1 (a) Measurement of chemical admixture dosage; (b) addition of chemical admixture to ready-mix truck.



9 5 '85

Fig. 3.2 Addition of fly ash to ready-mix truck.

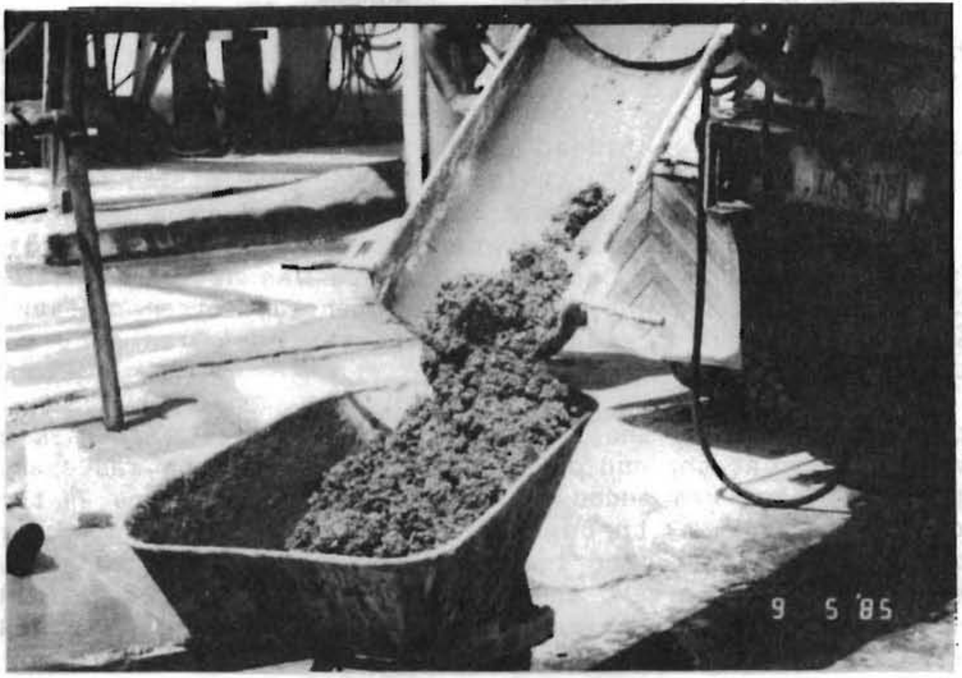


Fig. 3.3 Examination of concrete at ready-mix plant for proper consistency.

was achieved. After each addition of water, the concrete was mixed for five minutes.

Superplasticizer was added at the ready-mix plant to all mixes except 09, and 23 through 29. This was to achieve dispersion of the cement particles before significant hydration could occur, and to keep the mix in a plastic, cohesive state in transit from the ready-mix plant to the laboratory. Once the concrete was determined to have adequate consistency, it was dosed with superplasticizer. After five minutes of additional mixing, the concrete truck was sent to the laboratory.

Upon its arrival at the laboratory, the concrete was again mixed for five minutes. At the end of that time, the concrete was examined, and superplasticizer was added to all mixes except numbers 24 through 29. For mix numbers 23 through 26 and 29, water was added to the concrete at the laboratory to increase its slump. After the addition of water or superplasticizer, the concrete was mixed for five minutes. Once the concrete had the desired workability, as shown in Fig. 3.4, it was tested for fresh concrete properties and strength specimens were cast.

The history of each mix, from batching to casting of specimens, is given in Tables 3.5 through 3.33. Testing procedures followed are described in Section 3.6.

3.5 Corrected Mix Proportions

The mix proportions per cubic yard were calculated based on actual batch weights, moisture conditions, and measured air content of each mix. In these calculations, the unit weight of water was taken to be 62.5 pcf, and 3.10 was used as the specific gravity of cement. The volume of chemical admixture added to the concrete was included as part of the mixing water. Dosage rates of chemical admixtures are expressed in terms of ounces per one hundred pounds of cement plus fly ash. Corrected mix proportions for each mix are given in Table 3.34. Mix design constants are given in Table 3.35.

3.6 Test Procedures

The following procedures were followed in testing the properties of the fresh and hardened concrete and in preparing strength specimens.

3.6.1 Slump. The slump of each high strength concrete mix was measured at the ready-mix plant and the laboratory according to ASTM C143-78, as shown in Fig. 3.5.

3.6.2 Air content. The air content of each mix was measured according to ASTM C231-82, the pressure method, as shown in Fig. 3.6.

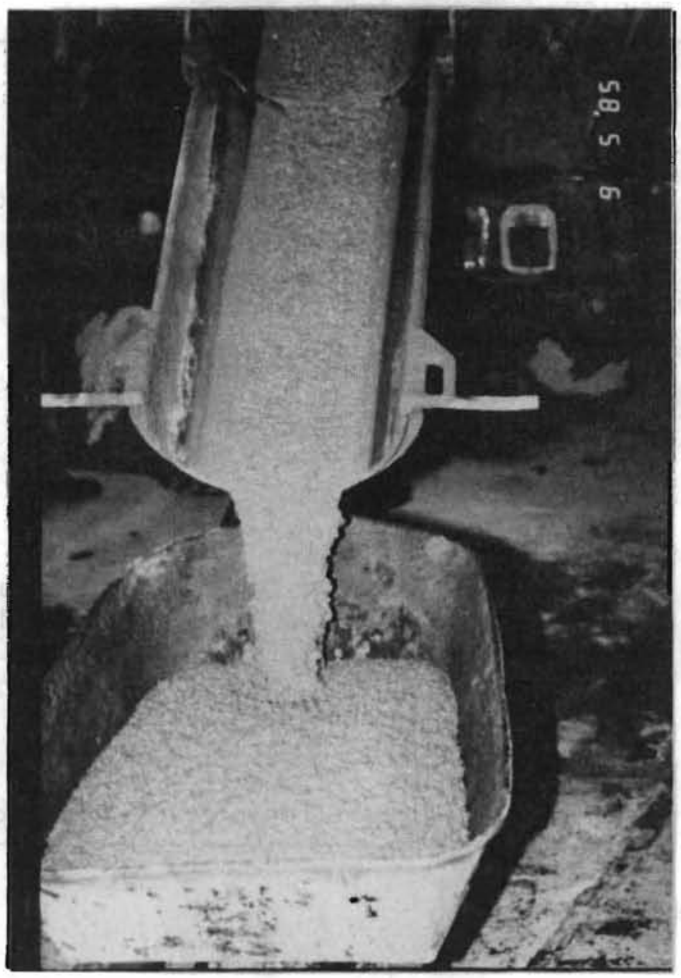


Fig. 3.4 Examination of concrete at laboratory for proper consistency after superplasticizer was added.

TABLE 3.5 History of mix number 01-107-00

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: JULY 3, 1985 - 5 YD^3
	AT READY-MIX PLANT
0	Concrete batched
5	Concrete finished mixing; added ten gallons of water.
12	Slump of concrete = 1-1/2 inches
20	Added 235 oz. of superplasticizer (4.42 oz/cwt); concrete mixed for five minutes and sent to laboratory.
	AT LABORATORY
65	Added 600 oz. of superplasticizer (11.28 oz/cwt); concrete mixed for five minutes.
75	Slump of concrete = 8-3/4 inches Temperature of concrete = 92.5°F Air content of concrete = 2.5% Unit weight of concrete = 149.7 pcf

NOTES: Mix very cohesive; sticky

TABLE 3.6 History of mix number 02-095-00

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: JULY 3, 1985 - 5 YD^3
	AT READY-MIX PLANT
0	Concrete batched
5	Concrete finished mixing; slump of concrete = 1-3/4 inches. Temperature of concrete = 90.5°F
14	Added 235 oz. of superplasticizer (5.22 oz/cwt); concrete mixed for five minutes and sent to laboratory
	AT LABORATORY
50	Slump of concrete estimated to be 1 inch; Temperature of concrete = 94.0°F
55	Added 600 oz. of superplasticizer (13.34 oz/cwt); concrete mixed for five minutes.
60	Slump of concrete = 10+ inches Temperature of concrete = 95.0°F
72	Unit weight of concrete = 147.3 pcf
80	Air content of concrete = 2.5%

NOTES: Appearance of mix very good; placed and finished easily.

TABLE 3.7 History of mix number 03-096-00

TIME SINCE BATCH, min.	DESCRIPTION
DATE CAST: JULY 5, 1985 - 4 YD^3	
AT READY-MIX PLANT	
0	Concrete batched.
5	Concrete finished mixing; Slump of concrete = 1-1/2 inches
7	Added 300 oz. of superplasticizer (7.98 oz/cwt); concrete mixed for five minutes.
13	Slump of concrete estimated to be 6 inches; concrete sent to laboratory.
AT LABORATORY	
35	Slump of concrete estimated to be 2 inches
37	Added 400 oz. of superplasticizer (10.64 oz/cwt); concrete mixed for five minutes.
50	Slump of concrete = 10+ inches Air content of concrete = 4.4% Temperature of concrete = 92.0°F Unit weight of concrete = 143.3 pcf

NOTES: Mix appeared bubbly, and very sticky. Unknown how air entrainment got into mix.

TABLE 3.8 History of mix number 04-100-00

TIME SINCE BATCH, min.	DESCRIPTION
DATE CAST: JULY 15, 1985 - 5 YD^3	
AT READY-MIX PLANT	
0	Concrete batched
5	Concrete finished mixing; slump of concrete = 1 inch
10	Added 375 oz. of superplasticizer (7.96 oz/cwt); concrete mixed for five minutes.
15	Slump of concrete estimated to be 5 inches; concrete sent to laboratory
AT LABORATORY	
55	Added 470 oz. of superplasticizer (9.98 oz/cwt); concrete mixed for five minutes
60	Slump of concrete = 7-1/2 inches Temperature of concrete = 84.0°F Air content of concrete = 2.3% Unit weight of concrete = 148.2 pcf

NOTES: Mix appeared very sticky and rocky; hard to finish.

TABLE 3.9 History of mix number 05-089-00.

TIME SINCE BATCH, min.	DESCRIPTION
DATE CAST: JULY 15, 1985 - 5 YD^3	
AT READY-MIX PLANT	
0	Concrete batched
5	Concrete finished mixing; added ten gallons of water
11	Slump of concrete = 1/2 inch Temperature of concrete = 76.0°F Added 340 oz. of superplasticizer (8.02 oz/cwt); concrete mixed for five minutes.
16	Slump of concrete estimated to be 4 inches; concrete sent to laboratory
AT LABORATORY	
55	Slump of concrete estimated to be 1 inch
58	Added 465 oz. of superplasticizer (10.97 oz/cwt); concrete mixed for five minutes
65	Slump of concrete = 8-3/4 inches Temperature of concrete = 82.0°F Air content of concrete = 2.5% Unit weight of concrete = 148.7 pcf

NOTES: Mix looked very good; not too sticky.

TABLE 3.10 History of mix number 06-097-00

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: JULY 17, 1985 - 5 YD^3
	AT READY-MIX PLANT
0	Concrete batched
5	Concrete finished mixing; added ten gallons of water
10	Added five gallons of water
15	Slump of concrete = 0 inch, but mix looked wet; some evidence of balling. Temperature of concrete = 83.0°F. Added 376 oz. of superplasticizer (8.04 oz/cwt); concrete mixed for five minutes.
20	Slump of concrete estimated to be 3 inches; concrete sent to laboratory
	AT LABORATORY
45	Slump of concrete = 0 inch, but still moist-looking; still some balling evident.
60	Added 658 oz. of superplasticizer (14.07 oz/cwt); concrete mixed for five minutes.
66	Slump of concrete = 7-3/4 inches; Temperature of concrete = 87.0°F
85	Air content of concrete = 2.5%
90	Unit weight of concrete = 148.7 pcf

NOTES: Mix looked good; shiny. Crust formed if not continuously agitated. Pretty sticky.

TABLE 3.11 History of mix number 07-098-00

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: JULY 29, 1985 - 5 YD^3
	AT READY-MIX PLANT
0	Concrete batched
10	Concrete finished mixing; added 30 gallons of water
15	Slump of concrete = 2 inches; Temperature of concrete = 84.5°F
23	Added 376 oz. of superplasticizer (8.00 oz/cwt); concrete mixed for five minutes and sent to laboratory
	AT LABORATORY
55	Slump of concrete = 1-1/2 inches
60	Added 470 oz. of superplasticizer (10.00 oz/cwt); concrete mixed for five minutes.
65	Slump of concrete = 10+ inches Temperature of concrete = 88.0°F Air content of concrete = 1.0% Unit weight of concrete = 147.7 pcf

NOTES: Cylinders show signs of segregation; shrinkage cracks on surfaces.

TABLE 3.12 History of mix number 08A-104-00 and 08B-104-00

TIME SINCE BATCH, min.		DESCRIPTION
		DATE CAST: AUGUST 5, 1985 - 5 YD^3
		AT READY-MIX PLANT
0		Concrete batched
5		Concrete finished mixing; added ten gallons of water
14		Slump of concrete = 1/2 inch; Temperature of concrete = 80.0°F; Added 395 oz. of superplasticizer (8.01 oz/cwt); concrete mixed for five minutes.
21		Slump of concrete estimated to be 6 inches; concrete sent to laboratory
		AT LABORATORY
57		Slump of concrete estimated to be 1/2 inch; Added 545 oz. of superplasticizer (11.05 oz/cwt); concrete mixed for five minutes.
62		Slump of concrete = 9-1/4 inches; Temperature of concrete = 84.5°F
76	Mix No. 08A-104-00 ↑	Air content of concrete = 2.5% Unit weight of concrete = 150.9 pcf
121	Mix No. 08B-104-00 ↓	Slump of concrete estimated to be 3 inches
126		Added 124 oz. of superplasticizer (2.83 oz/cwt); concrete mixed for five minutes
131		Slump of concrete = 9 inches; Air content of concrete = 2.6%; Temperature of concrete = 101.0°F; Unit weight of concrete = 150.9 pcf

NOTES: Mix looked very good, even after third dosing with superplasticizer. However, mix was borderline segregation after last addition.

TABLE 3.13 History of mix number 09-106-00

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: AUGUST 5, 1985 - 4 YD^3
	AT READY-MIX PLANT
0	Concrete batched
5	Concrete finished mixing; added five gallons of water
15	Slump of concrete = 1/2 inch Temperature of concrete = 82.5°F Concrete sent to laboratory
	AT LABORATORY
40	Concrete very dry; added 632 oz. of superplasticizer (15.98 oz/cwt); concreted mixed for five minutes
47	Slump of concrete = 10+ inches
52	Temperature of concrete = 84.0°F
57	Air content of concrete = 1.8% Unit weight of concrete = 150.8 pcf
72	Temperature of concrete = 89.0°F

NOTES: Concrete very soupy, but cohesive.

TABLE 3.14 History of mix number 10-094-00

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: SEPTEMBER 5, 1985 - 5 YD^3
	AT READY-MIX PLANT
0	Concrete batched
5	Concrete finished mixing; added ten gallons of water.
13	Added five gallons of water
18	Slump of concrete estimated to be 1/2 inch Temperature of concrete = 81.0°F Added 235 oz. of superplasticizer (5.22 oz/cwt); concrete mixed for five minutes, and sent to laboratory.
	AT LABORATORY
49	Slump of concrete estimated to be 1/2 inch
57	Added 500 oz. of superplasticizer (11.10 oz/cwt); concrete mixed for five minutes.
64	Slump of concrete = 8 inches Temperature of concrete = 83°F
79	Air content of concrete = 2.8% Unit weight of concrete = 148.8 pcf

NOTES: Mix looked good; workable and cohesive

TABLE 3.15 History of mix number 11-093-27

TIME SINCE BATCH, min.	DESCRIPTION
DATE CAST: SEPTEMBER 5, 1985 - 4 YD^3	
AT READY-MIX PLANT	
0	Concrete batched
5	Concrete finished mixing; added ten gallons of water
10	Temperature of concrete = 81.0°F Added five gallons of water
19	Slump of concrete = 1/2 inch Added 188 oz. of superplasticizer (5.19 oz/cwt); concrete mixed for five minutes, and sent to laboratory.
AT LABORATORY	
55	Slump of concrete estimated to be 1/2 inch Added 400 oz. of superplasticizer (11.03 oz/cwt); concrete mixed for five mintes
63	Slump of concrete = 10+ inches; Temperature of concrete = 87.0°F Unit weight of concrete = 151.3 pcf Air content of concrete = 1.3%

NOTES: Mix looked good, with good workabiity; could take no more superplasticizer without segregation.

TABLE 3.16 History of mix number 12-093-38

TIME SINCE BATCH, min.	DESCRIPTION
DATE CAST: SEPTEMBER 5, 1985 - 4-1/2 YD^3	
	AT READY-MIX PLANT
0	Concrete batched
8	Concrete finished mixing; added five gallons of water
13	Temperature of concrete = 88°F
15	Slump of concrete = 1/4 inch; added five gallons of water.
20	Slump of concrete = 0 inch; added 188 oz. of superplasticizer (5.21 oz/cwt); concrete mixed for five minutes, and sent to laboratory.
	AT LABORATORY
45	Slump of concrete estimated to be 0 inch; added 361 oz. of superplasticizer (10.00 oz/cwt); concrete mixed for five minutes.
50	First concrete from truck segregated; incomplete mixing; mixed another five minutes.
55	Slump of concrete = 6 inches; Temperature of concrete = 97.0°F; Air content of concrete = 2.0%; Unit weight of concrete = 148.8 pcf
95	Specimens finished; no bleeding apparent.

NOTES: Mix very difficult to handle; would not hold slump. Possible cause: cement loaded into silo before and during batching was possibly hot.

TABLE 3.17 History of mix number 13-100-00

TIME SINCE BATCH, min.	DESCRIPTION
DATE CAST: SEPTEMBER 10, 1985 - 4 YD^3	
	AT READY-MIX PLANT
0	Concrete batched
5	Concrete finished mixing; added ten gallons of water
11	Added five gallons of water
16	Slump of concrete = 1-3/8 inches Temperature of concrete = 90°F
19	Added 317 oz. of superplasticizer (7.97 oz/cwt); concrete mixed for five minutes, and sent to laboratory.
	AT LABORATORY
44	Slump of concrete estimated to be 6 inches
46	Added 200 oz. of superplasticizer (5.03 oz/cwt); concrete mixed for five minutes.
51	Slump of concrete = 10+ inches Temperature of concrete = 88.0°F; Air content of concrete = 0.9%; Unit weight of concrete = 149.1 pcf

NOTES: Mix seemed to segregate slightly.

TABLE 3.18 History of mix number 14-110-28

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: SEPTEMBER 10, 1985 - 4 YD^3
	AT READY-MIX PLANT
0	Concrete batched
10	Concrete finished mixing; Slump of concrete = 1 inch Temperature of concrete = 80.0°F
15	Added 317 oz. of superplasticizer (8.01 oz/cwt); concrete mixed for five minutes and sent to laboratory
	AT LABORATORY
40	Slump of concrete estimated to be 9 inches Temperature of concrete = 82°F Added 100 oz. of superplasticizer (2.53 oz/cwt); concrete mixed for five minutes
47	Slump of concrete = 10+ inches Unit weight of concrete = 149.6 pcf Air content of concrete = 1.35%
65	Specimens finished.

NOTES: Concrete looked very good; held slump well.

TABLE 3.19 History of mix number 15-112-38

TIME SINCE BATCH, min.	DESCRIPTION
DATE CAST: SEPTEMBER 10, 1985 - 4 YD^3	
AT READY-MIX PLANT	
0	Concrete batched
5	Concrete finished mixing; added eight gallons of water
11	Slump of concrete = 1/4 inch Temperature of concrete = 81.0°F Added 317 oz. of superplasticizer (8.03 oz/cwt); concrete mixed for five minutes, and sent to laboratory
AT LABORATORY	
40	Slump of concrete estimated to be 3 inches Added 200 oz. of superplasticizer (5.07 oz/cwt); concrete mixed for five minutes
45	Slump of concrete = 10+ inches Unit weight of concrete = 149.1 pcf Air content of concrete = 1.6% Temperature of concrete = 86.5°F

NOTES: Mix looked very good; cohesive, with good workability.

TABLE 3.20 History of mix number 16-107-00

TIME SINCE BATCH, min.	DESCRIPTION
DATE CAST: SEPTEMBER 17, 1985 - 4 YD^3	
	AT READY-MIX PLANT
0	Concrete batched
7	Concrete finished mixing; added ten gallons of water
13	Added five gallons of water
18	Slump of concrete = 1/2 inch Temperature of concrete = 81.0°F Added 317 oz. of superplasticizer (7.99 oz/cwt); concrete mixed for five minutes, and sent to laboratory
	AT LABORATORY
46	Slump of concrete estimated to be 1 inch Added 335 oz. of superplasticizer (8.45 oz/cwt); concrete mixed for five minutes
51	Slump of concrete = 10+ inches; mix segregated Unit weight of concrete = 151.1 pcf Air content of concrete = 0.75% Temperature of concrete = 84.0°F
60	Cast beams
75	Mix regains cohesiveness; cast cylinders

NOTES: Mix looked good while casting cylinders; concrete in beam molds segregated.

TABLE 3.21 History of mix number 17-100-00

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: SEPTEMBER 17, 1985 - 4 YD^3
	AT READY-MIX PLANT
0	Concrete batched
5	Concrete finished mixing; added 15 gallons of water
11	Cement balls; added 15 gallons of water
15	Fewer cement balls; added 15 gallons of water
20	Added five gallons of water
25	Slump of concrete = 1/2 inch; Temperature of concrete = 78.0°F; Added 317 oz. of superplasticizer (8.03 oz/cwt); concrete mixed for five minutes, and sent to laboratory
	AT LABORATORY
60	Slump of concrete estimated to be 1 inch
67	Added 345 oz. of superplasticizer (8.73 oz/cwt); concrete mixed for five minutes
79	Added 113 oz. of superplasticizer (2.98 oz/cwt); concrete mixed for five minutes.
84	Slump of concrete estimated to be 2 inches; Temperature of concrete = 87.0°F
90	Added 140 oz. of superplasticizer (3.80 oz/cwt); concrete mixed for five minutes
95	Slump of concrete = 1-1/2 inches; Temperature of concrete = 88°F; Unit weight of concrete = 145.0 pcf; Air content of concrete = 2.6%

NOTES: Mix very difficult to place and finish.

TABLE 3.22 History of mix number 18-111-35

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: SEPTEMBER 17, 1985 - 4 YD^3
	AT READY-MIX PLANT
0	Concrete batched
5	Concrete finished mixing; added five gallons of water
10	Slump of concrete = 1/2 inch; Temperature of concrete = 78.0°F;
15	Added 317 oz. of superplasticizer (7.85 oz/cwt); concrete mixed for five minutes, and sent to laboratory
	AT LABORATORY
60	Slump of concrete estimated to be 1/2 inch Added 475 oz. of superplasticizer (11.76 oz/cwt); concrete mixed for five minutes
66	Slump of concrete = 10+ inches; Temperature of concrete = 99.0°F; Unit weight of concrete = 146.0 pcf; Air content of concrete = 2.2%

NOTES: Mix showed good cohesion and placeability.

TABLE 3.23 History of mix number 19-103-00.

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: OCTOBER 8, 1985 - 4 YD^3
	AT READY-MIX PLANT
0	Concrete batched
5	Concrete finished mixing; added 10 gallons of water
10	Added 15 gallons of water
15	Added five gallons of water
20	Slump of concrete = 1/4 inch; Temperature of concrete = 70.0°F;
23	Added 156 oz. of superplasticizer (3.95 oz/cwt); concrete mixed for five minutes, and sent to laboratory
	AT LABORATORY
54	Slump of concrete estimated to be 0 inches Added 400 oz. of superplasticizer (10.13 oz/cwt); concrete mixed for five minutes
59	Slump of concrete = 6 inches;
65	Added 100 oz. of superplasticizer (2.60 oz/cwt); concreted mixed for five minutes
71	Slump of concrete = 9-1/4 inches Temperature of concrete = 77.5°F
86	Unit weight of concrete = 149.1 pcf; Air content of concrete = 1.8%

NOTES: Mix looked good.

TABLE 3.24 History of mix number 20-111-33

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: OCTOBER 8, 1985 - 4 YD^3
	AT READY-MIX PLANT
0	Concrete batched
5	Concrete finished mixing; Slump of concrete = 1-1/2 inches Temperature of concrete = 74.0°F
11	Added 317 oz. of superplasticizer (7.96 oz/cwt); concrete mixed for five minutes, and sent to laboratory
	AT LABORATORY
52	Added 396 oz. of superplasticizer (9.95 oz/cwt); concrete mixed for five minutes
57	Slump of concrete = 10+ inches; Temperature of concrete = 81.0°F Unit weight of concrete = 156.2 pcf; Air content of concrete = 0.7%

NOTES: Mix looked very good.

TABLE 3.25 History of mix number 21-112-34

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: OCTOBER 22, 1985 - 4 YD^3
	AT READY-MIX PLANT
0	Concrete batched
6	Concrete finished mixing; Slump of concrete = 1 inch Temperature of concrete = 70.0°F
11	Added 320 oz. of superplasticizer (8.06 oz/cwt); concrete mixed for five minutes, and sent to laboratory
	AT LABORATORY
50	Added 480 oz. of superplasticizer (12.09 oz/cwt); concrete mixed for five minutes
56	Slump of concrete = 10+ inches; Temperature of concrete = 76.0°F Unit weight of concrete = 153.8 pcf; Air content of concrete = 1.3%
88	Slump of concrete = 10 inches Temperature of concrete = 73.0°F

TABLE 3.26 History of mix number 22-110-34

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: JANUARY 21, 1986 - 4 YD^3
	AT READY-MIX PLANT
0	Concrete batched
-	Concrete finished mixing; added 20 gallons of water.
-	Slump of concrete = 1 inch
-	Added 320 oz. of superplasticizer (8.03 oz/cwt); concrete mixed for five minutes, and sent to laboratory
	AT LABORATORY
-	Slump of concrete = 1-1/2 inches;
-	Added 400 oz. of superplasticizer (10.04 oz/cwt); concrete mixed for five minutes.
-	Slump of concrete = 9-1/2 inches Temperature of concrete = 81.0° F

TABLE 3.27 History of mix number 23-067-00

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: JANUARY 29, 1986 - 4 YD^3
	AT LABORATORY
-	Slump of concrete = 1/2 inch Added eight gallons of water
-	Slump of concrete = 2-1/2 inches Temperature of concrete = 72.0°F Unit weight of concrete = 146.0 pcf Air content of concrete = 2.8%
-	Added 175 oz. of superplasticizer (7.53 oz/cwt); concrete mixed for five minutes
-	Slump of concrete = 6 inches

TABLE 3.28 History of mix number 24-065-00

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: FEBRUARY 5, 1986 - 4-1/2 YD^3
	AT LABORATORY
-	Slump of concrete = 1-1/2 inches Temperature of concrete = 73.0°F Added five gallons of water
-	Slump of concrete = 2-1/2 inches Unit weight of concrete = 144.0 pcf Air content of concrete = 2.9%

TABLE 3.29 History of mix number 25-056-00

TIME SINCE BATCH, min.	DESCRIPTION
	DATE CAST: FEBRUARY 11, 1986 - 3 YD^3
	AT LABORATORY
-	Slump of concrete = 0 inch Added nine gallons of water
-	Slump of concrete = 1/2 inch Added nine gallons of water
-	Slump of concrete = 3-1/2 inches Temperature of concrete = 52.0°F Air content of concrete = 2.2%

TABLE 3.30 History of mix number 26-057-00

TIME SINCE BATCH, min.	DESCRIPTION
DATE CAST: FEBRUARY 19, 1986 - 3 YD^3	
	AT LABORATORY
-	Slump of concrete = 1 inch Added six gallons of water
-	Slump of concrete = 2 inches Added four gallons of water
-	Slump of concrete = 2-3/4 inches Temperature of concrete = 74.0°F Air content of concrete = 3.6% Unit weight of concrete = 144.4 pcf

TABLE 3.31 History of mix number 27-060-00

TIME SINCE BATCH, min.	DESCRIPTION
DATE CAST: DECEMBER 16, 1985 - 3 YD^3	
	AT LABORATORY
-	Slump of concrete = 1-1/4 inches Temperature of concrete = 54.0°F Air content of concrete = 3.7% Unit weight of concrete = 144.0 pcf

TABLE 3.32 History of mix number 28-059-00

TIME SINCE BATCH, min.	DESCRIPTION
DATE CAST: DECEMBER 16, 1985 - 3 YD^3	
AT LABORATORY	
-	Slump of concrete = 0 inch Added five gallons of water
-	Slump of concrete = 3/4 inch Added five gallons of water
-	Slump of concrete = 2-1/4 inches Temperature of concrete = 64.0°F Air content of concrete = 1.9% Unit weight of concrete = 145.0 pcf

TABLE 3.33 History of mix number 29-060-00

TIME SINCE BATCH, min.	DESCRIPTION
DATE CAST: MARCH 4, 1986 - 3 YD^3	
AT LABORATORY	
-	Concrete dry, added six gallons of water
-	Slump of concrete = 1/2 inch Added eight gallons of water
-	Slump of concrete = 2-1/2 inches Temperature of concrete = 73.5°F Air content of concrete = ---% Unit weight of concrete = 144.0 pcf

TABLE 3.34 Corrected mix proportions per cubic yard for high strength concrete mixes.

MIX NUMBER	CEMENT, LBS.	FLY ASH, LBS.	SAND, LBS. (SSD)	COARSE AGGREGATE, LBS. (SSD)	WATER, LBS.	CHEMICAL ADMIXTURE, OZ/CWT			AIR CONTENT %
						WR/RET	SUPERPLASTICIZER	AEA	
01-107-00	1008	0	1049	1581	295	2.82	4.42/11.28	---	2.5
02-095-00	895	0	1101	1709	261	3.56	5.22/13.34	---	2.5
03-096-00	906	0	1059	1629	273	3.19	7.98/10.64	*	4.4
04-100-00	937	0	1013	1758	265	3.19	7.96/9.98	---	2.3
05-089-00	835	0	1207	1675	253	3.19	8.02/10.97	---	2.5
06-097-00	918	0	1042	1717	273	3.21	8.04/14.07	---	2.5
07-098-00	923	0	999	1726	309	3.19	8.00/10.00	---	1.0
08A-104-00	981	0	939	1745	281	3.21	8.01/11.05	---	2.5
08B-104-00	978	0	937	1741	282	3.20	19.06/2.83	---	2.6
09-106-00	995	0	933	1771	280	3.18	15.98	---	1.8
10-094-00	884	0	1082	1689	274	3.20	5.22/11.10	---	2.8
11-093-27	637	211	1012	1835	271	3.18	5.19/11.03	---	1.3
12-093-38	541	291	983	1811	281	3.19	5.21/10.00	---	2.0
13-100-00	937	0	925	1886	272	3.02	7.97/5.03	---	0.9
14-110-28	751	251	951	1771	266	3.01	8.01/2.53	---	1.4
15-112-38	651	353	938	1794	254	3.02	8.03/5.07	---	1.6
16-107-00	1005	0	989	1762	276	1.99	7.99/8.45	---	0.8
17-100-00	942	0	886	1641	326	2.00	8.03/8.73/3.80	---	2.6
18-111-35	681	305	787	1785	281	1.99	7.85/11.76	---	2.2
19-103-00	970	0	1030	1676	289	7.45	3.95/10.13/2.60	---	1.8
20-111-33	693	296	968	1984	257	1.99	7.96/9.95	---	0.7
21-112-34	697	302	1051	1841	263	2.01	8.06/12.09	---	1.3
22-110-34	684	295	1030	1804	291	2.00	8.03/10.04	---	1.3
23-067-00	625	0	1266	1692	287	3.19	7.53	---	2.8
24-065-00	610	0	1269	1775	256	3.00	------------------	---	2.9
25-056-00	527	0	1234	1833	285	3.19	------------------	---	2.2
26-057-00	538	0	1393	1683	257	4.23	------------------	---	3.6
27-060-00	543	0	1392	1562	289	----	------------------	1.06	3.7
28-059-00	557	0	1463	1625	263	----	------------------	---	1.9
29-060-00	559	0	1352	1686	311	4.26	------------------	---	---

* NO AEA INTENTIONALLY ADDED

TABLE 3.35 Design constants for high strength concrete mixes.

MIX NUMBER	CEMENT CONTENT, SACKS	FLY ASH CONTENT, SACKS, BY VOLUME	COARSE AGGREGATE CONTENT, %DRUW	WATER-TO-BINDER RATIO, BY WEIGHT	FLY ASH, % OF C + FA BY VOLUME
01-107-00	10.73	0	60.4	0.293	0
02-095-00	9.52	0	65.3	0.292	0
03-096-00	9.64	0	62.3	0.301	0
04-100-00	9.97	0	67.2	0.283	0
05-089-00	8.88	0	64.0	0.303	0
06-097-00	9.77	0	65.6	0.297	0
07-098-00	9.82	0	66.0	0.335	0
08A-104-00	10.44	0	66.7	0.286	0
08B-104-00	10.40	0	66.5	0.288	0
09-106-00	10.59	0	67.7	0.281	0
10-094-00	9.40	0	64.6	0.310	0
11-093-27	6.78	2.56	70.1	0.320	27.4
12-093-38	5.76	3.53	69.2	0.338	38.0
13-100-00	9.97	0	72.1	0.290	0
14-110-28	7.99	3.04	67.7	0.266	27.6
15-112-38	6.93	4.28	68.6	0.253	38.2
16-107-00	10.69	0	67.3	0.275	0
17-100-00	10.02	0	63.8	0.346	0
18-111-35	7.25	3.81	69.4	0.285	34.5
19-103-00	10.32	0	64.1	0.298	0
20-111-33	7.37	3.70	73.9	0.260	33.4
21-112-34	7.42	3.77	67.8	0.263	33.7
22-110-34	7.28	3.69	66.5	0.297	33.6
23-067-00	6.65	0	64.7	0.459	0
24-065-00	6.49	0	67.8	0.420	0
25-056-00	5.61	0	70.1	0.541	0
26-057-00	5.72	0	64.3	0.478	0
27-060-00	5.78	0	61.7	0.532	0
28-059-00	5.93	0	64.2	0.472	0
29-060-00	5.95	0	64.4	0.556	0

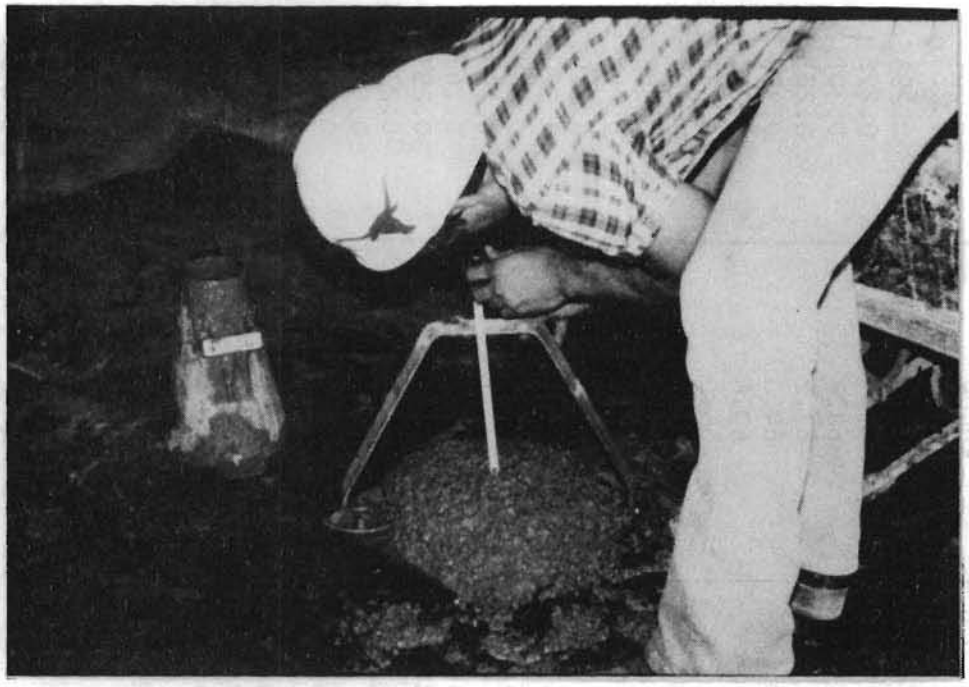
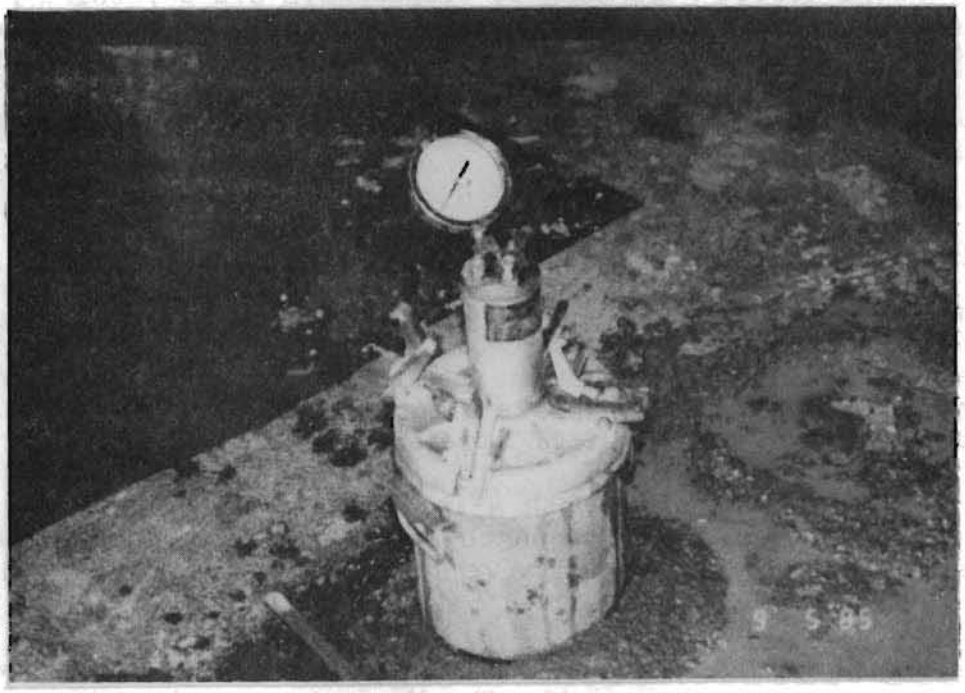


Fig. 3.5 Slump test.



9 5 85

Fig. 3.6 Air content test.

3.6.3 Unit weight. The unit weight of each concrete mix was measured according to ASTM C138-81, as shown in Fig. 3.7.

3.6.4 Test specimens. Strength specimens were prepared and cured according to ASTM C31-84, as shown in Fig. 3.8, except where otherwise noted. Cylindrical compressive strength test specimens were tested according to ASTM C39-84, and beams for measurement of flexural strength were tested according to either ASTM C78-84, third point loading, or ASTM C293-79, center point loading. Generally, flexural strength test results reported were obtained in third-point loading, except for tests comparing the two procedures. For all specimens, the rate of loading satisfied the limits established by ASTM test procedures.

3.7 Variables Studied

The following variables were studied in the experimental program. Given is a description of the approach taken in studying the effect of each variable on the strength test results of high strength concrete. Also included will be details of a pilot study in the production of high strength concrete for a TSDHPT project.

3.7.1 Specimen size. Both 4-in. x 8-in. and 6-in. x 12-in. cylinders for compressive strength tests were cast from several different mixes. The test results were compared at test ages ranging from 1 to 56 days.

The flexural strength test results obtained using two different beam sizes were compared, as well. The flexural strength of beams cast using 6-in. x 6-in. x 20-in. steel molds was compared to that of beams cast using 4-in. x 4-in. x 14-in. wood molds. The wooden molds were lacquered and oiled and the seams caulked to avoid any moisture loss from the fresh concrete. Beams were tested in both center point and third point loading, at a loading rate of approximately 150 psi per minute. Test age in flexure was seven days.

3.7.2 Mold material. Cylinders were cast in 4-in. x 8-in. molds made of steel, plastic or cardboard, and 6-in. x 12-in. molds made of steel or plastic. Cylinders were tested at ages between 1 and 91 days.

3.7.3 Curing conditions. The effect of different curing conditions on both the flexural and compressive strength of high strength concrete was studied. Beams and cylinders were either coated with a membrane-forming curing compound, cured in a fog room, or received no curing after removal from their molds. The curing compound was applied to the specimens after removal from their molds at 24 hours. Both the specimens which were treated with curing compound and those which received no curing were stored on shelves inside the laboratory. The ambient temperature in the laboratory ranged between 80 and 105 °F.

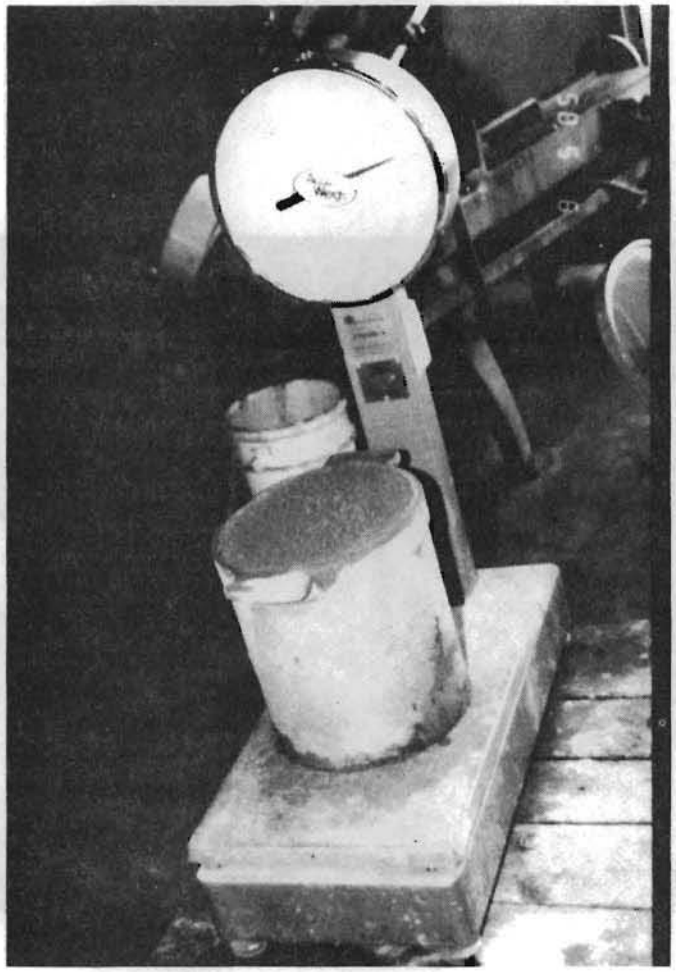


Fig. 3.7 Unit weight test.

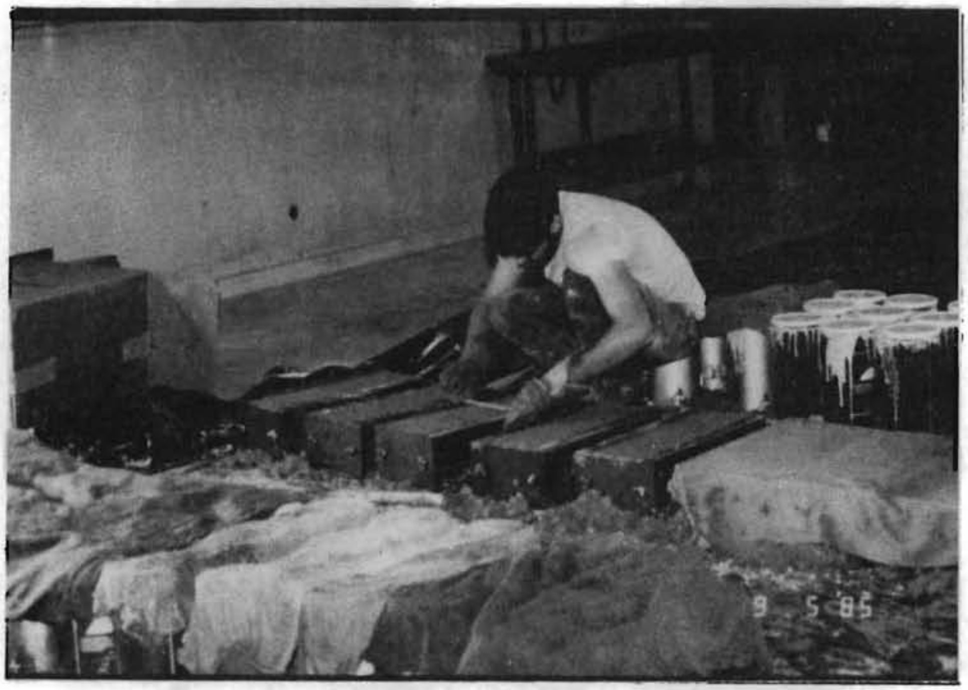


Fig. 3.8 Preparation of strength specimens.

3.7.4 Addition of superplasticizer. A commercially available naphthalene-based superplasticizer was added to all high strength concrete mixes except numbers 24 through 28, generally both at the ready-mix plant and at the laboratory. In mix numbers 08 and 09, however, the effect of time of addition of superplasticizer on both the flexural and compressive strength of high strength concrete was studied.

3.7.5 Capping method. The effect of the procedure used in capping high strength concrete on its compressive strength test results was studied. Three types of capping were studied. Two of these were sulfur-based capping compounds which were applied to the cylinders in molten form, and hardened when cooled. The other was a mechanical capping system consisting of aluminum restraining caps fitted with polyurethane inserts, which were placed on the cylinder ends. For one of the sulfur-based capping compounds, the cap was allowed to harden for different lengths of time before the cylinder was tested in order to determine if possible variations in cap strength would affect the cylinder strength test results. Also, the rough ends of some cylinders were sawed off prior to capping to determine if rough ends affected the results of compressive strength test results.

3.7.6 Consolidation. Cylinders cast in 4-in. x 8-in. and 6-in. x 12-in. molds from mix numbers 19 and 20 were compacted using either a 5/8-inch diameter rod, a 3/8-inch diameter rod, or a vibrator having a 3/4-inch diameter head, to determine if, and by how much, any differences in consolidation would affect strength test results.

3.7.7 Test age. Generally, for each high strength concrete mix, cylinders were tested at 1, 3, 7, 14, 28 and 56 days. For nearly half of the mixes, cylinders were also tested at 91 days and for a few mixes cylinders were tested at even later ages. Strength development after 28 days was investigated.

3.7.8 Field pilot study. High strength concrete was produced in the field for a project in Texas. The concrete was produced in a prestressing plant, equipped with a central-mix facility. The job specifications called for concrete having a 28-day compressive strength of 9,600 psi to be used in prestressed bridge girders. The contractor required that the concrete achieve a compressive strength of 7,400 psi in 14-16 hours, for form release. High strength concrete trial batches were performed, both with and without fly ash. The results are presented in Chapter 12.

CHAPTER 4

EFFECT OF SPECIMEN SIZE

4.1 Introduction

Using smaller specimens for evaluating concrete strength offers a number of advantages. These include less space required for storage, easier handling due to their lighter weight, less material required for casting the specimens and, most importantly for high strength concrete, a lower required maximum load capacity for testing machines. However, before the use of smaller strength specimens is included in concrete specifications, it must be determined if the strength results obtained from smaller specimens are equal to those obtained from conventional size specimens; and if not, a correlation be found. For this purpose, the strength results obtained from 4-in. x 8-in. cylinders and 4-in. x 4-in. x 14-in. beams were compared with those of 6-in. x 12-in. cylinders and 6-in. x 6-in. x 20-in. beams.

4.2 Compressive Strength Tests

The results obtained from 4-in. x 8-in. cylinders and 6-in. x 12-in. cylinders are given in Tables 4.1 and 4.2. Test results shown are the average of two cylinders, unless otherwise noted. The data are plotted in Figs. 4.1 and 4.2.

As shown in Fig. 4.1, for cylinders cast in steel molds, the compressive strength of 6-in. x 12-in. cylinders was greater than that of 4-in. x 8-in. cylinders in all cases except one, in which case they were equal. On the average, compressive strength results obtained from 4-in. x 8-in. cylinders cast in steel molds equalled 93 percent of those obtained from 6-in. x 12-in. cylinders cast in steel molds. The same trend is observed in Fig. 4.2 for cylinders cast in plastic molds, except that, on the average, 4-in. x 8-in. cylinders tested at 94 percent of 6-in. x 12-in. cylinders.

The above results differ from those obtained by Peterman and Carrasquillo [20]. As shown in Fig. 4.3, they found that 4-in. x 8-in. cylinders cast in steel molds tested approximately ten percent higher than 6-in. x 12-in. cylinders cast in steel molds.

Figs. 4.4 through 4.7 are from a report prepared by Janak [13] comparing test results obtained from 4-in. x 8-in. versus 6-in. x 12-in. cylinders at various test ages. In Fig. 4.8, the line representing actual test data at all ages reflects that, on an average, the 4-in. x 8-in. cylinders tested approximately three percent higher than 6-in. x 12-in. cylinders. However, when the data are grouped according to compressive strength, as in Table 4.3, it is seen that the percentage by which 4-in. x 8-in. cylinders test higher than 6-in. x 12-in.

TABLE 4.1 Compressive strength results for 4-in. x 8-in. and 6-in. x 12-in. cylinders cast in steel molds.

MIX NUMBER	CONCRETE AGE AT TEST, days	4-IN. X 8-IN. CYLINDERS, psi (a)	6-IN. X 12-IN. CYLINDERS, psi (b)	RATIO, a:b
01-107-00	28	9320	11,190	0.83
02-095-00	28	9410	10,990	0.86
03-096-00	7	8530	8730	0.98
	28	8670	9920 *	0.87
06-097-00	28	10,360	10,850	0.96
	56	11,260 *	11,610	0.97
07-098-00	1	6840	7100	0.96
	7	8480	8470	1.00
08A-104-00	1	7200	7580	0.95
	3	8120	8710	0.93
	7	8580	9360	0.92
	14	9440	9940	0.95
	29	9970 *	10,610 *	0.94
	56	10,360 *	11,260	0.92

* Test result of one cylinder.

TABLE 4.2 Compressive strength results for 4-in. x 8-in. and 6-in. x 12-in. cylinders cast in plastic molds.

MIX NUMBER	CONCRETE AGE AT TEST, days	4-IN. X 8-IN. CYLINDERS, psi (a)	6-IN. X 12-IN. CYLINDERS, psi (b)	RATIO, a:b
08A-104-00	1	7450	8160	0.91
	3	8070	8480	0.95
	7	9440	9240	1.02
	29	9680 *	10,350	0.93
09-106-00	1	7260	8030	0.90
	3	7750	8530	0.91
	7	8730	9220	0.95
	14	9180	9810	0.94
	56	10,100 *	10,500	0.96
19-103-00	1	6980	6940	1.01
	28	9730	10,930	0.89
	56	11,050 *	11,860 *	0.93
20-111-33	28	10,750	11,620	0.93
	56	11,590 *	13,150	0.88

* Test result of one cylinder

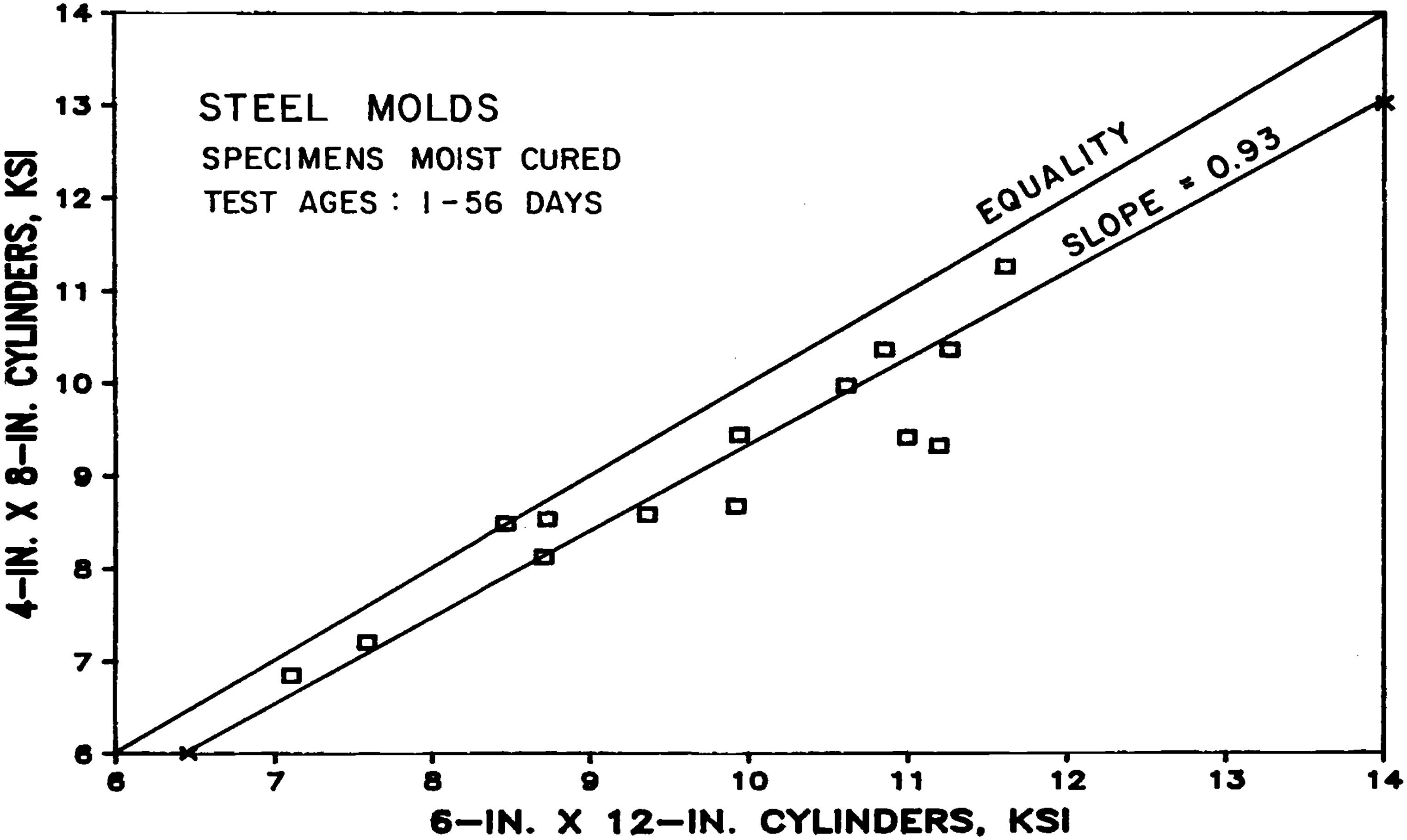


Fig. 4.1 Comparison of test results obtained from 4-in. x 8-in. cylinders cast in steel molds to 6-in. x 12-in. cylinders cast in steel molds.

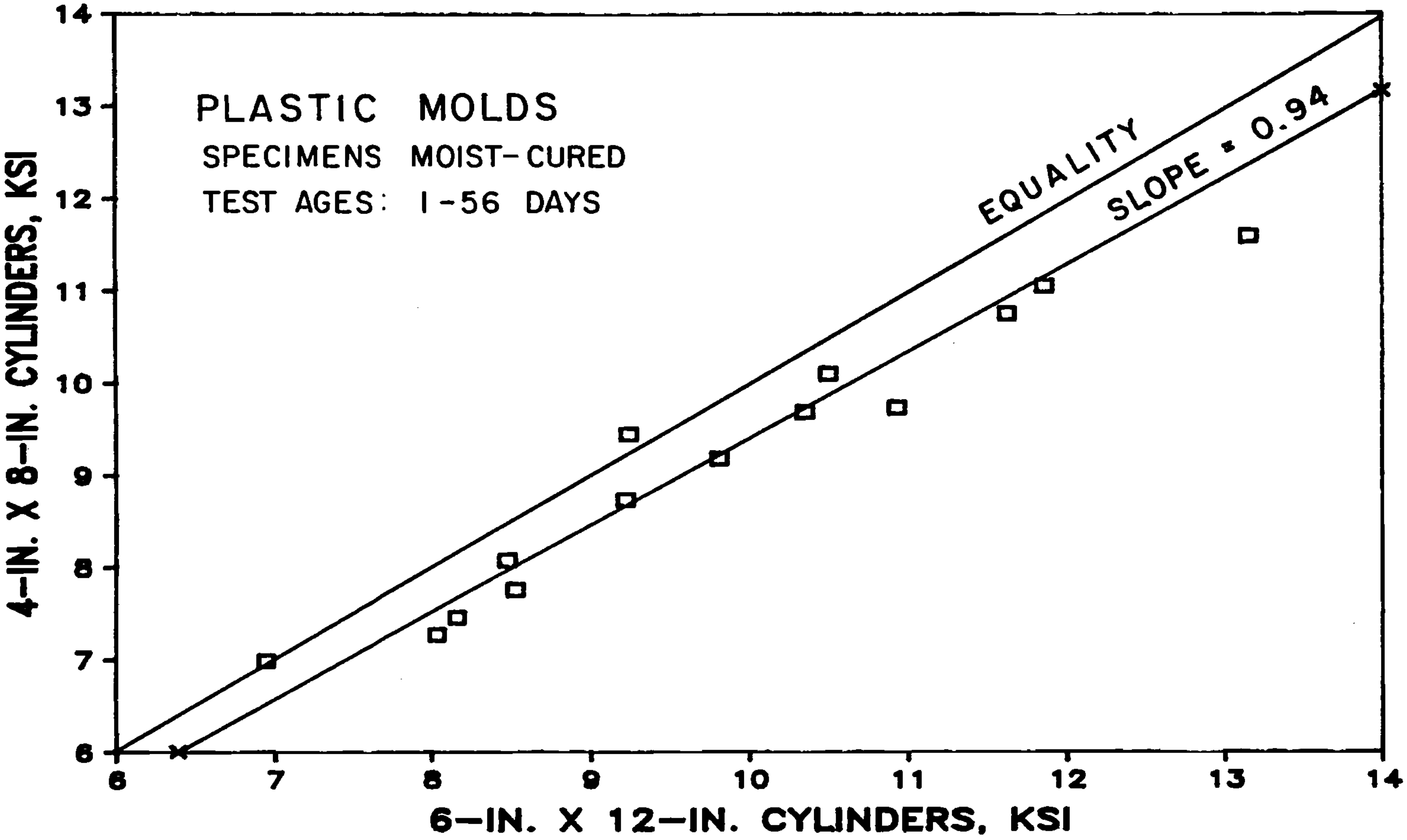


Fig. 4.2 Comparison of test results obtained from 4-in. x 8-in. cylinders cast in plastic molds to 6-in. x 12-in. cylinders cast in plastic molds.

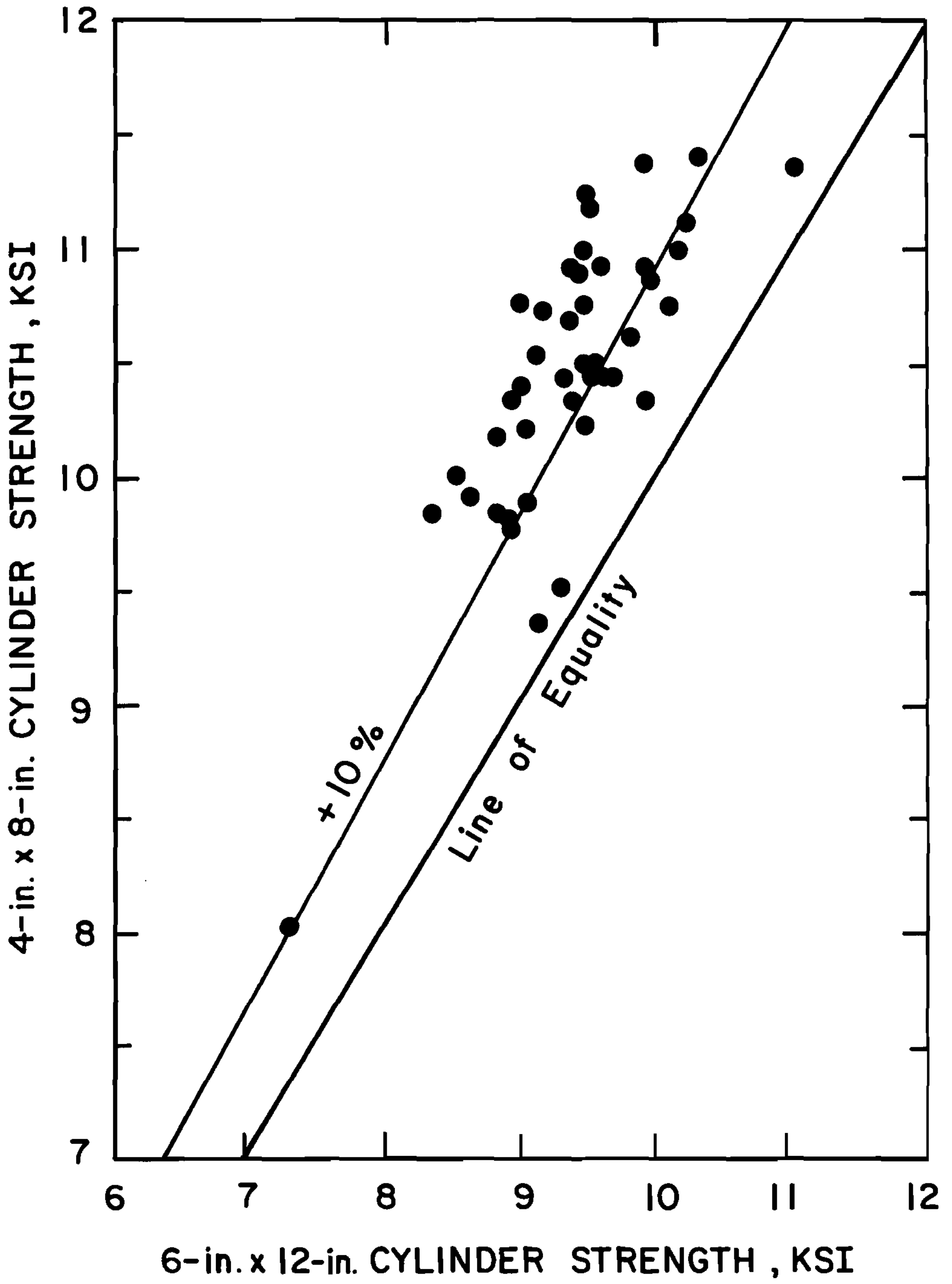


Fig. 4.3 Comparison of the 28-day compressive strength of high strength concrete specimens cast in 4-in. x 8-in. and 6-in. x 12-in. rigid steel molds [20].

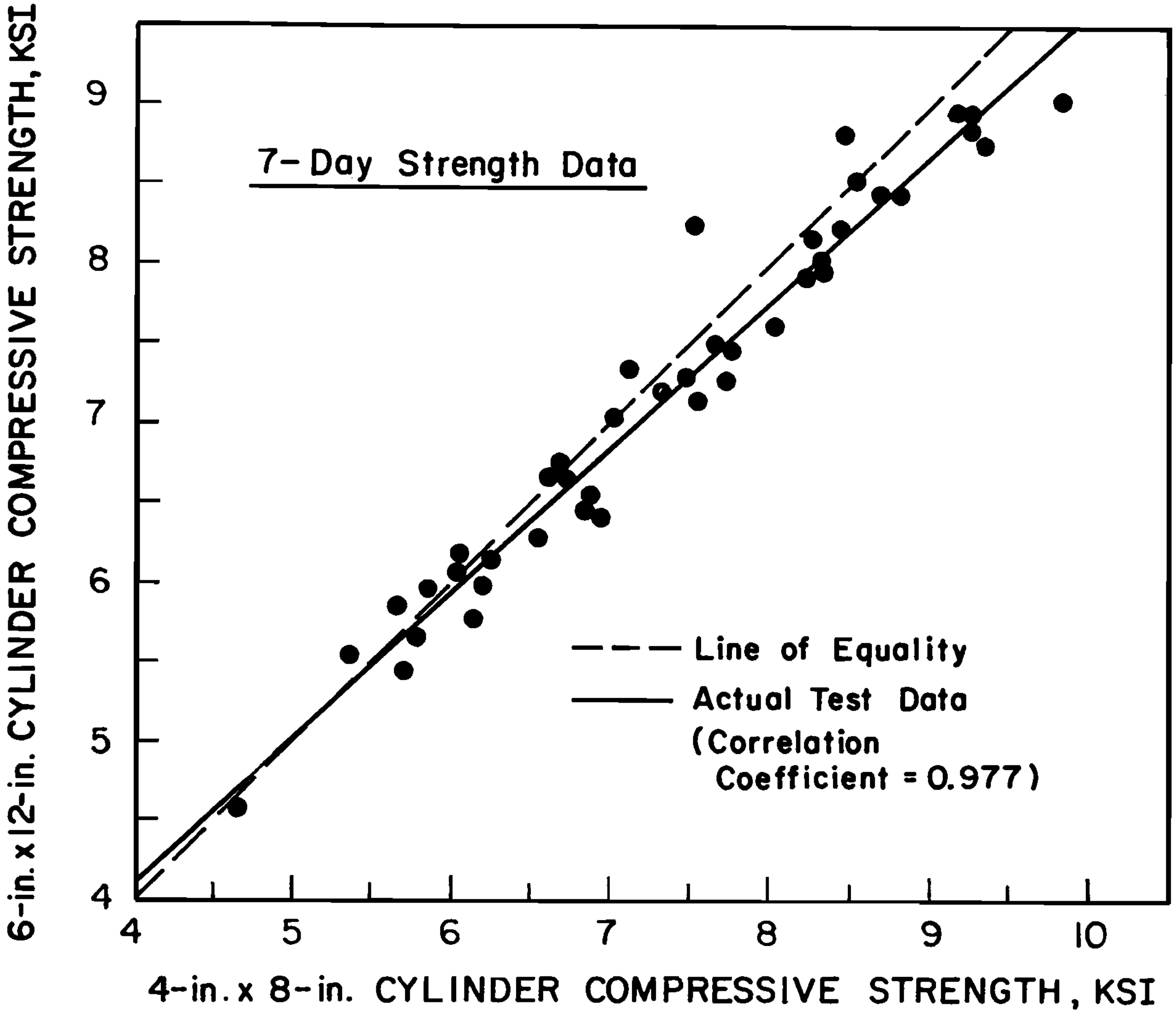


Fig. 4.4 4-in. x 8-in. versus 6-in. x 12-in. cylinder test results at 7 days [13].

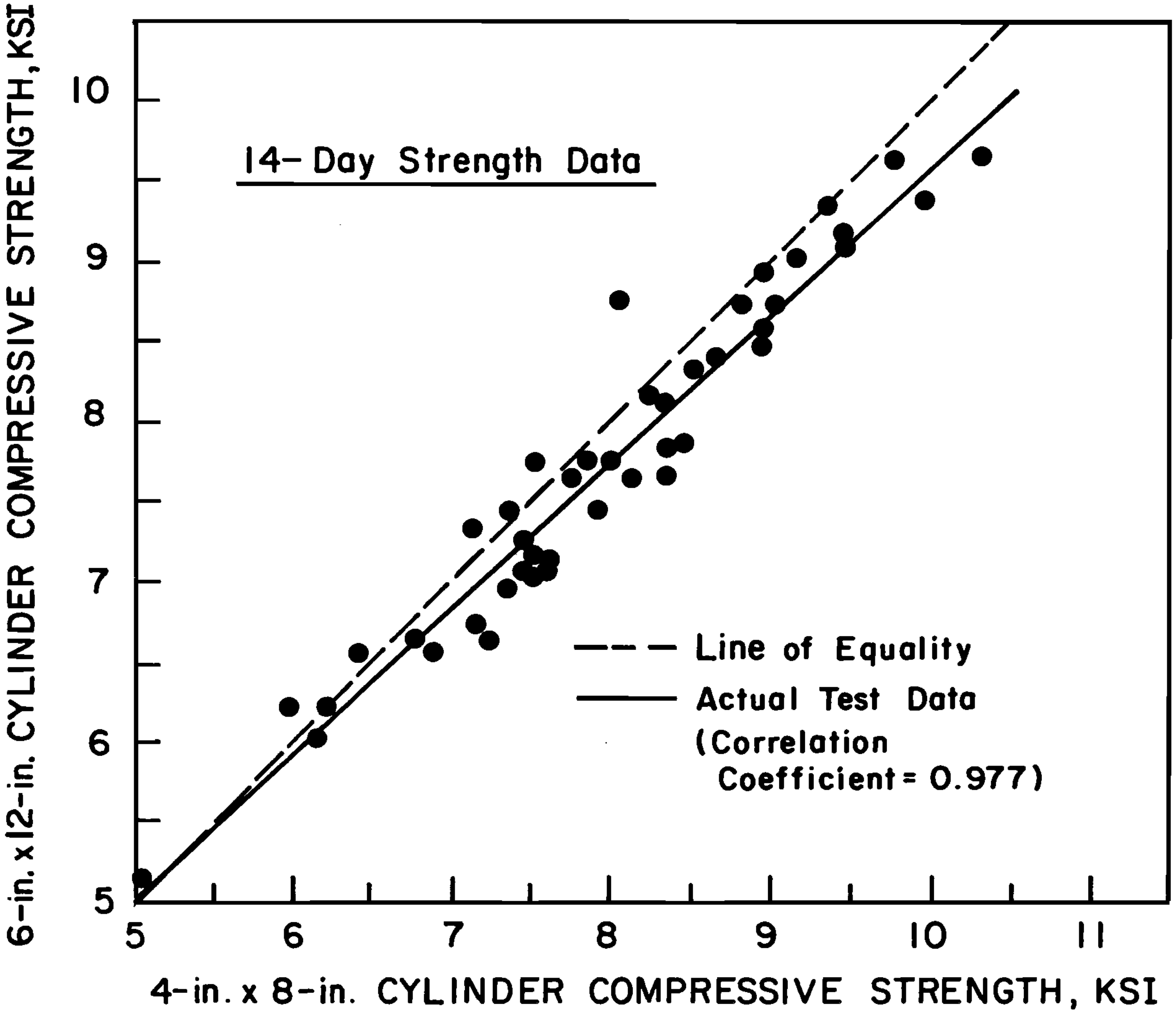


Fig. 4.5 4-in. x 8-in. versus 6-in. x 12-in. cylinder test results at 14 days. [13].

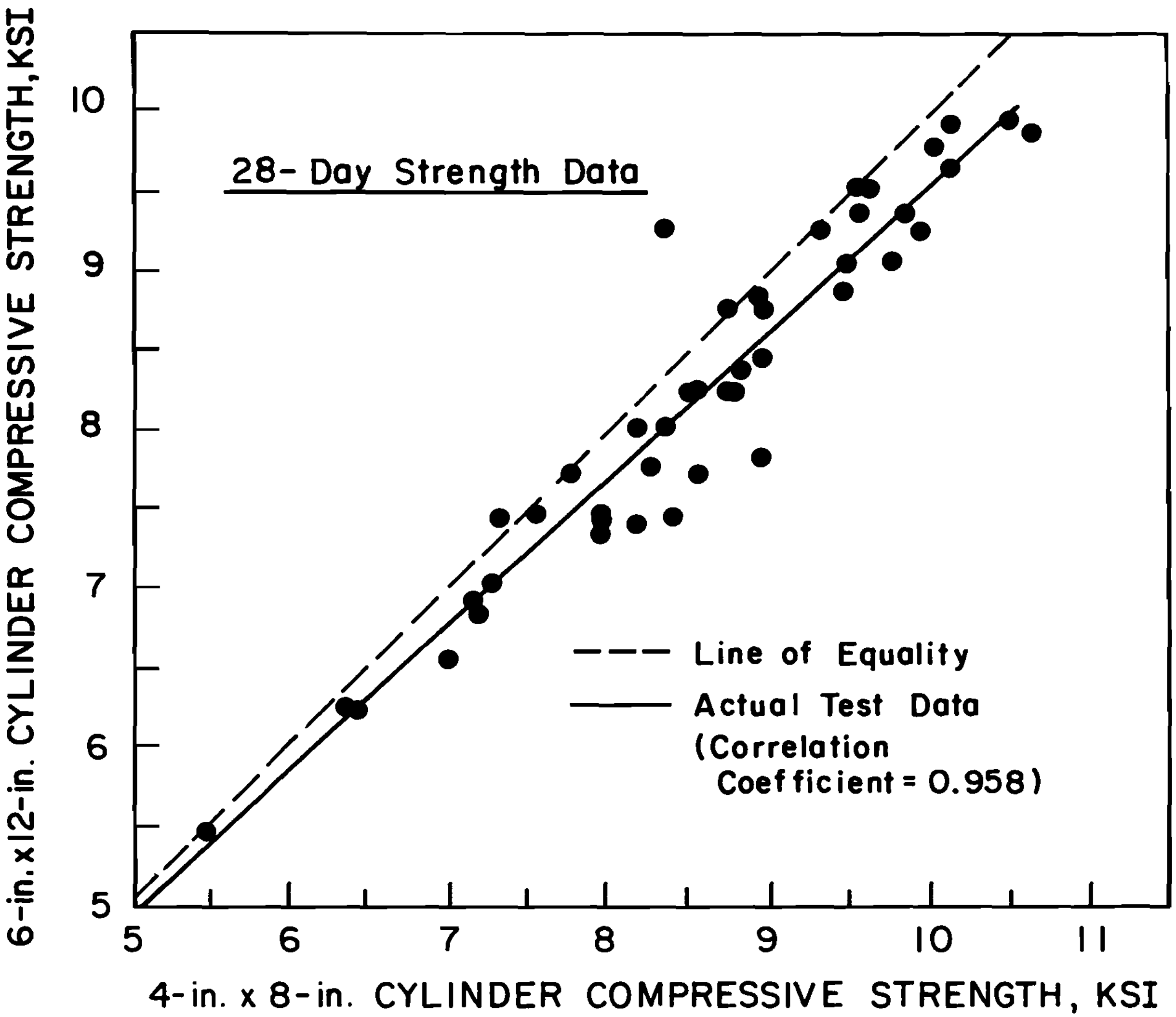


Fig. 4.6 4-in. x 8-in. versus 6-in. x 12-in. cylinder test results at 28 days [13].

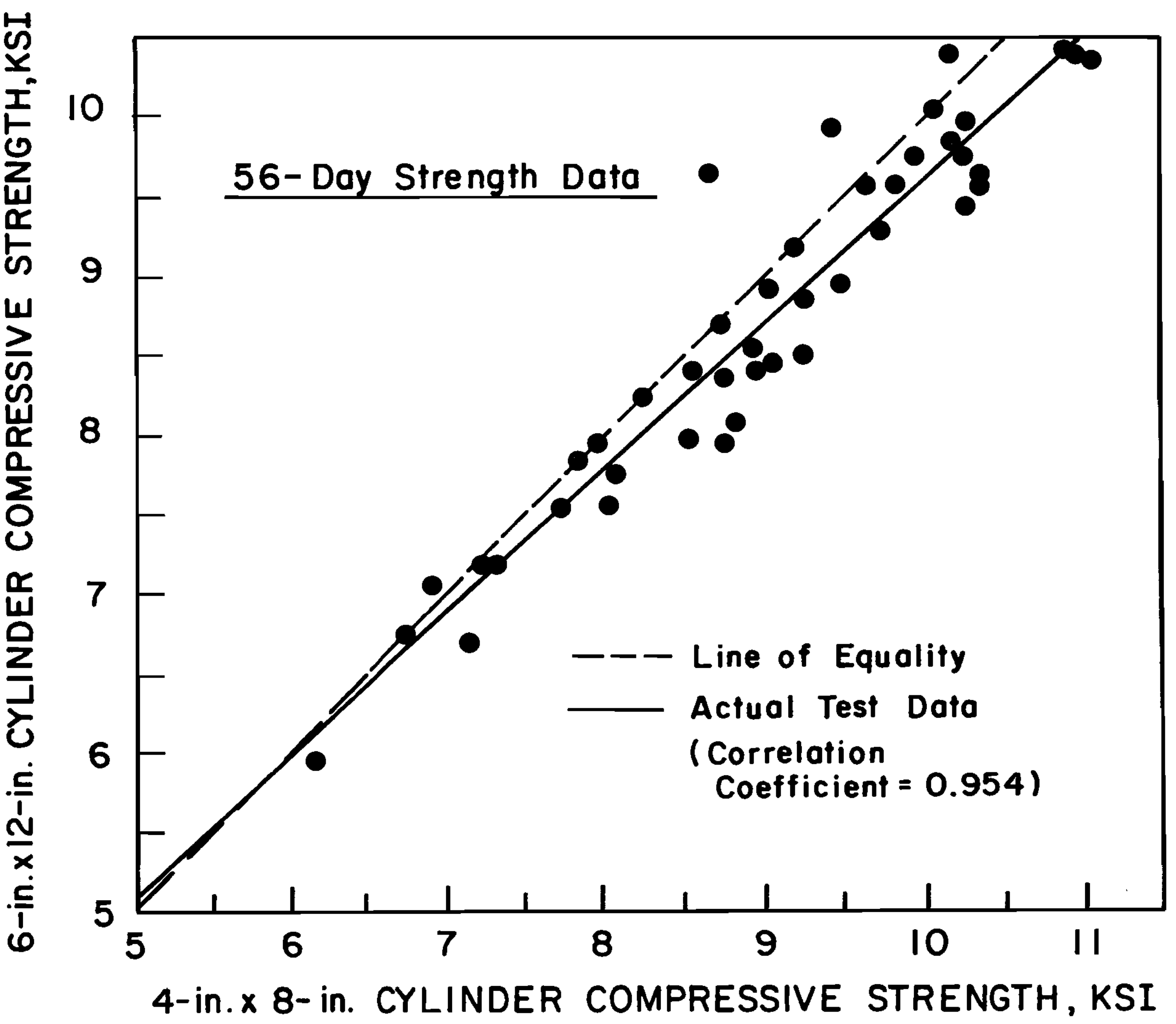


Fig. 4.7 4-in. x 8-in. versus 6-in. x 12-in. cylinder test results at 56 days [13].

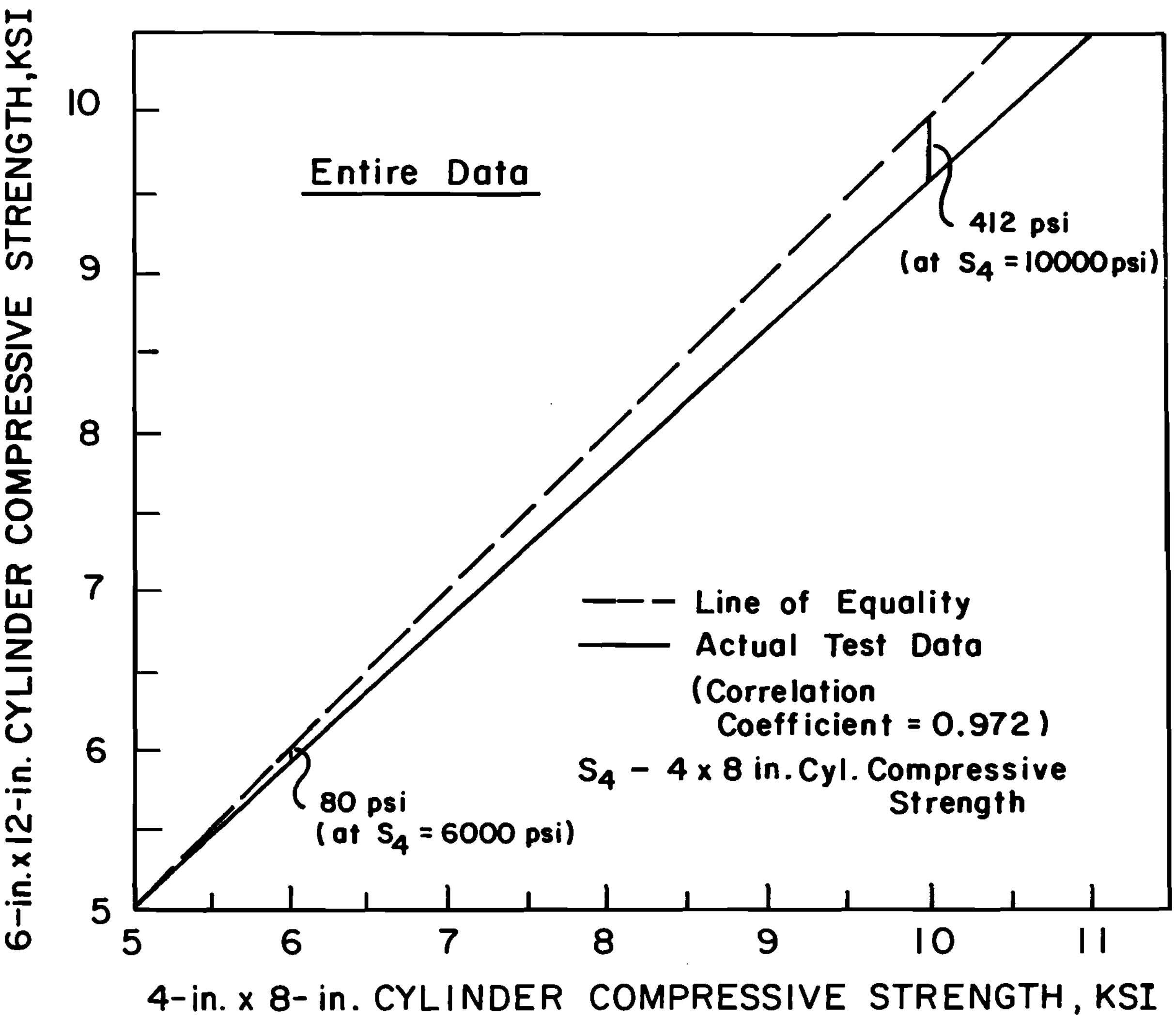


Fig. 4.8 Correlation of 4-in. x 8-in. cylinder strength to 6-in. x 12-in. cylinder strength [13].

TABLE 4.3 Correlation of 4-in. x 8-in. cylinder strength to 6-in. x 12-in. cylinder strength, when data are grouped according to concrete strength [13].

NUMBER OF DATA SETS	S_4 (RANGE)	STRENGTH DIFFERENCE $S_4 - S_6$ (AVERAGE)	STRENGTH RATIO S_6/S_4 (AVERAGE)
1	4,000 - 5,000	106	.977
7	5,000 - 6,000	-13	1.003
24	6,000 - 7,000	122	.981
41	7,000 - 8,000	228	.970
53	8,000 - 9,000	303	.965
33	9,000 - 10,000	324	.966
16	10,000 -11,000	442	.957
1	11,000 - 12,000	627	.943

S_4 - 4 x 8-in. Cylinder Compressive Strength (psi)
S_6 - 6 x 12-in. Cylinder Compressive Strength (psi)
Data Set - Average S_4 Value of 3 Test Cylinders and Corresponding Average S_6 Value of 3 Test Cylinders

cylinders increases with increasing concrete strength, from two percent for 6,000-7,000 psi concrete to six percent for 11,000-12,000 psi concrete.

4.3 Flexural Strength Tests

The test data obtained for 4-in. x 4-in. x 14-in. and 6-in. x 6-in. x 20-in. beams are presented in Table 4.4. All tests were performed at seven days. Data shown are the average of three beams tested, unless otherwise noted.

On the average, for beams tested in third point loading, the smaller 4-in. x 4-in. x 14-in. beams gave strengths which were five percent higher than the strengths obtained from 6-in. x 6-in. x 20-in. beams. This corresponded to a maximum of 40 psi for the beams tested.

For beams tested in center point loading, the 4-in. x 4-in. x 14-in. beams tested, on the average, at strengths which were 3 percent lower than those obtained from 6-in. x 6-in. x 20-in. beams. Two of the smaller size specimen sets tested at only 92 percent of the 6-in. x 6-in. x 20-in. beam strength. However, the smaller beams from mix number 26-057-00, which had a strength variation of 185 psi between the highest and lowest individual beam strength, tested six percent higher than the companion 6-in. x 6-in. x 20-in. beams.

TABLE 4.4A Test results of 4-in. x 4-in. x 14-in. and 6-in. x 6-in. x 20-in. beams, tested in third point loading.

MIX NUMBER	4-IN. X 4-IN. X 14-IN. BEAMS, psi (a)	6-IN. X 6-IN. X 20-IN. BEAMS, psi (b)	RATIO, a:b
22-110-34	1440	1400	1.03
24-065-00	870	830	1.05
26-057-00	676	640	1.06

TABLE 4.4B Test results of 4-in. x 4-in. x 14-in. and 6-in. x 6-in. x 20-in. beams, tested in center point loading.

MIX NUMBER	4-IN. X 4-IN. X 14-IN. BEAMS, psi (a)	6-IN. X 6-IN. X 20-IN. BEAMS, psi (b)	RATIO, a:b
22-110-34	1550 *	1660	0.93
24-065-00	930	1020	0.91
26-057-00	773 **	727	1.06

* Average of two beams
**Large variation (24%) in test results

CHAPTER 5

EFFECT OF MOLD MATERIAL

5.1 Introduction

The use of molds made of materials other than steel, such as cardboard or plastic, offers advantages in ease of handling and time savings. However, the strength test results from cylinders cast in these less rigid molds should be correlated to those from cylinders cast in steel molds. This was done for both 6-in. x 12-in. molds and 4-in. x 8-in. molds.

5.2 6-in. x 12-in. Cylinder Molds

The results obtained from 6-in. x 12-in. cylinders cast in plastic or steel molds are presented in Table 5.1. Data shown are the average of two cylinders tested, unless otherwise noted. This data is plotted in Fig. 5.1. The results obtained from 6-in. x 12-in. cylinders cast in plastic molds was, on the average, 97 percent of that obtained from 6-in. x 12-in. cylinders cast in steel molds. Results obtained by Peterman and Carrasquillo [20] are given in Table 5.2.

5.3 4-in. X 8-in. Cylinder Molds

The results obtained from 4-in. x 8-in. cylinders cast in plastic versus steel molds are given in Table 5.3, and those for cardboard versus steel molds are given in Table 5.4. Data are the average of two cylinders tested, unless otherwise noted. The data from Tables 5.3 and 5.4 is plotted in Figs. 5.2 and 5.3, respectively.

On the average, 4-in. x 8-in. cylinders cast in cardboard molds gave strength results equal to those cast in steel molds, while those cast in plastic molds yielded strengths one percent higher than 4-in. x 8-in. cylinders cast in steel molds. Peterman and Carrasquillo [20], however, found that 4-in. x 8-in. cylinders cast in cardboard molds achieved only 90 percent of the strength attained by cylinders cast in steel molds, on the average. Their data are shown in Fig. 5.4.

TABLE 5.1 Comparison of strength of 6-in. x 12-in. cylinders cast in steel and plastic molds.

MIX NUMBER	TEST AGE, days	PLASTIC MOLD, psi (a)	STEEL MOLD, psi (b)	RATIO, a:b
06-097-00	7	9240 *	9380 *	0.99
	14	10,110	10,030 *	1.01
	28	10,460 *	10,850	0.96
	56	11,650	11,610	1.00
07-098-00	1	7190	7100	1.01
	3	7700	7800	0.99
	7	8390	8470	0.99
	14	8980	8940	1.00
	28	9660	9800	0.99
	56	9980	10,210	0.98
08A-104-00	1	8160	7580	1.08
	3	8480	8710	0.97
	7	9240	9360	0.99
	14	9700 *	9940	0.98
	29	10,350	10,610 *	0.98
09-106-00	1	8030	7530	1.07
	3	8530	8520	1.00
	7	9220	9210	1.00
	14	9810	9740	1.01
	56	10,500	10,870	0.97
10-094-00	28	10,450 *	9870	1.06
	56	11,220 *	11,420 *	0.98
11-093-27	28	9080	10,100 *	0.90
	56	9370	11,690 *	0.80
	91	11,440 *	12,430 *	0.92
12-093-38	28	8680	9410	0.92
	56	9690	9760	0.99
13-100-00	28	8390	8670	0.97
	56	9530	10,520	0.91
	91	10,850	11,650	0.93
14-110-28	28	11,180 *	9880 *	1.13
	56	11,350	12,190	0.91
	91	12,850	13,650 *	0.94

TABLE 5.1 Comparison of strength of 6-in. x 12-in. cylinders cast in steel and plastic molds. (continued)

MIX NUMBER	TEST AGE, days	PLASTIC MOLD, psi (a)	STEEL MOLD, psi (b)	RATIO, a:b
15-112-38	28	11,320 *	11,470 *	0.99
	56	12,680	12,700	1.00
16-107-00	28	10,110	10,150	1.00
	56	10,690	11,660 *	0.92
	91	11,000	12,330	0.89
17-100-00	28	8900	9570	0.93
	56	9550	9970	0.96
	91	9920	10,750	0.92
18-111-35	28	10,360	11,030	0.94
	56	11,230	11,820	0.95

* Test result of one cylinder.

TABLE 5.2 28-day test results of 6-in. x 12-in. cylinders cast in steel and plastic molds, from Peterman and Carrasquillo [20].

MIX NUMBER	PLASTIC MOLD, psi (a)	STEEL MOLD, psi (b)	RATIO, a:b
Q	8230	8890	0.93
R	10,730	9500	1.13
S	8930	9560	0.93
T	10,960	10,210	1.07

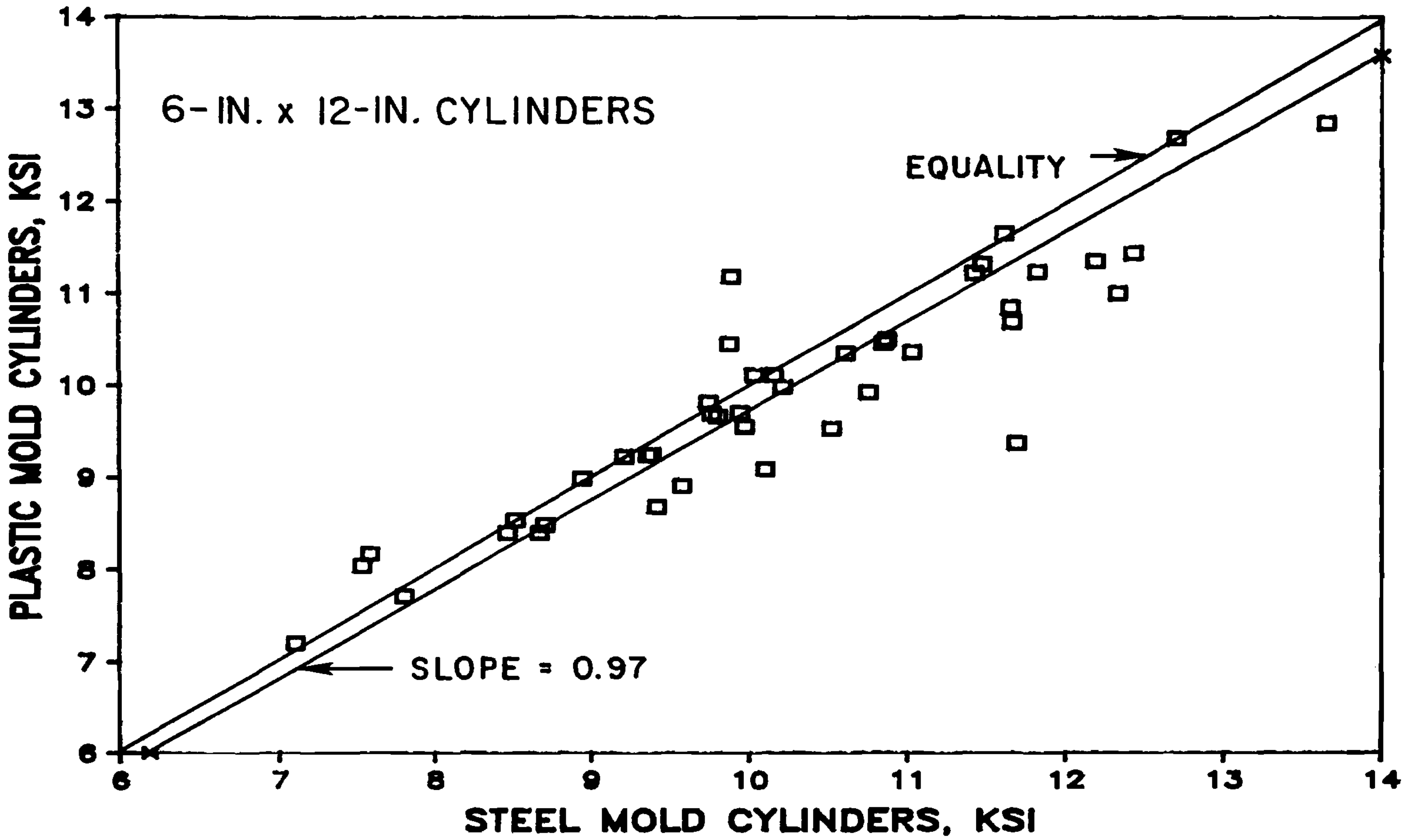


Fig. 5.1 Compressive strength of 6-in. x 12-in. cylinders cast in steel molds versus plastic molds.

TABLE 5.3 Comparison of strength of 4-in. x 8-in. cylinders cast in steel and plastic molds.

MIX NUMBER	TEST AGE, days	PLASTIC MOLD, psi (a)	STEEL MOLD, psi (b)	RATIO, a:b
08A-104-00	1	7450	7200	1.03
	3	8070	8120	0.99
	7	9440	8580	1.10
	29	9680 *	9970 *	0.97
	56	10,040	10,360 *	0.97

* Test result of one cylinder.

TABLE 5.4 Comparison of strength of 4-in. x 8-in. cylinders cast in steel and cardboard molds.

MIX NUMBER	TEST AGE, days	PLASTIC MOLD, psi (a)	STEEL MOLD, psi (b)	RATIO, a:b
01-107-00	28	9060	9320	0.97
02-095-00	28	8970	9410	0.95
06-097-00	28	10,830	10,360	1.04
07-098-00	1	6950	6840	1.01
08A-104-00	1	7360	7200	1.02
	7	8910	8580	1.04
	29	9980	9970 *	1.00

* Test result of one cylinder.

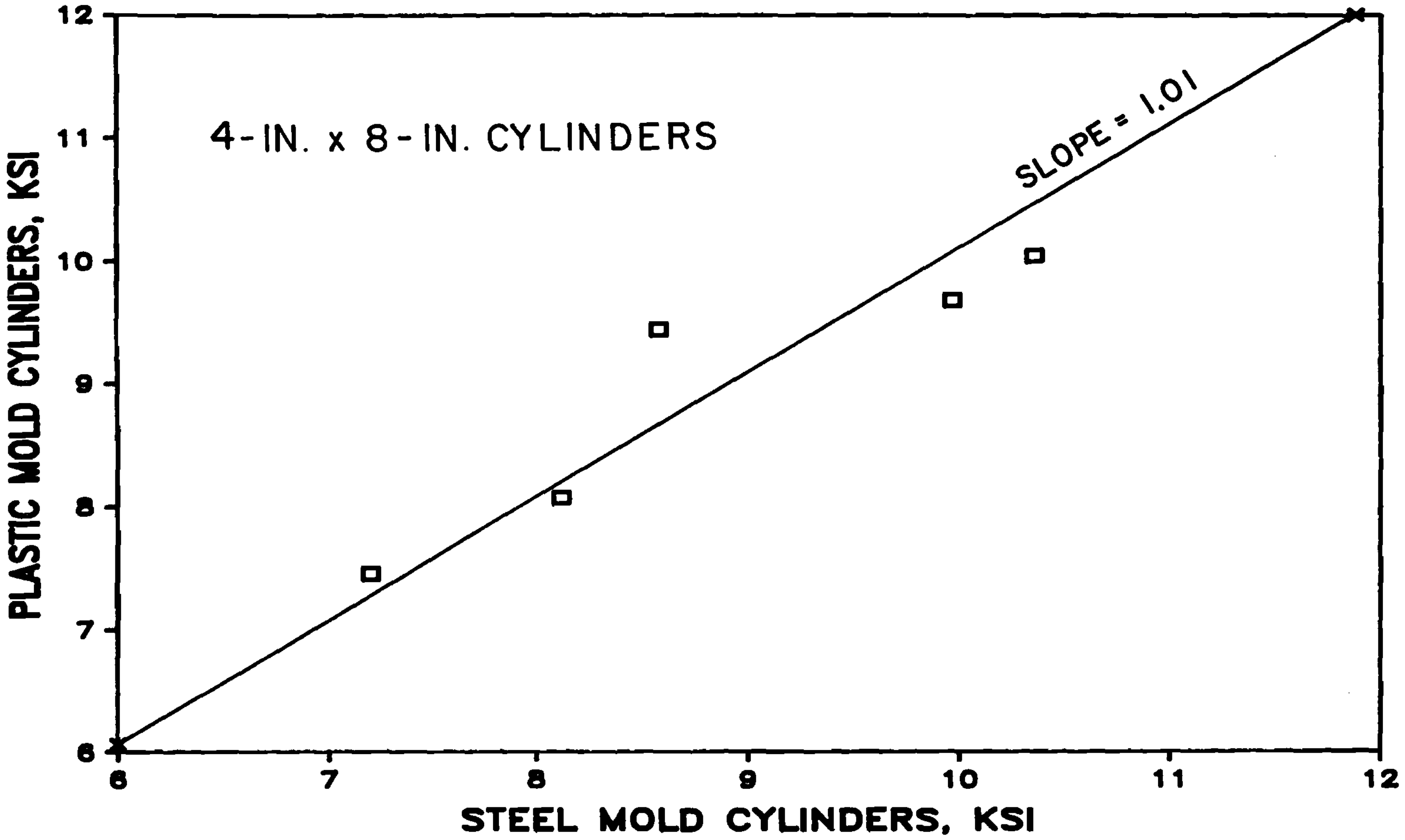


Fig. 5.2 Compressive strength of 4-in. x 8-in. cylinders cast in steel molds versus plastic molds.

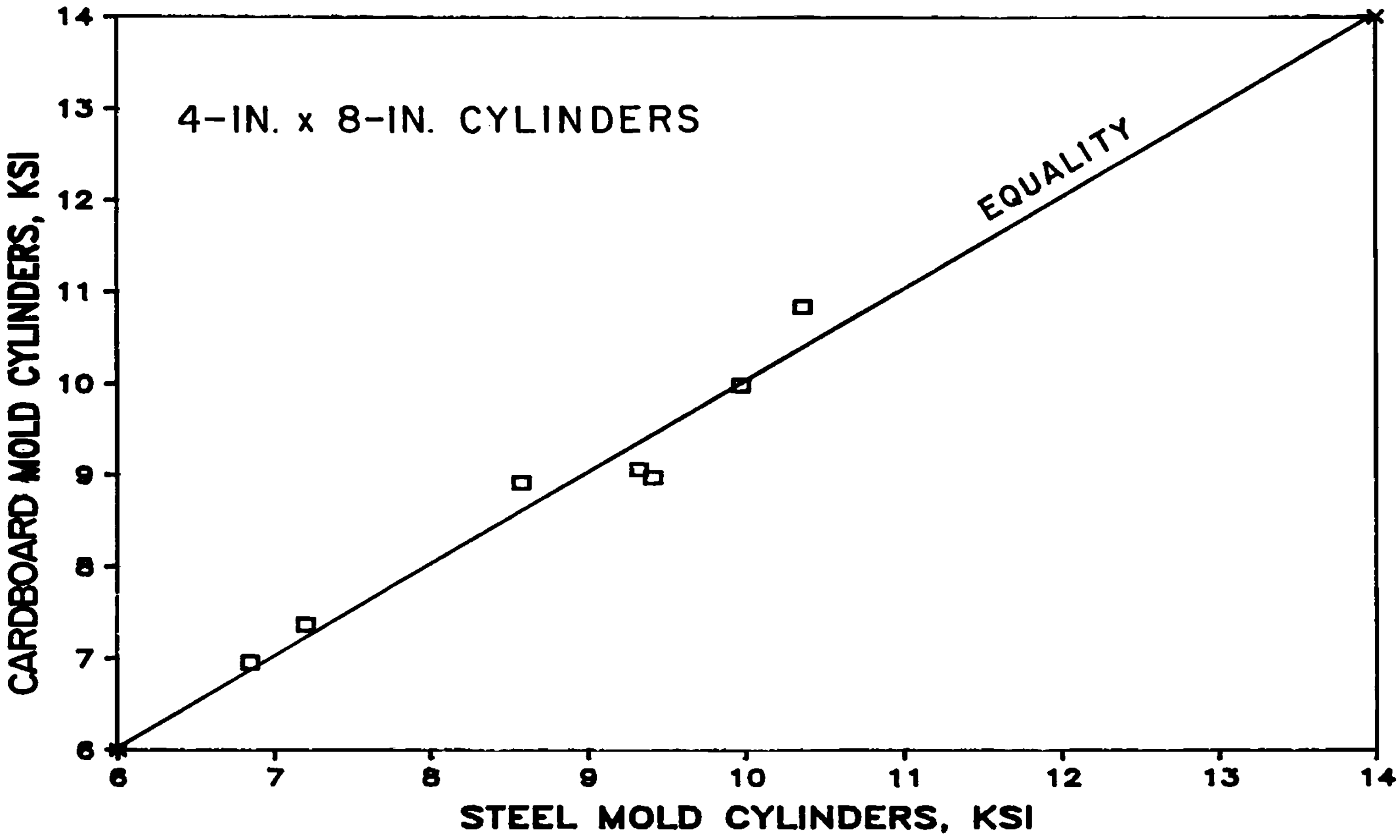


Fig. 5.3 Compressive strength of 4-in. x 8-in. cylinders cast in steel molds versus cardboard molds.

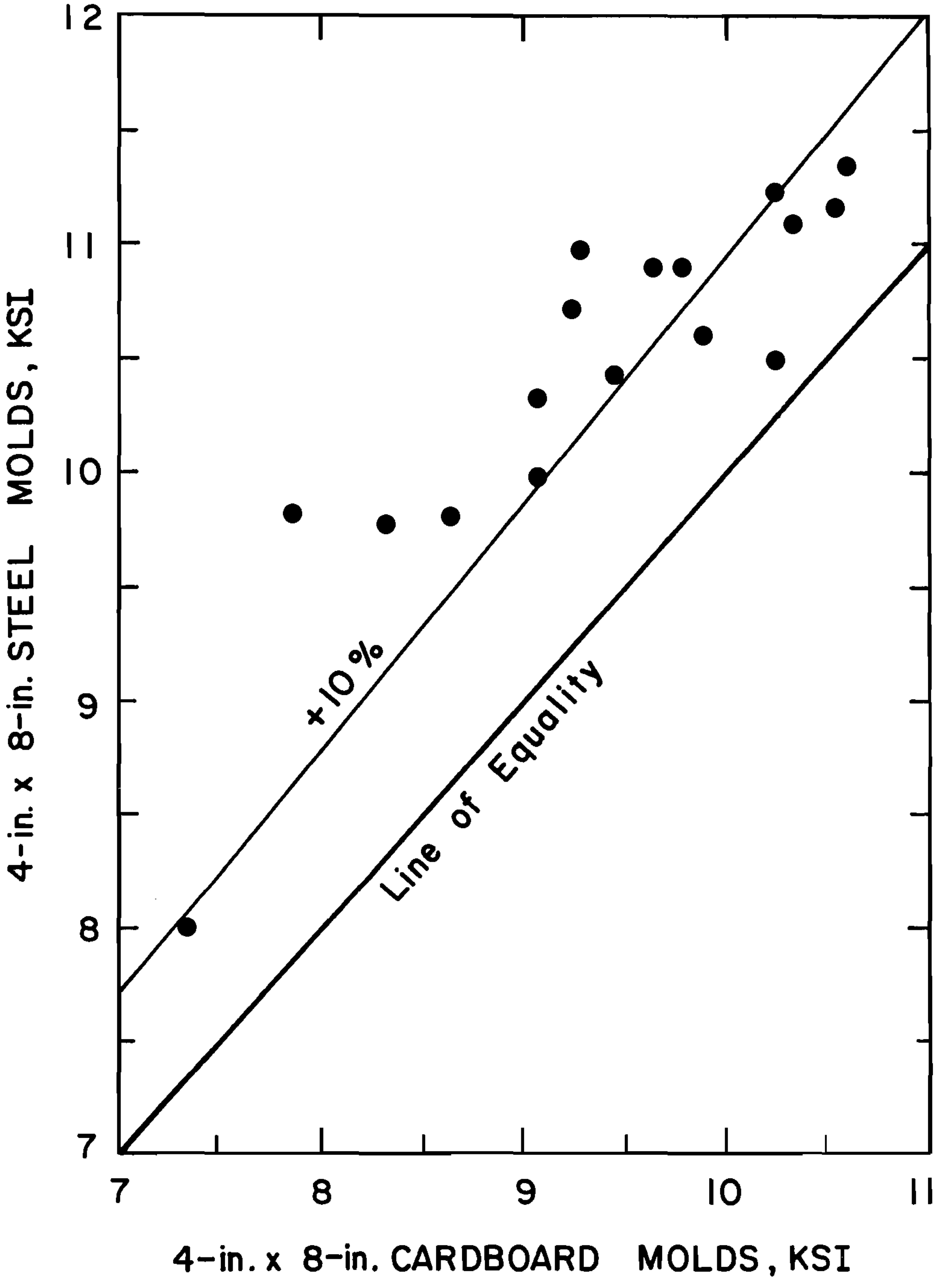


Fig. 5.4 Comparison of the 28-day compressive strength of high strength concrete specimens cast in 4-in. x 8-in. cardboard and rigid steel molds [20].

CHAPTER 6

EFFECT OF CURING CONDITIONS

6.1 Introduction

Three different curing methods were studied to determine the effect of curing conditions on both the compressive and flexural strength of high strength concrete. The curing methods included fog room curing, application of curing compound after mold removal, and no curing treatment at all after mold removal.

6.2 Compressive Strength Tests

The compressive strength of 6-in. x 12-in. cylinders cured in a fog room is compared to that of 6-in. x 12-in. cylinders coated with curing compound in Table 6.1. Data are the average of two cylinders tested, unless otherwise noted. These results are graphed in Figs. 6.1 and 6.2, according to test age. Fig. 6.1 presents data from cylinders tested prior to 15 days, and Fig. 6.2 presents data from cylinders tested between 28 and 91 days.

In general, the strength of 6-in. x 12-in. cylinders treated with curing compound and tested prior to 15 days was three percent higher than that of cylinders cured in a fog room. This is probably due to the high temperature, between 80 and 105°F, in which the specimens coated with curing compound were stored, thus accelerating the hydration process, as opposed to the 73.4 ± 3°F temperature of the fog room. However, for cylinders tested between 28 and 91 days, those coated with curing compound attained, on the average, only 96 percent of the strength attained by cylinders cured in the fog room. For concrete strengths higher than 11,000, the beneficial effect of continued fog curing over the use of curing compounds is more significant. Thus, the early effects of accelerated hydration are negated by inadequate curing. Similar results are found for 6-in. x 12-in. cylinders receiving no curing after mold removal, as shown in Table 6.2

6.3 Flexural Strength Tests

Data on the effect of curing conditions on the flexural strength of high strength concrete is given in Table 6.3. Beams were tested in third point loading, and data are the average of two beams tested, unless otherwise noted.

It can be seen that the flexural strength of high strength concrete is affected much more significantly than the compressive

TABLE 6.1 Effect of curing conditions on compressive strength of 6-in. x 12-in. cylinders: fog room vs. curing compound.

MIX NUMBER	TEST AGE, days	CURING COMPOUND, psi (a)	FOG ROOM, psi (b)	RATIO, a:b
07-098-00	3	7930 *	7800	1.02
	7	8500	8470	1.00
	14	9070	8940	1.01
	28	9490	9800	0.97
	3	8120	7700	1.05
	7	8730	8390	1.04
	14	9200	8980	1.02
	28	9290	9660	0.96
	56	9400	9980	0.94
10-094-00	28	10,230	9870	1.04
	56	10,450	11,420	0.92
	4	8910	8730	1.02
	7	9390	8770	1.07
	28	9980	10,450 *	0.96
	56	10,520	11,220 *	0.94
11-093-27	28	9580	10,100 *	0.95
	56	9940	11,690 *	0.85
	4	7780	7490	1.04
	7	8110	7730	1.05
	28	8830	9080	0.97
	56	9480 *	9370	1.01
12-093-38	28	8940	9410	0.95
	56	9900	9760	1.01
	4	7440	7180	1.04
	7	7700	7310	1.05
	28	8480	8680	0.98
13-100-00	28	9100	8673	1.05
	56	10,580 *	10,520	1.01
	3	7670	7610	1.01
	7	8290	7660	1.08
	28	8890	8390	1.06
	56	9340	9530	0.98

TABLE 6.1 Effect of curing conditions on compressive strength of 6-in. x 12-in. cylinders: fog room vs. curing compound. (continued)

MIX NUMBER	TEST AGE, days	CURING COMPOUND, psi (a)	FOG ROOM, psi (b)	RATIO, a:b
04-110-28	28	10,830 *	9880 *	1.10
	56	11,190	12,190	0.92
	91	11,390	13,650 *	0.83
	3	8990	8830	1.02
	7	9870	9710	1.02
	28	10,330	11,180 *	0.92
	56	10,940	11,350	0.96
15-112-38	28	10,990	11,470 *	0.96
	56	11,240	12,700	0.88
	3	8790	8910	0.99
	7	9970	9600	1.04
	28	10,540	11,320 *	0.93
	56	11,320	12,680	0.89
16-107-00	28	9920	10,150	0.98
	56	10,140	11,660 *	0.87
	91	10,530	12,330	0.85
	3	8110	7940	1.02
	7	8740	8640	1.01
	28	9590	10,110	0.95
17-100-00	7	8500	7950	1.07
	28	9270	8900	1.04
18-111-35	7	9890	9210	1.07
	28	10,750	10,360	1.04

* Test result of one cylinder

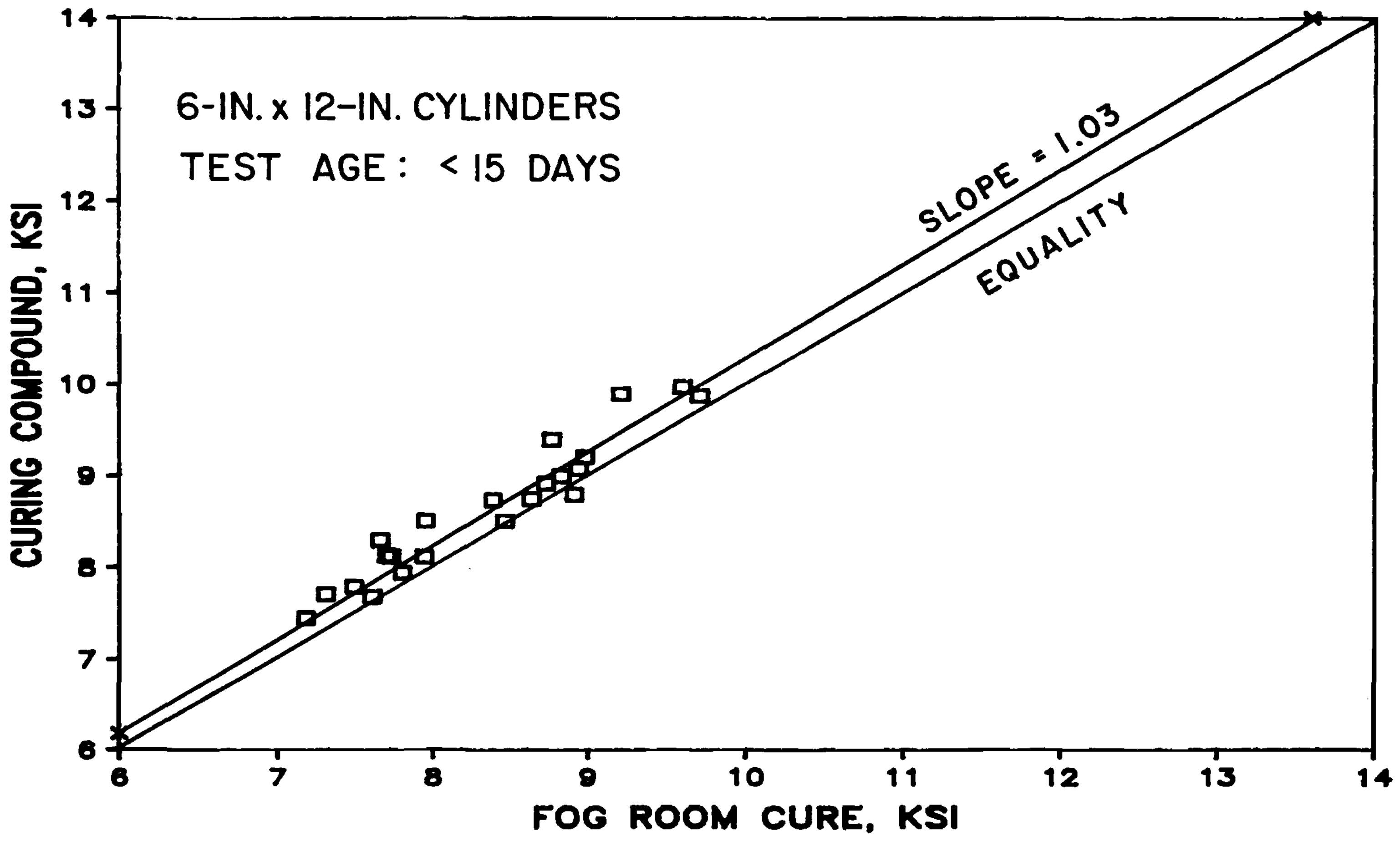


Fig. 6.1 Effect of curing method on the compressive strength of 6-in. x 12-in. cylinders at early ages. Cylinders tested within 15 days of casting.

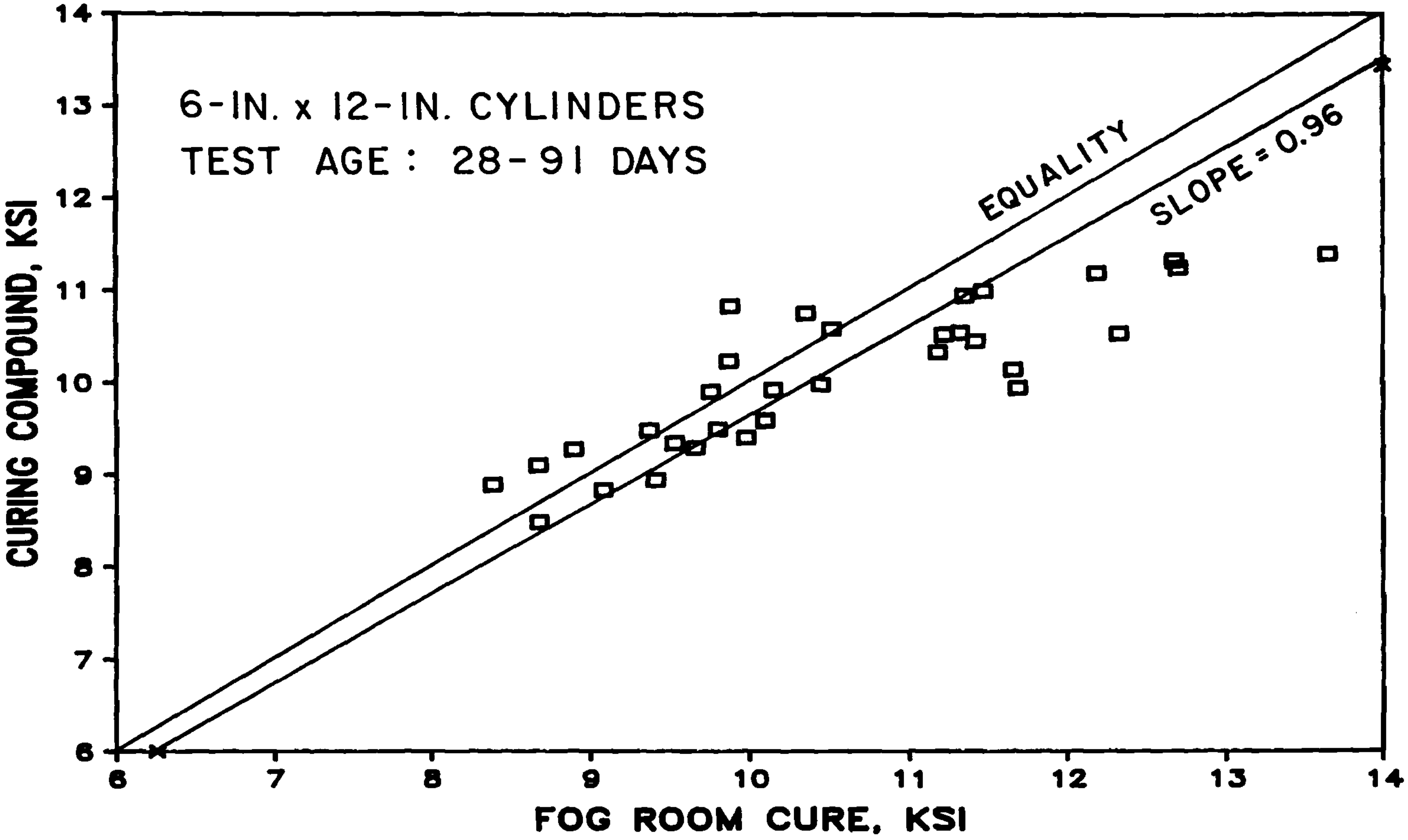


Fig. 6.2 Effect of curing method on the compressive strength of 6-in. x 12-in. cylinders at later ages. Cylinders tested between 28 and 91 days after casting.

TABLE 6.2 Effect of curing conditions on compressive strength of 6-in. x 12-in. cylinders: fog room vs. no curing.

MIX NUMBER	TEST AGE, days	NO CURING, psi (a)	FOG ROOM, psi (b)	RATIO, a:b
07-098-00	28	9250	9800	0.94
	28	9170	9660	0.95

TABLE 6.3 Effect of curing conditions on flexural strength of 6-in. x 6-in. x 20-in. beams.

MIX NUMBER	TEST AGE, days	CURING COMPOUND, psi (a)	FOG ROOM, psi (b)	RATIO, a:b
07-098-00	3	560	1030	0.54
	28	690	1090	0.63
10-094-00	7	720	1240 *	0.58
	28	780	1320	0.59
11-093-27	7	710	1100	0.65
	28	770	1320 *	0.58
12-093-38	7	770 *	1160	0.66
13-100-00	7	580	1030	0.56
	28	680	1300	0.52
14-110-28	7	560	1140	0.49
	28	770 *	1390	0.56
15-112-38	7	900 *	1430 *	0.63
	28	920	1430	0.64
16-107-00	7	570	1010	0.56
	28	800	1310	0.62

* Test result of one beam.

strength by inadequate curing methods. As shown in Fig. 6.3, the flexural strength of beams coated with curing compound was only 58 percent of that of beams cured in a fog room. This could be due to the formation of shrinkage cracks, which would reduce the beam's flexural capacity by introducing discontinuities in the concrete surface during testing. If the beam surface is allowed to dry, it tries to shrink, but is restrained by the interior of the beam, which is still moist. Thus, tension exists at the beam surface prior to loading, which reduces the apparent stress at failure. Another possible explanation is that the microstructure of the paste is weakened when a curing compound is used. Thus, the flexural strength, which is more dependent on paste characteristics than the compressive strength, is reduced much more than is the compressive strength of the concrete. It should also be noted that the effect of accelerated hydration is not apparent in the flexural strength test results at early ages, as it was in the case of compressive strength.

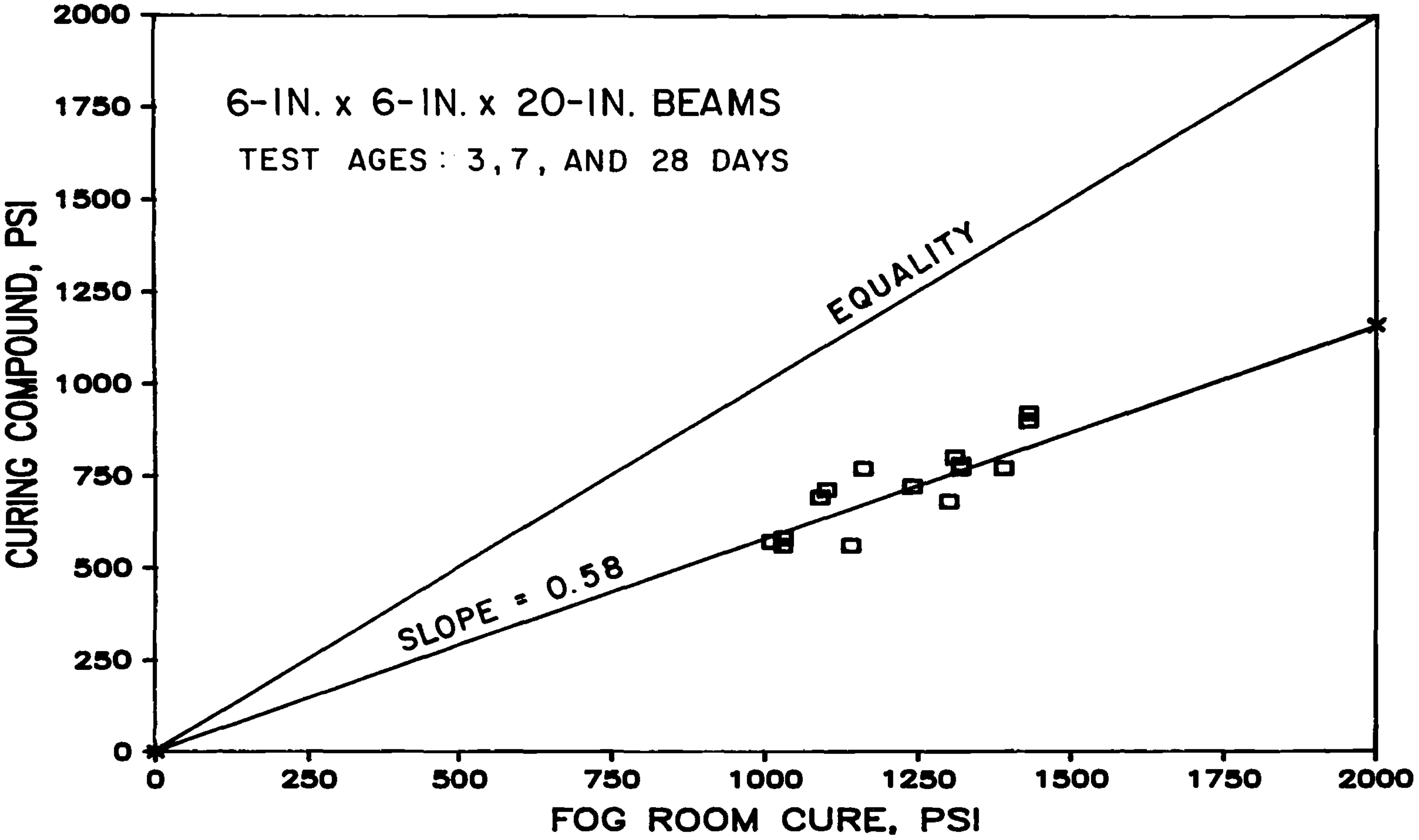


Fig. 6.3 Effect of curing method on the flexural strength of 6-in. x 6-in. x 20-in. beams.

CHAPTER 7

EFFECT OF ADDITION OF SUPERPLASTICIZER

7.1 Introduction

Currently, TSDHPT Specification 437.7 allows high range water reducing admixtures to be added only at the job site. Redosing with the admixture is allowed if slump loss occurs. However, in order to achieve and maintain thorough mixing and plasticity of high strength concrete mixes, which generally have very low slumps and high contents of binder materials and coarse aggregate, it may be necessary to add a high range water reducer to the mix at the ready-mix plant.

The effect of time of addition of superplasticizer, and redosing with superplasticizer, on the compressive and flexural strength of high strength concrete was studied in mix numbers 08A-104-00, 08B-104-00, and 09-106-00. Details of these mixes were given in Chapter 3. Test results will be presented and discussed in this chapter.

7.2 Time of Addition

Two similar high strength concrete mixes were batched. For one mix, number 08A-104-00, the superplasticizer was added to the concrete following initial mixing at the ready-mix plant and at the laboratory, approximately 15 minutes and one hour after batching, respectively. Rates of addition were 8.01 oz/cwt and 11.05 oz/cwt, respectively. For the other mix, number 09-106-00, no superplasticizer was added at the ready-mix plant, and 15.98 oz/cwt were added to the concrete at the laboratory, approximately 40 minutes after it was batched. It was noted that, although both mixes had a one-half inch slump after being batched, the concrete which was dosed with superplasticizer at the ready-mix plant was cohesive upon arrival at the laboratory, whereas the other mix, which received no superplasticizer at the ready-mix plant, was powdery and not cohesive upon arrival at the laboratory. Both mixes were brought to a slump of greater than nine inches with the addition of superplasticizer at the laboratory.

7.2.1 Effect on compressive strength. The compressive strength test results for mix numbers 08A and 09 are given in Table 7.1. Data given are the average of two 6-in. x 12-in. steel mold cylinders tested, unless otherwise noted. These results are plotted in Fig. 7.1.

It can be seen, from both the table and figure, that as test age increases, the effect of time of addition of superplasticizer becomes more significant. In this case, the strength of the concrete to which

TABLE 7.1 Effect of time of addition of superplasticizer on the compressive strength of high strength concrete.

TEST AGE, days	MIX NO. 08A, psi (a)	MIX NO. 09, psi (b)	RATIO, a:b
1	7580	7530	1.01
3	8710	8520	1.02
7	9360	9210	1.02
14	9940	9740	1.02
29	10,610 *	10,140	1.05
56	11,260	10,870	1.04

* Test result of one cylinder.

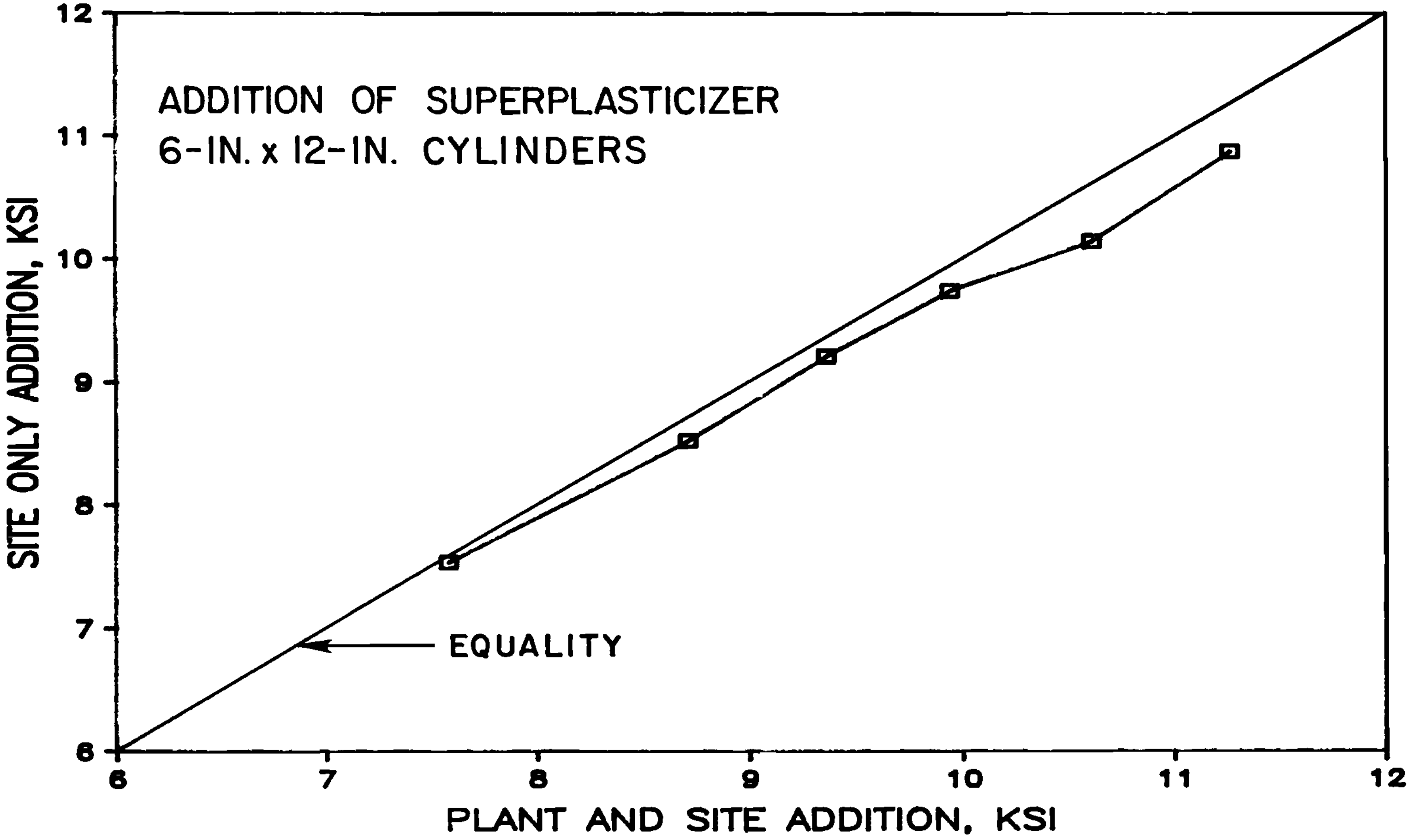


Fig. 7.1 Effect of early addition of superplasticizer on the compressive strength of 6-in. x 12-in. cylinders.

superplasticizer had been added at the ready-mix plant and at the laboratory was 390 psi higher at 56 days than the strength of the concrete which received no superplasticizer at the ready-mix plant. Although these data reflect the results of only on comparison, the trend is evident.

7.2.2 Effect on flexural strength. The results for the flexural strength tests are given in Table 7.2. Data shown is the average of two beams tested. These results are plotted in Fig. 7.2.

The flexural strength of concrete to which superplasticizer was added both at the ready-mix plant and at the laboratory, like its compressive strength, was higher than that of concrete to which superplasticizer was added at the laboratory only. However, whereas the difference in flexural strength at one and three days was 15 and 18 percent, respectively, the difference at seven days was only six percent.

7.3 Redosing

In order to study the effect of redosing with superplasticizer on the compressive and flexural strength of high strength concrete, the admixture was added to mix number 08-104-00 at three different times, thus creating mix number 08A-104-00 and 08B-104-00. Superplasticizer was added to mix number 08A at the ready-mix plant and at the laboratory, approximately 15 and 60 minutes after batching, respectively. Addition rates were 8.01 oz/cwt and 11.05 oz/cwt. Strength specimens were cast. Then, at approximately two hours after the concrete was batched, a third dosage of superplasticizer was added at the rate of 2.83 oz/cwt. This last addition brought the slump of the concrete to nine inches, although the temperature of the concrete was over 100°F, and more strength specimens were cast.

7.3.1 Effect on compressive strength. The compressive strength test results of 6-in. x 12-in. steel mold cylinders are presented in Table 7.3. Data shown are the average of two cylinders tested, unless otherwise noted. The results are plotted in Fig. 7.3. It is clear that the addition of a third dosage of superplasticizer did not affect the strength of the concrete in this case. It should be kept in mind that, although only one test was conducted, the addition of superplasticizer to concrete which was over two hours old and at a temperature of 101°F with a three-inch slump, increased the slump of the concrete to nine inches and did not detrimentally affect its strength.

7.3.2 Effect on flexural strength. The results of the flexural strength tests are presented in Table 7.4. Data shown are the average

TABLE 7.2 Effect of time of addition of superplasticizer on the flexural strength of high strength concrete.

TEST AGE, days	MIX NO. 08A, psi (a)	MIX NO. 09, psi (b)	RATIO, a:b
1	820	710	1.15
3	1160	980	1.18
7	1210	1140	1.06

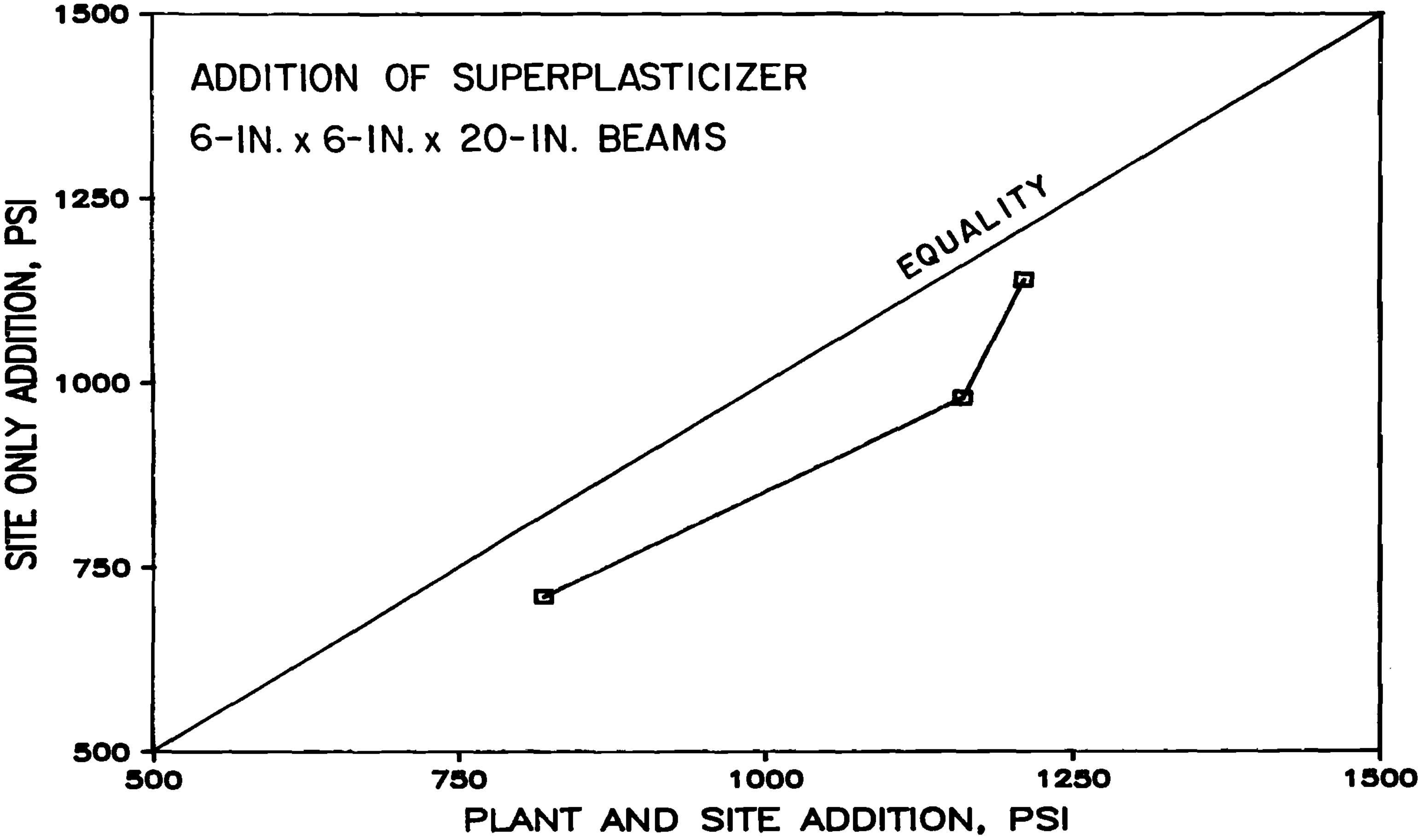


Fig. 7.2 Effect of early addition of superplasticizer on the flexural strength of 6-in. x 6-in. x 20-in. beams.

TABLE 7.3 Effect of redosing with superplasticizer on the compressive strength of high strength concrete.

TEST AGE, days	MIX NO. 08A, psi (a)	MIX NO. 08B, psi (b)	RATIO, a:b
1	7580	7560	1.00
3	8710	8510	1.02
7	9360	9420	0.99
14	9940	10,100	0.98
29	10,610 *	10,630	1.00
56	11,260	11,360	0.99

* Test result of one cylinder.

TABLE 7.4 Effect of redosing with superplasticizer on the flexural strength of high strength concrete.

TEST AGE, days	MIX NO. 08A, psi (a)	MIX NO. 08B, psi (b)	RATIO, a:b
1	820	730	1.12
3	1160	1020	1.14
7	1210	1230	0.98

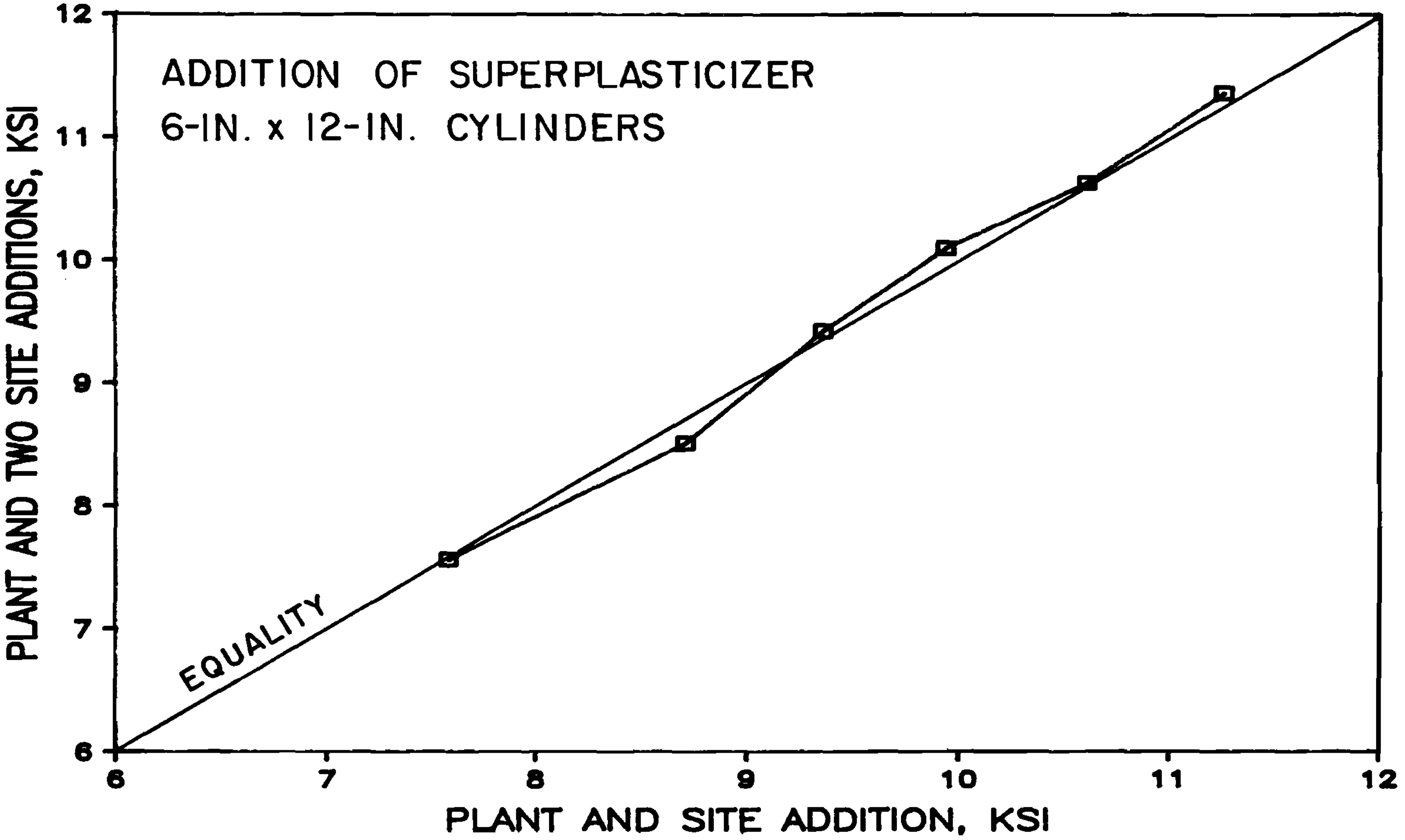


Fig. 7.3 Effect of redosing with superplasticizer on the compressive strength of 6-in. x 12-in. cylinders.

of two beams tested. The results are plotted in Fig. 7.4. Although the early flexural strength of concrete from mix 08A was higher than that of mix 08B, the strengths were approximately equal at seven days.

7.4 Discussion

When a naphthalene-based superplasticizer is added to concrete, it is adsorbed onto the cement particles and disperses cement agglomerates by imparting to them a net negative surface charge. The slump of the concrete is increased through the freeing of bound water and the repulsion of like-charged particles. However, the extent to which the addition of a superplasticizer can achieve these effects is dependent on the age of the concrete, or degree of cement hydration, at the time of additon, as found by the author in a previous study [19].

The higher strength of mix number 08A, which was dosed with superplaticizer at the ready-mix plant and once at the laboratory, over mix number 09, which was dosed with superplasticizer only at the laboratory, could be attributed to either one or both of the following factors. One factor which could have caused the strength increase is the redosing of mix number 08A, whereas mix number 09 received only one addition of superplasticizer. It has been reported [11] that the strength of concrete is increased with each addition of superplasticizer up to three additions, as shown in Fig. 7.5. Another possible factor is the earlier time of addition of the superplasticizer to mix number 08A. It would seem that more complete dispersion of the cement particles could be achieved with earlier addition of the superplasticizer to concrete, since any bonding due to hydration products would be younger and weaker. Better dispersion of cement particles would lead to more complete hydration, better paste-to-aggregate bonds, and a less porous paste, all of which contribute to increased concrete strength. That the difference in flexural strength was much more pronounced than the difference in compressive strength for these mixes can be attributed to the fact that the flexural strength of concrete is more dependent on paste properties than the compressive strength, such as aggregate bond and structure of hydration products. Regardless of the cause, the results show that the concrete which is dosed with superplasticizer at the ready-mix plant and the site has higher compressive and flexural strength than concrete which is dosed with superplasticizer at the site only.

The third addition of superplasticizer to mix number 08 did not affect the compressive strength nor the seven-day flexural strength of the concrete. This agrees with the findings shown in Fig. 7.5. However, the flexural strength at one and three days of mix number 08A was significantly higher than that of mix number 08B. This could be due to the dispersion of hydration products and possible retardation of

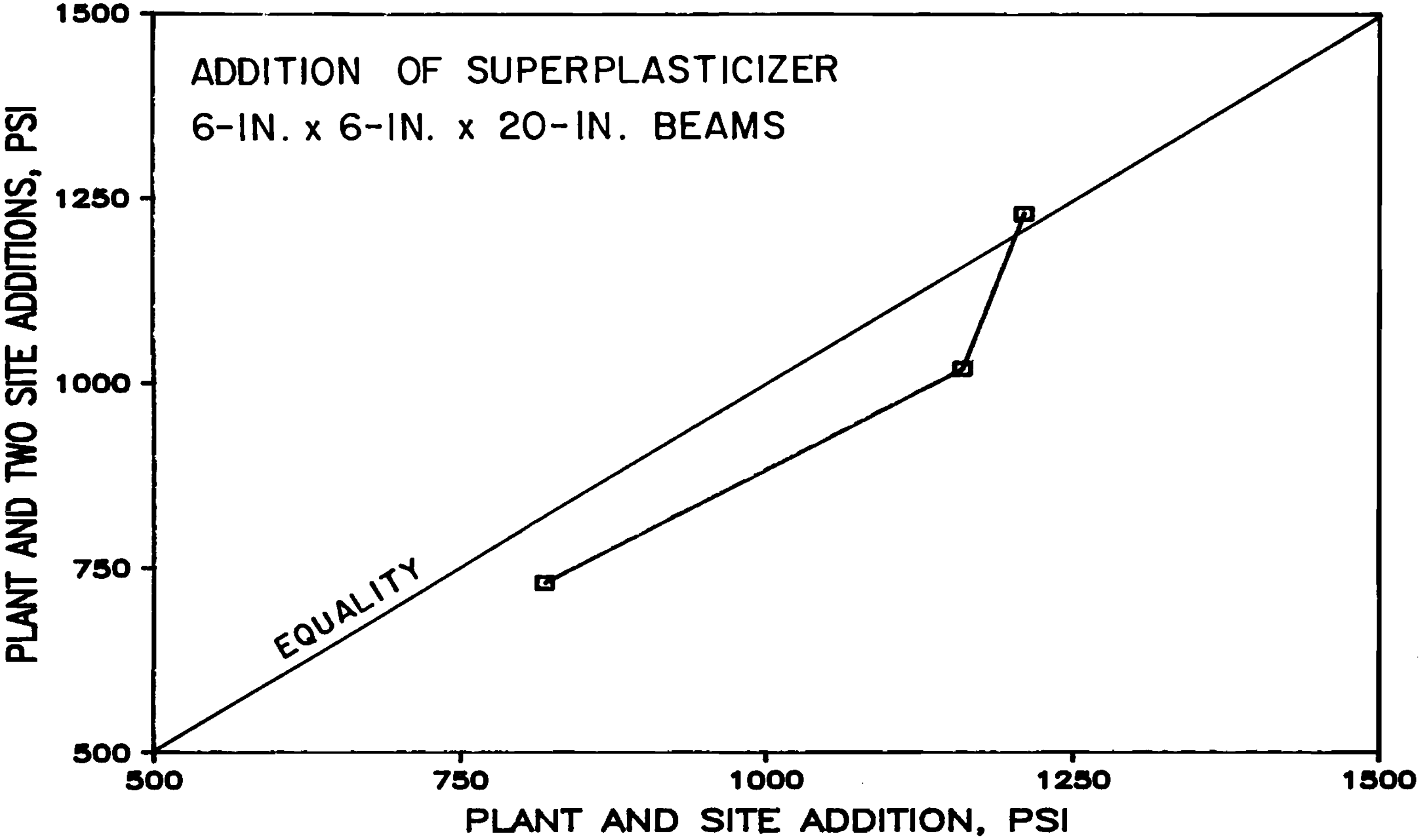


Fig. 7.4 Effect of redosing with superplasticizer on the flexural strength of 6-in. x 6-in. x 20-in. beams.

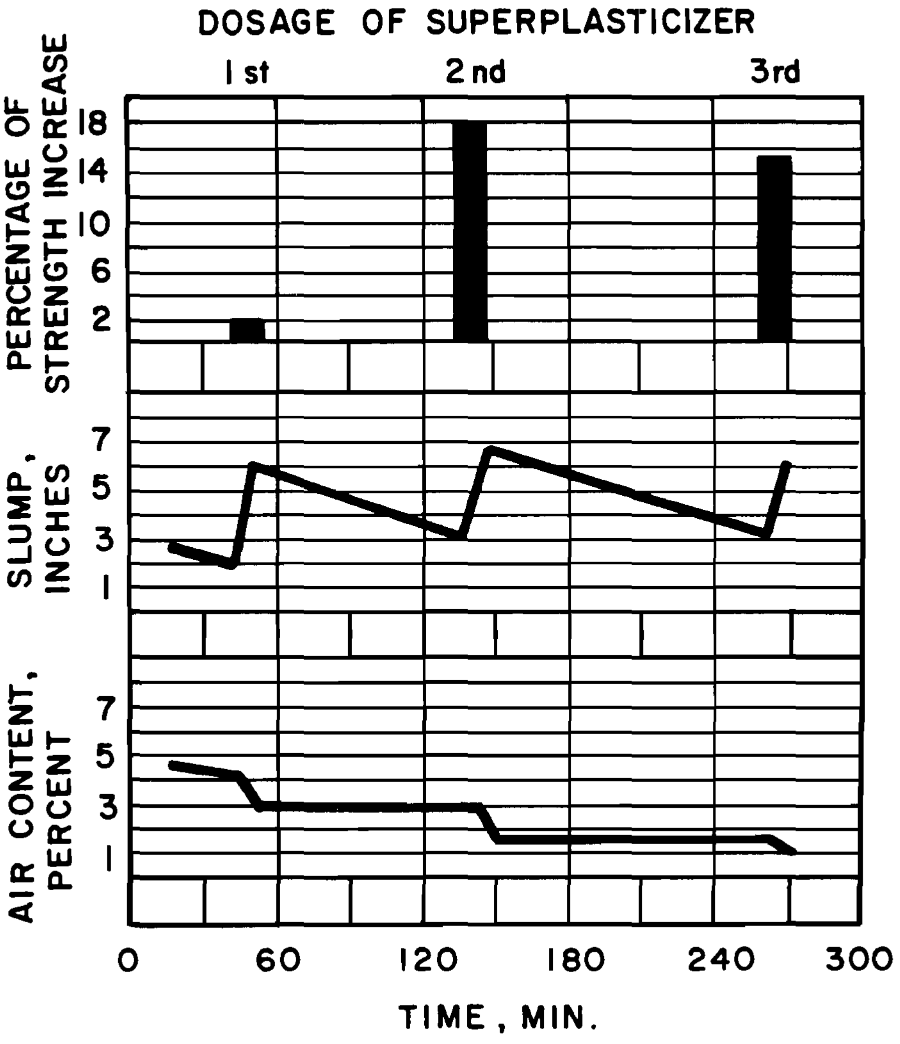


Fig. 7.5 Effect of repeated dosages of superplasticizer on slump, air content and compressive strength of concrete [11].

the concrete when the third dosage of superplasticizer was added at two hours after batching, thus delaying strength gain. Again, since the flexural strength of concrete is more sensitive to paste characteristics than is the compressive strength, the flexural strength is more likely to reflect subtle differences.

CHAPTER 8

EFFECT OF CAPPING METHOD

8.1 Introduction

Concrete cylinders are capped prior to testing to ensure that the applied load is distributed uniformly over the cross-sectional area of the test specimen. According to ASTM Standard C617, caps should be approximately 1/8-inch thick, and have equal to or greater strength than that of the concrete being tested. Also, if sulfur mortar is to be used, the cap should be allowed to harden for at least two hours before testing.

There is some question whether sulfur capping compounds can develop adequate strength for testing high strength concrete cylinders. To study this, different capping methods were used to test high strength concrete. Also, for one capping compound, the caps were allowed to harden for various lengths of time before testing the concrete.

8.2 Type of Cap Used

Two different sulfur-based capping compounds and a mechanical capping system, comprised of aluminum caps fitted with polyurethane inserts, were used to test high strength concrete cylinders. Both 6-in. x 12-in. and 4-in. x 8-in. cylinders were tested. For some tests, the ends of the cylinders were cut off to remove irregular end conditions.

8.2.1 Effect on 6-in. x 12-in. cylinder strength. The test results for high strength 6-in. x 12-in. cylinders are given in Table 8.1. Results shown are the average of at least two cylinders tested. Data from Table 8.1 are plotted in Fig. 8.1 along with data obtained for concrete strengths below 6,000 psi. For concrete strengths above 10,000 psi, although the high strength sulfur capping compound gave higher test results than did the normal strength sulfur capping compound, the test results obtained from cylinders tested with the aluminum and polyurethane caps were, on the average, higher than either. For concrete cylinders having a compressive strength of less than 10,000 psi, the test results obtained from cylinders tested using the aluminum and polyurethane caps were approximately equal to those obtained from cylinders tested which were capped with the high strength sulfur capping compound.

8.2.2 Effect on 4-in. x 8-in. cylinder strength. The results of 4-in. x 8-in. cylinders tested using different capping methods are presented in Table 8.2. Results shown are the average of at least two cylinders tested. Although the data is limited to two sets of tests,

TABLE 8.1 Effect of cap type on compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete.

MIX NUMBER	CAP TYPE*	TEST AGE, days	CAP AGE, min.	END CONDITIONS	STRENGTH, psi
09-106-00	S	121	59	uncut	11,140
	S	121	67	cut	11,350
	HSS	121	64	uncut	11,800
	HSS	121	70	cut	11,900
	AP	130	N.A.	uncut	13,350
	AP	130	N.A.	cut	13,020
	HSS	217	120 +	uncut	10,650
	AP	217	N.A.	uncut	11,840
19-103-00	HSS	154	120 +	uncut	11,830
	AP	154	N.A.	uncut	12,960
	HSS	175	120 +	uncut	12,770
	AP	175	N.A.	uncut	12,730
20-111-33	HSS	153	120 +	uncut	11,640
	AP	153	N.A.	uncut	14,300
	HSS	175	120 +	uncut	13,500
	AP	175	N.A.	uncut	13,170
21-112-34	HSS	56	---	uncut	15,310
	AP	56	N.A.	uncut	16,540
	HSS	97	---	uncut	16,110
	AP	97	N.A.	uncut	17,670
24-065-00	S	28	120 +	uncut	7270
	HSS	28	120 +	uncut	7750
	AP	28	N.A.	uncut	7530
	HSS	42	120 +	uncut	8190
	AP	42	N.A.	uncut	8010
25-056-00	HSS	28	120 +	uncut	5980
	AP	28	N.A.	uncut	6020
26-057-00	HSS	28	120 +	uncut	5580
	AP	28	N.A.	uncut	5440
27-060-00	HSS	36	---	uncut	6420
	AP	36	N.A.	uncut	6230
28-059-00	HSS	34	---	uncut	7090
	AP	34	N.A.	uncut	6750
29-060-00	HSS	28	120 +	uncut	5970
	AP	28	N.A.	uncut	6070

* S = Sulfur mortar
HSS = High strength sulfur mortar
AP = Aluminum caps fitted with polyurethane inserts.

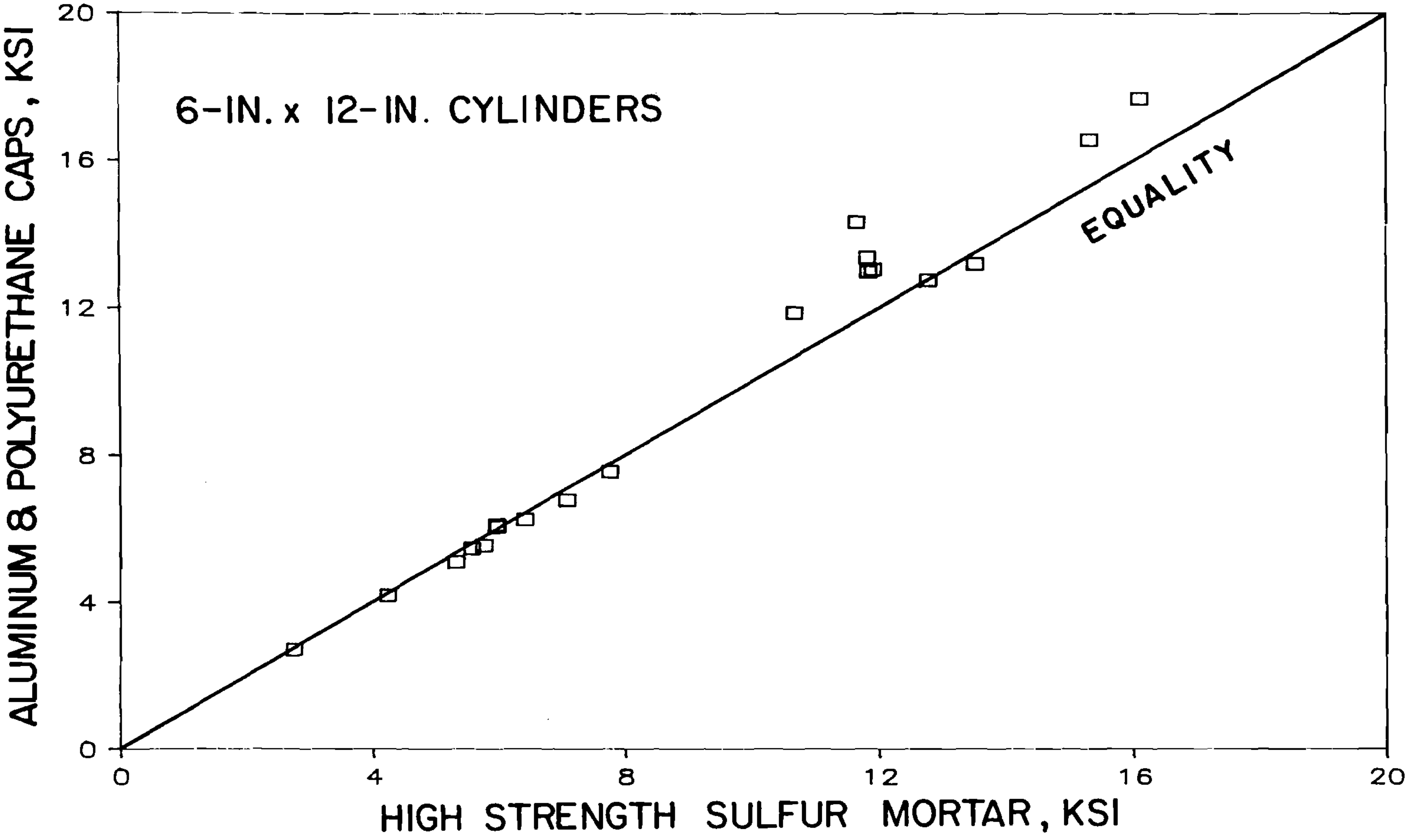


Fig. 8.1 Compressive strength of 6-in. x 12-in. cylinders tested using aluminum and polyurethane caps versus cylinders capped with high strength sulfur mortar.

TABLE 8.2 Effect of cap type on compressive strength of 4-in. x 8-in. cylinders cast from high strength concrete.

MIX NUMBER	CAP TYPE	TEST AGE, days	STRENGTH, psi	RATIO, OTHER:HIGH STRENGTH SULFUR
09-106-00	Sulfur	175	11,820	0.98
	High strength sulfur	175	12,090	1.00
	Aluminum caps w/polyurethane	175	13,050	1.08
23-067-00	High strength sulfur	28	7870	1.00
	Aluminum caps w/polyurethane	28	7720	0.98

the results tend to agree with those obtained from tests conducted using 6-in. x 12-in. cylinders. That is, at higher strength levels, cylinders tested using the aluminum and polyurethane caps achieved slightly higher strengths than those capped with the high strength sulfur mortar, and at lower strength levels, both capping methods yielded approximately equal test results.

8.3 Age of Cap

Since ASTM Standard C617 specifies that when sulfur capping compound is to be used, the caps should be allowed to harden for at least two hours prior to testing, a study of the effect of cap age was performed using 6-in. x 12-in. cylinders cast from mix number 06-097-00. The high strength sulfur capping compound was used, and tests were conducted at cap ages of 30, 120 and 240 minutes. Test results are presented in Table 8.3. Data are the average of two cylinders tested. From the results of this test, for the particular capping compound used, there is no advantage in allowing the cap to harden past 30 minutes.

8.4 Discussion

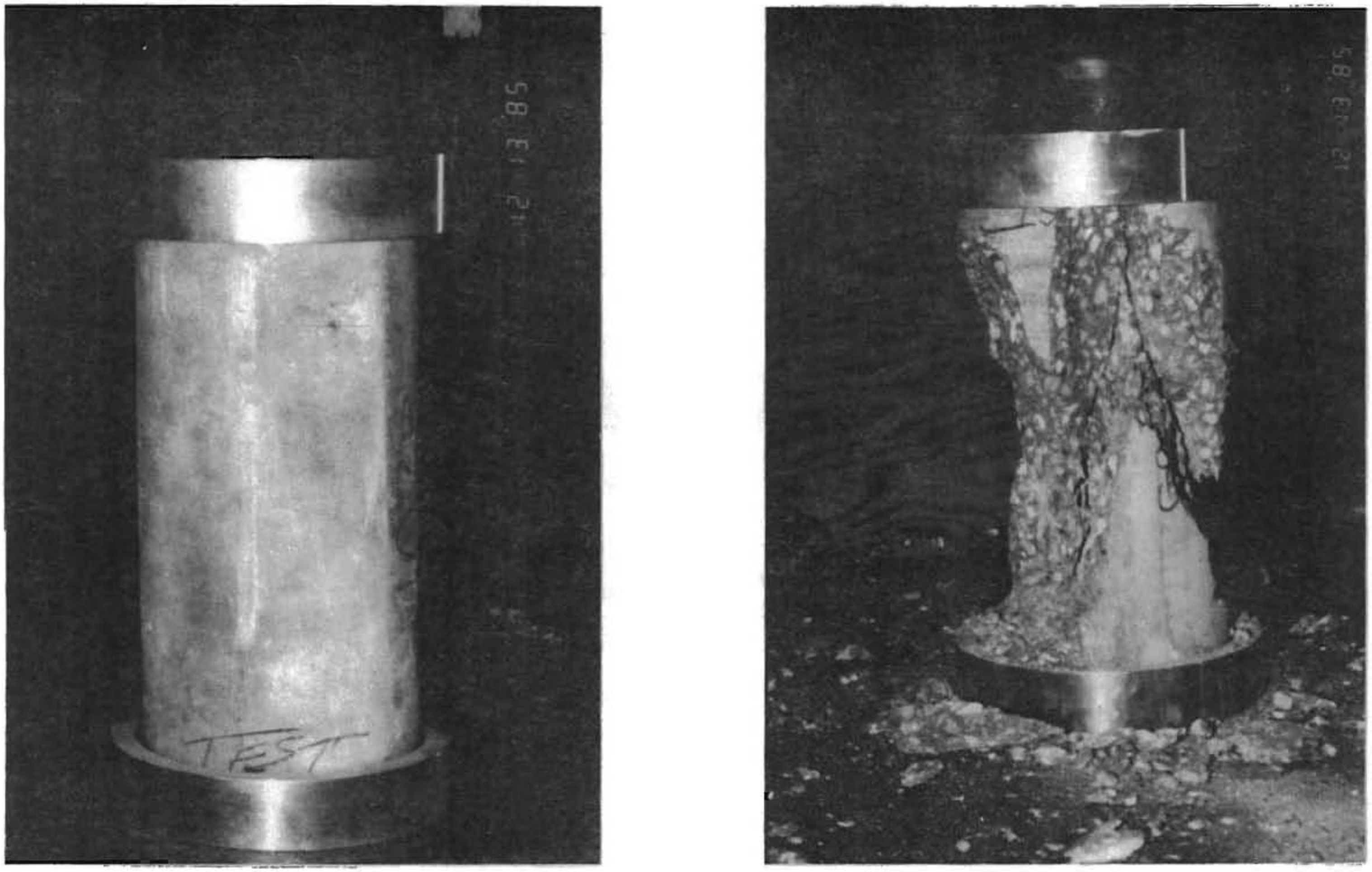
The use of aluminum caps with polyurethane inserts in testing concrete cylinders is not only convenient but it may also prove to be a better capping method than sulfur for testing high strength concrete.

With the use of the mechanical capping system, the need for melting pots, capping stands, sulfur compound and assorted accessories is eliminated. In addition, the capping of a specimen would no longer require the time of a skilled technician, who must ensure the proper planeness, perpendicularity and thickness of a sulfur cap.

The test results presented in this chapter indicate that for concrete strengths above 10,000 psi, cylinders tested using the mechanical capping system achieve much higher strength than those capped using sulfur capping compound. This may be due to any of several possible reasons. One of these is that the strength of the sulfur capping compounds used in this study may not have been adequate to fully develop the strength of the concrete cylinders, whereas the mechanical cap did. Another reason is that the use of the mechanical cap may be better able to distribute the applied load over the cross-sectional area of the cylinder, thereby removing stress concentrations due to irregular end conditions. Still another possible reason is that the mechanical capping method may provide more confinement of the cylinder ends than the sulfur caps provide. A high strength cylinder, before and after testing using the aluminum caps with polyurethane pads, is shown in Fig. 8.2. Sharp, angular failure planes are evident in the cone failure. However, the ends of the cylinders are sheared off to the depth they are set inside of the caps. From this last

TABLE 8.3 Effect of cap age on compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete.

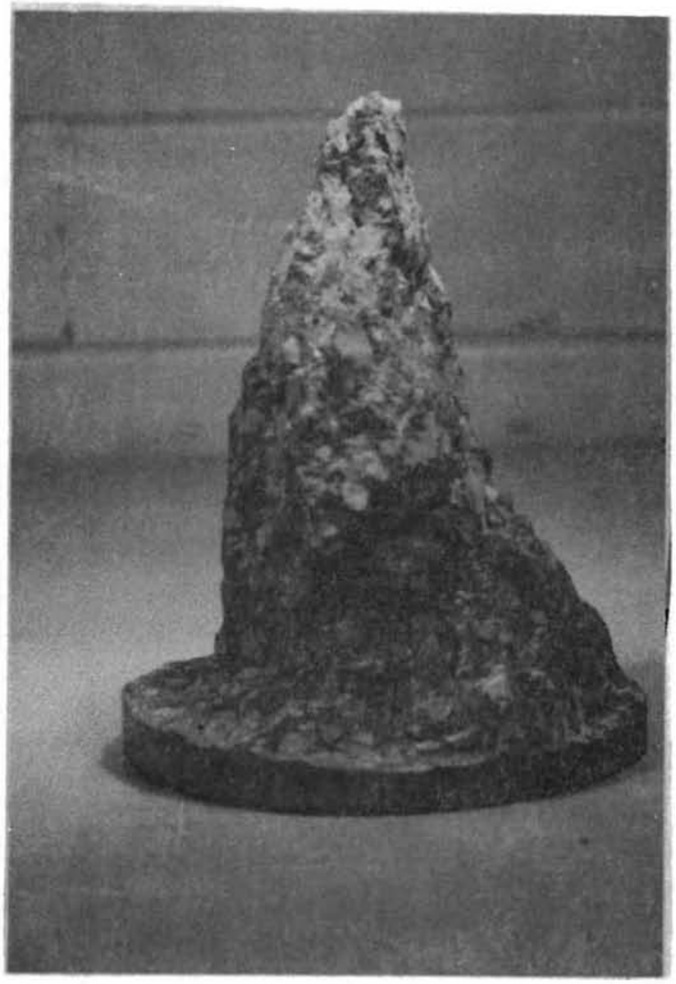
CAP AGE, min	CYLINDER STRENGTH, psi
30	11,480
120	11,490
240	11,550



(a)

(b)

Fig. 8.2 6-in. x 12-in. cylinder tested using aluminum and polyurethane caps: (a) cylinder ready for testing; (b) failure of cylinder.



(c)

Fig. 8.2 6-in. x 12-in. cylinder tested using aluminum and polyurethane caps: (c) cone and sheared bottom.

observation, it would seem that, indeed, for concrete strengths above 10,000 psi, the use of the mechanical caps provide significant lateral confinement of the cylinder ends.

For concrete having compressive strengths of between 6,000 psi and 10,000 psi, the use of aluminum and polyurethane caps did not seem to affect the test results significantly as compared to results obtained from companion cylinders capped with high strength sulfur mortar. However, the aluminum and polyurethane caps appear to yield higher test results than the high strength sulfur mortar when used in testing concrete having a compressive strength greater than 10,000 psi.

CHAPTER 9

EFFECT OF CONSOLIDATION

9.1 Introduction

ASTM Specifications C31 and C192 call for compaction by rodding for concrete having slumps of greater than three inches, and by rodding or vibration for concrete having a slump of three inches or less. Both 6-in. x 12-in. and 4-in. x 8-in. cylinders were cast and consolidated either by rodding or by internal vibration, and the effect on concrete strength examined.

9.2 Effect on 6-in. x 12-in. Cylinder Strength

The test results for 6-in. x 12-in. cylinders compacted either by internal vibration or rodding are presented in Table 9.1. Data shown are the average of two cylinders tested. As expected, adequate compaction of high slump concrete was achieved using both methods as indicated by the similar strength. It should be noted that minimal vibration of the high slump concrete did not affect is strength detrimentally.

9.3 Effect on 4-in. x 8-in. Cylinder Strength

Test results for 4-in. x 8-in. cylinders compacted by internal vibration using a vibrator having a 3/4-inch diameter head, or by rodding using either a 3/8-inch or 5/8-inch diameter rod, are presented in Table 9.2. Data are the average of two cylinders tested, unless otherwise noted. On the average, cylinders compacted by internal vibration or with a 5/8-inch diameter rod achieved equal (99 percent) strength to cylinders compacted using a 3/8-inch diameter rod.

Table 9.1 Effect of consolidation on strength of 6-in. x 12-in. cylinders cast from high strength concrete.

MIX NUMBER	SLUMP OF CONCRETE, inches	TEST AGE, days	TYPE OF COMPACTION 3/4" VIBRATOR	5/8" ROD	RATIO
20-111-33	10 +	1	5630	5610	1.00
		28	12,440	11,620	1.07
19-103-00	9-1/4	1	7170	6940	1.03
		28	10,020	10,930	0.92
		91	12,440	12,270	1.01

TABLE 9.2 Effect of consolidation on strength of 4-in. x 8-in. cylinders cast from high strength concrete.

MIX NUMBER	SLUMP OF CONCRETE, inches	TEST AGE, days	TYPE OF COMPACTION			RATIO	
			1 3/4-IN. VIBRATOR	2 5/8-IN. ROD	3 3/8-IN. ROD	1/3	2/3
20-111-33	10 +	1	5540	5410	5340 *	1.04	1.01
		28	10,890 *	10,750	10,370	1.05	1.04
		56	11,290	11,590 *	11,700 *	0.97	0.99
19-103-00	9-1/4	1	7180	6980	7140	1.01	0.98
		28	9730	9730	10,190	0.95	0.95
		56	10,300	11,050 *	11,180 *	0.92	0.99

* Test result of one cylinder

CHAPTER 10

EFFECT OF TEST AGE

10.1 Introduction

High strength concrete gains considerable strength after 28 days, especially if the mix contains fly ash or other pozzolans. In addition, full design strength is not usually required from the concrete during construction. For these reasons, the design strength of high strength concrete should be specified at an age later than 28 days, such as 56 or 91 days.

In this chapter, strength gain characteristics of high strength concrete mixes with and without fly ash are studied. These will include test ages of up to 91 days.

10.2 Strength Gain Curves

Tables 10.1 through 10.4 contain 6-in. x 12-in. cylinder test results for all mixes containing no fly ash, according to water-to-cement ratio. Data from high strength concrete mixes containing less than 30 percent fly ash are presented in Table 10.5, and data from mixes containing greater than 30 percent fly ash are presented in Tables 10.6 and 10.7, according to water-to-binder ratio. Strength versus time curves for mix numbers 01 through 21 are shown in Appendix A. A typical strength versus time curve is shown in Fig. 10.1.

10.3 Strength Gain: Percent of 28-day

The strength gain versus time as a percentage of the concrete's 28-day compressive strength is given for each mix in Tables 10.8 through 10.12, according to water-to-cement ratio, and fly ash content. From Tables 10.8 through 10.10, it can be seen that the strength gain characteristics of mixes containing no fly ash are approximately equivalent for mixes having water-to-cement ratios below 0.350. On the average, at 1 day, mixes containing no fly ash achieve approximately 70 percent of their 28-day compressive strength, while at 3, 7 and 14 days, the percentage strength gains are 81, 86 and 94 percent, respectively. It should be noted that all mixes were dosed with a superplasticizing admixture.

For mixes containing fly ash, the strength gain at all ages as a percentage of the 28-day strength is lower than for mixes containing no fly ash. At one day, mixes containing fly ash, on the average, achieve only 61 percent of their 28-day strength, while at 3, 7 and 14 days they achieve 78, 83 and 91 percent, respectively. Percentage strength

TABLE 10.1 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes having a water-to-cement ratio between 0.270 and 0.290.

MIX NUMBER	WATER-TO-CEMENT RATIO	TEST AGE, days	COMPRESSIVE STRENGTH, psi
16-107-00	0.275	1	7050
		3	7940
		7	8640
		14	9410
		28	10,150
		56	11,660 *
		92	12,330
09-106-00[a]	0.281	1	7530
		3	8520
		7	9210
		14	9740
		29	10,140
		56	10,870
04-100-00	0.283	1	7560
		3	9070
		7	9730
		14	10,280
		28	11,060
		56	11,840
08A-104-00	0.286	1	7580
		3	8710
		7	9360
		14	9940
		29	10,610 *
		56	11,260
08B-104-00[b]	0.288	1	7560
		3	8510
		7	9420
		14	10,100
		29	10,630 *
		56	11,360

* Test result of one cylinder.

[a] Superplasticizer added only at site

[b] Received three additions of superplasticizer

TABLE 10.2 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes having a water-to-cement ratio between 0.290 and 0.300

MIX NUMBER	WATER-TO-CEMENT RATIO	TEST AGE, days	COMPRESSIVE STRENGTH, psi
13-100-00	0.290	1	6940
		3	7610
		7	7660
		14	8270
		28	8670
		56	10,520
		91	11,650
02-095-00	0.292	1	5020[a]
		3	8940
		7	9170
		14	10,330
		28	10,990
		56	12,140
01-107-00	0.293	1	7530
		3	8680
		7	9200
		14	10,560
		28	11,190
		56	11,790
06-097-00	0.297	1	7500
		3	8700
		7	9380 *
		14	10,030 *
		28	10,850
		56	11,610
19-103-00	0.298	1	6940
		7	9200
		14	10,030
		28	10,930
		56	11,860 *
		91	12,270

* Test result of one cylinder

[a] Mix was over-retarded

TABLE 10.3 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes having a water-to-cement ratio between 0.300 and 0.340

MIX NUMBER	WATER-TO-CEMENT RATIO	TEST AGE, days	COMPRESSIVE STRENGTH, psi
03-096-00	0.301	1	6310
		3	7620
		7	8730
		14	9430
		28	9920 *
		56	10,410
05-089-00	0.303	1	6550
		3	8250
		7	9150
		14	9700
		28	10,440
		56	11,280
10-094-00	0.310	1	7670
		4	8730
		7	8770
		14	9590
		28	10,450 *
		56	11,420
		91	12,130 *
07-098-00	0.335	1	7100
		3	7800
		7	8470
		14	8940
		28	9800
		56	10,210

* Test result of one cylinder

TABLE 10.4 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes having a water-to-cement ratio between 0.340 and 0.550

MIX NUMBER	WATER-TO-CEMENT RATIO	TEST AGE, days	COMPRESSIVE STRENGTH, psi
17-100-00	0.346	1	6800
		7	7950
		28	9570
		56	9970
		92	10,750
24-065-00	0.420	28	7750
		42	8190
23-067-00	0.459	28	7870[a]
28-059-00	0.472	34	7090
26-057-00	0.478	28	5580
27-060-00	0.532	36	6420
25-056-00	0.541	28	5980

[a] Test results of 4-in. x 8-in. cylinders.

TABLE 10.5 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes containing less than 30 percent fly ash.

MIX NUMBER	WATER-TO-CEMENT RATIO	TEST AGE, days	COMPRESSIVE STRENGTH, psi
14-110-28	0.266	1	6990
		3	8830
		7	9710
		14	10,080
		28	11,180 *
		56	12,190
		91	13,650 *
11-093-27	0.320	1	6450
		4	7490
		7	7730
		14	8430
		28	9560
		56	11,690 *
		91	12,430 *

* Test results of one cylinder.

TABLE 10.6 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes containing more than 30 percent fly ash, and having a water-to-binder ratio between 0.250 and 0.270

MIX NUMBER	WATER-TO-CEMENT RATIO	TEST AGE, days	COMPRESSIVE STRENGTH, psi
15-112-38	0.253	1	6780
		3	8910
		7	9600
		14	10,720 *
		28	11,470 *
		56	12,700
20-111-33	0.260	1	5610
		7	9810
		14	11,140
		28	11,620
		56	13,150
21-112-34	0.263	1	4970
		3	9440
		7	11,920
		14	13,490
		21	14,250
		56	15,310
		97	16,110

* Test result of one cylinder

TABLE 10.7 Compressive strength of 6-in. x 12-in. cylinders cast from high strength concrete mixes containing more than 30 percent fly ash, and having a water-to-binder ratio between 0.270 and 0.340

MIX NUMBER	WATER-TO-CEMENT RATIO	TEST AGE, days	COMPRESSIVE STRENGTH, psi
18-111-35	0.285	1	7070
		7	9210
		28	11,030
		56	11,820
		91	12,170 *
22-110-34	0.297	28	12,430
12-093-38	0.338	1	6050
		4	7180
		7	7310
		14	8030
		28	9410
		54	9760
		91	10,990

* Test result of one cylinder

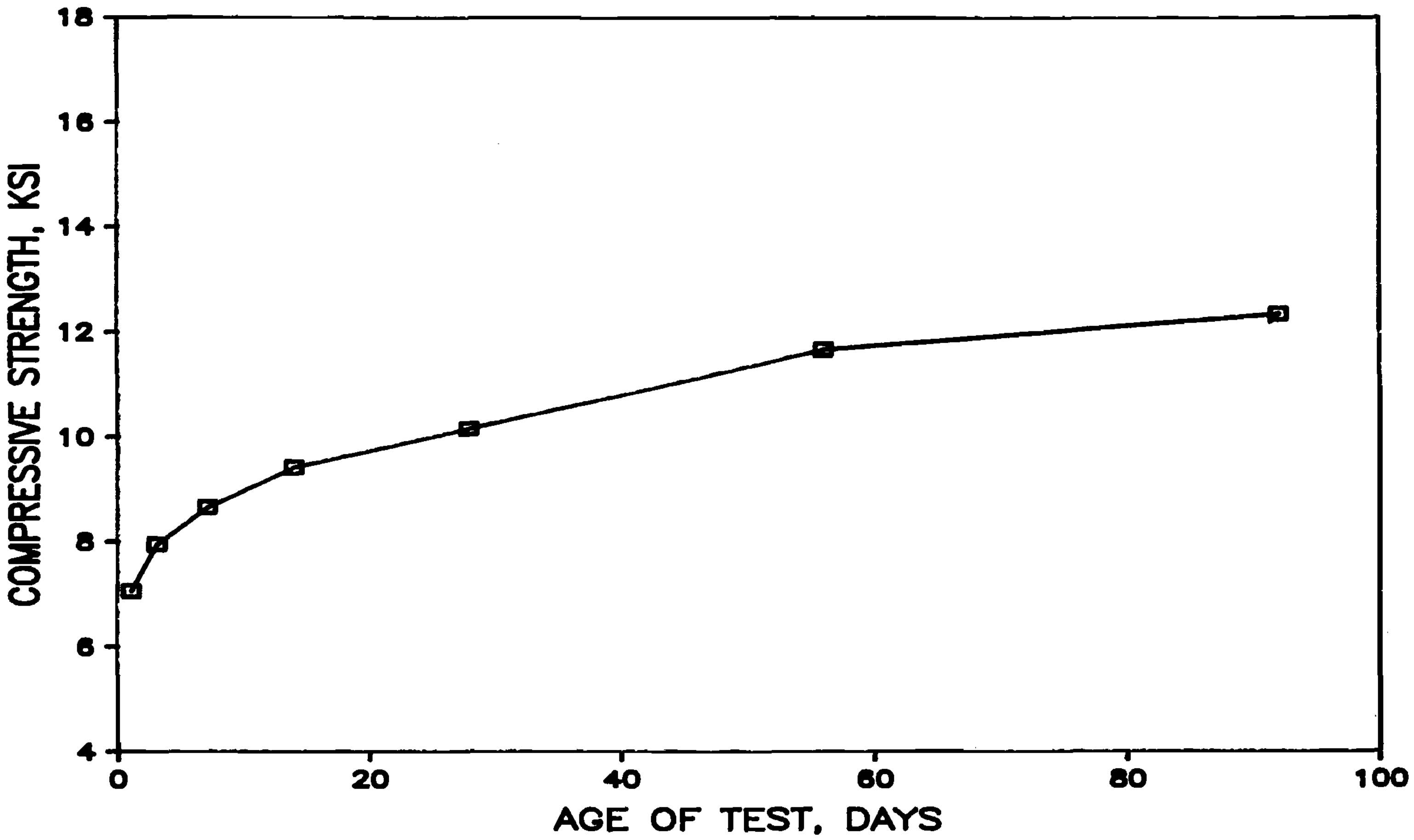


Fig. 10.1 Strength versus time curve for Mix #16-107-00.

TABLE 10.8 Strength gain characteristics, based on 28-day strength, of high strength concrete mixes containing no fly ash, and having a water-to-cement ratio between 0.270 and 0.290

MIX NUMBER	WATER-TO-CEMENT RATIO	PERCENTAGE STRENGTH GAIN, 28-DAY, %				
		1	3	7	14	28
16-107-00	0.275	69.5	78.2	85.1	92.7	100.0
09-106-00[a]	0.281	74.3	84.0	90.8	96.1	100.0
04-100-00	0.283	68.4	82.0	88.0	93.0	100.0
08A-104-00	0.286	71.4	82.1	88.2	93.7	100.0
08B-104-00[b]	0.288	71.1	80.1	88.6	95.0	100.0
Average		70.9	81.3	88.1	94.1	-----

[a] Superplasticizer added at laboratory only.

[b] Superplasticizer added at ready-mix plant and twice at laboratory.

TABLE 10.9 Strength gain characteristics, based on 28-day strength, of high strength concrete mixes containing no fly ash, and having a water-to-cement ratio between 0.290 and 0.300

MIX NUMBER	WATER-TO-CEMENT RATIO	PERCENTAGE STRENGTH GAIN, 28-DAY, %				
		1	3	7	14	28
13-100-00	0.290	80.1	87.8	88.4	95.4	100.0
02-095-00	0.292	45.7[a]	81.4	83.4	94.0	100.0
01-107-00	0.293	67.3	77.6	82.2	94.4	100.0
06-097-00	0.297	69.1	80.2	86.5	92.4	100.0
19-103-00	0.298	63.5	----	84.2	91.8	100.0
Average		70.0	81.8	84.9	93.6	-----

[a] Mix was over-retarded.

TABLE 10.10 Strength gain characteristics, based on 28-day strength, of high strength concrete mixes containing no fly ash, and having a water-to-cement ratio between 0.300 and 0.350

MIX NUMBER	WATER-TO-CEMENT RATIO	PERCENTAGE STRENGTH GAIN, 28-DAY, %				
		1	3	7	14	28
03-096-00	0.301	63.6	76.8	88.0	95.1	100.0
05-089-00	0.303	62.7	79.0	87.6	92.9	100.0
10-094-00	0.310	73.4	83.5	83.9	91.8	100.0
07-098-00	0.335	72.5	79.6	86.4	91.2	100.0
17-100-00	0.346	71.1	----	83.1	----	100.0
Average		68.7	79.7	85.8	92.8	-----

TABLE 10.11 Strength gain characteristics, based on 28-day strength, of high strength concrete mixes containing less than 30 percent fly ash.

MIX NUMBER	WATER-TO-CEMENT RATIO	PERCENTAGE STRENGTH GAIN, 28-DAY, %				
		1	3	7	14	28
14-110-28	0.266	62.5	79.0	86.9	90.2	100.0
11-093-27	0.320	67.5	78.4	80.9	88.2	100.0
Average		65.0	78.7	83.9	89.2	-----

TABLE 10.12 Strength gain characteristics, based on 28-day strength, of high strength concrete mixes containing more than 30 percent fly ash.

MIX NUMBER	WATER-TO-CEMENT RATIO	PERCENTAGE STRENGTH GAIN, 28-DAY, %				
		1	3	7	14	28
15-112-38	0.253	59.1	77.7	83.7	93.5	100.0
20-111-33	0.260	48.3	----	84.4	95.9	100.0
18-111-35	0.285	64.1	----	83.5	----	100.0
12-093-38	0.338	64.3	76.3	77.7	85.3	100.0
Average		59.0	77.0	82.3	91.6	-----

gain curves based on 28-day compressive strength are shown for each mix in Appendix B.

10.4 Strength Gain: Percent of 56-day

The strength gain versus time characteristics of high strength concrete mixes are given in Tables 10.13 through 10.17, based on 56-day compressive strength. For mixes containing no fly ash, there is no appreciable difference in strength gain characteristics for water-to-cement ratios less than 0.350, as seen in Table 10.13 through 10.15. Based on their 56-day strengths, these mixes, on the average, showed strength gains of approximately 65, 75, 80, 86 and 92 percent at 1, 3, 7, 14 and 28 days, respectively.

Strength gain characteristics of mixes containing fly ash are given in Table 10.16 and 10.17, based on 56-day strength. The two mixes containing less than 30 percent fly ash exhibited considerably different strength gain characteristics. On the average, mixes containing fly ash achieved strength gains of approximately 52, 68, 75, 82 and 90 percent of the 56-day strength at 1, 3, 7, 14 and 28 days, respectively. Again, as in strength gain based on 28-day strength, mixes containing fly ash have a slower rate of strength gain, especially at earlier ages, than mixes containing no fly ash. For instance, mixes containing fly ash achieved only 52 percent of their 56-day strength at 1 day, whereas mixes containing no fly ash achieved 65 percent. However, this gap decreased with increasing test age, until at 28 days, mixes containing fly ash reached 90 percent of their 56-day strength, and mixes not containing fly ash achieved 92 percent. Strength gain curves, based on 56-day tests, are shown for each mix in Appendix C.

10.5 Strength Gain: Percent of 91-day

The strength gain characteristics, based on 91-day strengths, of mixes containing no fly ash are given in Table 10.18. As shown in the table, mixes not containing fly ash achieved 60, 67, 71, 77, 84 and 94 percent of their 91-day strength at 1, 3, 7, 14, 28 and 56 days, respectively.

Table 10.19 presents the strength gain characteristics of mixes containing fly ash. Again, the early strength gain of the mixes containing fly ash was much lower than that of the mixes containing no fly ash. However, at 56-days, both mixes with and without fly ash achieved approximately 93 to 94 percent of their 91-day strength. Strength gain curves based on 91-day strengths of each mix are presented in Appendix D.

TABLE 10.13 Strength gain characteristics, based on 56-day strength, of high strength concrete mixes containing no fly ash, and having a water-to-cement ratio between 0.270 and 0.290

MIX NUMBER	WATER-TO-CEMENT RATIO	PERCENTAGE STRENGTH GAIN, 56-day, %					
		1	3	7	14	28	56
16-107-00	0.275	60.5	68.1	74.1	80.7	87.1	100.0
09-106-00[a]	0.281	69.3	78.4	84.7	89.6	93.3	100.0
04-100-00	0.283	63.9	76.6	82.2	86.8	93.4	100.0
08A-104-00	0.286	67.3	77.4	83.1	88.3	94.2	100.0
08B-104-00[b]	0.288	66.6	74.9	82.9	88.9	93.6	100.0
Average		65.5	75.1	81.4	86.9	92.3	-----

[a] Superplasticizer added at laboratory only.

[b] Superplasticizer added at ready-mix plant and twice at laboratory.

TABLE 10.14 Strength gain characteristics, based on 56-day strength, of high strength concrete mixes containing no fly ash, and having a water-to-cement ratio between 0.290 and 0.300

MIX NUMBER	WATER-TO-CEMENT RATIO	PERCENTAGE STRENGTH GAIN, 56-day, %					
		1	3	7	14	28	56
13-100-00	0.290	66.0	72.3	72.8	78.6	82.4	100.0
02-095-00	0.292	41.4[a]	73.6	75.5	85.1	90.5	100.0
01-107-00	0.293	63.9	73.6	78.0	89.6	94.9	100.0
06-097-00	0.297	64.6	74.9	80.8	86.4	93.5	100.0
19-103-00	0.298	58.5	----	77.6	84.6	92.2	100.0
Average		63.3	73.6	76.9	84.9	90.7	

a Mix was over-retarded.

TABLE 10.15 Strength gain characteristics, based on 56-day strength, of high strength concrete mixes containing no fly ash, and having a water-to-cement ratio between 0.300 and 0.350

MIX NUMBER	WATER-TO-CEMENT RATIO	PERCENTAGE STRENGTH GAIN, 56-day, %					
		1	3	7	14	28	56
03-096-00	0.301	60.6	73.2	83.9	90.6	95.3	100.0
05-089-00	0.303	58.1	73.1	81.1	86.0	92.6	100.0
10-094-00	0.310	67.2	76.4	76.8	84.0	91.5	100.0
07-098-00	0.335	69.5	76.4	83.0	87.6	96.0	100.0
17-100-00	0.346	68.2	----	79.7	----	96.0	100.0
Average		64.7	74.8	80.9	87.1	94.3	-----

TABLE 10.16 Strength gain characteristics, based on 56-day strength, of high strength concrete mixes containing less than 30 percent fly ash.

MIX NUMBER	WATER-TO-CEMENT RATIO	PERCENTAGE STRENGTH GAIN, 56-day, %					
		1	3	7	14	28	56
14-110-28	0.266	57.3	72.4	79.7	82.7	91.7	100.0
11-093-27	0.320	55.2	64.1	66.1	72.1	81.8	100.0
Average		56.3	68.3	72.9	77.4	86.8	----

TABLE 10.17 Strength gain characteristics, based on 56-day strength, of high strength concrete mixes containing more than 30 percent fly ash.

MIX NUMBER	WATER-TO-CEMENT RATIO	PERCENTAGE STRENGTH GAIN, 56-day, %					
		1	3	7	14	28	56
15-112-38	0.253	53.4	70.2	75.6	84.4	90.3	100.0
20-111-33	0.260	42.7	----	74.6	84.7	88.4	100.0
21-112-34	0.263	32.5	61.7	77.9	88.1	----	100.0
18-111-35	0.285	59.8	----	77.9	----	93.3	100.0
12-093-38	0.338	62.0	73.6	74.9	82.3	96.4	100.0
Average		50.1	68.5	76.2	84.9	92.1	-----

TABLE 10.18 Strength gain characteristics, based on 91-day stength, of high strength concrete mixes containing no fly ash.

MIX NUMBER	WATER-TO-CEMENT RATIO	PERCENTAGE STRENGTH GAIN, 91-DAY, %						
		1	3	7	14	28	56	91
16-107-00	0.275	57.2	64.4	70.1	76.3	82.3	94.6	100.0
13-100-00	0.290	59.6	65.3	65.8	71.0	74.4	90.3	100.0
19-103-00	0.298	56.6	----	75.0	81.7	89.1	96.7	100.0
10-094-00	0.310	63.2	72.0	72.3	79.1	86.2	94.2	100.0
17-100-00	0.346	63.3	----	74.0	----	89.0	92.7	100.0
Average		60.0	67.2	71.4	77.0	84.2	93.7	-----

TABLE 10.19 Strength gain characteristics, based on 91-day stength, of high strength concrete mixes containing fly ash.

MIX NUMBER	WATER-TO-CEMENT	PERCENTAGE STRENGTH GAIN, 91-DAY, %						
		1	3	7	14	28	56	91
14-110-28	0.266	51.2	64.7	71.1	73.9	81.9	89.3	100.0
11-093-27	0.320	51.9	60.3	62.2	67.8	76.9	94.1	100.0
21-112-34	0.263	30.9	58.6	74.0	83.7	----	95.0	100.0
18-111-35	0.285	58.1	----	75.7	----	90.6	97.1	100.0
12-093-38	0.338	55.1	65.3	66.5	73.1	85.6	88.8	100.0
Average		49.4	62.2	69.9	74.6	83.8	92.9	-----

10.6 Discussion

The strength gain characteristics of mixes both with and without fly ash are shown in Table 10.20. Percent strength gain is calculated on the basis of 28, 56, and 91 day strengths. These data are plotted in Figs. 10.2 through 10.4.

In all cases, the early strength gain of mixes containing fly ash was was lower than that of mixes containing no fly ash. However, at later ages, both mixes with and without fly ash achieved approximately equal percentages, the mixes with fly ash being only 2 to 3 percent lower. It should be noted that the mix which had the lowest water-to-binder ratio contained 38 percent fly ash, thereby illustrating the decreased water demand of fly ash as compared to cement. In fact, four of the eight mixes containing fly ash had lower water-to-cement ratios than any of the mixes containing cement only. The lowest strength of any of these four mixes at 28 days was 11,180 psi, and the highest above 14,250 psi. The highest 28-day compressive strength of the mixes containing no fly ash was 11,190 psi. At 56 days, the mix containing fly ash which broke at 11,180 psi at 28 days (mix number 14) broke at 12,190 psi. The mix containing no fly ash which had the highest 28-day strength (mix number 01) had a strength of 11,790 psi at 56 days. It is clear that the water reduction and strength gain provided by the use of the fly ashes used in this study were beneficial to the production of high strength concrete mixes.

The strength gained between 28 days and 56 days was, on the average for all mixes, eight to ten percent of the 56-day strength, or nine to eleven percent of the 28-day strength. Thus, by specifying the concrete to be tested for design strength at 56 days, significant savings could be made on material costs. For example, if concrete having a compressive strength of 10,000 psi is required, specifying it to be tested at 56 days would call for concrete having only 9,200 psi at 28 days. Even greater savings could be achieved by specifying the test age to be later, say 91 days. In this case, the concrete would be required to have a strength of only 8500 psi at 28 days.

Percentages in the above example are approximate values only, based on the test results presented in this chapter. Strength gain characteristics should be determined for the actual high strength concrete mix to be used.

TABLE 10.20 Average strength gain characteristics for mixes with and without fly ash based on various test ages.

MIX NUMBER	TEST AGE, days	PERCENTAGE STRENGTH GAIN, %						
		1	3	7	14	28	56	91
No fly ash	28	70	81	86	94	100	--	--
Fly ash	28	61	78	83	91	100	--	--
No fly ash	56	65	75	80	86	92	100	--
Fly ash	56	52	68	75	82	90	100	--
No fly ash	91	60	67	71	77	84	94	100
Fly ash	91	49	62	70	75	84	93	100

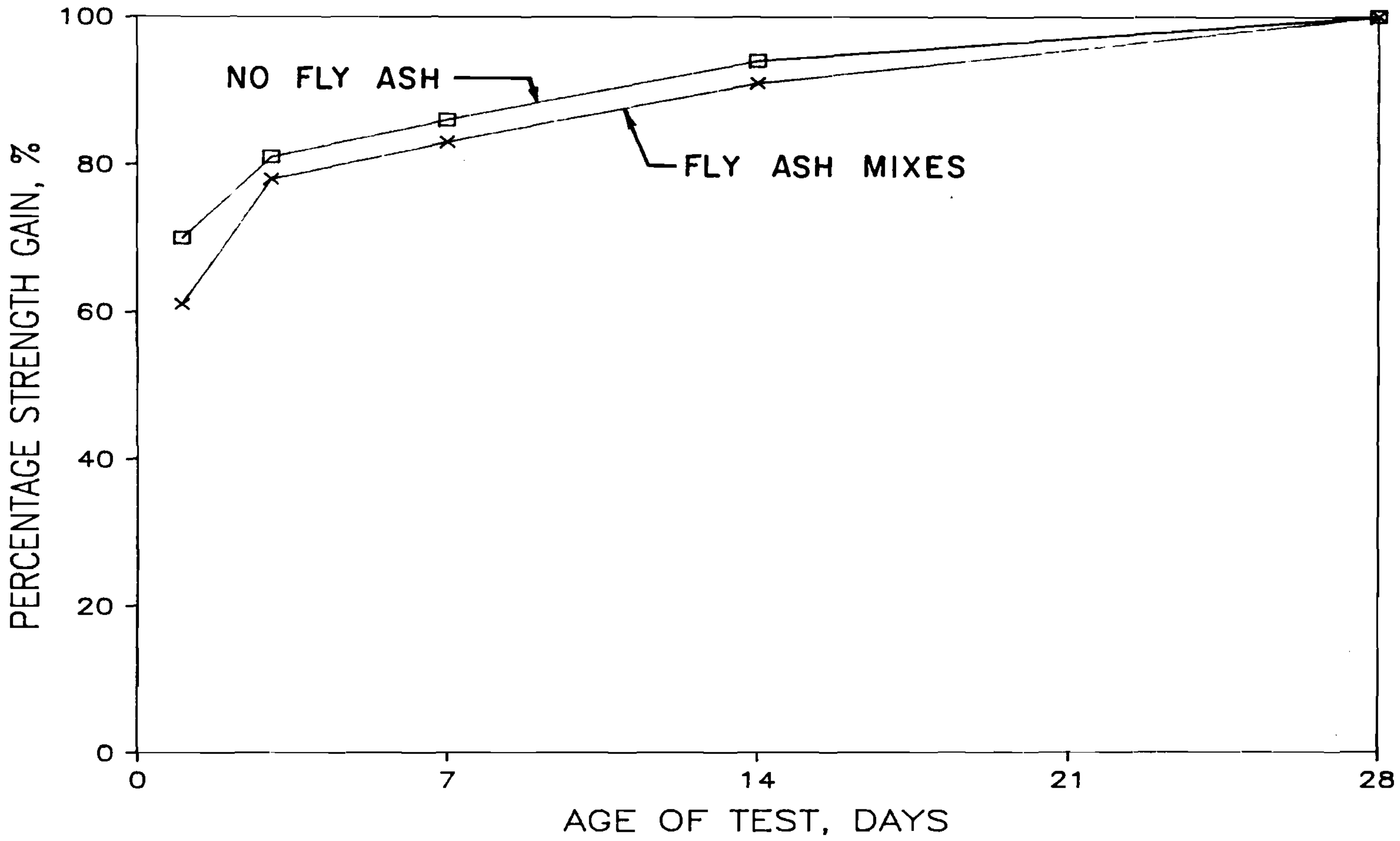


Fig. 10.2 Strength gain, based on 28-day compressive strength, of mixes containing no fly ash versus mixes containing fly ash.

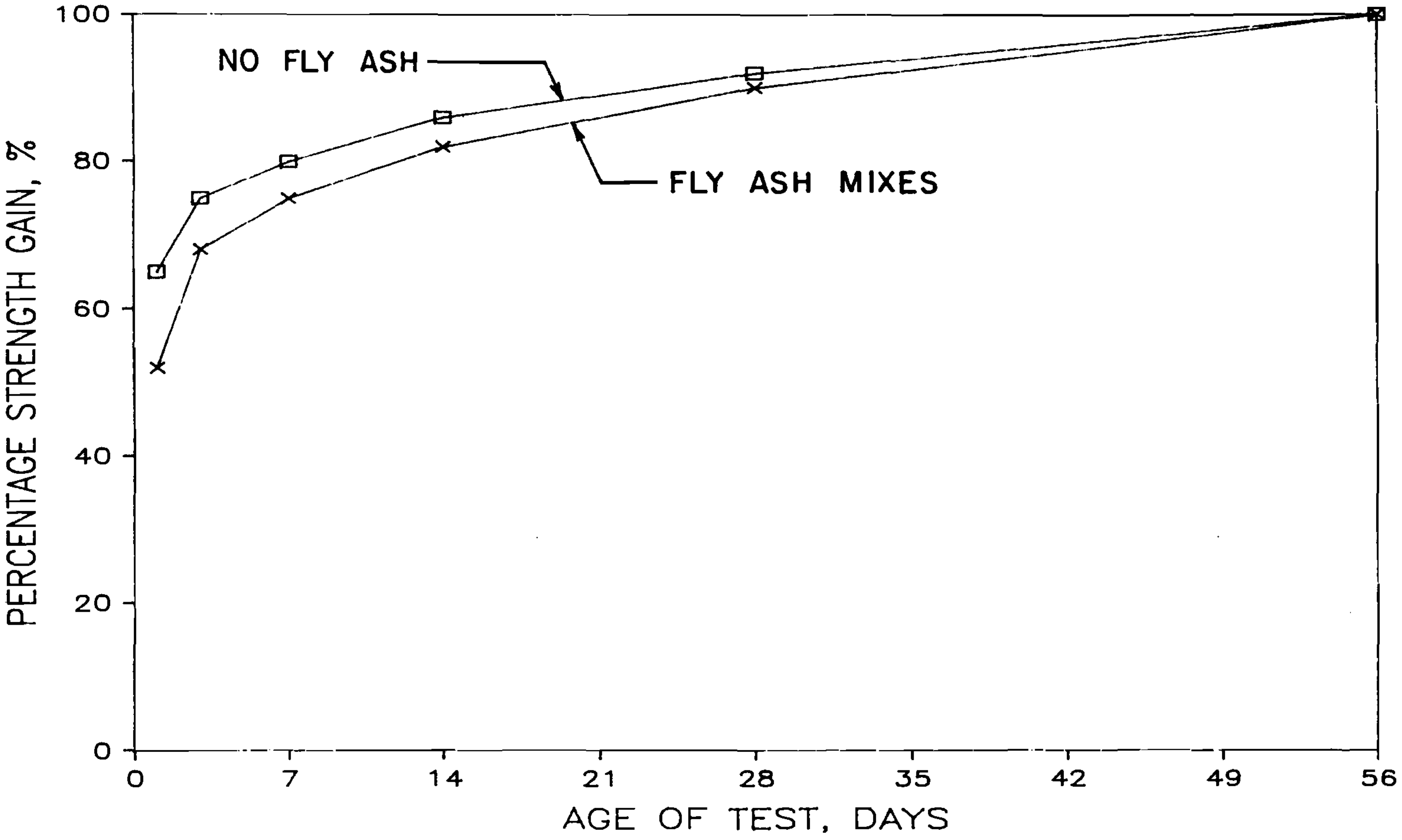


Fig. 10.3 Strength gain, based on 56-day compressive strength, of mixes containing no fly ash versus mixes containing fly ash.

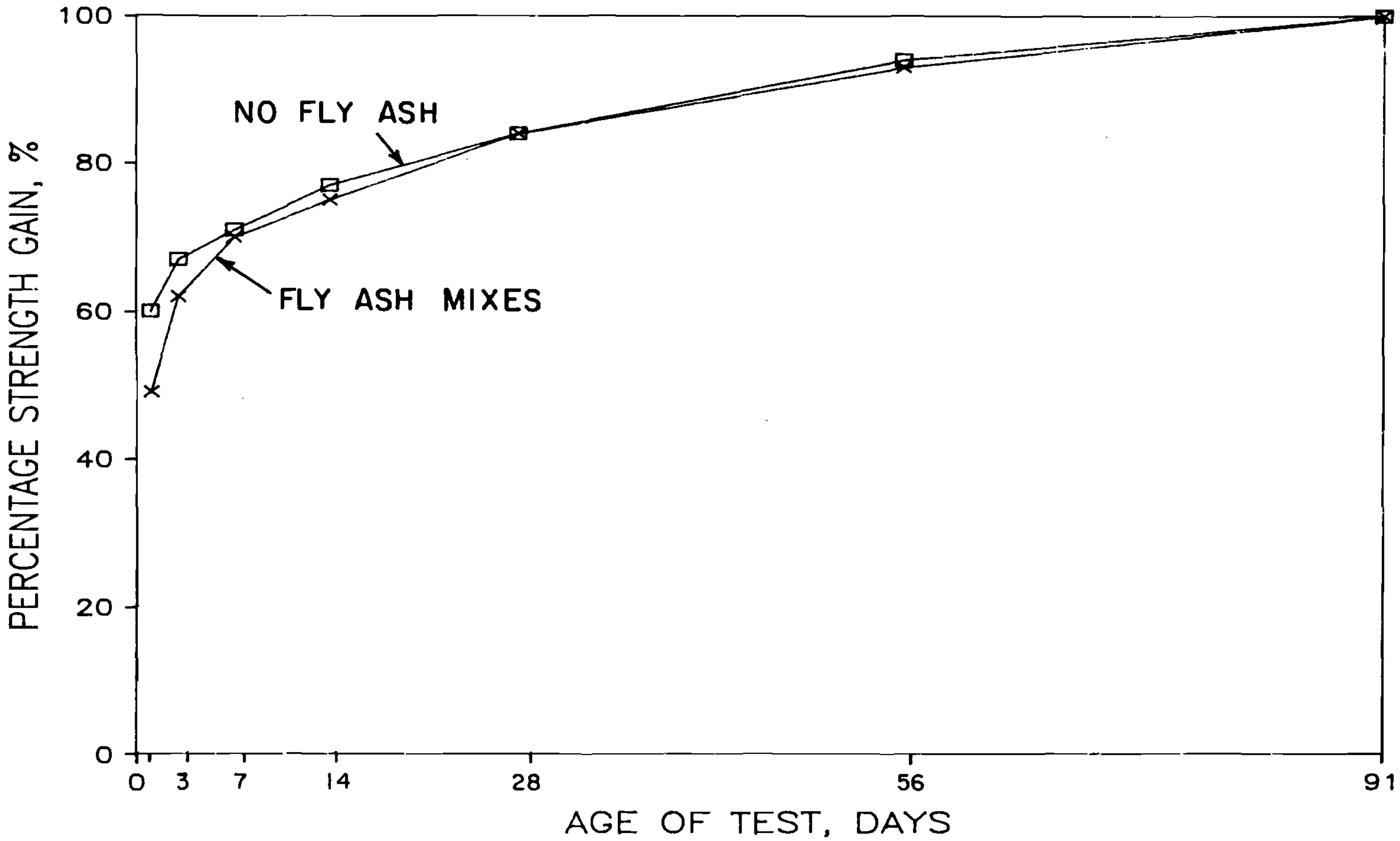


Fig. 10.4 Strength gain, based on 91-day compressive strength, of mixes containing no fly ash versus mixes containing fly ash.

CHAPTER 11

ADDITIONAL FINDINGS

11.1 Introduction

In addition to the topics discussed in Chapters 4 through 10, several other observations can be made regarding the behavior and experimental results of the high strength concrete mixes tested in the course of this study. These will include the effect of the coarse aggregate source, the relationship between the 7-day flexural and 28-day compressive strength of high strength concrete, and a comparison between test results obtained with third point and center point loading.

11.2 Effect of Coarse Aggregate Source

Five different coarse aggregates were used. Three of these were 3/8-inch crushed limestone from different pits. The fourth was a 1-inch crushed limestone from one of the above-mentioned pits. The fifth was a 3/4-inch crushed limestone, also from one of the above-mentioned pits. The properties of these aggregates were given in Table 3.1.

In those mixes using coarse aggregates A and C having a 3/8-in. maximum size, examination of the failure surface of compressive strength specimens tested at 28 days showed no bond failure between the coarse aggregate and paste. All failure planes propagated through the coarse aggregate. In the mixes using coarse aggregate type E, most failure planes passed through the coarse aggregates. However, some bond failure was apparent, probably due to the larger 3/4-inch aggregate, and relatively low (7,000 psi) 28-day strength.

The mixes using coarse aggregates B and D having a 1-in. and 3/8-in. maximum size, respectively, achieved very high strengths. The failure surfaces in compressive strength specimens containing aggregate B exhibited some bond failure at 28-day strength, probably due, in part, to the large 1-in. nominal aggregate size. Mix number 21, which contained coarse aggregate D, showed no signs of bond failure in compressive strength specimens which broke at 14,250 psi at 21 days. However, the same type of aggregate was used in mix number 22, and some bond failure occurred in specimens which broke at 12,430 psi at 28 days.

From the above observations, it would appear that the use of coarse aggregates A, C and E in the high strength concrete mixes limited their compressive strength. At higher strength levels, these aggregates became the weak link within the concrete. Thus, the paste was forced to compensate for the coarse aggregate's weakness. This could explain why mixes using these aggregates, in spite of having low water-to-cement or water-to-binder ratios, exhibited relatively lower compressive strengths when compared to those mixes containing coarse aggregate B or D at equal test ages.

11.3 Third Point Loading Versus Center Point Loading

Flexural strength test results depend on the test method used. In general, flexural strength test results obtained using center point loading will be higher than those obtained from third point loading. Data obtained from this study are shown in Table 11.1. For 6-in. x 6-in. x 20-in. beams, those tested with center point loading achieved flexural strengths which were on the average sixteen percent higher than those tested in third point loading. The same trend was observed for 4-in. x 4-in. x 14-in. beams, except that the difference in strength was approximately nine percent.

The two test methods are represented schematically in Fig. 11.1. When a beam is tested in center point loading, the cross-section of the beam subjected to maximum moment, and therefore maximum stress, is located at the point where load is applied, as shown in Fig. 11.1a. Therefore, if failure occurs at that cross-section, then the result reflects the flexural capacity of the concrete along that plane only. If failure occurs at some point along the beam other than where the load is applied, the actual flexural capacity of the concrete at that point is lower than that measured, because the moment, and stress, at that point are lower than at the point of loading. Therefore, for failure at a cross-section other than at mid-span, the actual maximum stress at failure should be calculated based on the actual moment at that cross-section.

When beams are tested using third point loading, there is a region of the beam equal to 1/3 of its span length which is subjected to maximum moment, as shown in Figure 11.1b. Therefore, failure could occur at any cross-section within that length, and no correction would be needed since the failure surface would have been subjected to maximum stress.

These same principles can be used in explaining the difference in test results obtained from the two test methods. Assuming that a 6-in. x 6-in. x 20-in. beam is to be tested having a flexural capacity at midspan "M" of 700 psi, and at cross-section "A", which is 1-1/2 inches away from the midspan, of only 650 psi, due to differences in compaction, location of aggregate, microcracking, etc., as shown in Figure 11.2. If this beam is loaded in center point loading, it will achieve an apparent flexural capacity of 700 psi, and failure will occur at midspan. At the time of failure, the stress at cross-section A is only 580 psi, as shown in Figure 11.3. However, if the beam is loaded using third point loading, it will fail at a stress of 650 psi, and the failure will occur at cross-section A. The stress at midspan

TABLE 11.1 Comparison of test results obtained from testing high strength flexural beam specimens in third point loading and center point loading; a) 6-in. x 6-in. x 20-in. beams; b) 4-in. x 4-in. x 14-in. beams.

MIX NUMBER	CENTER POINT LOADING FLEXURAL STRENGTH, psi (1)	THIRD POINT LOADING FLEXURAL STRENGTH, psi (2)	RATIO, 1:2
22-110-34	1660	1400	1.19
23-067-00	860	820	1.05
24-065-00	1020	830	1.23
25-056-00	740	630	1.17
26-057-00	730	640	1.14
27-060-00	780	660	1.18
28-059-00	780	670	1.16
25-056-00	860	760	1.13
AVERAGE			1.16

(a)

MIX NUMBER	CENTER POINT LOADING FLEXURAL STRENGTH, psi (1)	THIRD POINT LOADING FLEXURAL STRENGTH, psi (2)	RATIO, 1:2
22-110-34	1550	1440	1.08
24-065-00	930	870	1.07
26-057-00	770	680	1.13
AVERAGE			1.09

(b)

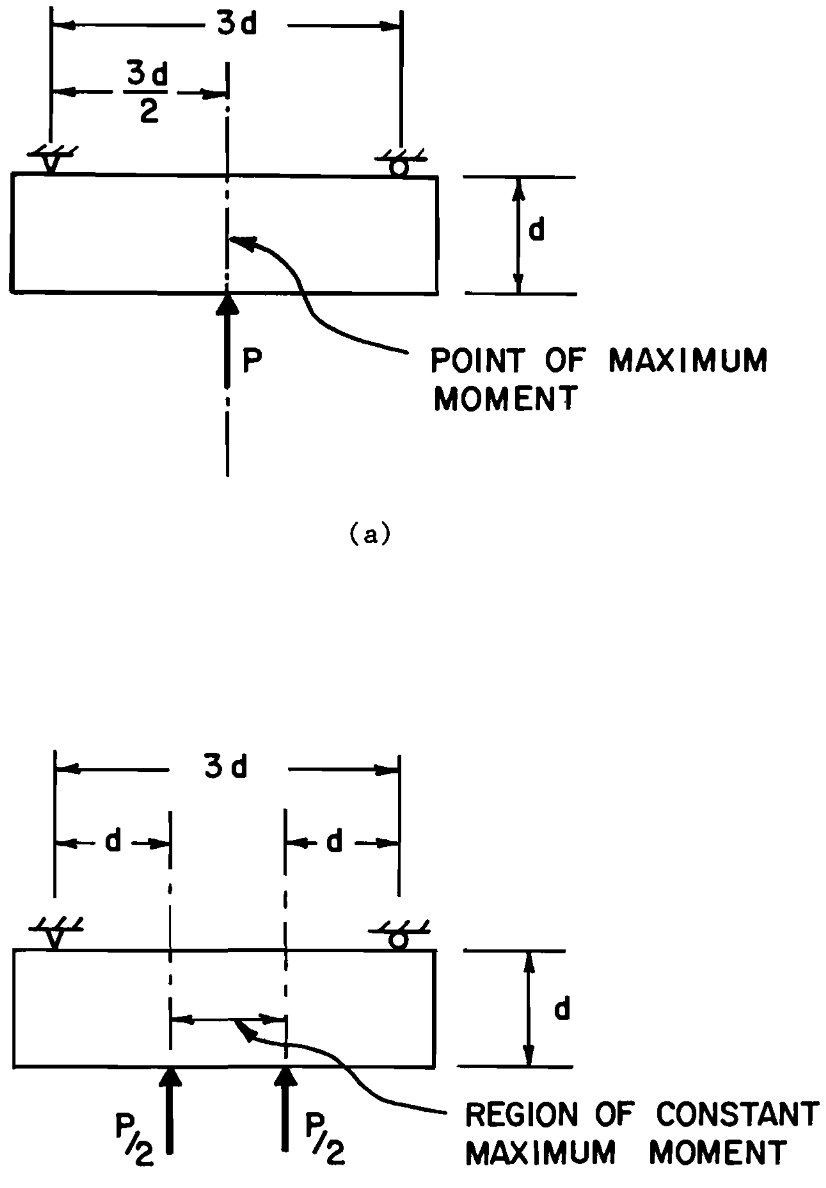


Fig. 11.1 Schematic representation of test set-up for (a) center point loading; (b) third-point loading.

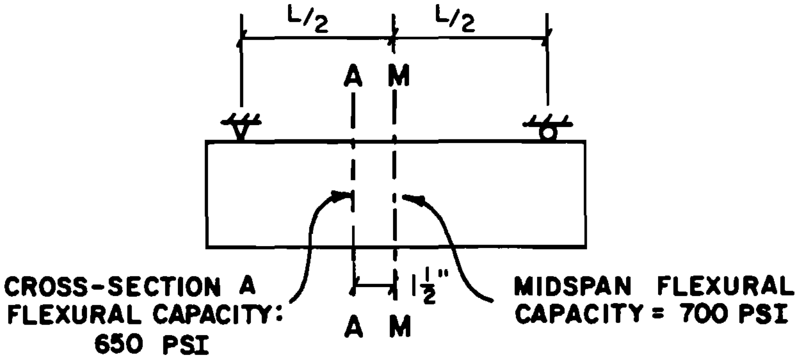


Fig. 11.2 Schematic representation of beam to be tested.

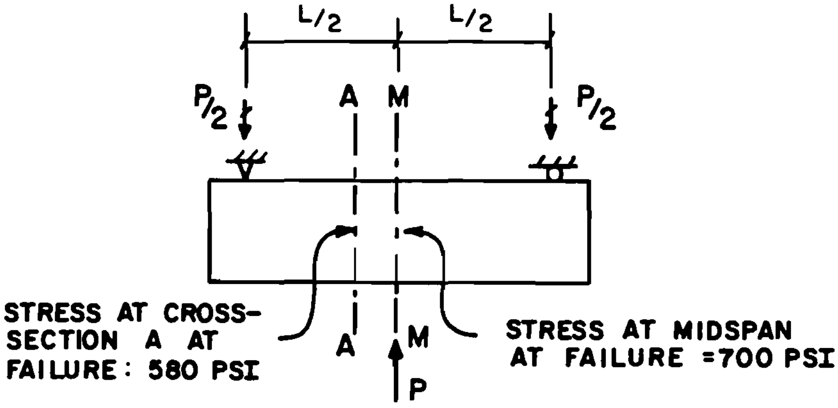


Fig. 11.3 Beam tested in center point loading; failure occurs at midspan at 700 psi.

would also be 650 psi, as it would be at all cross-sections between the two points of loading, as shown in Figure 11.4.

Thus, since it is more probable that a weak cross-section will exist within six inches in the beam length than at a fixed point (midspan) in the beam length, it is probable that flexural strength test results obtained from third point loading will be lower than test results obtained from center point loading, as the results of this study indicate. Applying the same concept to the smaller, 4-in. x 4-in. x 14-in. beams, results obtained from center point loading would be higher than those from third point loading, but not by as wide a margin as in the case of 6-in. x 6-in. x 20-in. beams. This is due to the shorter length of constant moment in the smaller beams tested in third point loading, being only four inches as opposed to six inches for the larger beams. Again, the results obtained in this study regarding 4-in. x 4-in. x 14-in. beams, although limited, seem to agree with this theory.

11.4 Seven-Day Flexural Strength Versus 28-Day Compressive Strength

Current Texas Highway Department concrete specifications [26] assume the relationship between 28-day compressive strength and 7-day center point flexural strength to be six-to-one. In this study, the relationship between these strengths was investigated to determine if the ratio of six-to-one is applicable to high strength concrete.

Tables 11.2 and 11.3 present the 7-day flexural strength and 28-day compressive strength test results obtained in this study. Flexural strength was determined by third point loading. As seen in these tables, the average ratio of 28-day compressive strength to 7-day flexural strength for all mixes, regardless of fly ash content, is slightly above nine-to-one. Converting this to reflect test results obtained using center point loading, as discussed in section 11.3, yields a ratio of eight-to-one. Test data, corrected from third point loading to center point loading by multiplying the former by 1.16, are plotted in Fig. 11.5.

Based on the eight-to-one relationship found in this study, the TSDHPT concrete specifications could prove to be unconservative if they specify 7-day flexural strength and 28-day compressive strength based on a six-to-one ratio. For instance, according to TSDHPT Specifications, based on a six-to-one ratio, concrete required to achieve 9,000 psi compressive strength at 28 days or 1,500 psi flexural strength at 7 days are the same concrete. If the concrete has a flexural strength of 1,500 psi at 7 days, it will have, on the average, a 28-day compressive strength of 12,000 psi, which is 3,000 psi in excess of the required 28-day compressive strength. On the other hand, if the concrete is designed so that it has a 28-day compressive strength of 9,000 psi, at 7 days its flexural strength will be only 1,125 psi, on the average, well below the 1,500 psi specified.

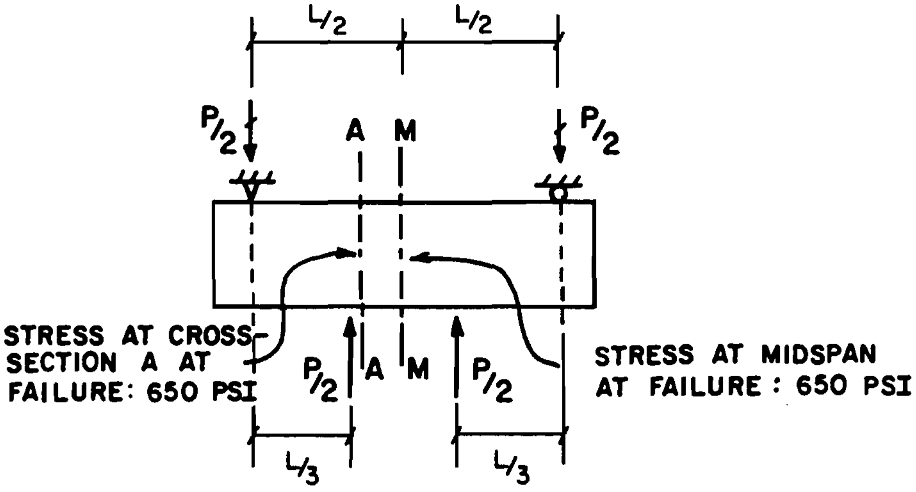


Fig. 11.4 Beam tested in third-point loading; failure occurs at cross-section A at 650 psi.

TABLE 11.2 Flexural strength at seven days versus compressive strength at 28 days for high strength concrete mixes containing no fly ash.

MIX NUMBER	28-DAY CYLINDER, psi (a)	7-DAY BEAM, psi (b)	RATIO, a:b
01-107-00	11,190	1230	9.10
02-095-00	10,990	1060	10.37
03-096-00	9920 *	1090	9.10
04-100-00	11,060	1090 *	10.15
05-089-00	10,440	970	10.76
06-097-00	10,850	1100	9.86
08A-104-00	10,610 *	1210	8.77
08B-104-00	10,630	1230	8.64
09-106-00	10,140	1140	8.89
10-094-00	9870	1240 *	7.96
13-100-00	8670	1030	8.42
16-107-00	10,150	1010	10.02
17-100-00	9570	1020 *	9.43
19-103-00	10,930	1270	8.61
24-065-00	7750	830	9.34
25-056-00	5980	630	9.49
26-057-00	5580	640	8.72
AVERAGE			9.27

*Test result of one test specimen.

TABLE 11.3 Flexural strength at seven days versus compressive strength at 28-days for high strength concrete mixes a) mixes containing less than 30 percent fly ash; b) mixes containing more than 30 percent fly ash.

MIX NUMBER	28-DAY CYLINDER, psi (1)	7-DAY BEAM, psi (2)	RATIO, 1:2
11-093-27	10,100 *	1100	9.18
14-110-28	9880 *	1140	8.67
AVERAGE			8.93

*Test result of one test specimen

(a)

MIX NUMBER	28-DAY CYLINDER, psi (1)	7-DAY BEAM, psi (2)	RATIO, 1:2
12-093-38	9410	1160	8.11
15-112-38	11,470 *	1430 *	8.02
18-111-35	11,030	910 *	12.12
20-111-33	11,620	1200 *	9.68
22-110-34	12,430	1400	8.88
AVERAGE			9.36

*Test result of one test specimen.

(b)

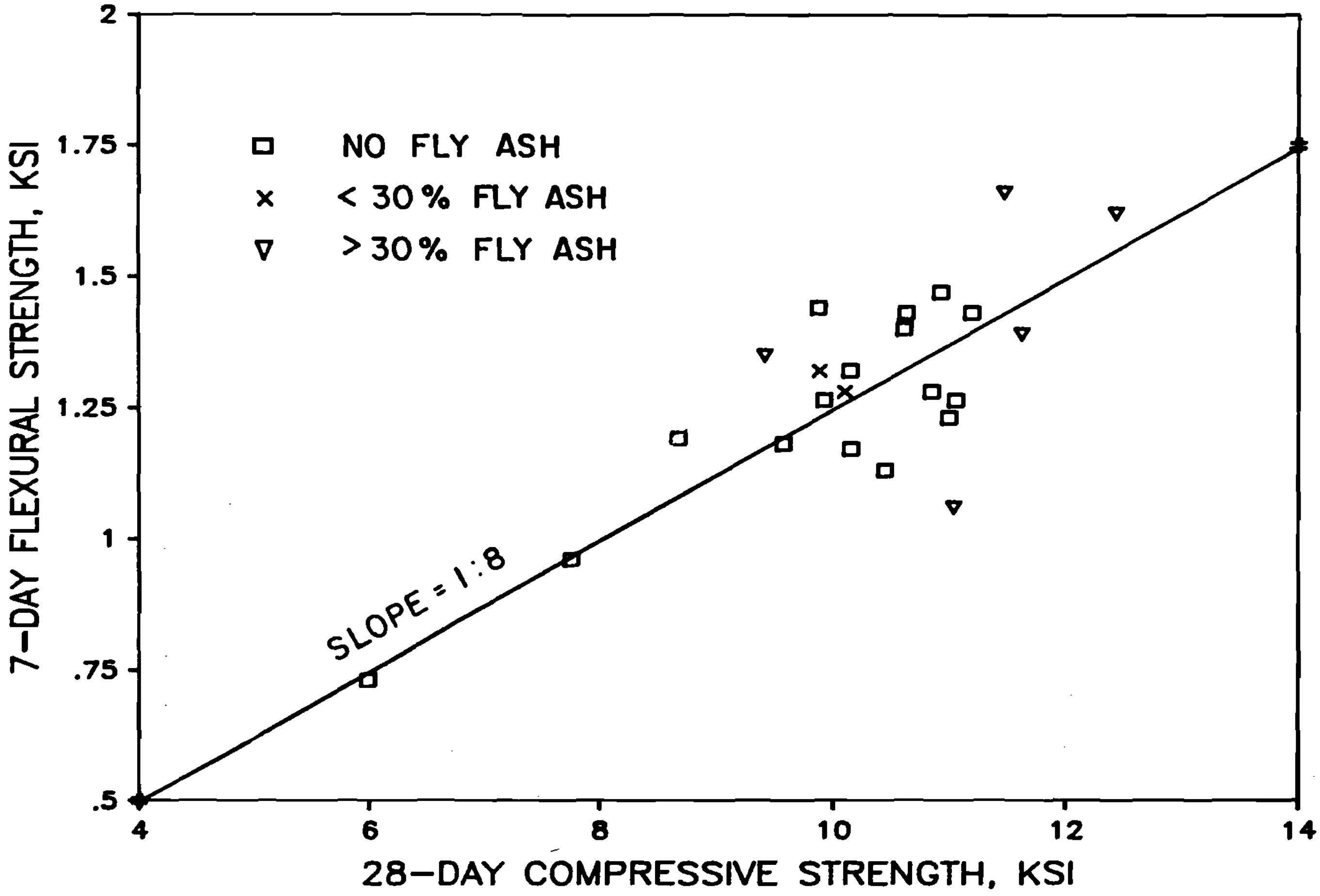


Fig. 11.5 28-day compressive strength of 6-in. x 12-in. cylinders versus 7-day flexural strength of 6-in. x 6-in. x 20-in. beams.

Based on these findings, it is recommended that concrete strength be specified according to design and construction requirements. If a given compressive strength is required to sustain construction or design loads, that strength should be specified at the time required. If an early indicator is desired to determine if the concrete will gain adequate strength, an earlier test age and required strength at that age, either compressive or flexural, should be specified which would accurately predict the strength at later ages. On the other hand, if the concrete is required to have a given flexural strength at 7 days due to construction loads, that required strength should be specified.

CHAPTER 12

RESULTS OF FIELD PILOT STUDY

12.1 Introduction

Trial batches were performed in a prestressing plant in Amarillo, Texas, to produce a high strength concrete mix for use in a Texas Highway Department Project. Job specifications called for the concrete compressive strength to be at least 7,400 psi for early release of the prestressing tendons, and 9,600 psi at 28 days. A "Special Provision to Item 421 Concrete for Structures" and "Supplement No. 2 to Construction Bulletin C-11" were included with the project specifications to cover the use of fly ash in concrete, and to provide guidelines for performing high strength concrete trial batches incorporating fly ash. These documents are included in Appendix E.

12.2 Material Properties

The properties of the materials used in the trial batches are given in Table 12.1. As shown, all trial batches consisted of 1-inch nominal maximum size crushed limestone, natural sand, Type III cement, Type B (ASTM Class C) fly ash, a retarding/water-reducing chemical admixture, and a high range water reducing chemical admixture.

12.3 Trial Batch Information

Eight trial batches were performed. Mix proportions per cubic yard and fresh concrete properties are presented in Table 12.2. For purposes of calculating mix proportions, the unit weight of water was taken as 62.5 pcf, and mixes were assumed to contain 1.5 percent entrapped air. Chemical admixtures are included as part of the mixing water. The slump of concrete corresponds to that after the superplasticizer was added.

For each trial batch, all ingredients except the superplasticizer were batched and mixed in a central-mix drum. After mixing for approximately four minutes, the concrete was examined for cohesiveness. If the concrete was not cohesive, water was added. Once the concrete was cohesive, the superplasticizer was added. After being mixed for approximately four more minutes, the concrete was emptied into a truck equipped with a "side-winder", or auger, which was used to discharge the concrete into the forms.

The concrete from the trial batches was used to cast T-beams. For all mixes except numbers 1 and 2, the concrete placed easily, requiring a minimum of vibration. The concrete from trial batch numbers 1 and 2, however, was extremely harsh, and difficult to place. Additional dosing with a superplasticizer would probably have improved

TABLE 12.1 Properties of materials used in high strength concrete trial batches.

MATERIAL	DESCRIPTION	
Fine aggregate	ASTM C-33	
	Natural river sand	
	Percent voids content:	37%
	BSG_{ssd}:	2.62
	Loose unit weight_{ssd}:	103.44 pcf
Coarse aggregate	ASTM C-33 No. 57 (1 inch to No. 4)	
	Crushed limestone	
	Percent voids content:	47.6%
	BSG_{ssd}:	2.76
	Loose unit weight:	90.37 pcf
Cement	ASTM C-150 Type III	
	BSG:	3.10
Fly ash	ASTM C-618 Class C	
	TSDHPT Type B	
	BSG:	2.65
Chemical Admixture		
WR-R A	ASTM C-494 Type D	
	Aqueous solution of hydrolized starch	
	SG:	1.20-1.24
	Percent solids:	44-50%
	pH:	5.9-9.5
	Dosage:	2-4 oz/cwt
WR-R B	ASTM C-494 Type D	
	Lignosulphonate	
	SG:	1.19
	Percent solids:	42.4%
	Dosage:	4 oz/cwt
HRWR	ASTM C-494 Type A or F	
	Naphthalene	
	SG:	1.20
	Percent solids:	39.1%
	Dosage:	
	Type A	4 oz/cwt
	Type F	16 oz/cwt

TABLE 12.2 Mix proportions per cubic yard and fresh concrete properties for high strength concrete trial batches.

TRIAL BATCH NO.	1	2	3	4	5	6	7	8
Cement, lbs.	608	609	602	561	559	568	528	559
Fly ash, lbs.	205	206	203	239	238	193	225	208
Sand, lbs. (SSD)	1108	1112	1146	1113	1108	1171	1170	1108
Coarse Agg., lbs. (SSD)	2078	2079	2035	2092	2082	2080	2086	2083
Water, lbs.	231	229	236	227	234	224	224	242
RWR-A, oz/cwt	3.03	2.02	2.02	2.04	2.04	2.00	2.03	- --
RWR-B, oz/cwt	- --	- --	- --	- --	- --	- --	- --	6.23
HRWR, oz/cwt	16.04	20.32	24.24	22.45	22.45	22.40	24.86	26.89
w/(C+FA) ratio, by wt.	0.284	0.281	0.293	0.284	0.294	0.294	0.298	0.316
Fly ash content, % by vol	28.3	28.4	28.3	33.3	33.3	28.4	33.3	30.3
C+FA content, "sacks"	9.02	9.05	8.93	8.95	8.91	8.45	8.42	8.54
Slump, in.	3	3-3/4	9	4-3/4	8-1/4	8	9	10
Concrete Temp., °F	66	68	70	69	70	70	69	72
Unit wt., pcf	156.7	156.9	156.4	156.7	156.3	156.9	156.8	155.6

the workability, and placeability, of these mixes. Appearance and placement of the concrete is shown in Figs. 12.1 through 12.4.

Several 4-in. x 8-in. cylinders were cast from each trial batch for purposes of strength evaluation. These cylinders were then subjected to the same curing as the prestressed T-beams. After preset, the beams and cylinders received steam-curing for 14-17 hours. Details are given in Table 12.3

12.4 Test Results

Cylinders were tested to determine the strength of the concrete at release (approximately 16-18 hours) and at seven days. The results are presented in Table 12.4. The compressive strengths of the trial mixes at release and 7-days are shown with respect to the specification requirements in Figure 12.5.

As shown in Figure 12.5, six of the eight trial batches achieved the required release strength at 16-18 hours, and all batches easily surpassed the 28-day required strength when tested at seven days. The mixes which were cured at 150°F for five hours had release strengths which were much higher than those of mixes cured at only 125°F for five hours despite having a lower binder content. It is probable that had trial batch numbers 1 and 5 been cured at 150°F, these mixes would have achieved the required release strength within 16-18 hours, also.

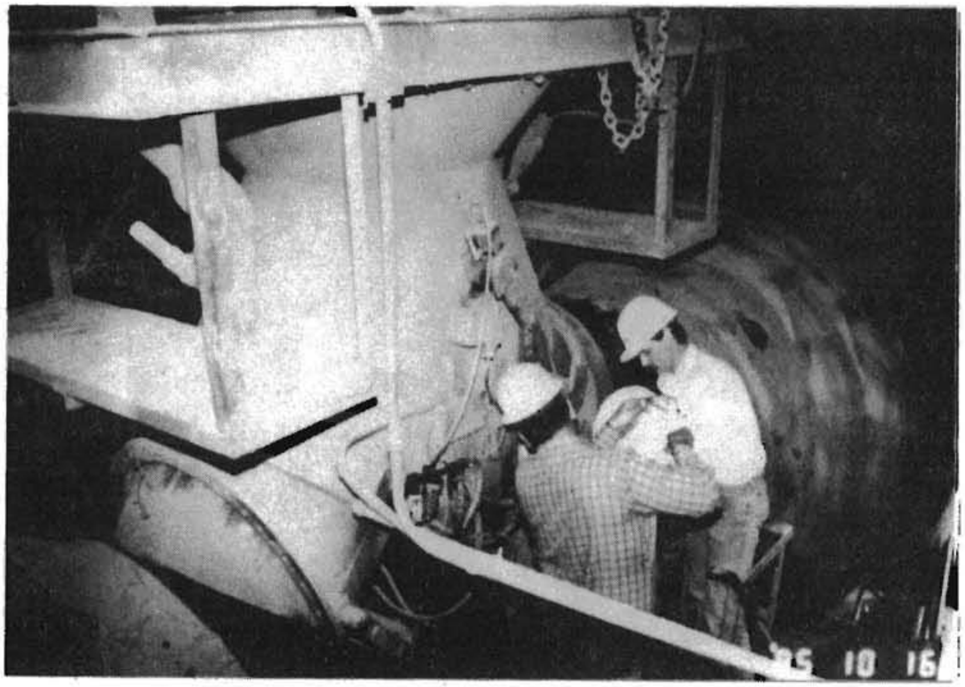


Fig. 12.1 Addition of superplasticizer to central-mix drum.

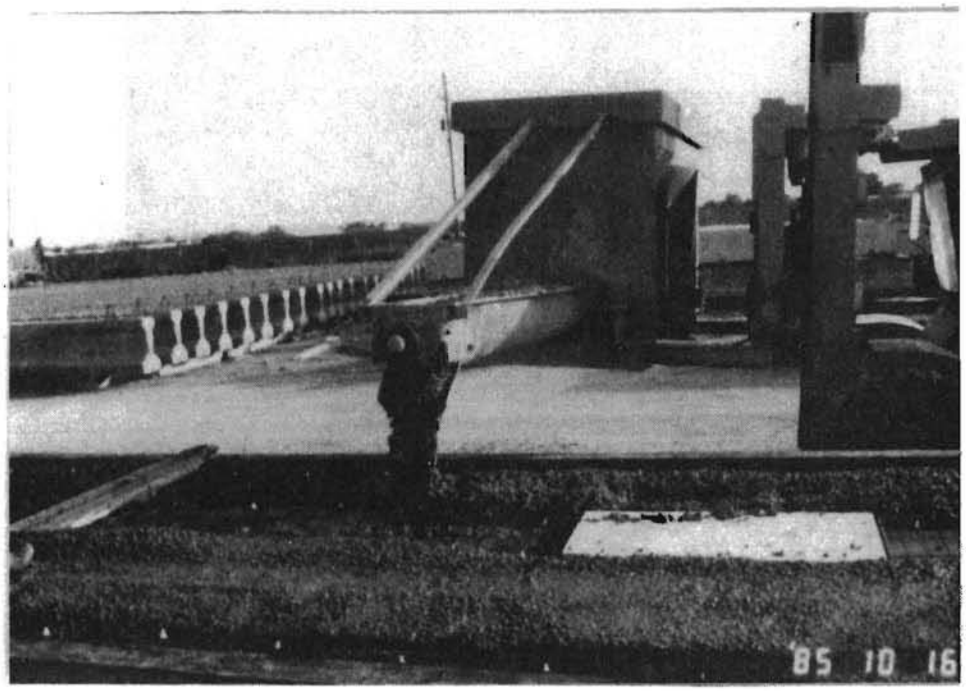


Fig. 12.2 Placement of concrete into prestressed forms.

Fig. 12.3 Finishing of concrete.

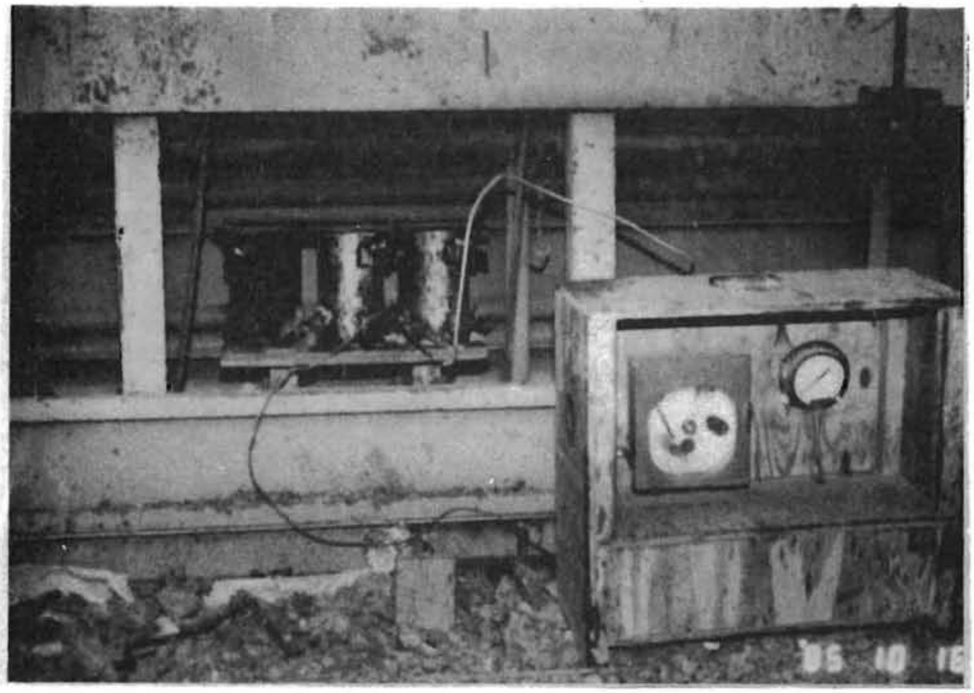


Fig. 12.4 Strength specimens cured in prestressing bed.

TABLE 12.3 Curing received by each trial batch.

TRIAL BATCH NUMBER	STEAM CURING RECEIVED
1 through 5	> 100 °F for nine hours 125 °F for five hours
6 through 8	> 100 °F for twelve hours 150 °F for five hours

TABLE 12.4 Test results obtained from high strength concrete trial batches.

TRIAL BATCH NUMBER	RELEASE STRENGTH, psi	7-DAY STRENGTH, psi
1	7240	10,990
2	8590	11,620
3	8030	12,100
4	7710	11,620
5	7350	11,940
6	8670	10,750
7	8900	10,830
8	9300	10,590

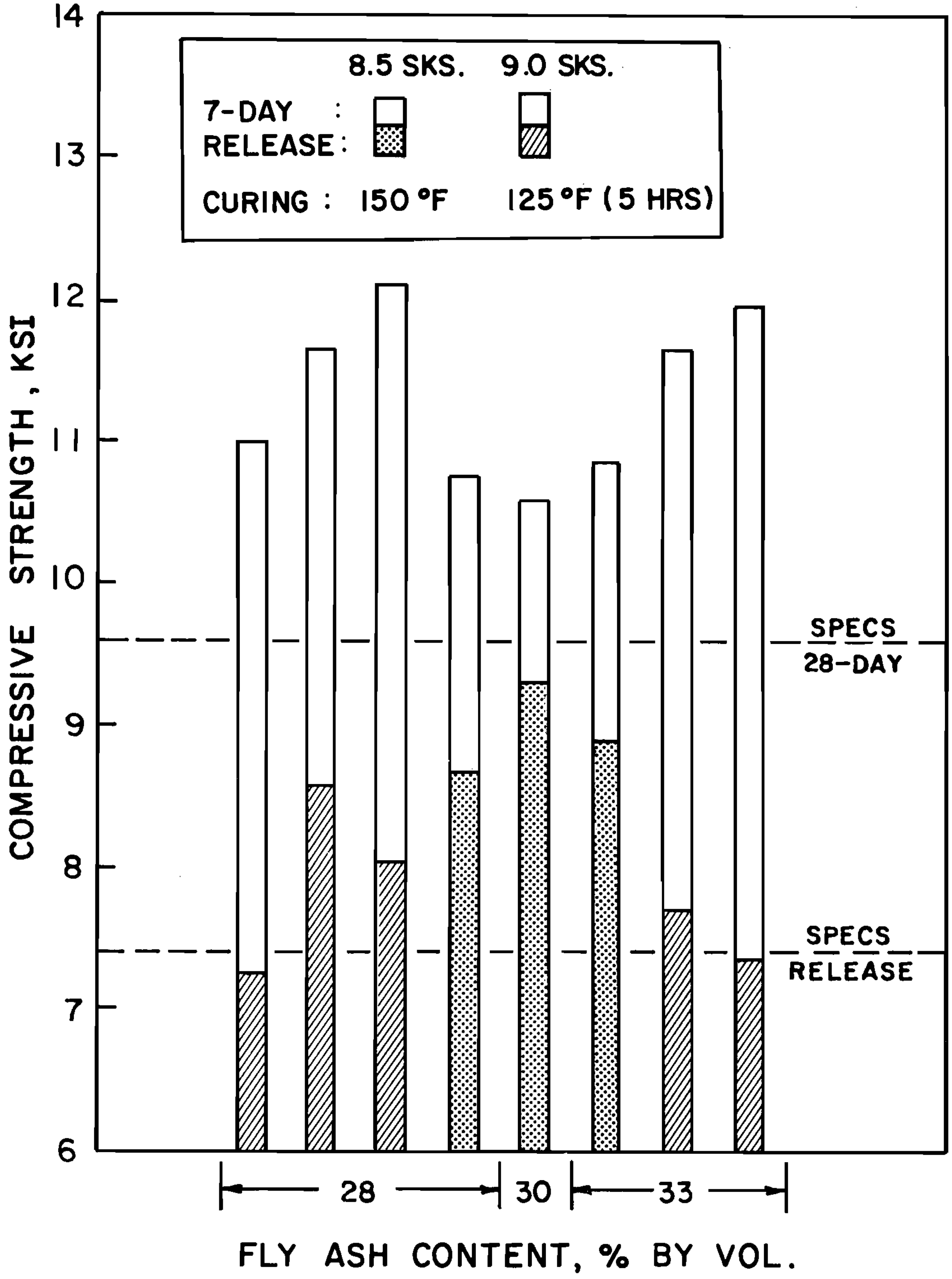


Fig. 12.5 Compressive strength test results at release and 7 days for high strength concrete trial batches conducted at prestressing plant.

CHAPTER 13

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

13.1 Summary

The objective of this research program was to determine if various quality control procedures are applicable to the production of high strength concrete, and to develop guidelines for the production of high strength concrete in the field. The following variables were studied:

a) specimen size;

b) mold material used in casting specimens;

c) curing conditions;

d) time of initial addition of superplasticizer;

e) redosing with superplasticizer;

f) type of capping material used;

g) age of cap at testing;

h) effect of consolidation;

i) test age;

j) 28-day compressive strength versus 7-day flexural strength;

k) effect of fly ash content.

13.2 Conclusions

Based on the test results obtained from this research study, the following conclusions can be drawn:

1) The compressive strength of 4-in. x 8-in. cylinders is on the order of seven percent lower than that of 6-in. x 12-in. cylinders, for concrete strengths ranging from 7,000 psi to 12,000 psi.

2) The flexural strength of 4-in. x 4-in. x 14-in. beams is on the order of five percent higher than that of 6-in. x 6-in. x 20-in. beams, when tested in third point loading. When tested in center point loading, the flexural strength of 4-

in. x 4-in. x 14-in. beams is similar to that of 6-in. x 6-in. x 20-in. beams.

3) The compressive strength of 6-in. x 12-in. cylinders cast in single-use plastic molds is similar to that of 6-in. x 12-in. cylinders cast in rigid steel molds.

4) The compressive strength of 4-in. x 8-in. cylinders cast in single-use plastic or cardboard molds is similar to that of 4-in. x 8-in. cylinders cast in rigid steel molds.

5) The compressive strength of 6-in. x 12-in. cylinders is decreased when cured using a curing compound, rather than in a fog room.

6) The flexural strength of concrete is significantly decreased when specimens are cured with a curing compound, rather than in a fog room. Beams coated with curing compound achieved on the order of only 58 percent of the flexural strength attained by specimens cured in a fog room.

7) Concrete to which superplasticizer is added at both the ready-mix plant and the job site achieved a compressive strength at 56-days which was on the order of five percent higher than a similar mix to which superplasticizer was added at the site only.

8) Concrete to which superplasticizer is added at both the ready-mix plant and the job site achieved a flexural strength which was slightly higher than that of concrete to which superplasticizer was added at the site only.

9) High strength concrete which is redosed with superplasticizer to restore high slump has compressive and flexural strength at least equal to that of the same concrete before redosing, up to a total of three additions of the superplasticizer.

10) The compressive strength of concrete cylinders capped using a high strength sulfur-based capping compound was not significantly affected by the age of the cap at testing, within the range from 30 minutes to four hours.

11) For concrete strengths below 8,000 psi, 6-in. x 12-in. cylinders capped with high strength sulfur mortar achieved strengths which were slightly higher than cylinders tested using aluminum caps fitted with polyurethane inserts. However, for concrete strengths above 10,000 psi, 6-in. x 12-in. cylinders tested with aluminum caps fitted with polyurethane inserts achieved strengths which were on the order of eleven percent higher than those of

cylinders which were capped with high strength sulfur mortar. A similar trend occurs when testing 4-in. x 8-in. cylinders.

12) Cylinders capped with high strength sulfur mortar consistently tested higher than cylinders capped with another lower strength sulfur mortar.

13) For high slump (9+ inches) concrete, method of consolidation, either rodding or vibration, does not affect the compressive strength test results of the concrete.

14) Concrete mixes containing no fly ash gained on the order of nine percent of their 28-day strength between 28 days and 56 days, and nineteen percent of their 28-day strength between 28 days and 91 days.

15) Concrete mixes containing Type B fly ash gained on the order of eleven percent of their 28-day strength between 28 days and 56 days, and nineteen percent of their 28-day strength between 28 days and 91 days.

16) Concrete mixes containing fly ash achieved equal slump to mixes not containing fly ash, at much lower water-to-binder ratios.

17) The concrete mixes which achieved the highest 28-day strengths contained fly ash.

18) The type of coarse aggregate used in producing high strength concrete may limit the concrete strength.

19) The flexural strength of 6-in. x 6-in. x 20-in. beams obtained from center point loading are on the order of sixteen percent higher than those obtained from third point loading.

20) The flexural strengths of 4-in. x 4-in. x 14-in. beams obtained from center point loading are on the order of nine percent higher than those obtained from third point loading.

21) On the average, the relationship between the compressive strength of 6-in. x 12-in. cylinders and the flexural strength of 6-in. x 6-in. x 20-in. beams tested in center point loading is eight-to-one.

22) High strength concrete can be, and has been, produced for use in Texas highway applications.

13.3 Recommendations for Further Research

Based on the findings of the study presented herein, the following directions for further investigation are suggested:

1) Study the effect of the use of fly ash in high strength concrete on creep at early ages, simulating prestressing applications.

2) Study the effect of entrained air on the durability and strength of high strength concrete.

3) Study the durability of high strength concrete cured with curing compound, in both highway and structural applications.

4) Study the use of plant-added extended life superplasticizers in the production of high strength concrete.

APPENDIX A

STRENGTH VERSUS TIME CURVES

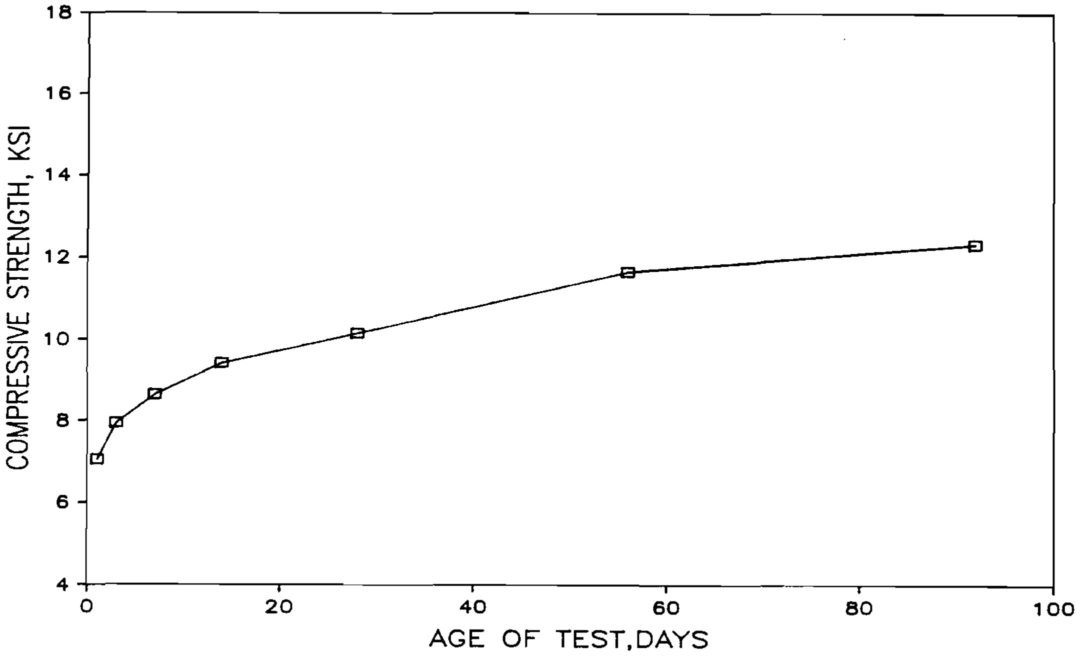


Fig. A.1 Strength versus time curve for Mix #16-107-00.

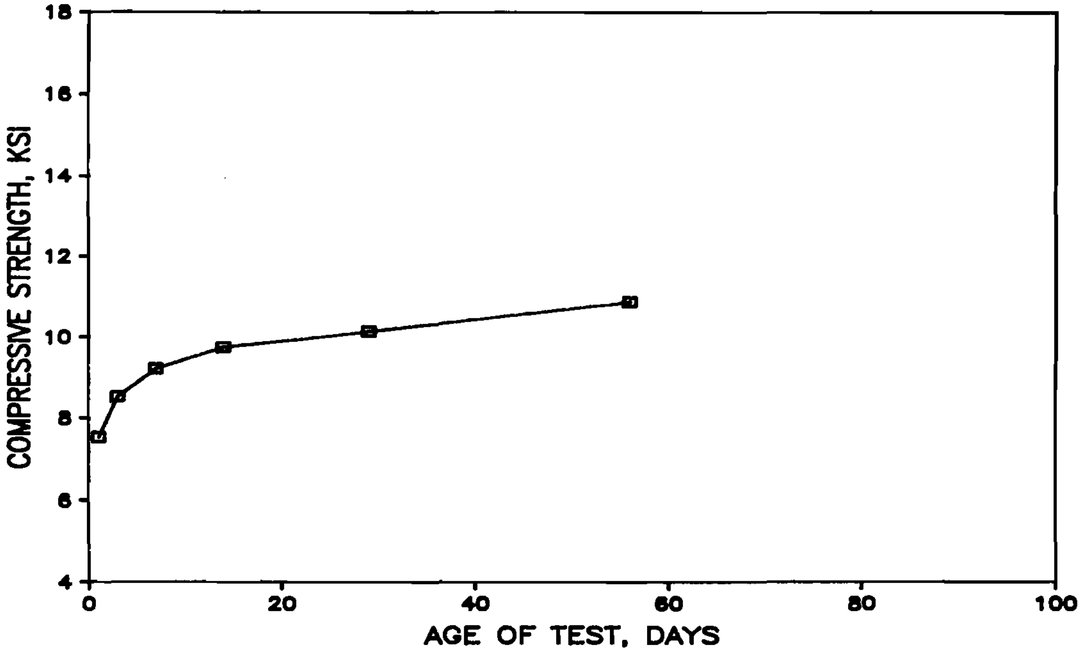


Fig. A.2 Strength versus time curve for Mix #09-106-00.

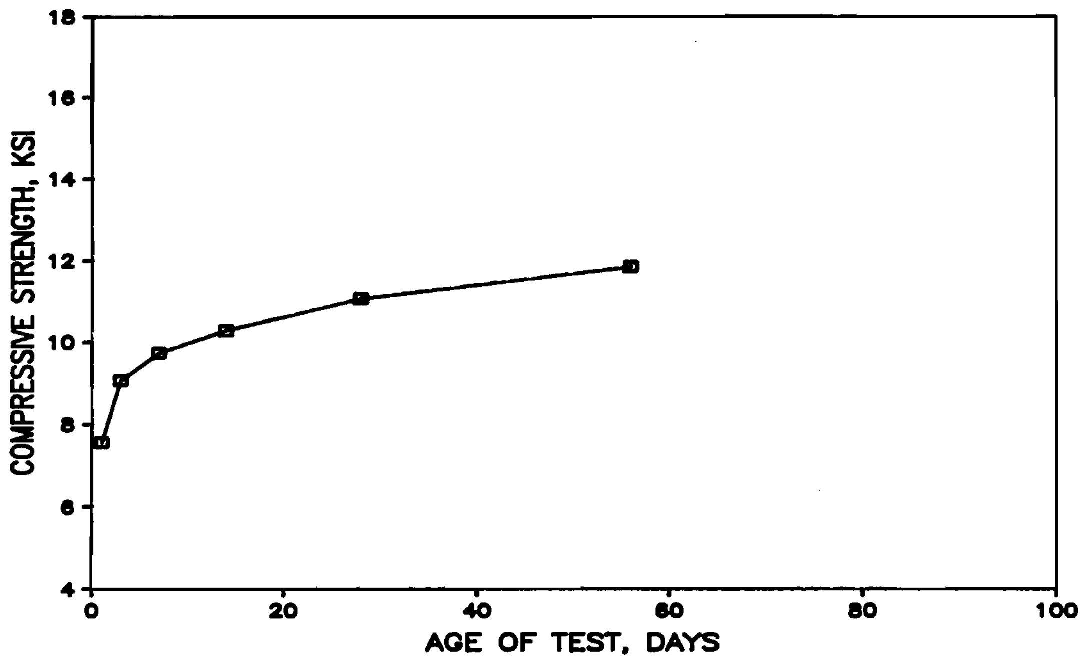


Fig. A.3 Strength versus time curve for Mix #04-100-00.

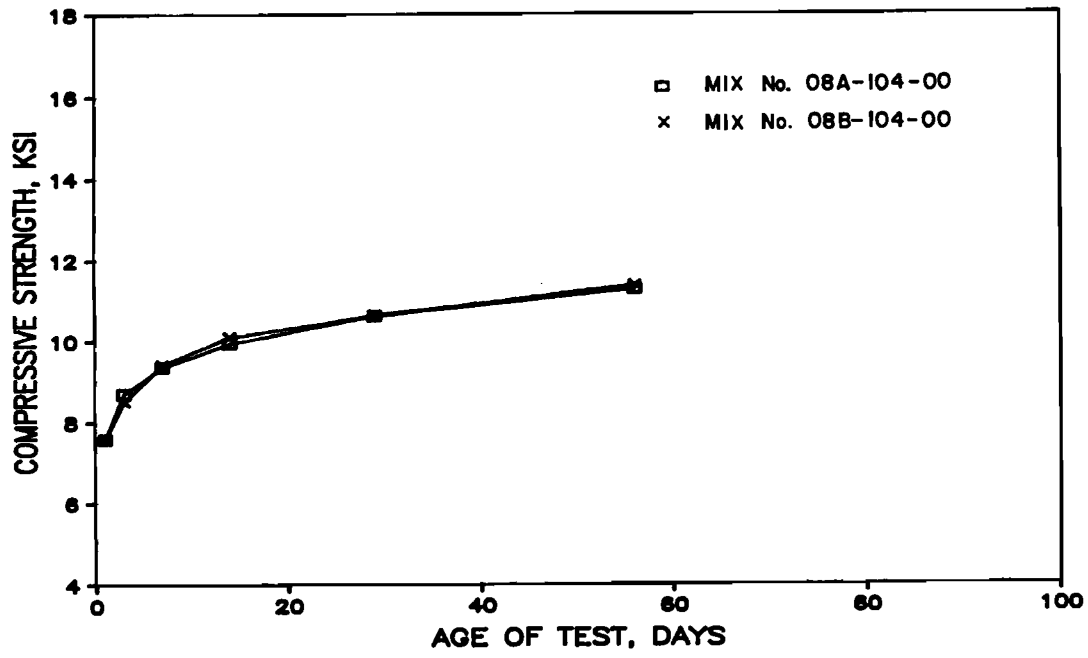


Fig. A.4 Strength versus time curve for Mix #08A & B-104-00.

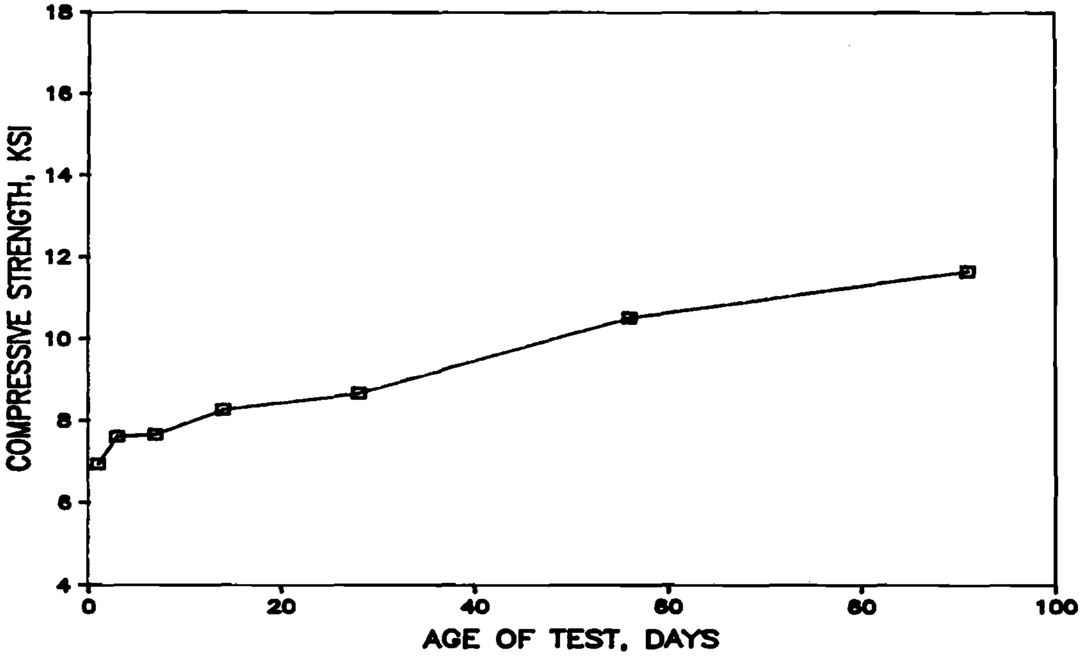


Fig. A.5 Strength versus time curve for Mix #13-100-00.

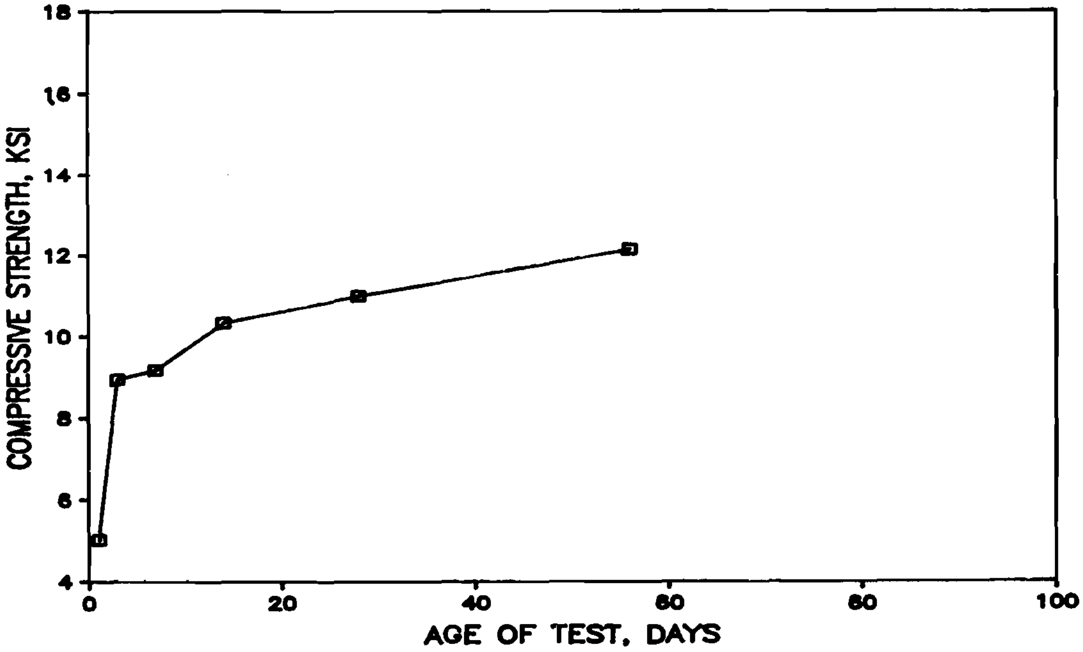


Fig. A.6 Strength versus time curve for Mix #02-095-00.

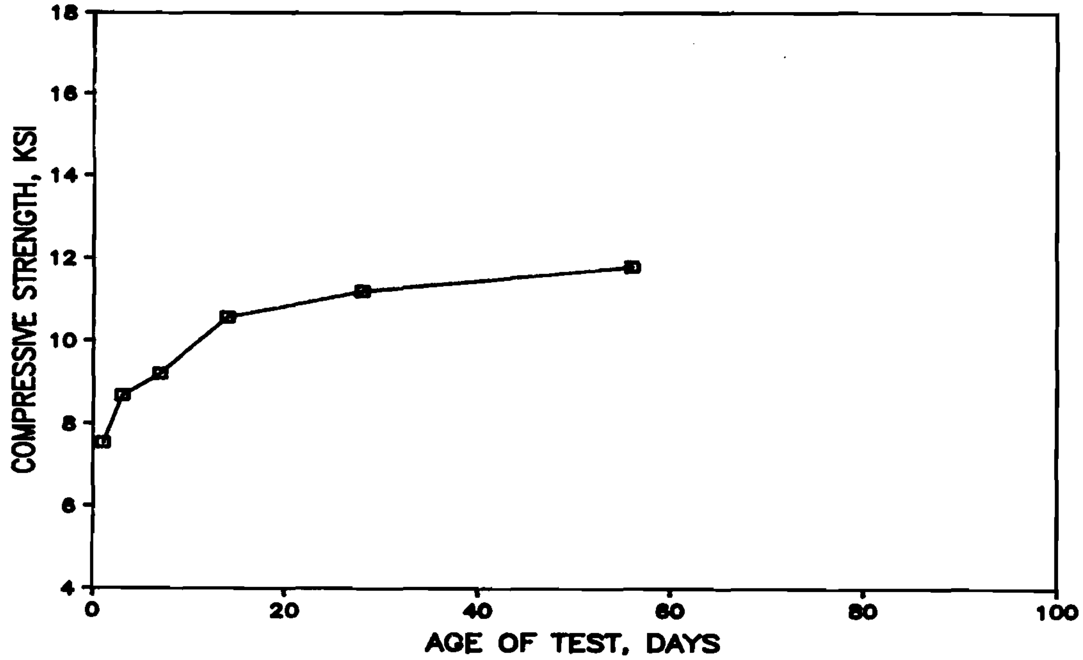


Fig. A.7 Strength versus time curve for Mix #01-107-00.

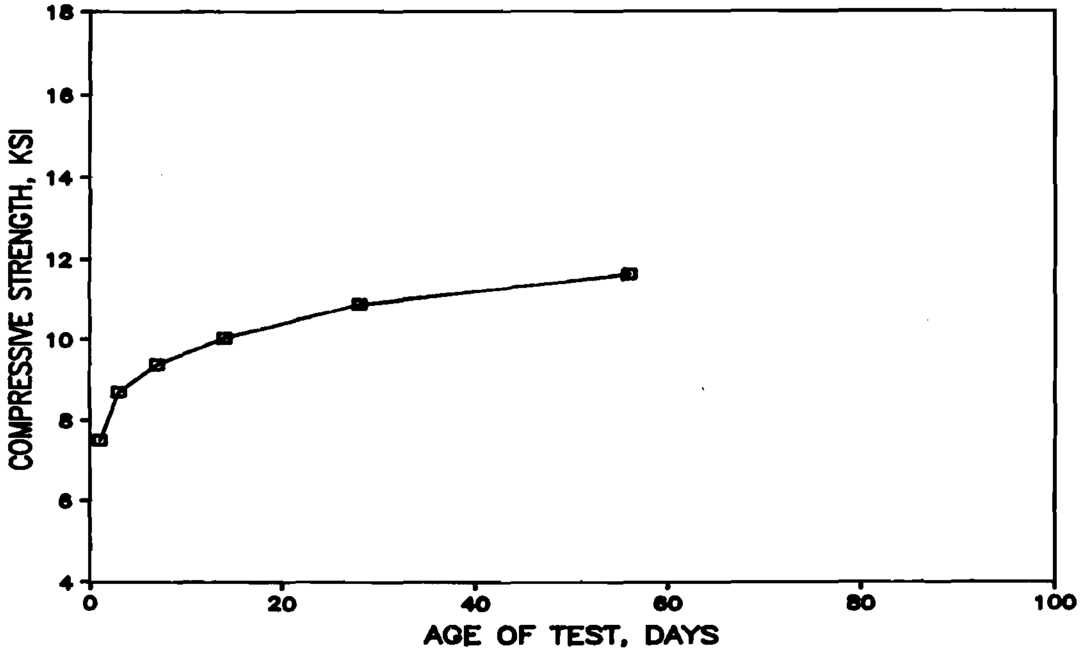


Fig. A.8 Strength versus time curve for Mix #06-097-00.

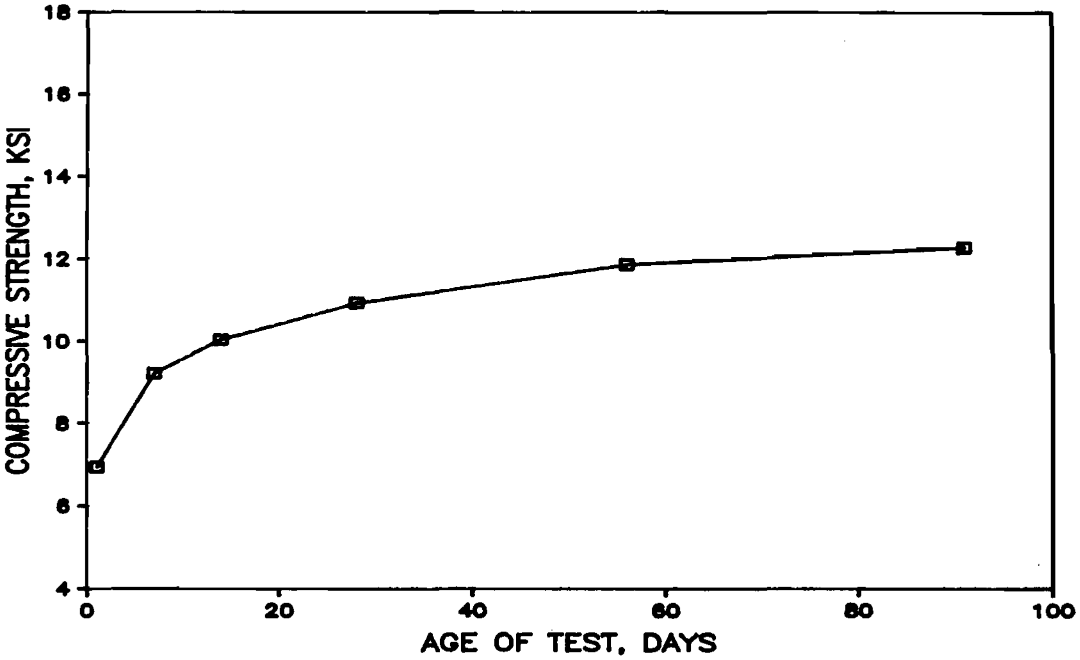


Fig. A.9 Strength versus time curve for Mix #19-103-00.

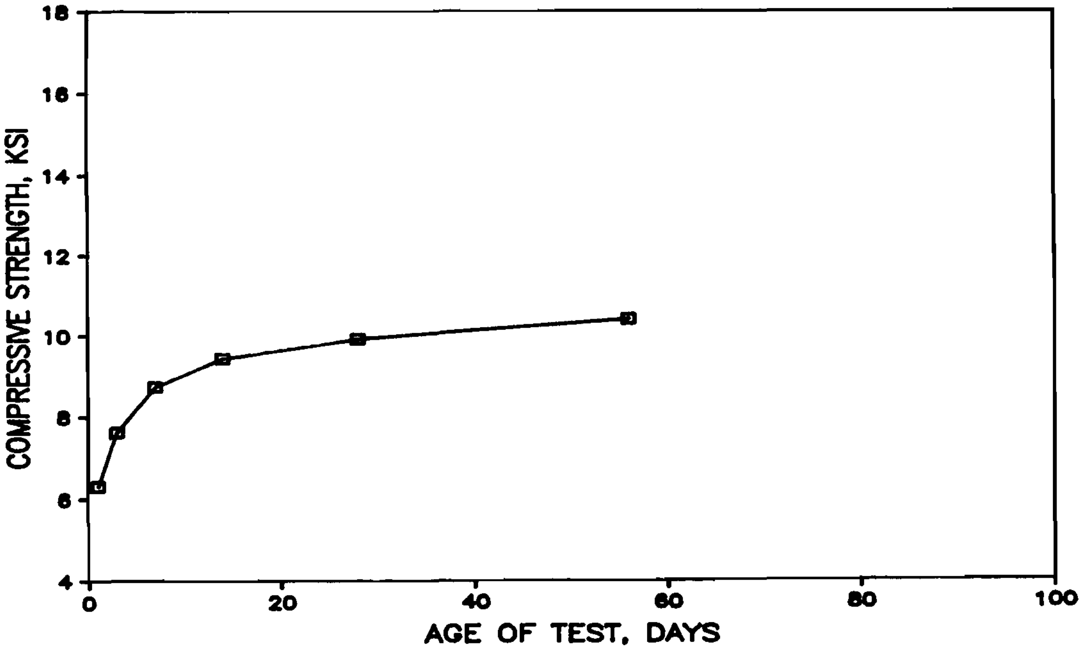


Fig. A.10 Strength versus time curve for Mix #03-096-00.

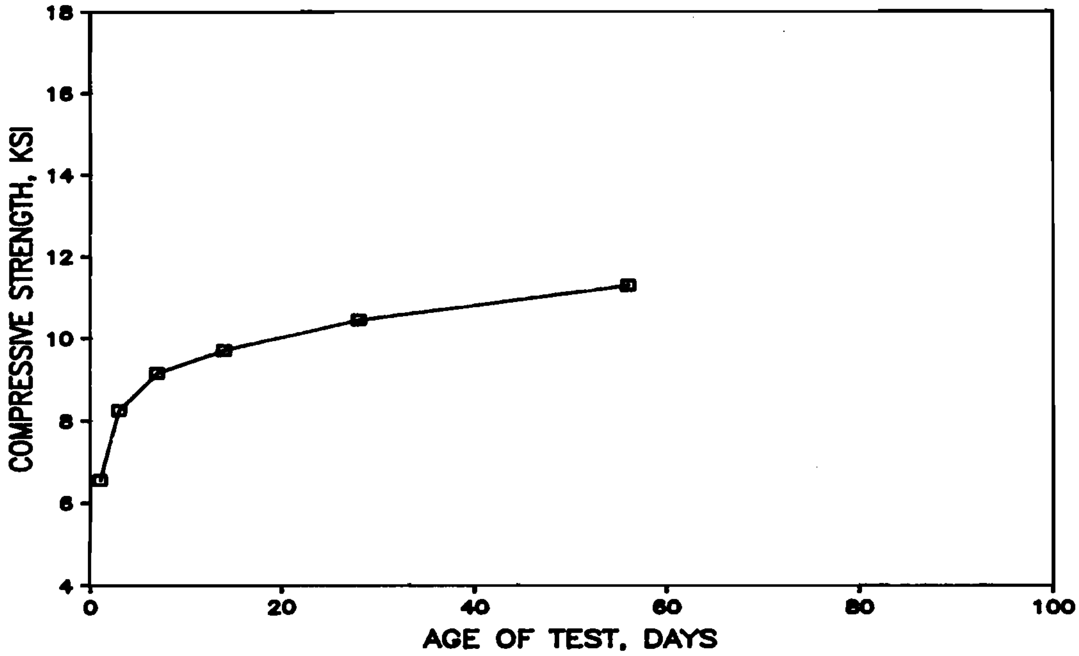


Fig. A.11 Strength versus time curve for Mix #05-089-00.

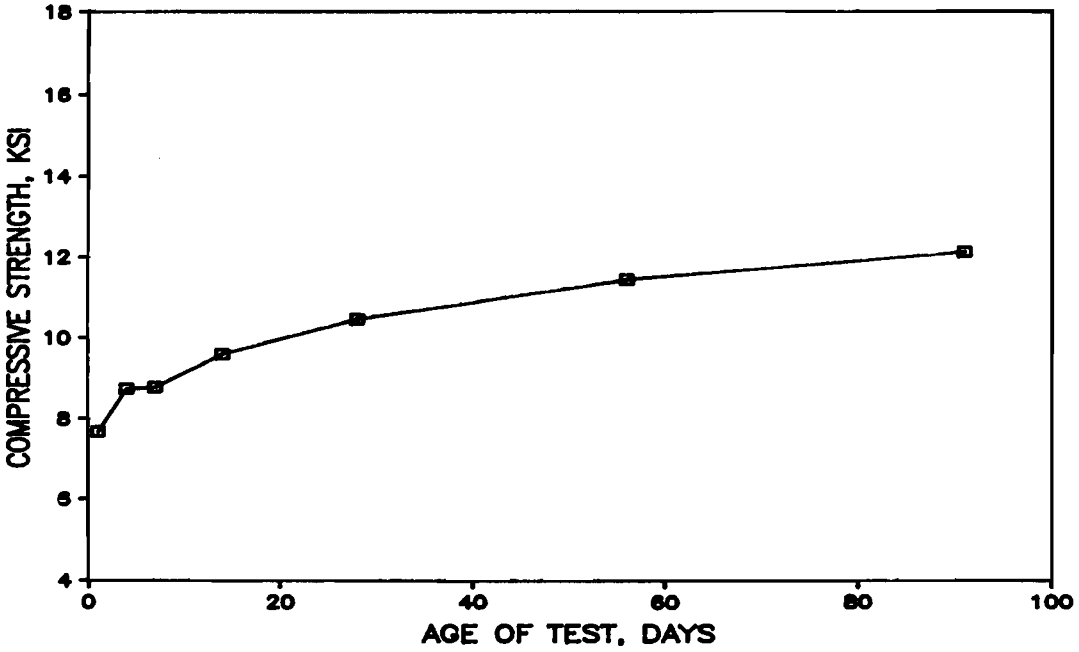


Fig. A.12 Strength versus time curve for Mix #10-094-00.

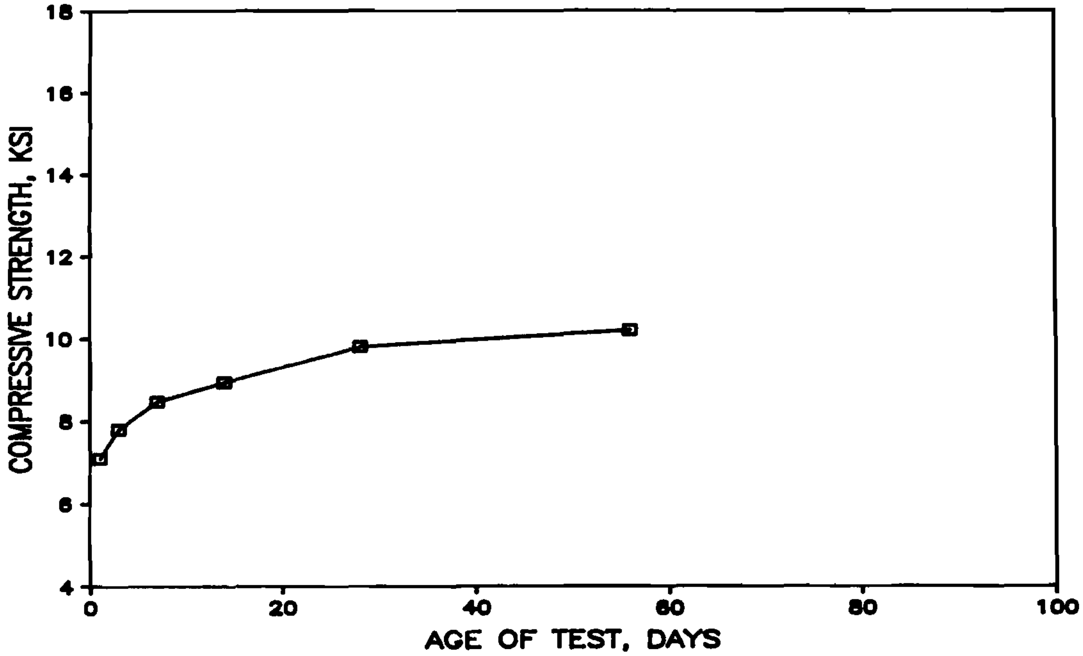


Fig. A.13 Strength versus time curve for Mix #07-098-00.

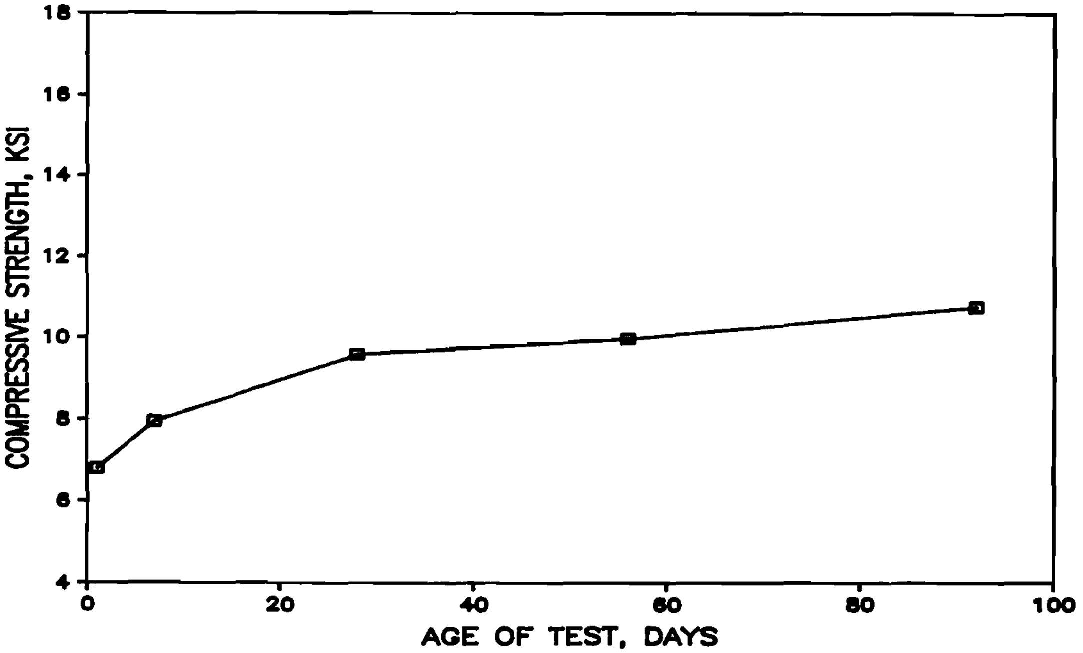


Fig. A.14 Strength versus time curve for Mix #17-100-00.

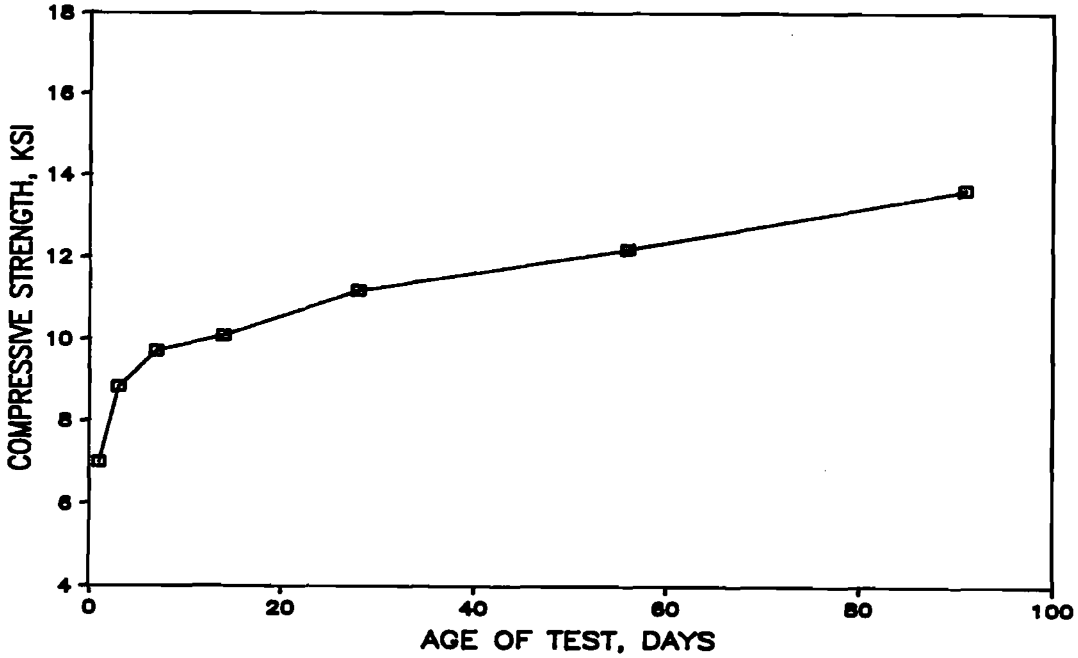


Fig. A.15 Strength versus time curve for Mix #14-110-28.

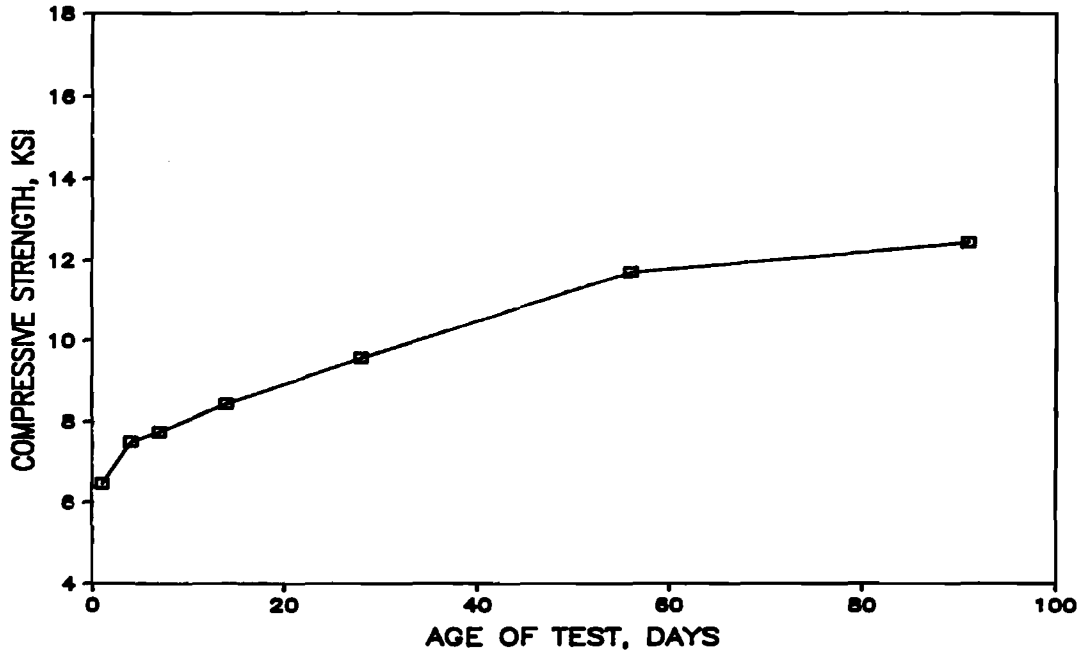


Fig. A.16 Strength versus time curve for Mix #11-093-27.

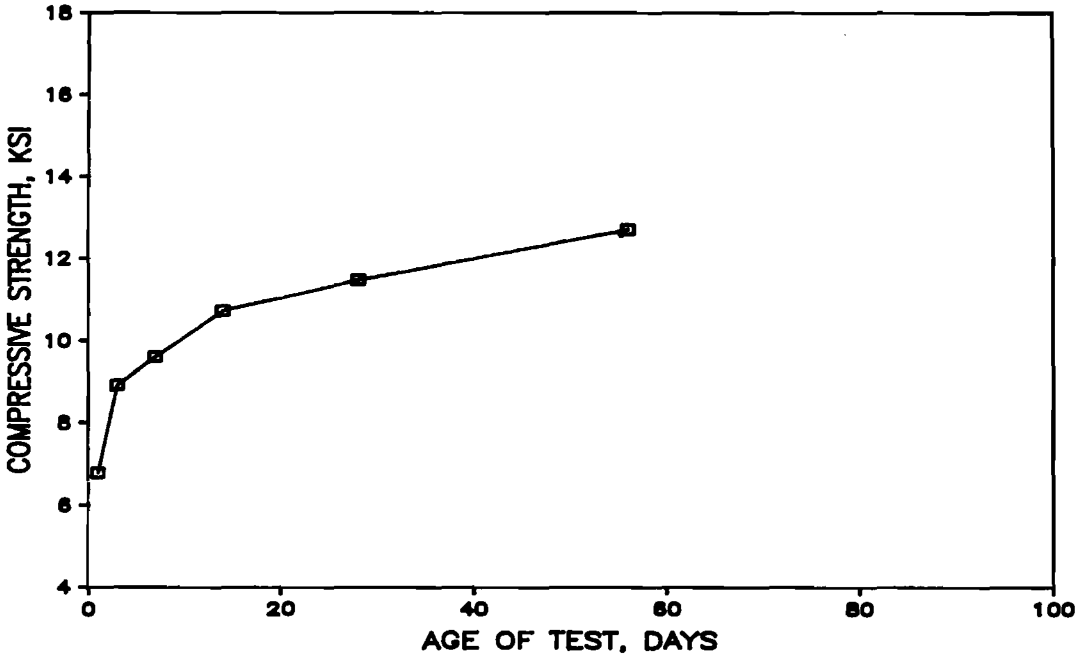


Fig. A.17 Strength versus time curve for Mix #15-112-38.

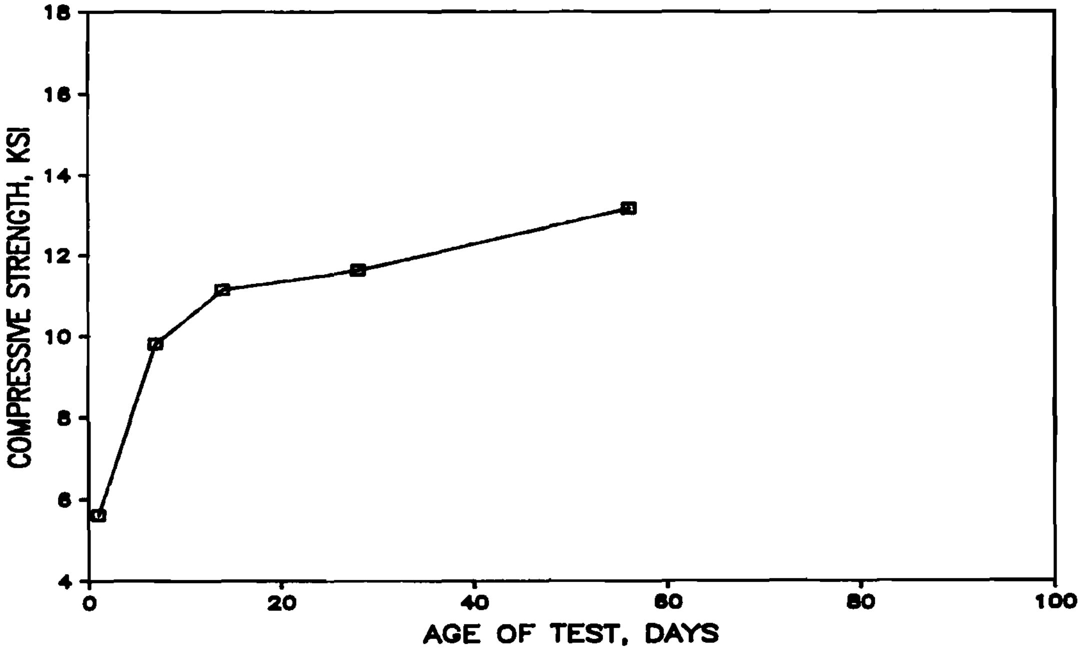


Fig. A.18 Strength versus time curve for Mix #20-111-33.

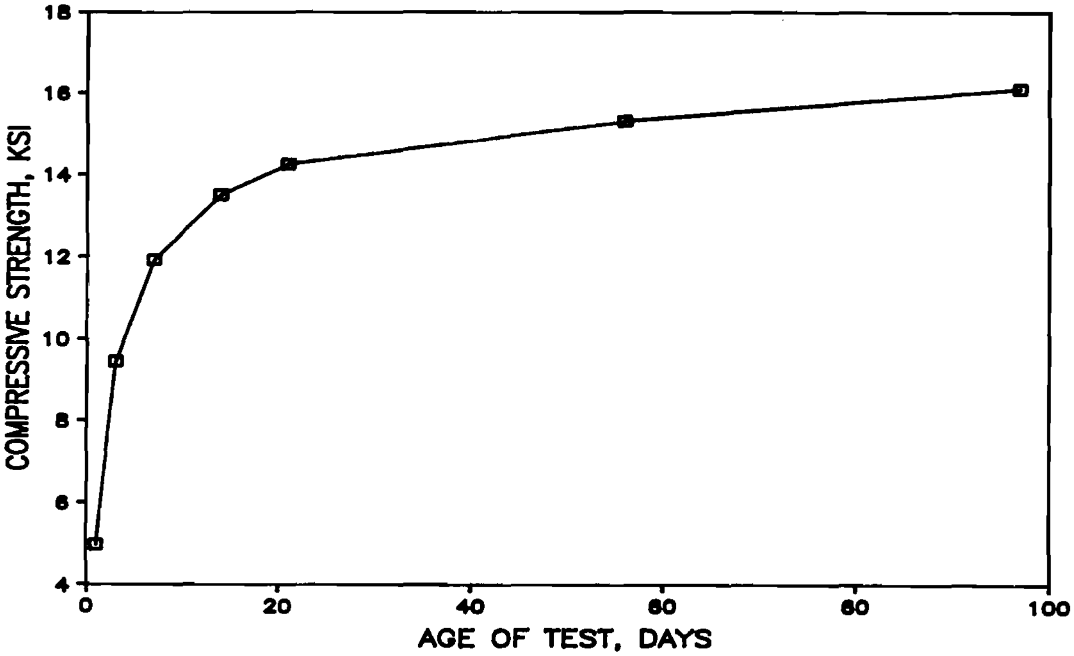


Fig. A.19 Strength versus time curve for Mix #21-112-34.

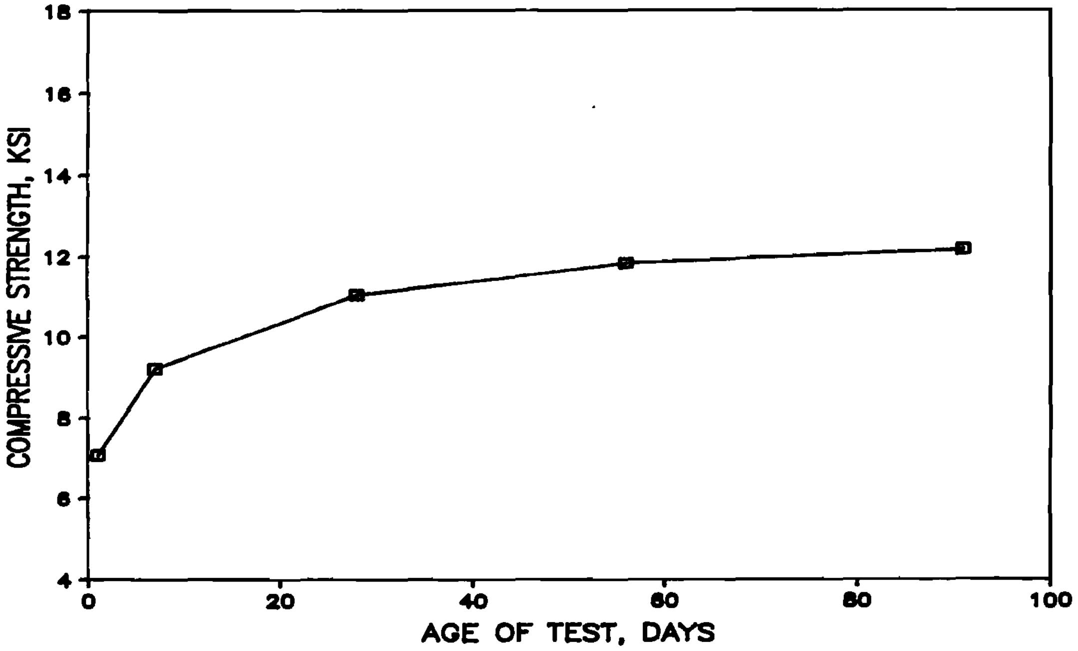


Fig. A.20 Strength versus time curve for Mix #18-111-35.

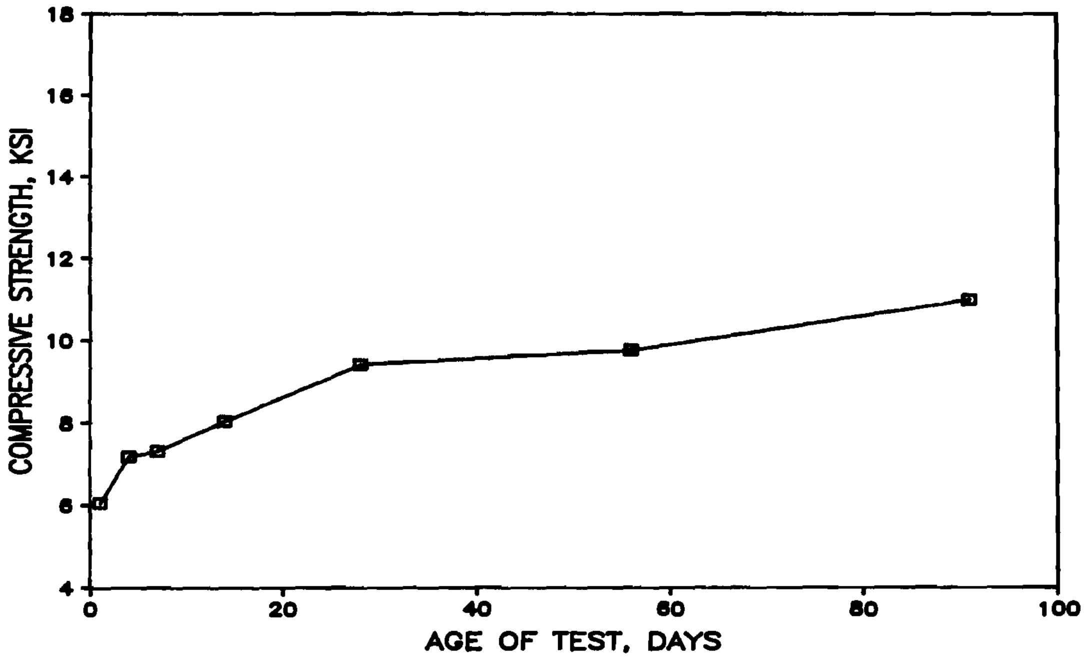


Fig. A.21 Strength versus time curve for Mix #12-093-38.

APPENDIX B

PERCENTAGE STRENGTH GAIN CURVES, 28-DAY

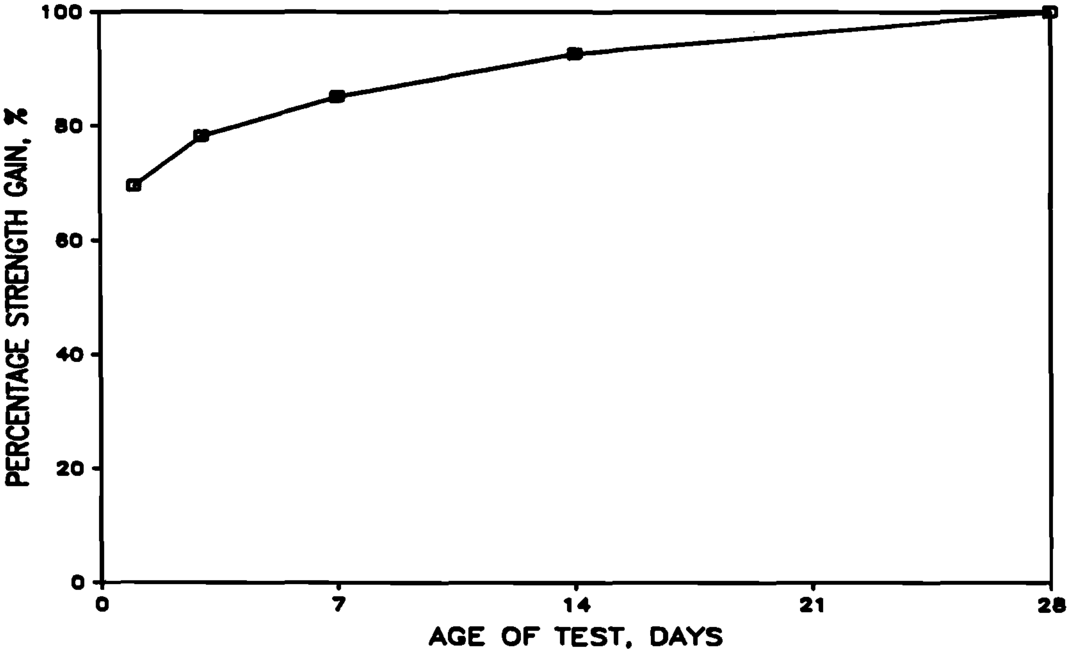


Fig. B.1 Percent strength gain, 28-day, for Mix #16-107-00.

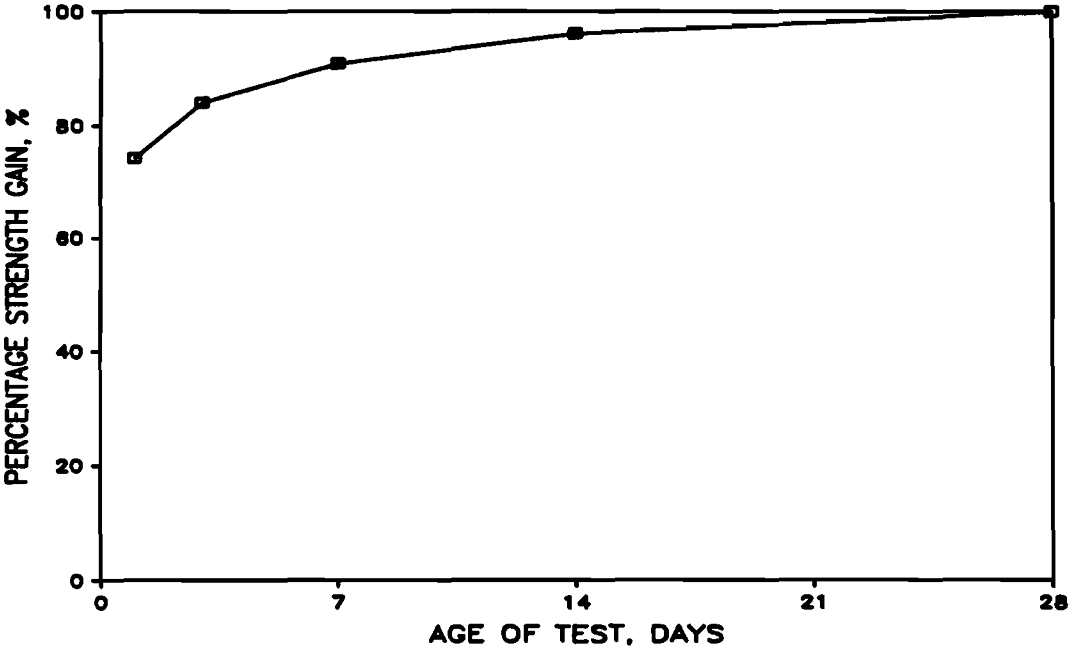


Fig. B.2 Percent strength gain, 28-day, for Mix #09-106-00.

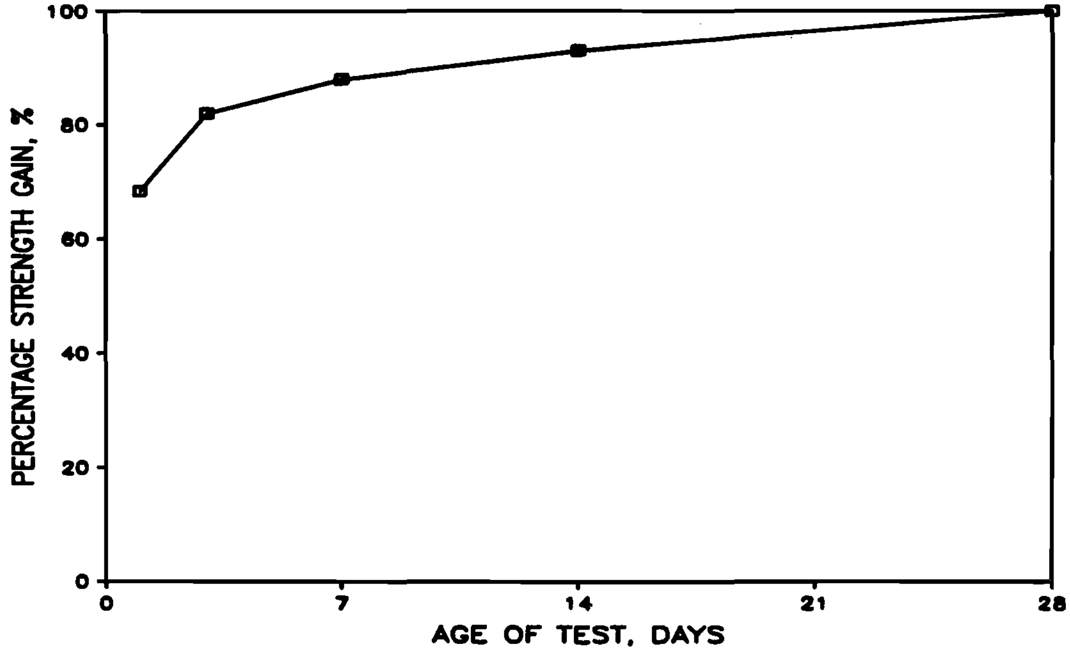


Fig. B.3 Percent strength gain, 28-day, for Mix #04-100-00.

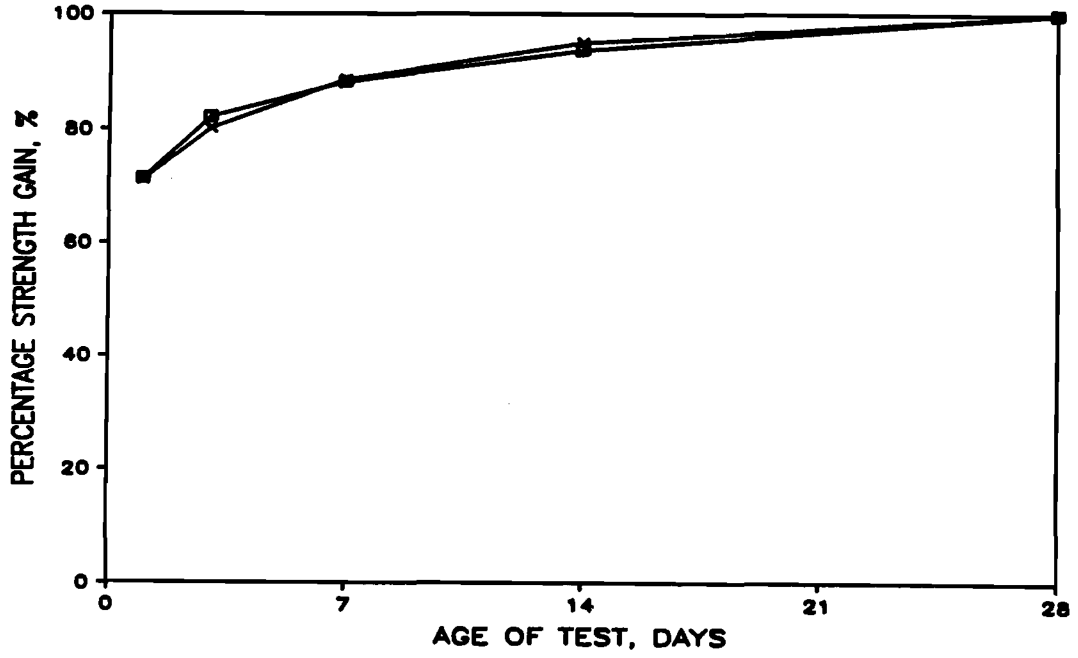


Fig. B.4 Percent strength gain, 28-day, for Mix #08A & B-104-00.

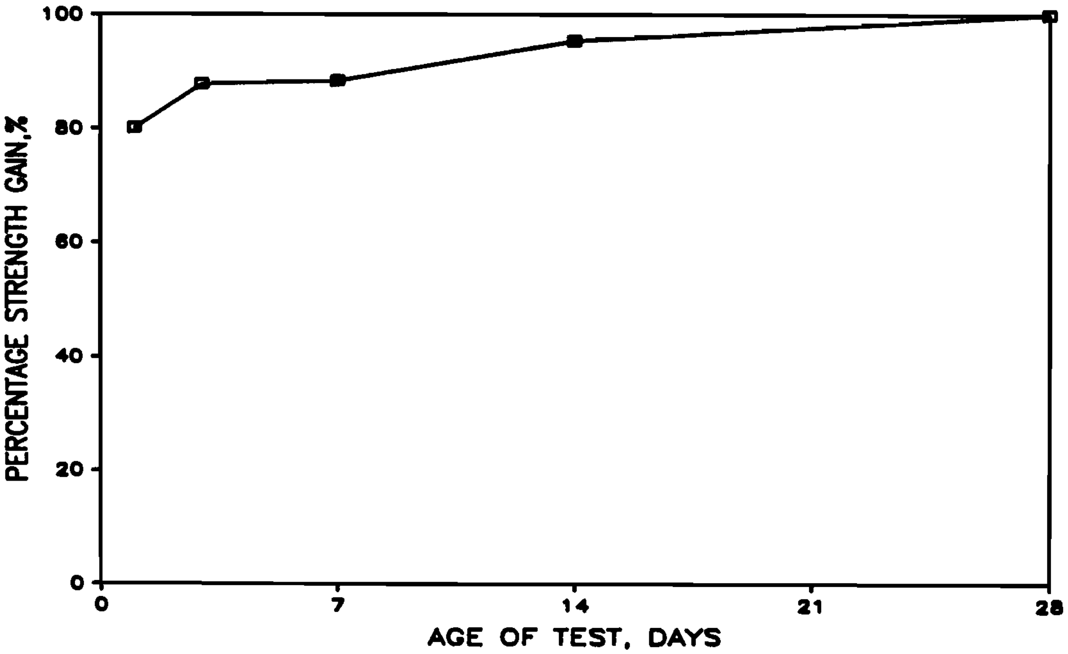


Fig. B.5 Percent strength gain, 28-day, for Mix #13-100-00.

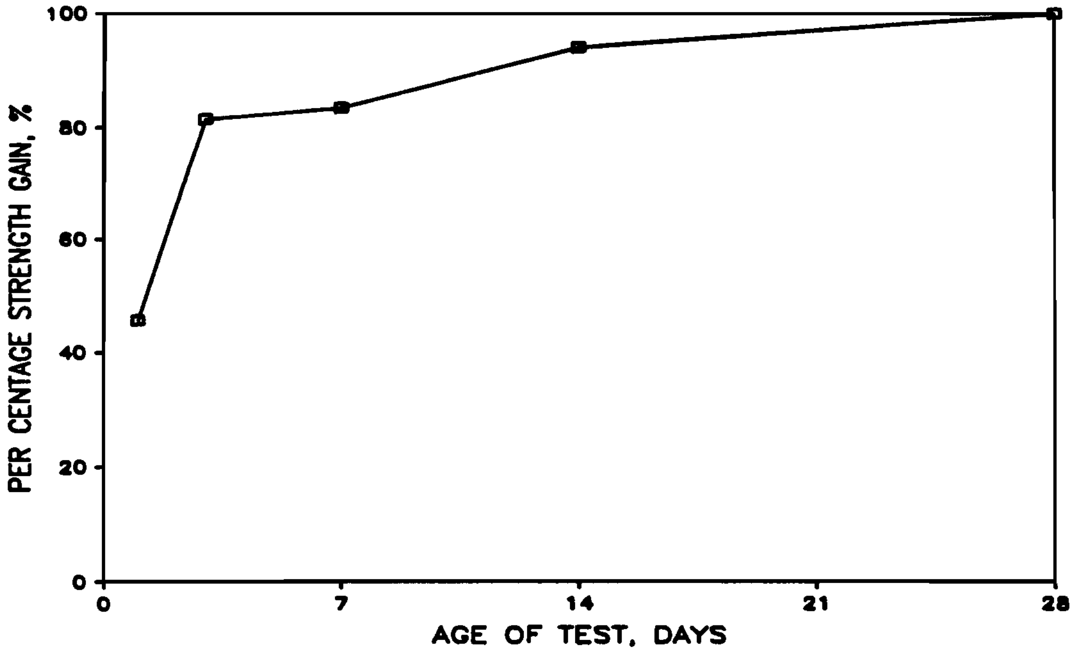


Fig. B.6 Percent strength gain, 28-day, for Mix #02-095-00.

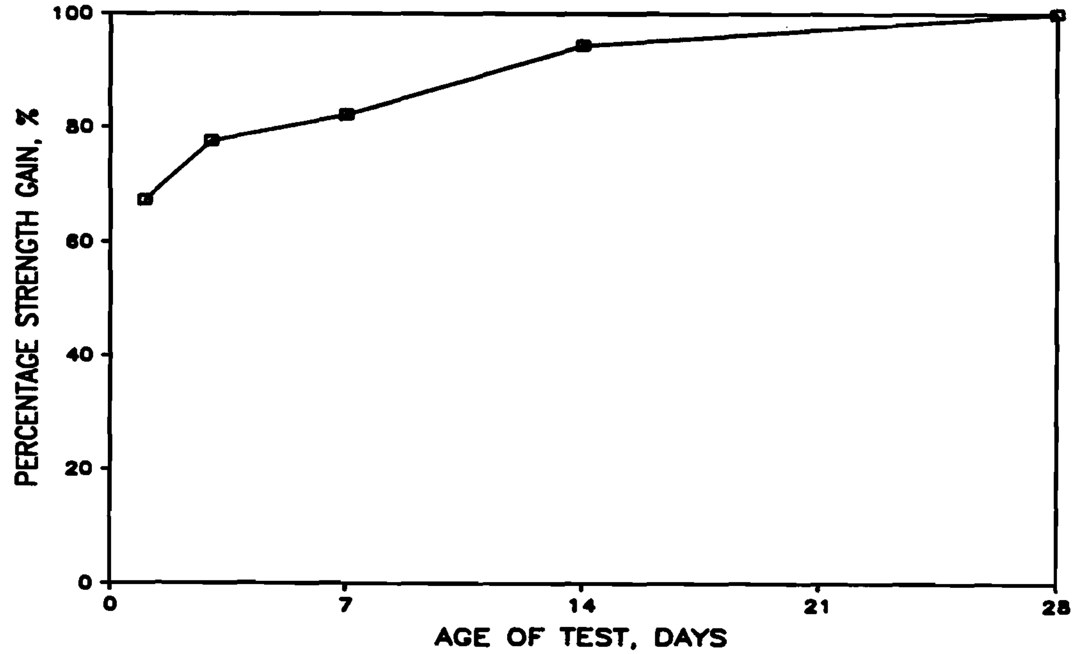


Fig. B.7 Percent strength gain, 28-day, for Mix #01-107-00.

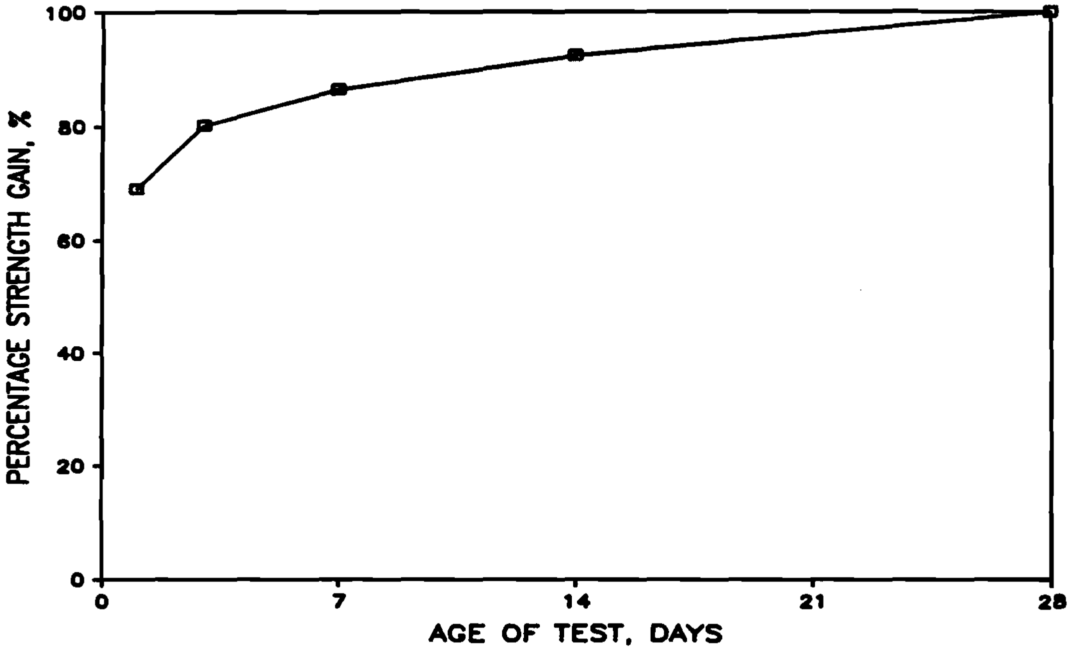


Fig. B.8 Percent strength gain, 28-day, for Mix #06-097-00.

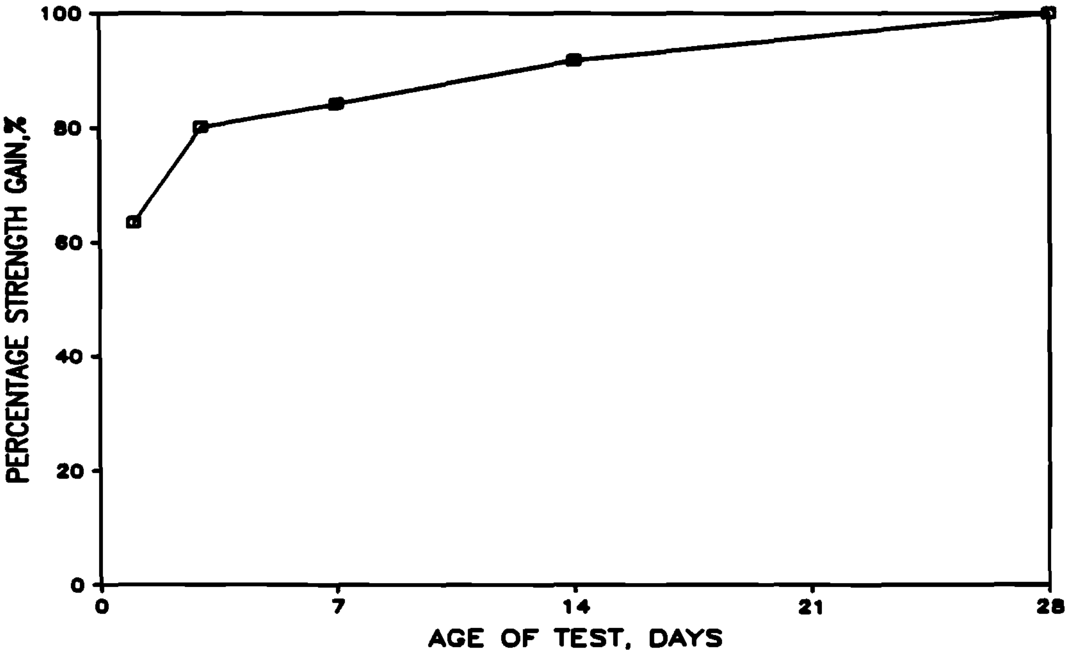


Fig. B.9 Percent strength gain, 28-day, for Mix #19-103-00.

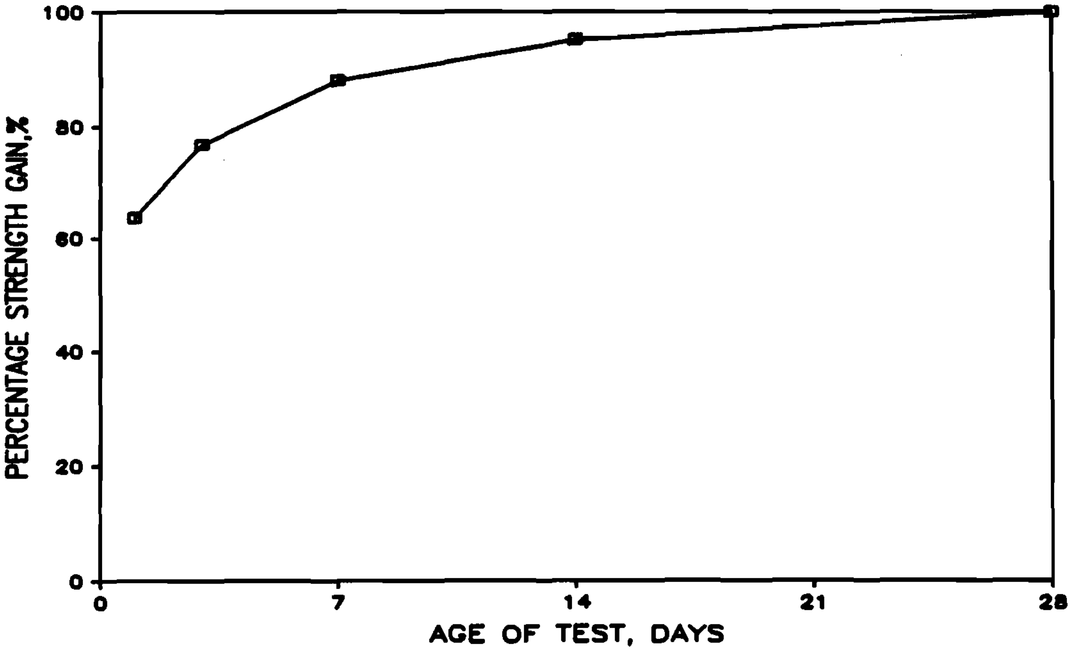


Fig. B.10 Percent strength gain, 28-day, for Mix #03-096-00.

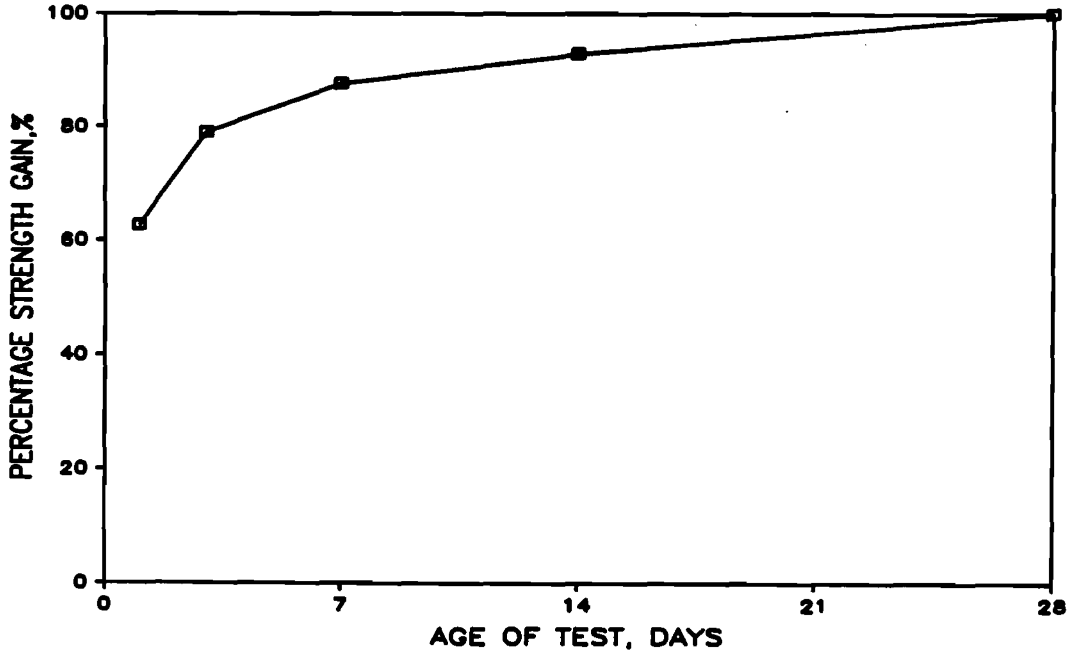


Fig. B.11 Percent strength gain, 28-day, for Mix #05-089-00.

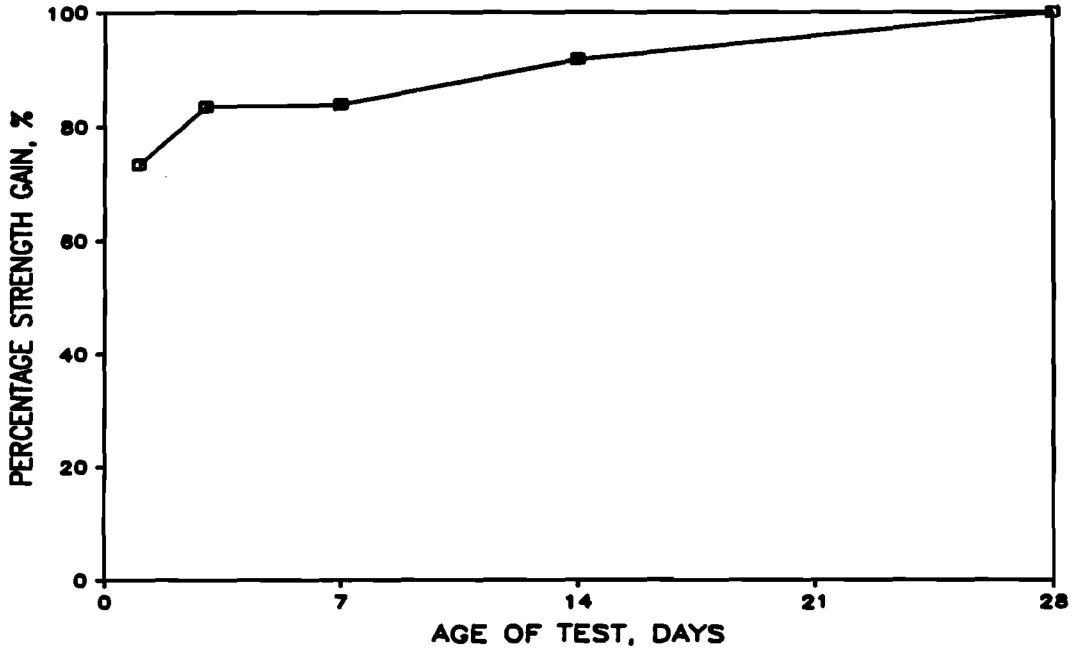


Fig. B.12 Percent strength gain, 28-day, for Mix #10-094-00.

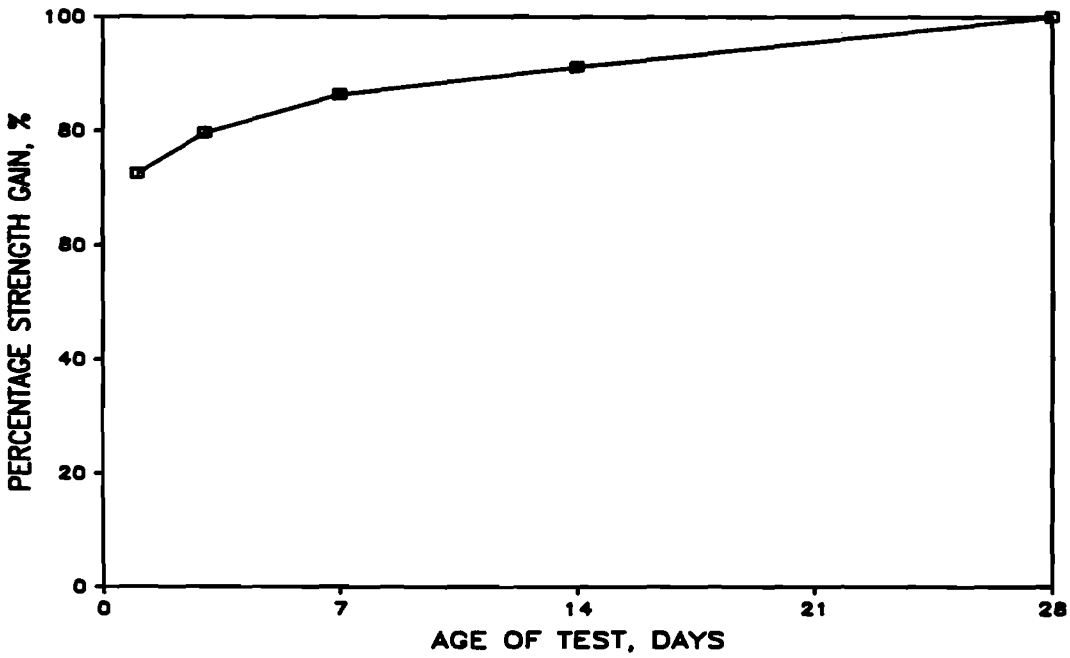


Fig. B.13 Percent strength gain, 28-day, for Mix #07-098-00.

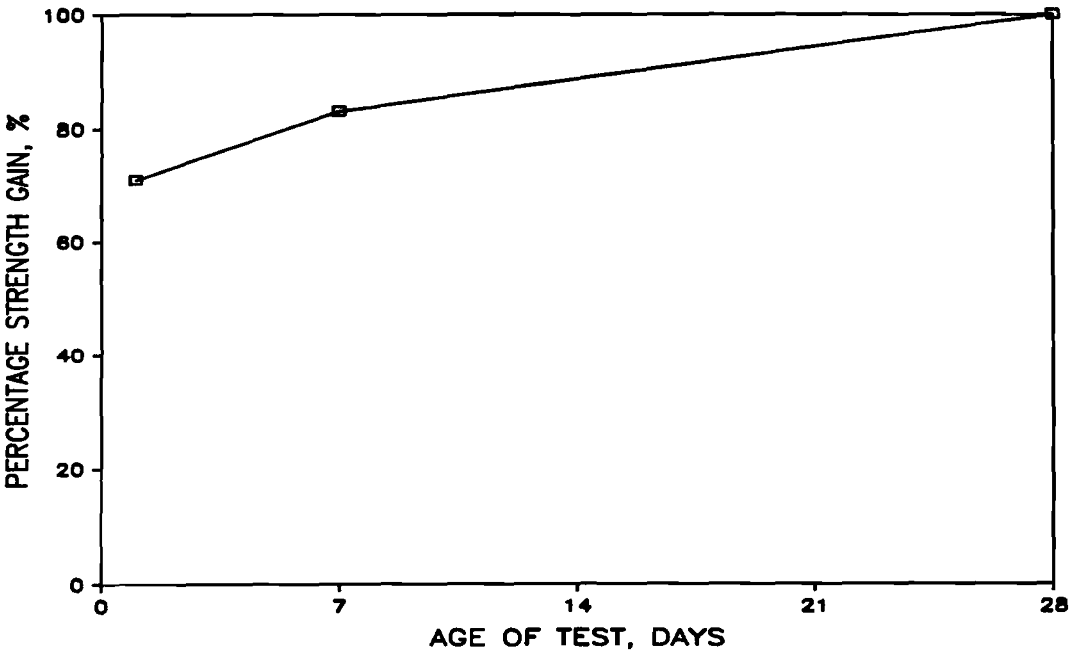


Fig. B.14 Percent strength gain, 28-day, for Mix #17-100-00.

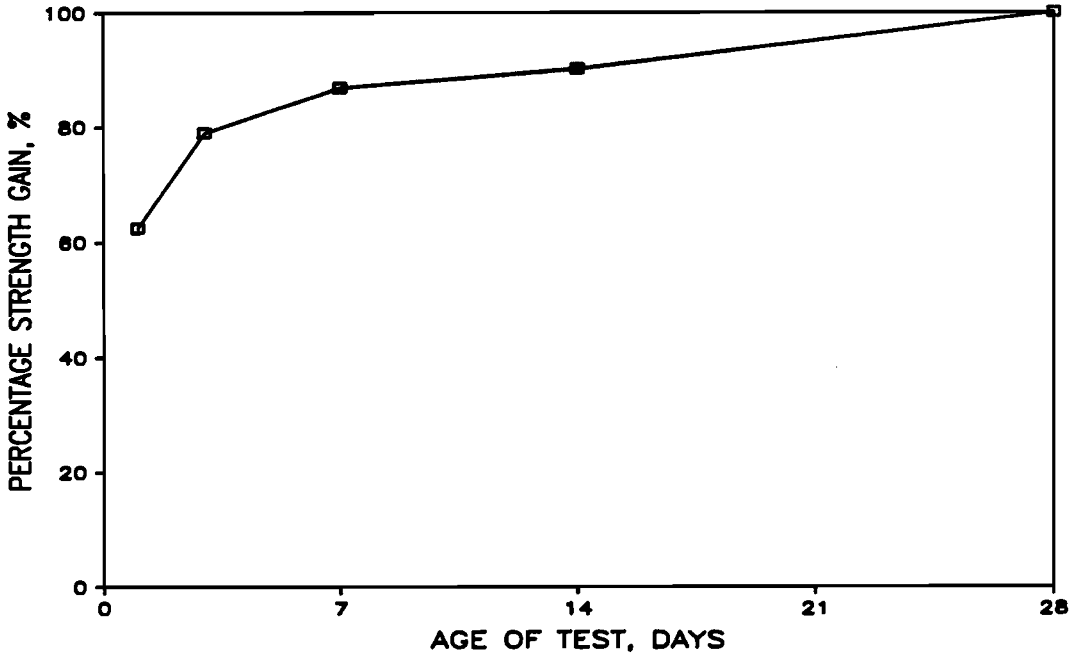


Fig. B.15 Percent strength gain, 28-day, for Mix #14-110-28.

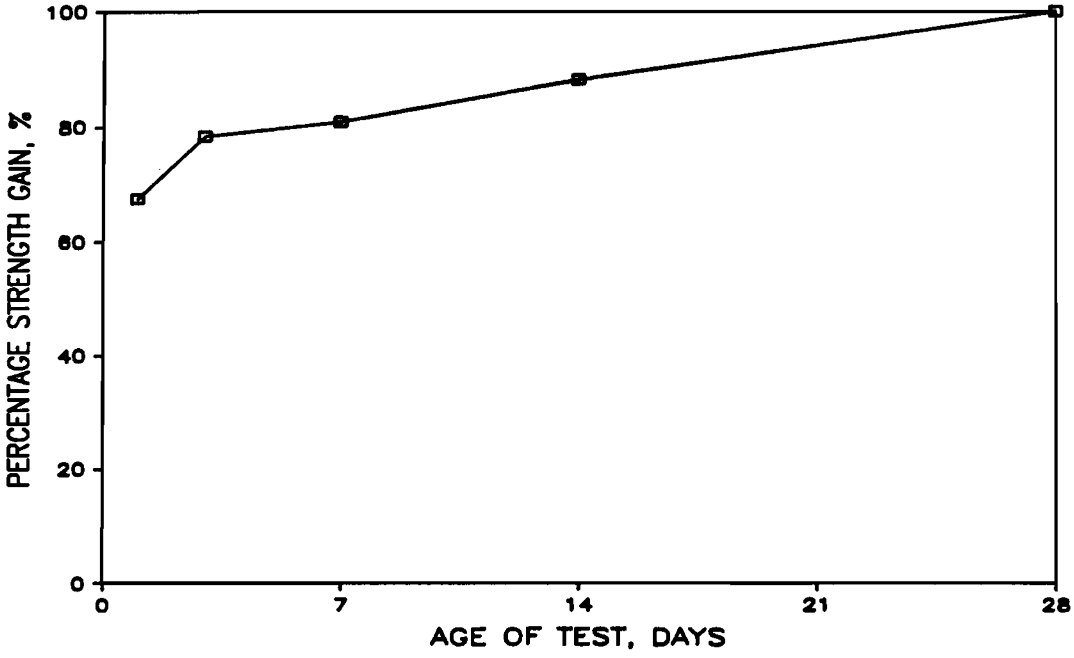


Fig. B.16 Percent strength gain, 28-day, for Mix #11-093-27.

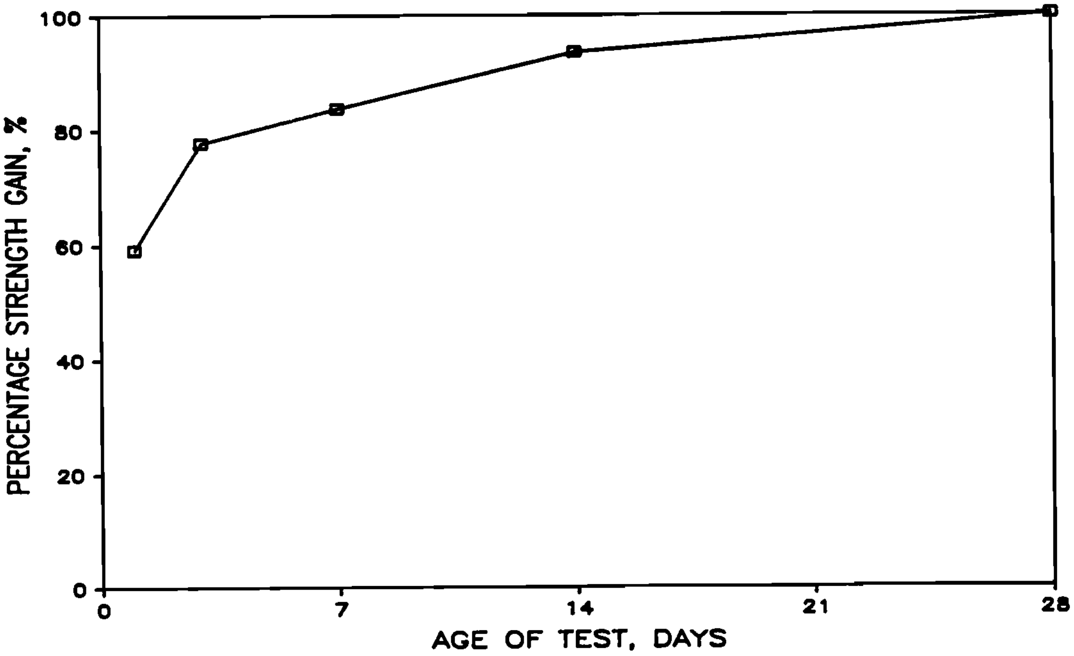


Fig. B.17 Percent strength gain, 28-day, for Mix #15-112-38.

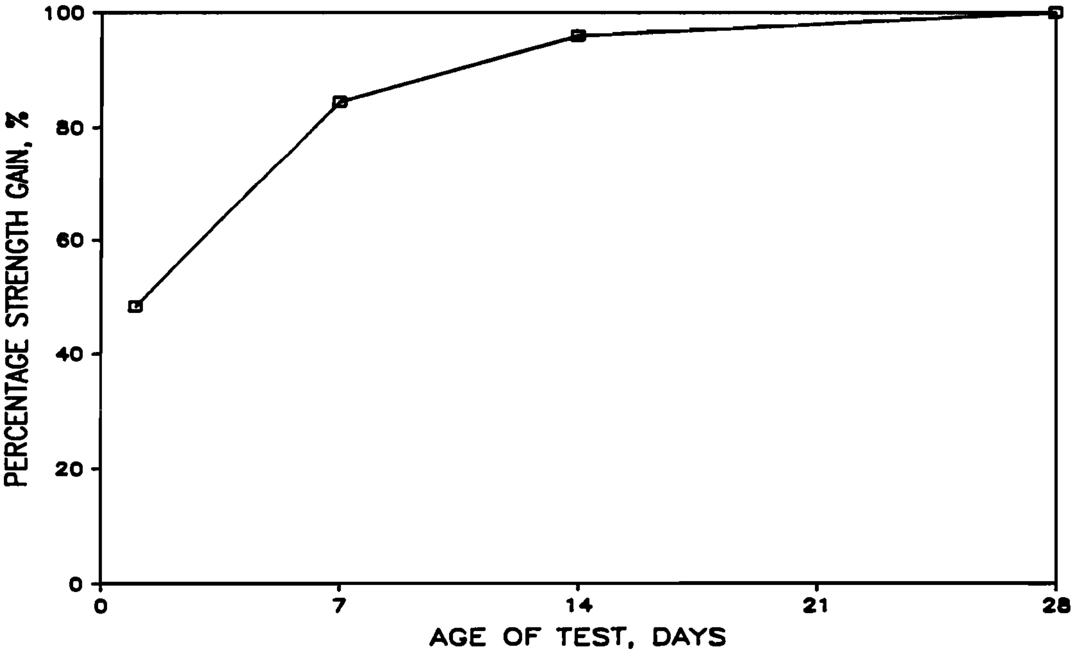


Fig. B.18 Percent strength gain, 28-day, for Mix #20-111-33.

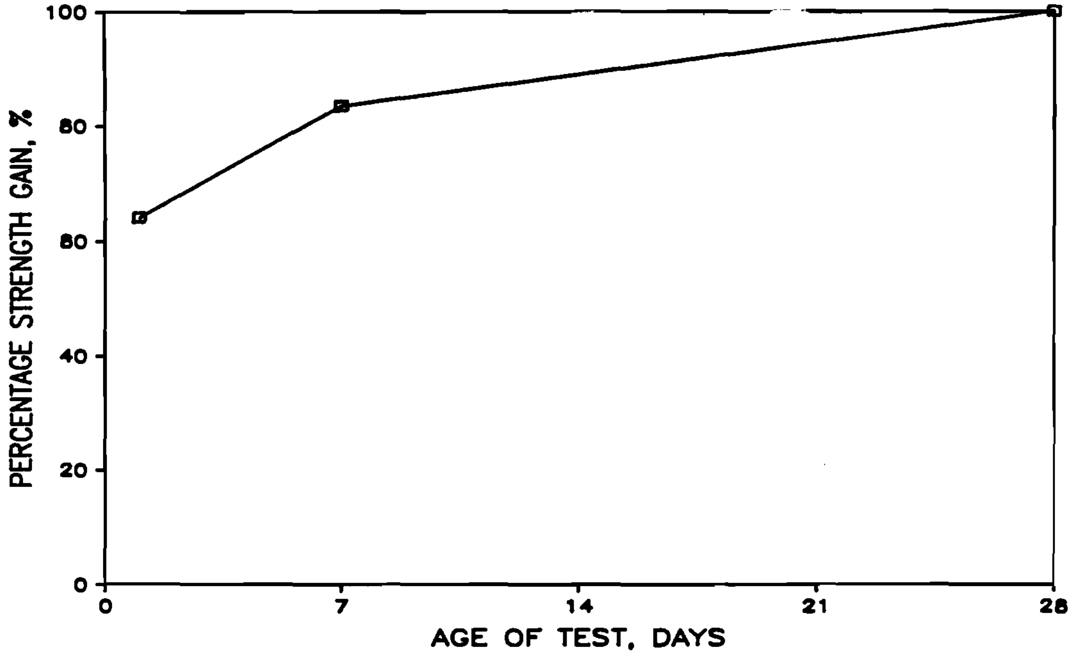


Fig. B.19 Percent strength gain, 28-day, for Mix #18-111-35.

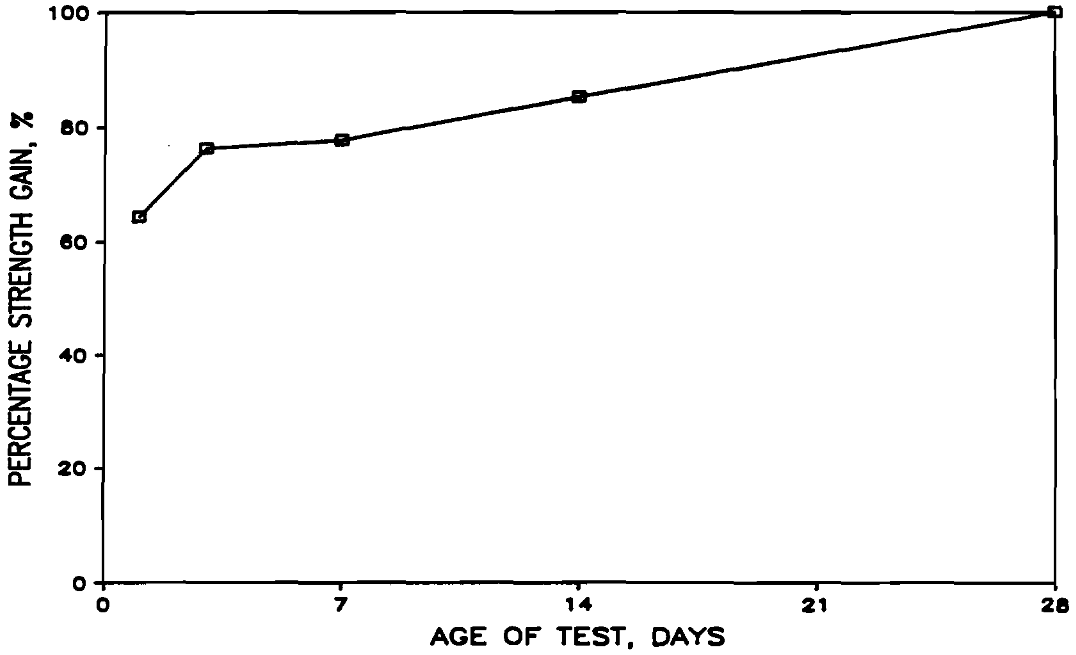


Fig. B.20 Percent strength gain, 28-day, for Mix #12-093-38.

APPENDIX C

PERCENTAGE STRENGTH GAIN CURVES, 56-DAY

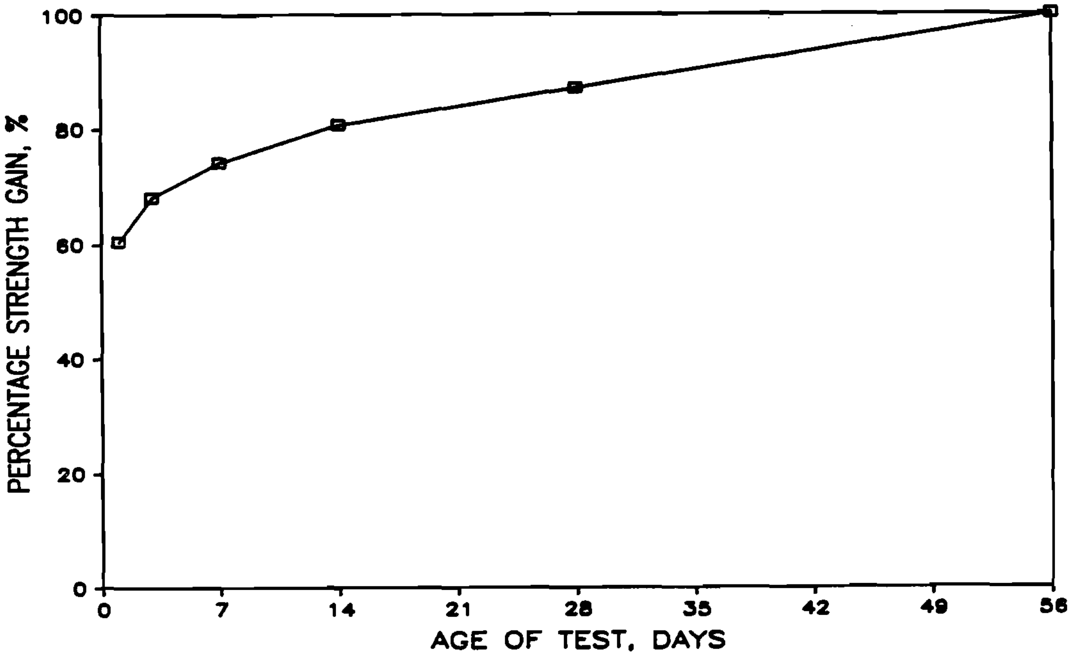


Fig. C.1 Percent strength gain, 56-day, for Mix #16-107-00.

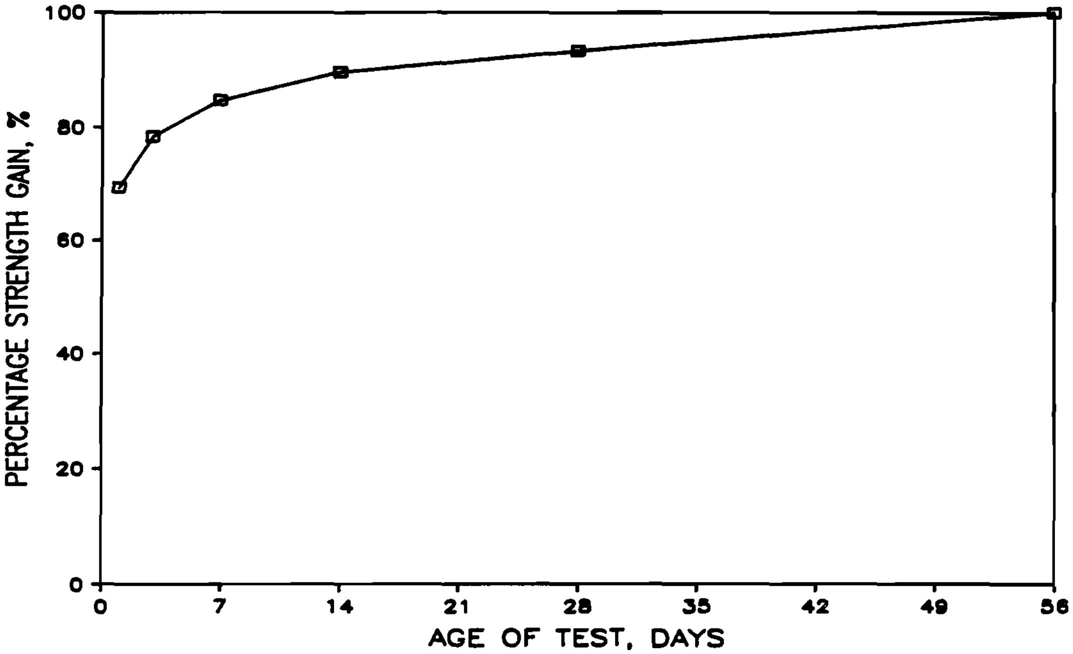


Fig. C.2 Percent strength gain, 56-day, for Mix #09-106-00.

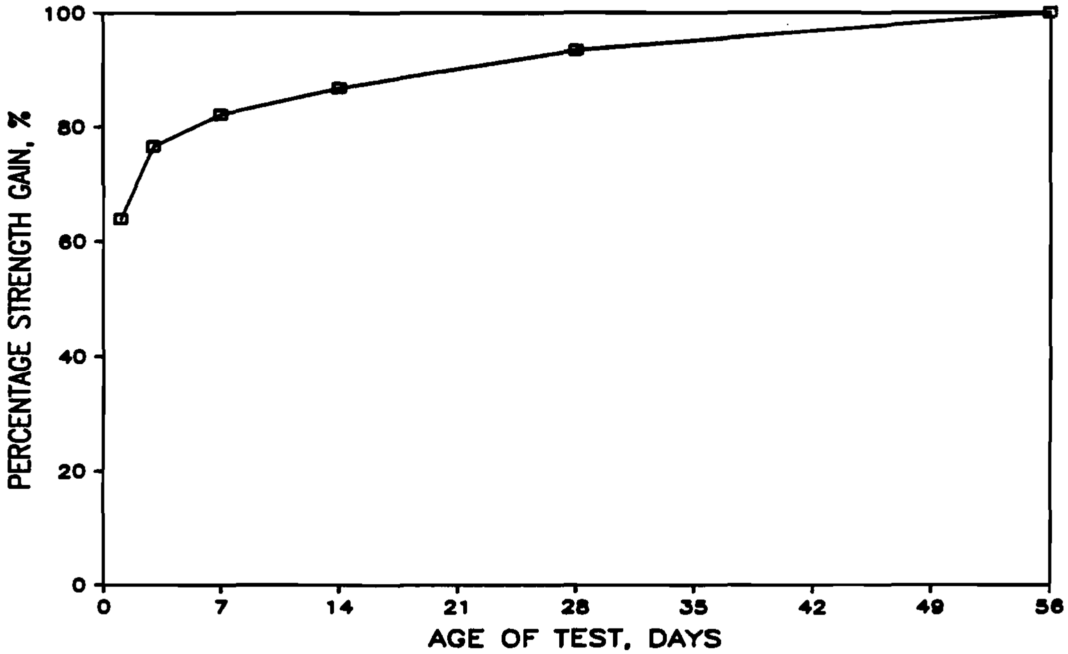


Fig. C.3 Percent strength gain, 56-day, for Mix #04-100-00.

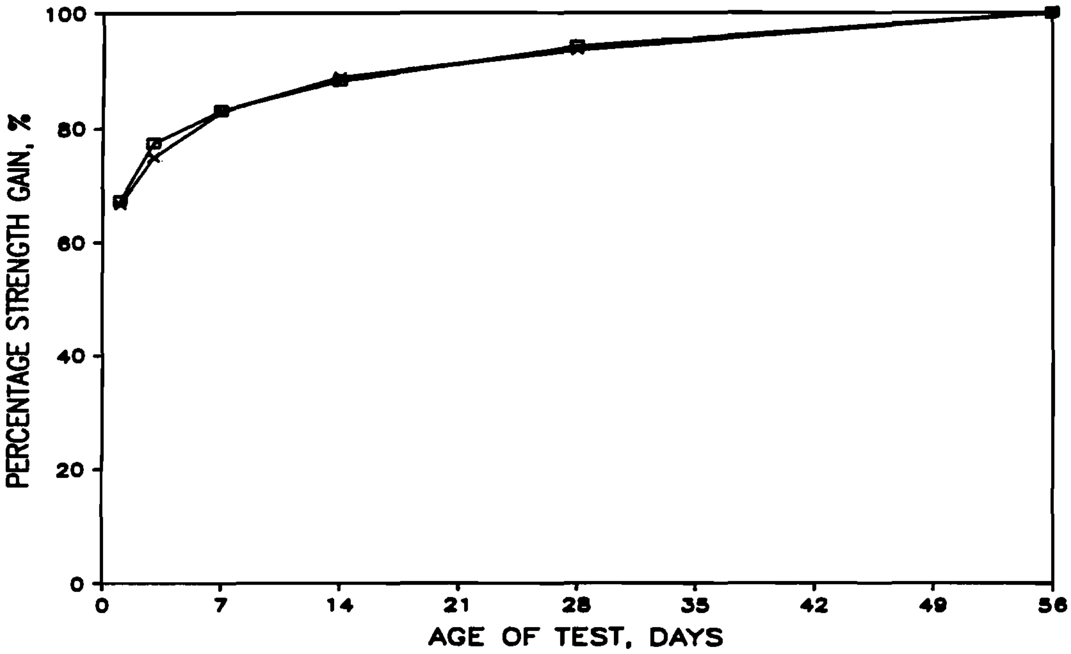


Fig. C.4 Percent strength gain, 56-day, for Mix #08A & B-104-00.

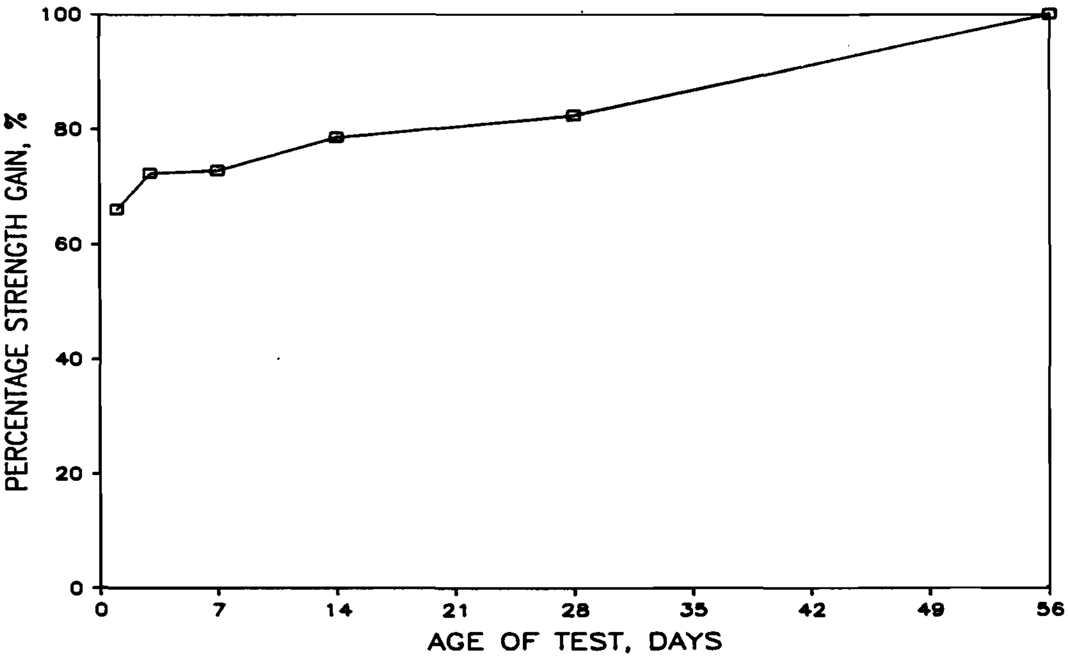


Fig. C.5 Percent strength gain, 56-day, for Mix #13-100-00.

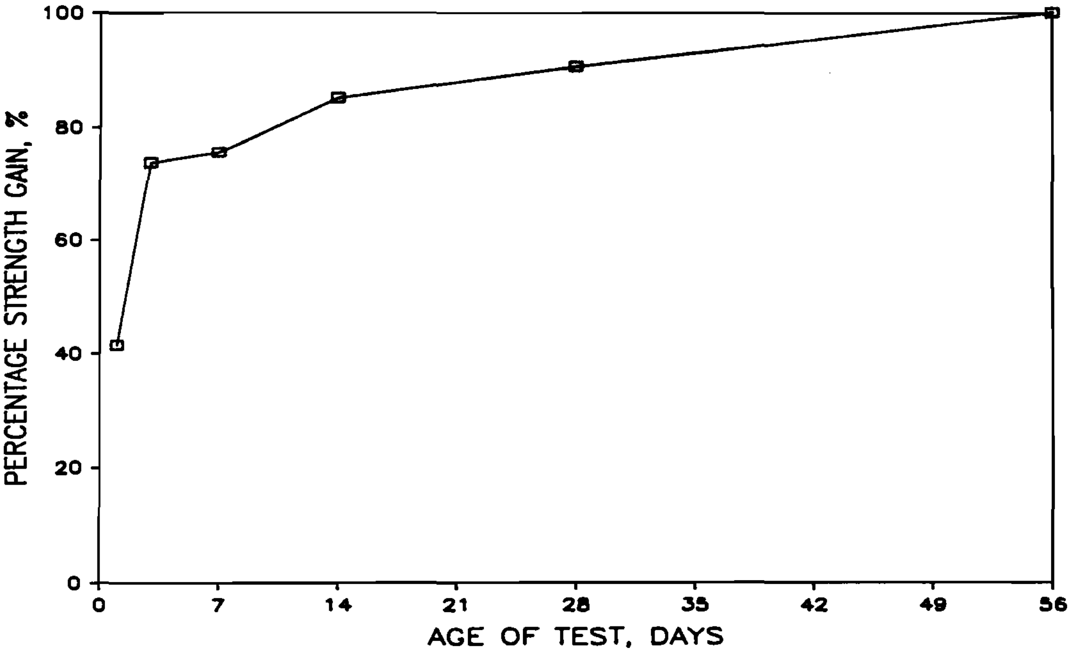


Fig. C.6 Fercent strength gain, 56-day, for Mix #02-095-00.

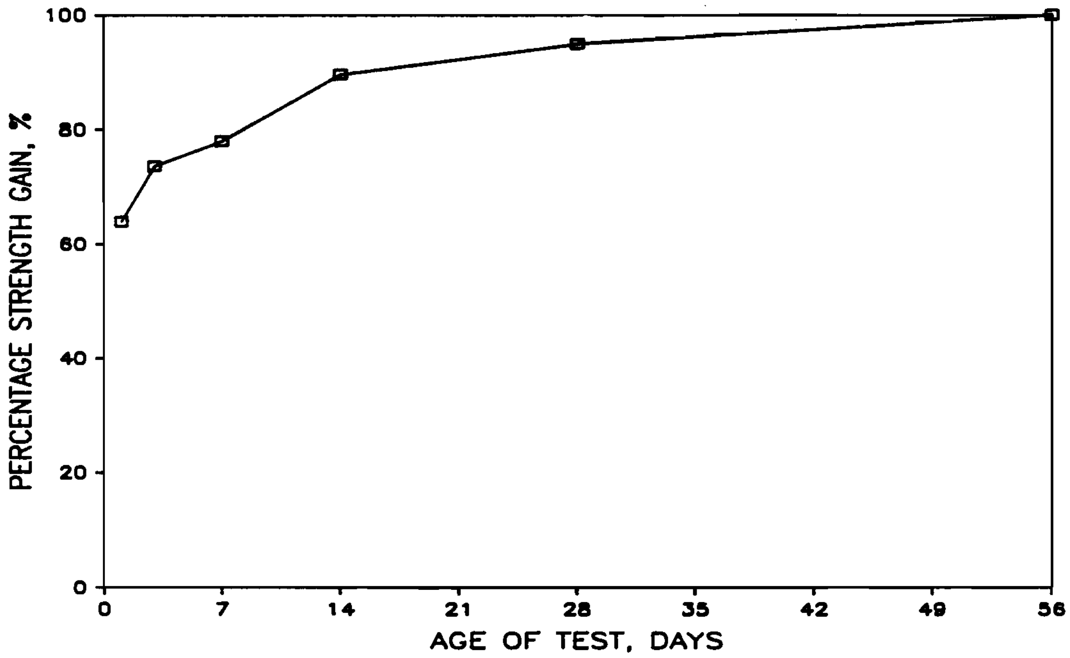


Fig. C.7 Percent strength gain, 56-day, for Mix #01-107-00.

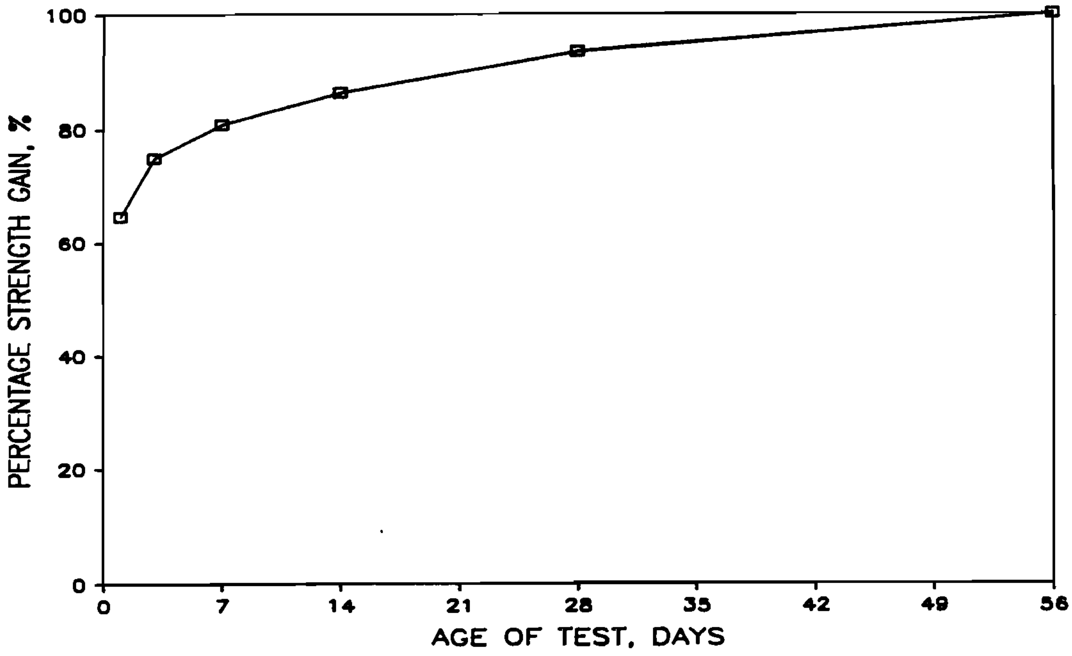


Fig. C.8 Percent strength gain, 56-day, for Mix #06-097-00.

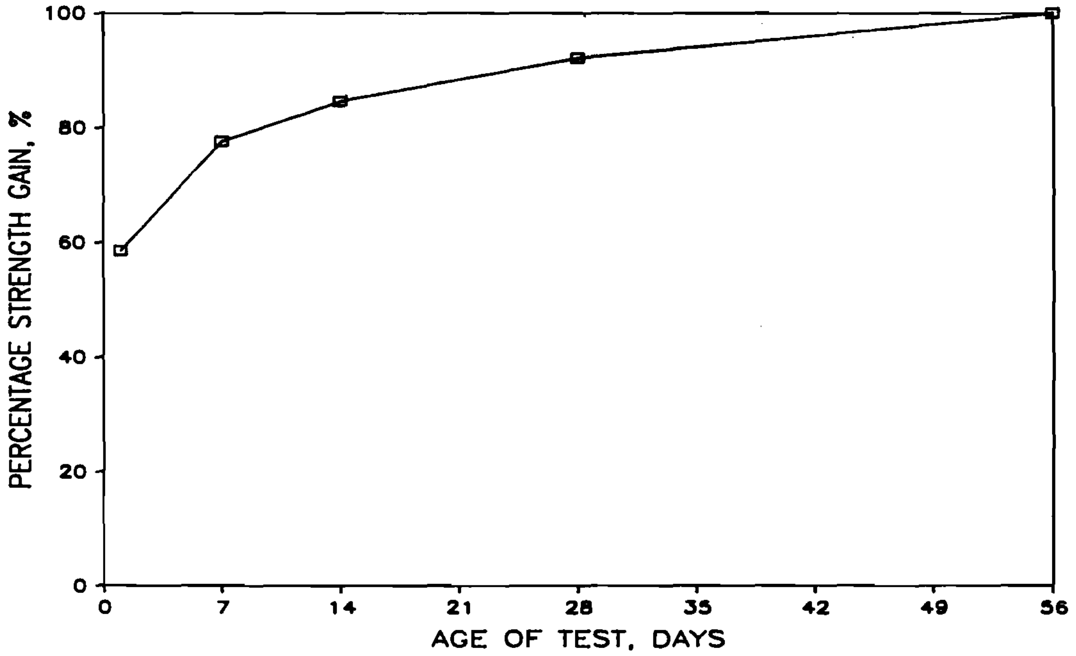


Fig. C.9 Percent strength gain, 56-day, for Mix #19-103-00.

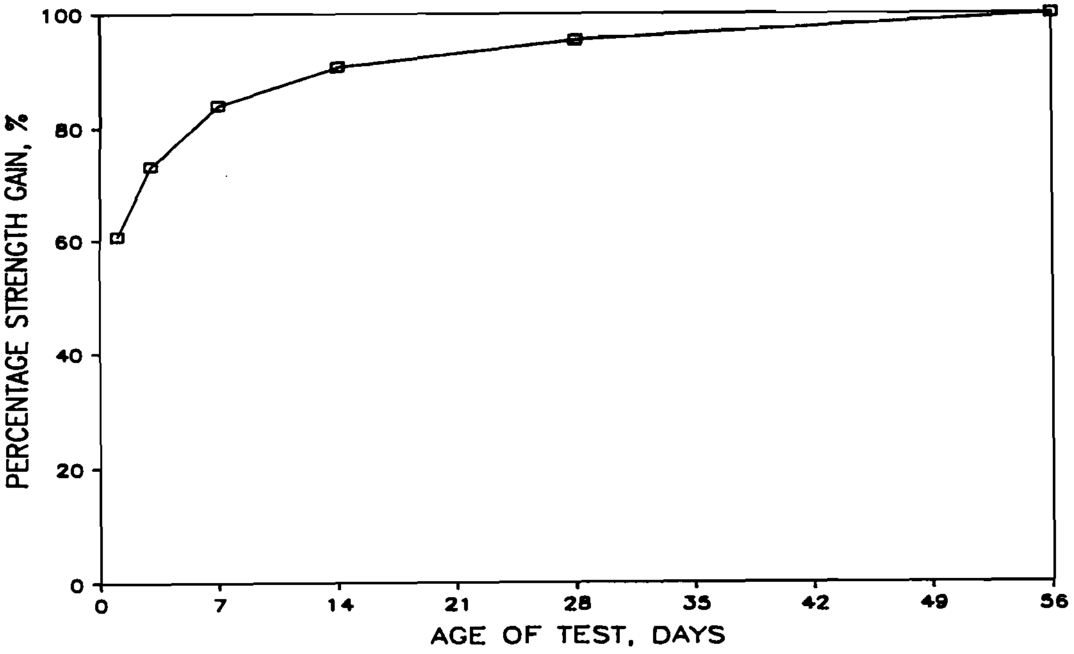


Fig. C.10 Percent strength gain, 56-day, for Mix #03-096-00.

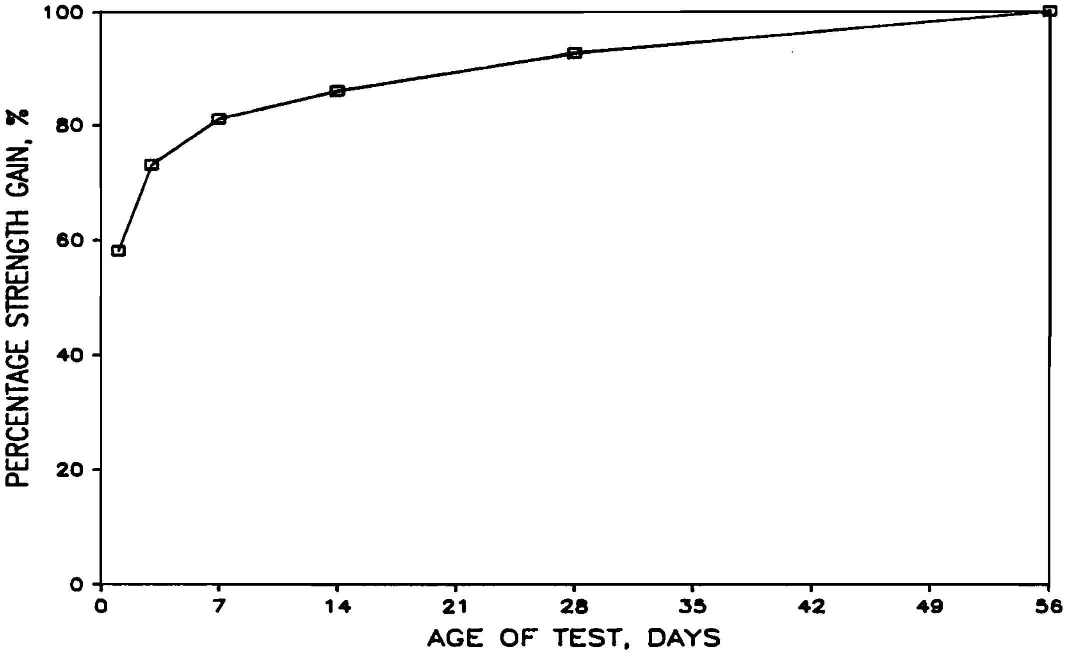


Fig. C.11 Percent strength gain, 56-day, for Mix #05-089-00.

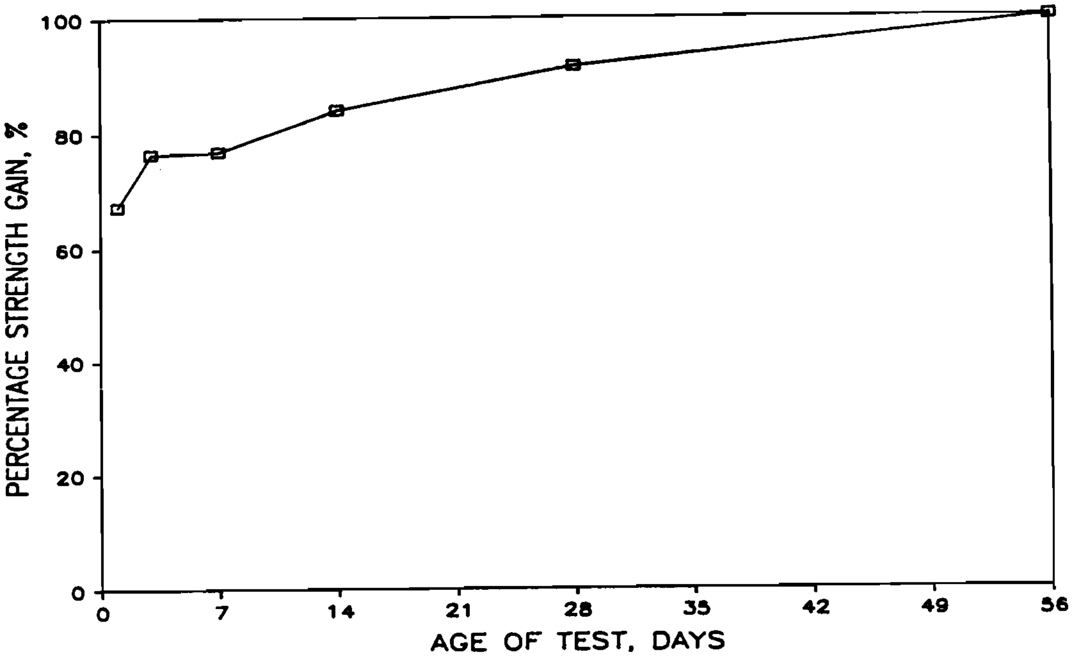


Fig. C.12 Percent strength gain, 56-day, for Mix #10-094-00.

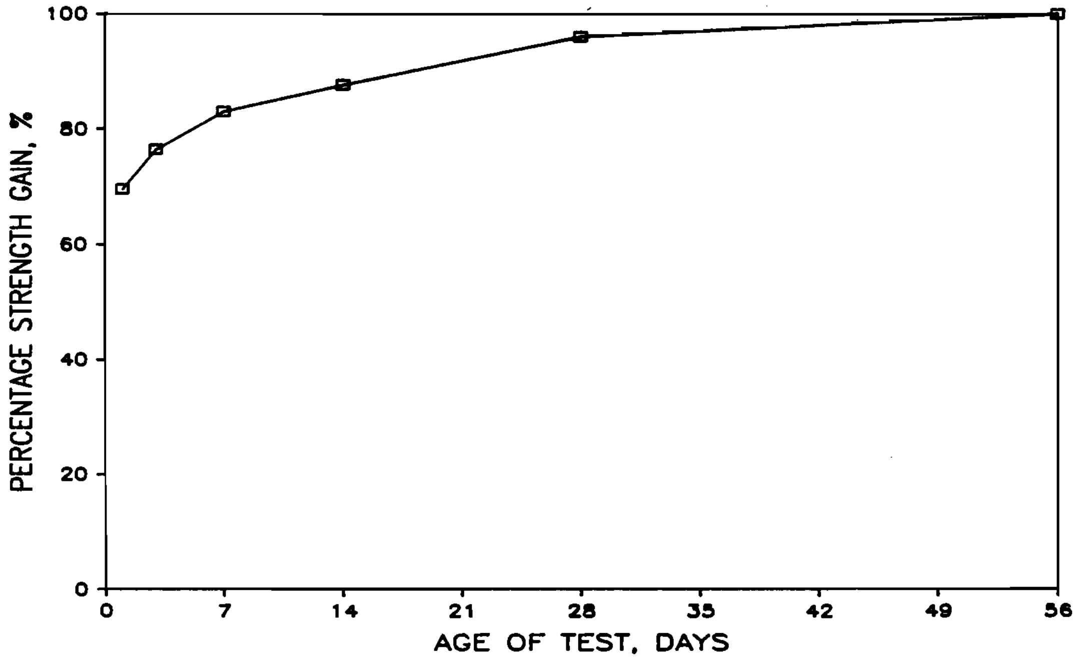


Fig. C.13 Percent strength gain, 56-day, for Mix #07-098-00.

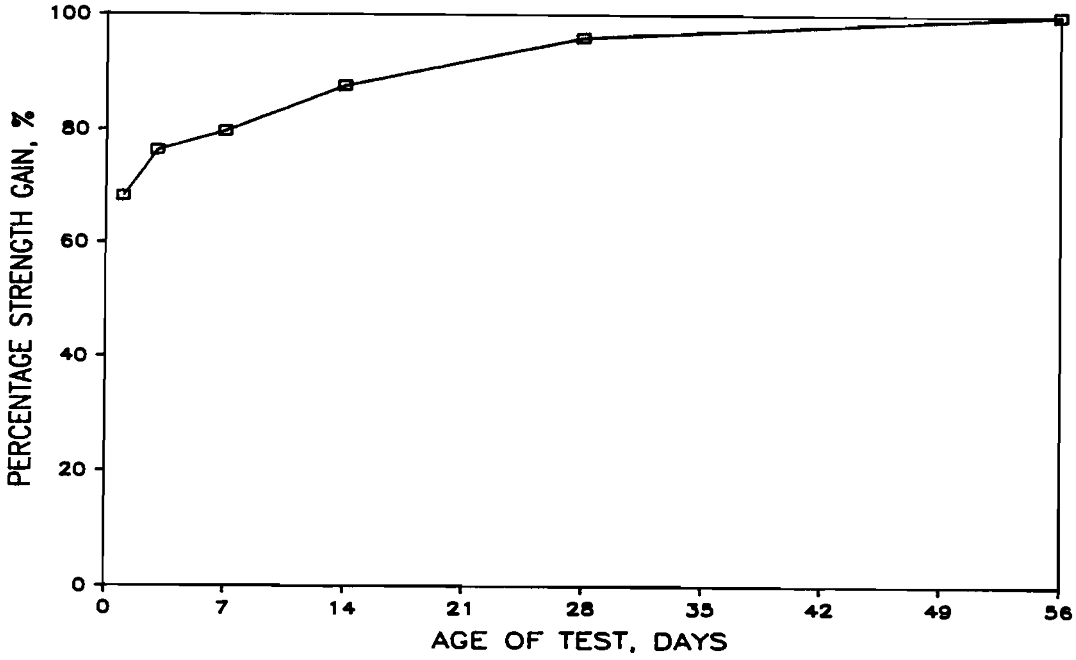


Fig. C.14 Percent strength gain, 56-day, for Mix #17-100-00.

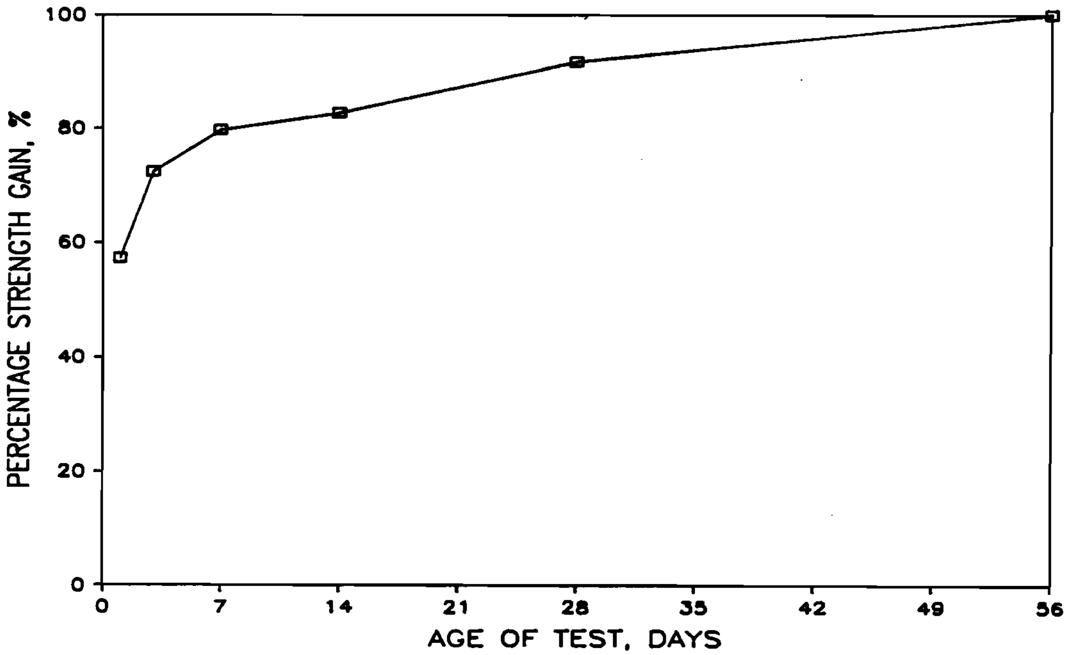


Fig. C.15 Percent strength gain, 56-day, for Mix #14-110-28.

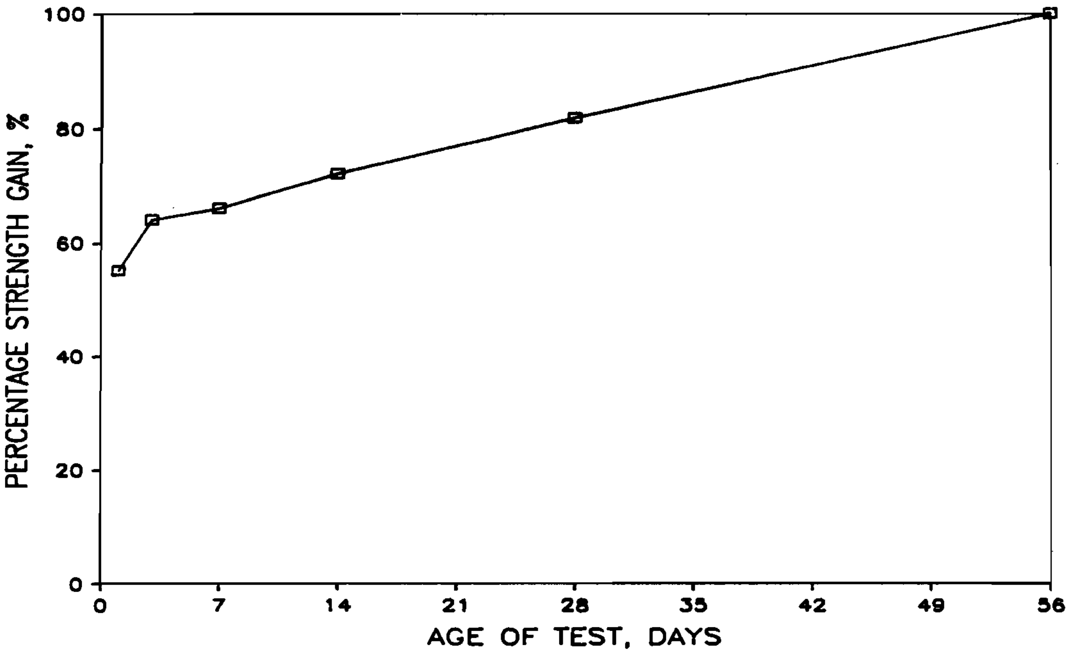


Fig. C.16 Percent strength gain, 56-day, for Mix #11-093-27.

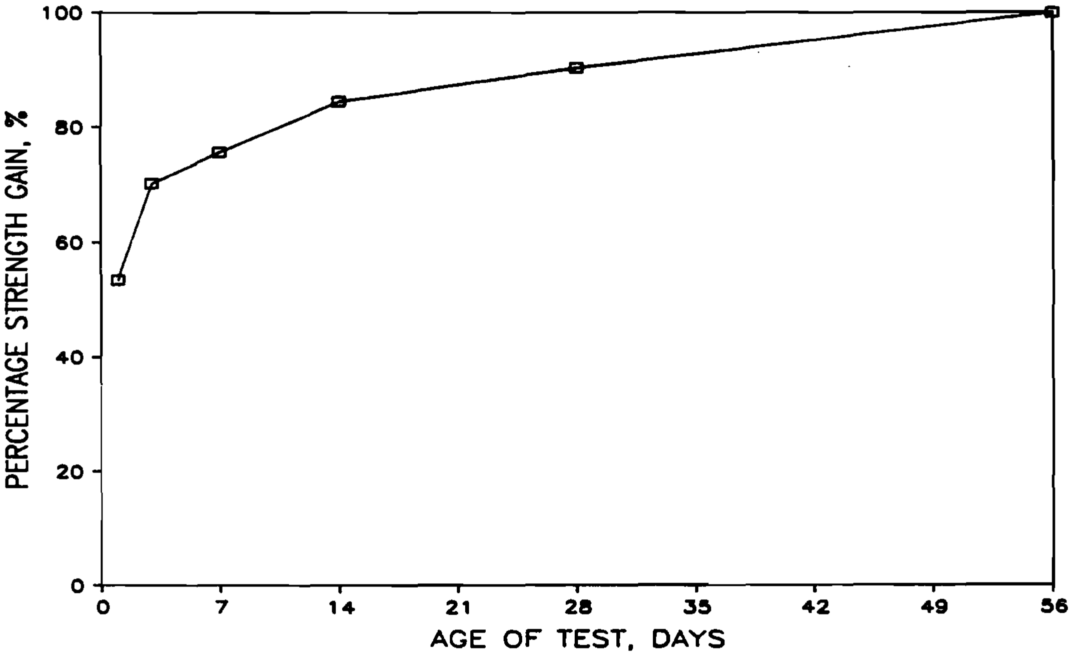


Fig. C.17 Percent strength gain, 56-day, for Mix #15-112-38.

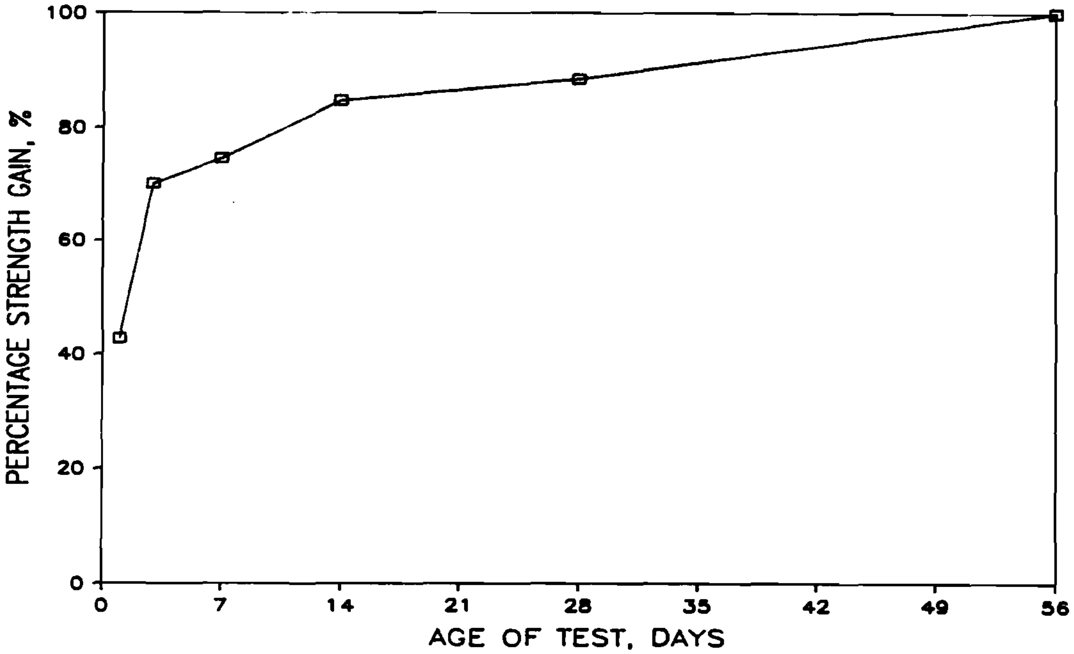


Fig. C.18 Percent strength gain, 56-day, for Mix #20-111-33.

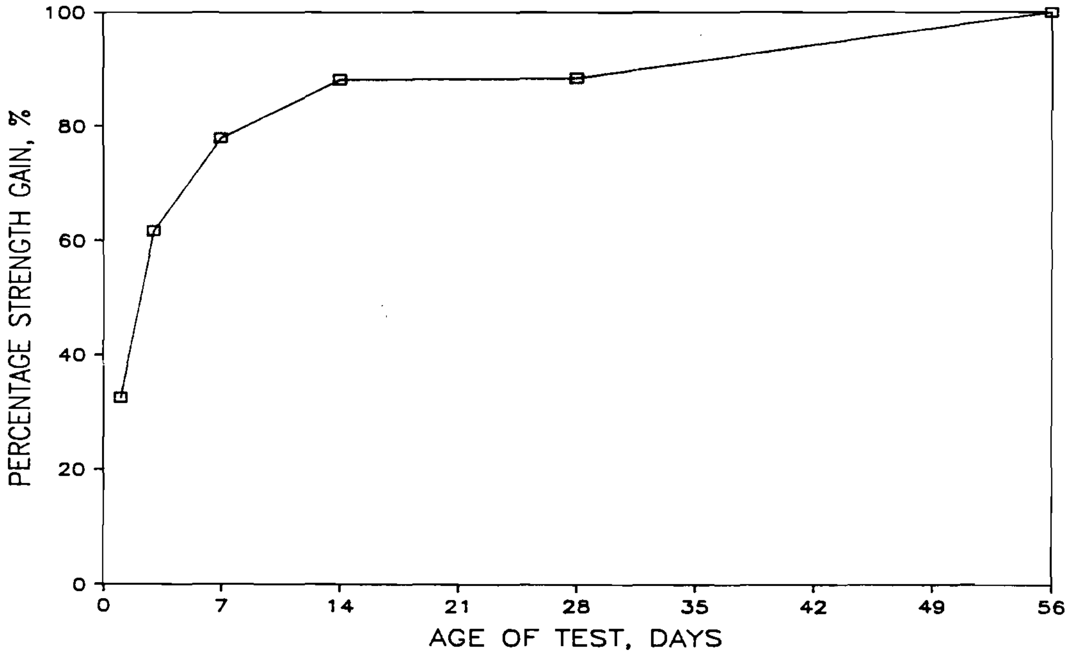


Fig. C.19 Percent strength gain, 56-day, for Mix #21-112-34.

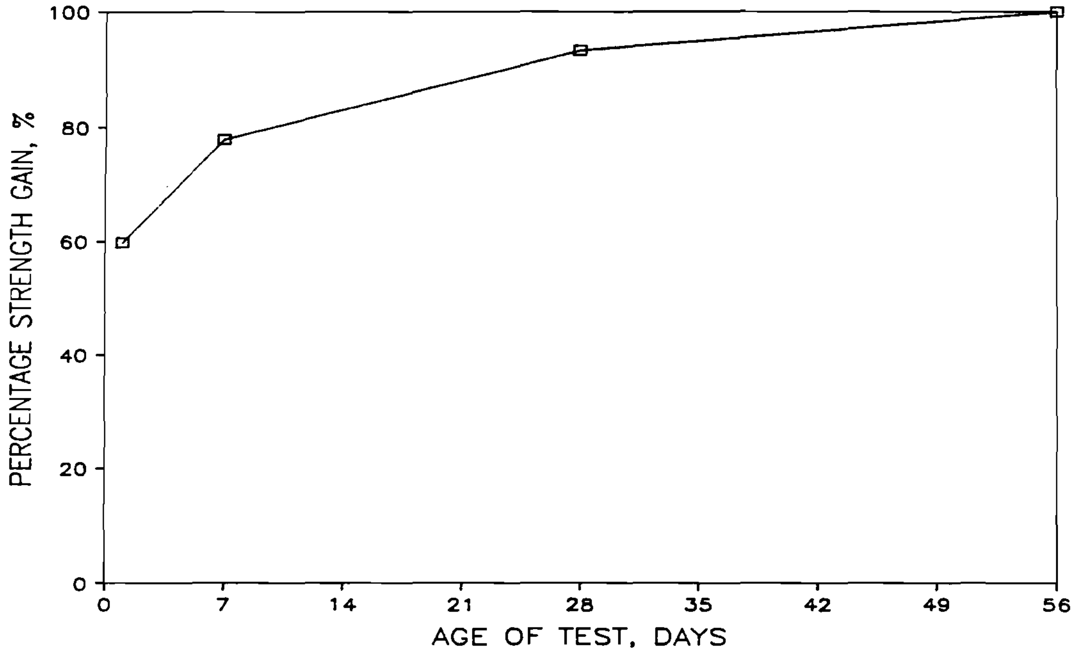


Fig. C.20 Percent strength gain, 56-day, for Mix #18-111-35.

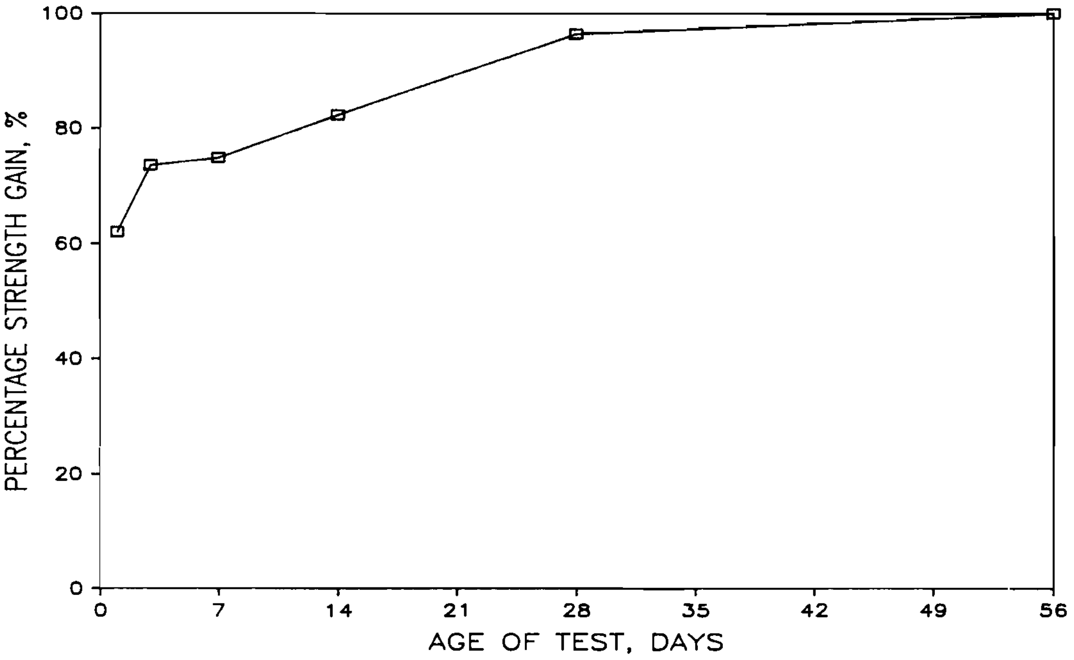


Fig. C.21 Percent strength gain, 56-day, for Mix #12-093-38.

APPENDIX D

PERCENTAGE STRENGTH GAIN CURVES, 91-DAY

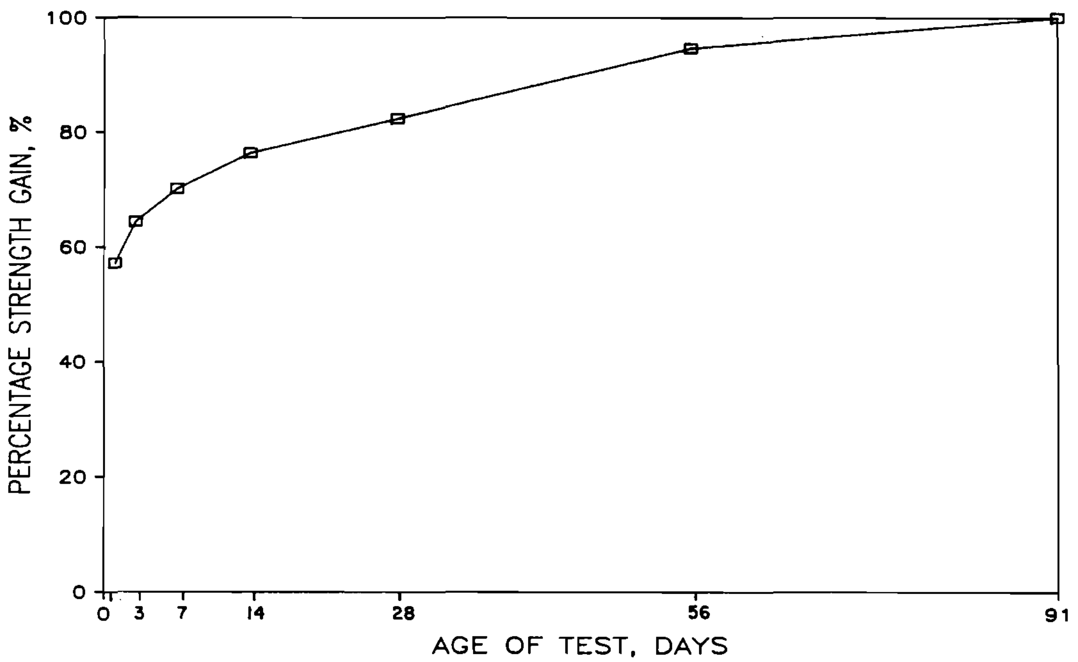


Fig. D.1 Percent strength gain, 91-day, for Mix #16-107-00.

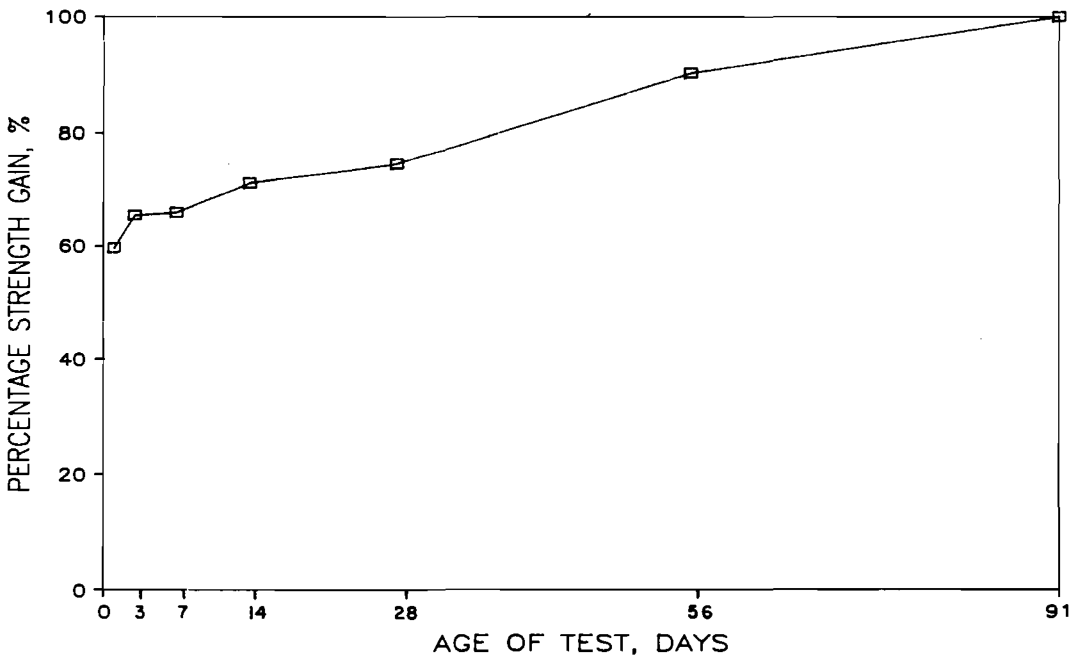


Fig. D.2 Percent strength gain, 91-day, for Mix #13-100-00.

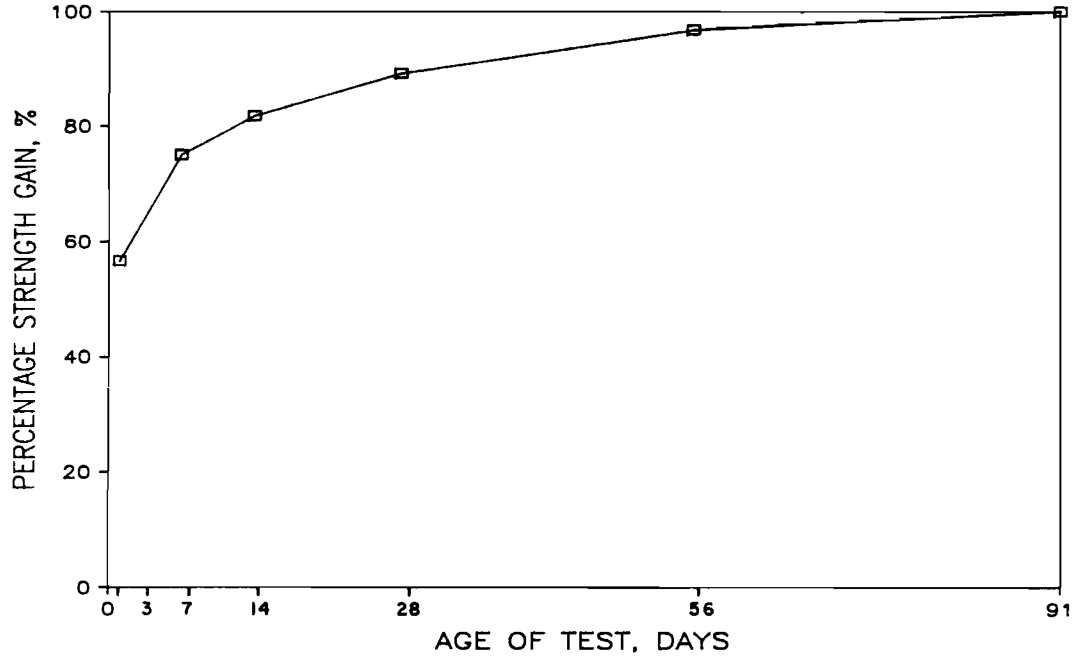


Fig. D.3 Percent strength gain, 91-day, for Mix #19-103-00.

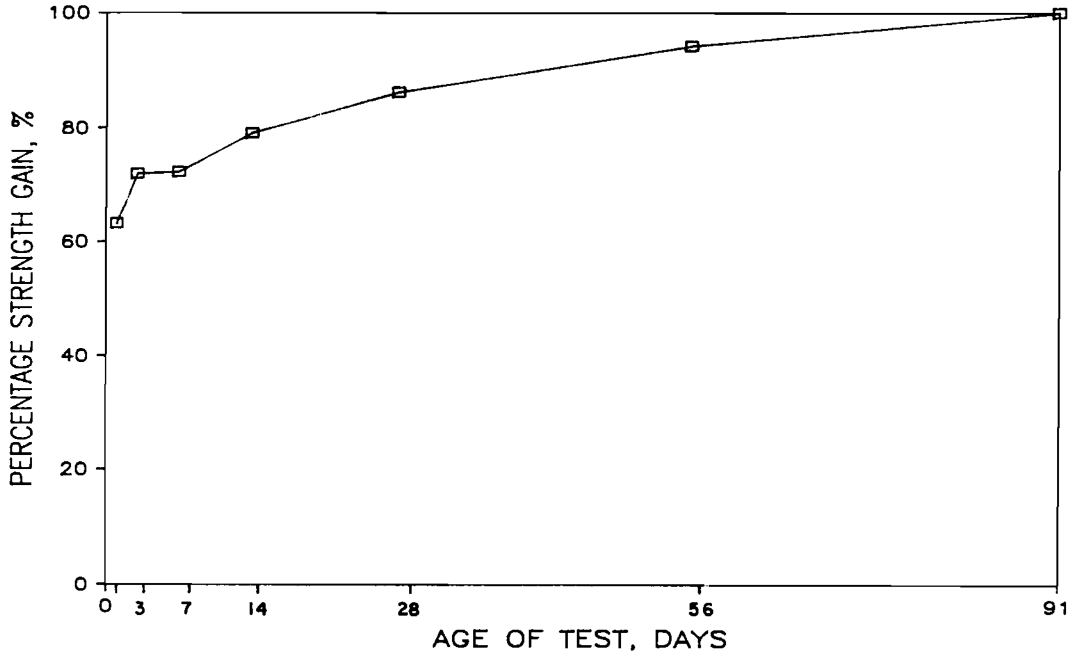


Fig. D.4 Percent strength gain, 91-day, for Mix #10-094-00.

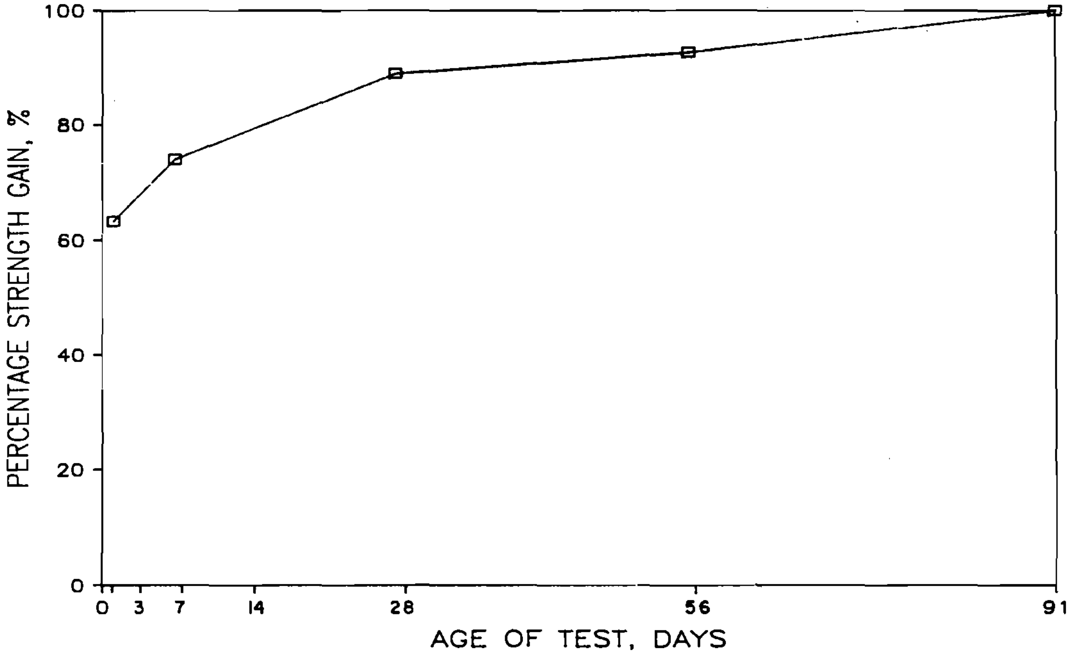


Fig. D.5 Percent strength gain, 91-day, for Mix #17-100-00.

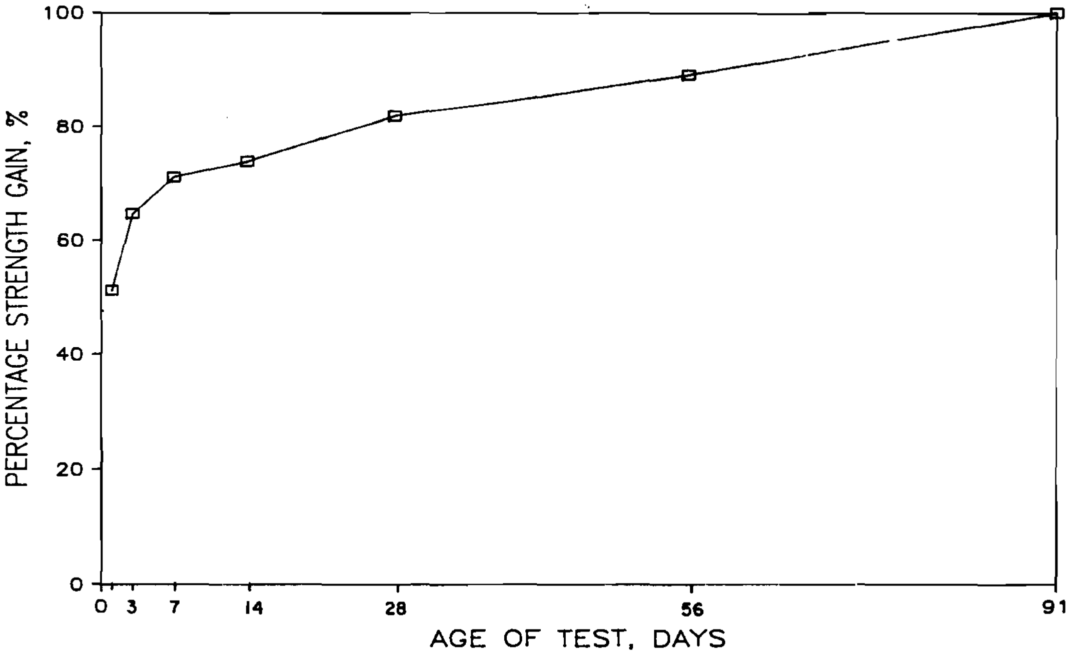


Fig. D.6 Percent strength gain, 91-day, for Mix #14-110-28.

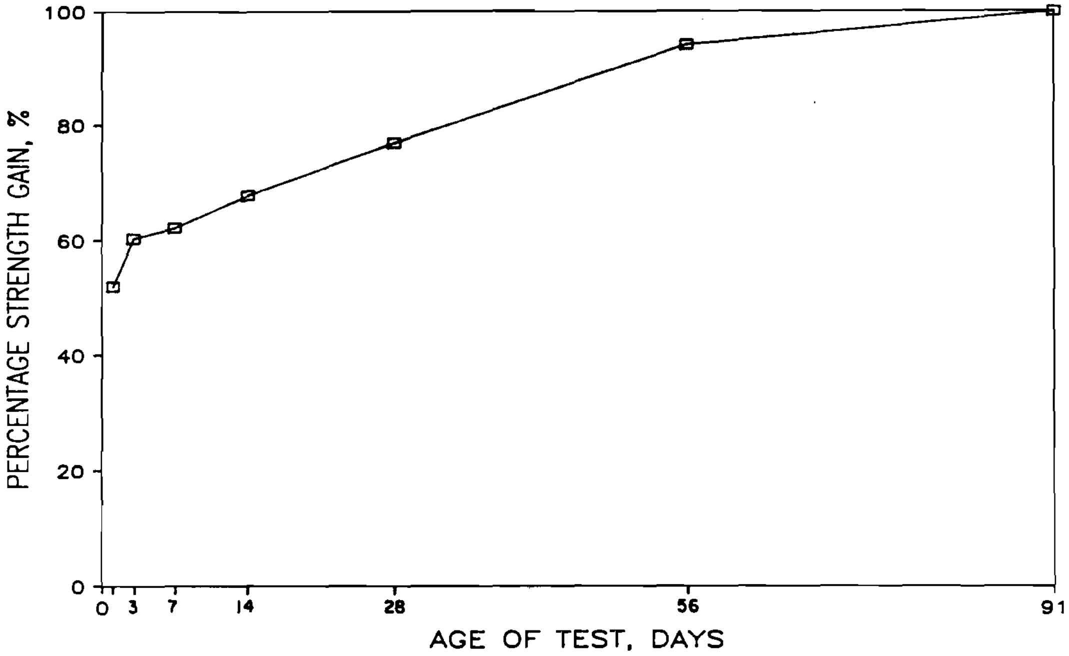


Fig. D.7 Percent strength gain, 91-day, for Mix #11-093-27.

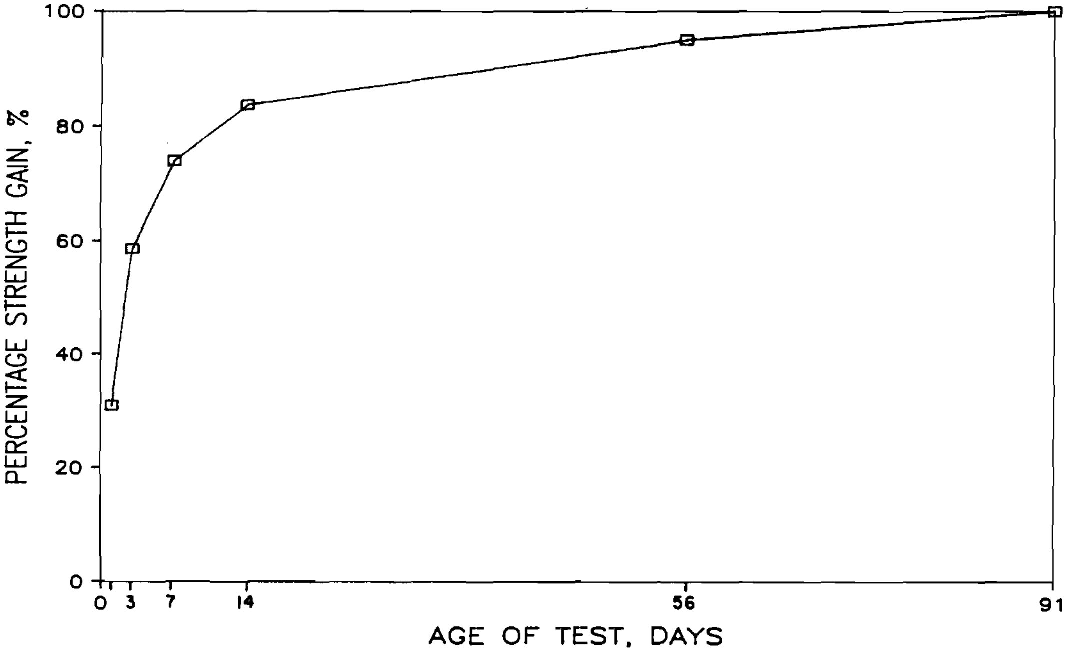


Fig. D.8 Percent strength gain, 91-day, for Mix #21-112-34.

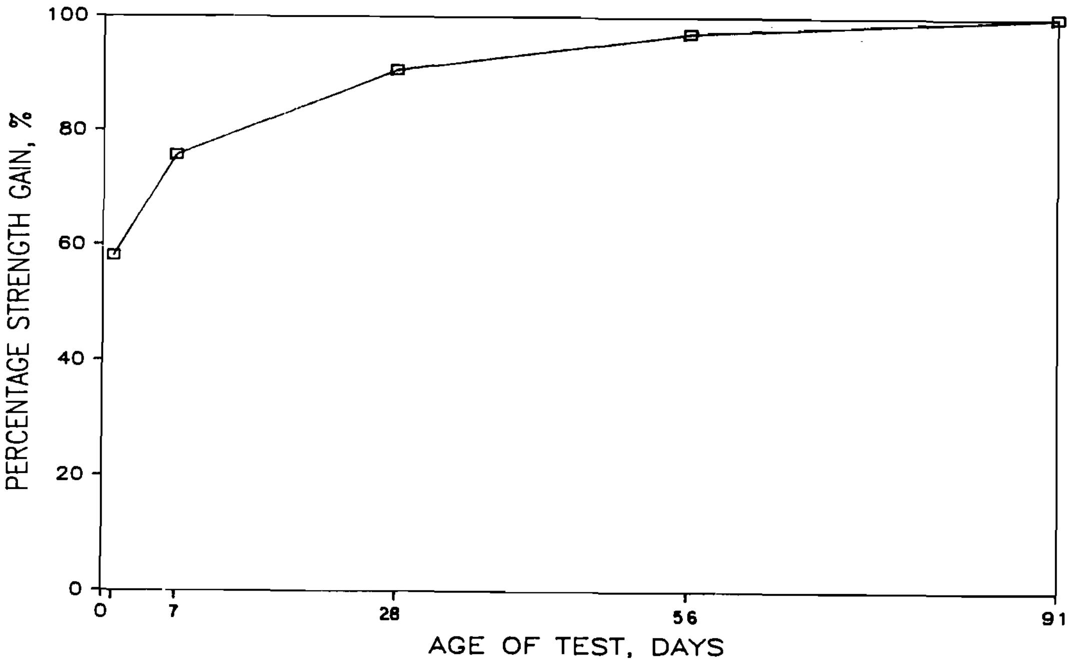


Fig. D.9 Percent strength gain, 91-day, for Mix #18-111-35.

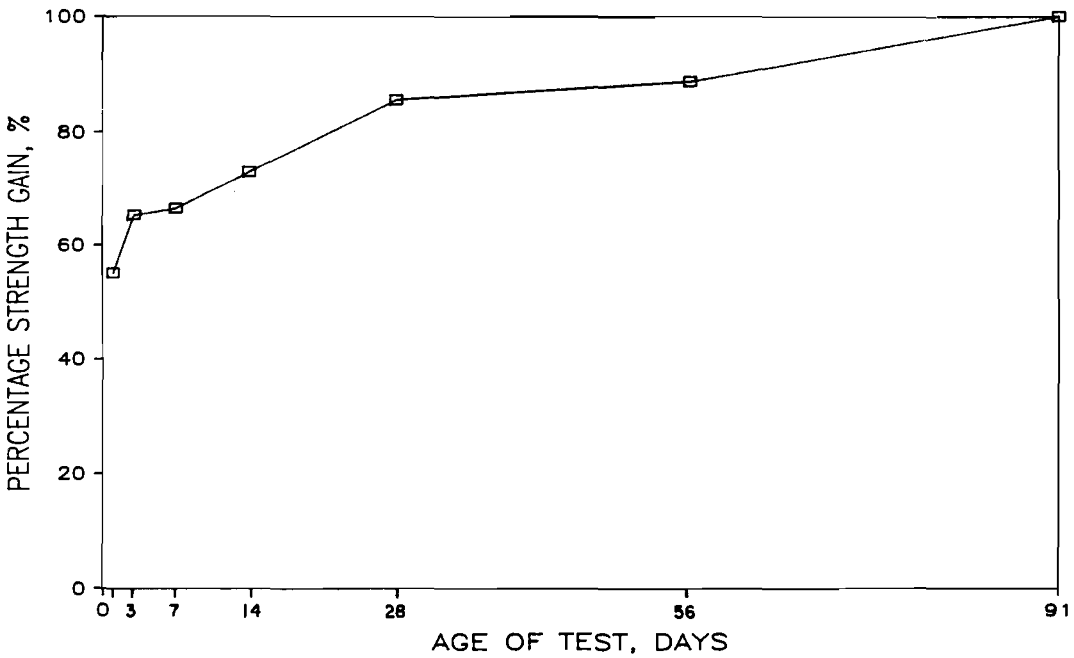


Fig. D.10 Percent strength gain, 91-day, for Mix #12-093-38.

APPENDIX E

DOCUMENTS APPENDED TO SPECIFICATIONS FOR FIELD PILOT STUDY

SPECIAL PROVISION
TO
ITEM 421

Swisher County
Control 67-2-33
PROJECT I 27-7(46)379
IH 27

CONCRETE FOR STRUCTURES

For this project, Item 421, "Concrete for Structures", of the Standard Specifications, is hereby amended with respect to the clauses cited below and no other clauses or requirements of this item are waived or changed hereby.

Article 421.2. Material (1) Cement is supplemented by the following:

For the items, "Prestressed Concrete Structures", "Reinforced Concrete Pipe Culverts" and "Concrete Box Culverts" the Contractor has the option of using Portland Cement or Portland Cement Plus Fly Ash as defined herein.

When Fly Ash is used, then "Cement" shall also be defined as "Cement Plus Fly Ash." "Cement Plus Fly Ash" shall be composed of Portland Cement of the type specified and 20 to 35 percent Fly Ash by absolute volume. Fly Ash shall conform to the Departmental Materials Specification D-9-8900, "Fly Ash."

Article 421.7. Classification and Mix Design is supplemented by the following:

Construction Bulletin C-11 and Supplement thereto, together with the attached Supplement No. 2 to Construction Bulletin C-11 shall be used for the design of concrete mixes which are to contain fly ash.

Article 421.7. Classification and Mix Design. The eighth paragraph is hereby voided and replaced with the following:

The Contractor shall have the option of using a water-reducing or water-reducing, retarding admixture with all classes of concrete, except where the use of specific admixtures is required in this or other items.

Article 421.9. Quality of Concrete. The last sentence of the third paragraph is voided and replaced by the following:

Specimen will be tested in accordance with Test Methods Tex-420-A or Tex-418-A modified as follows:

Apparatus

1. Models a. general - The following provisions apply to both reusable and single-use molds, etc.: Molds shall be constructed in the form of right circular cylinders which stand with cylindrical axis vertical and the top open to receive the concrete. Molds shall have a nominal inside height equal to twice the nominal inside diameter. The average diameter of a mold shall not differ from the nominal diameter by more than 1%. No diameter of a mold shall differ from any other diameter at the same mold by more than 2%. The average height shall not differ from the nominal height by more than 2%. The planes of the top rim of the mold and the bottom shall be perpendicular to the axis of the mold within 0.5 degree (approximately equivalent to 1/8 inch in 12 inches).

2. Tamping Rod: Two sizes are specified, one 5/8" in diameter and approximately 24" long for consolidating 6" X 12" cylinders and the other is 3/8" in diameter and approximately 12" long for consolidating 4" X 8" cylinders. Each shall be a round, straight steel rod with at least the tamping end rounded to a hemispherical tip of the same diameter as the rod.

Test Specimens. The standard specimens shall be 6" X 12" cylinder or 4" X 8" cylinder. They shall be subject to the same tolerances as for the molds.

SUPPLEMENT NO. 2 TO CONSTRUCTION BULLETIN C-11

DESIGN OF CONCRETE CONTAINING FLY ASH AND HIGH STRENGTH CONCRETE

1. General

This supplement is a guidelines for the design of portland cement concrete containing fly ash. Guidelines for high strength concrete are also included. Where conflict exists between these guidelines and the specifications, the specifications shall govern.

Fly ash is used to replace a portion of the portland cement in a concrete mix. The amount it replaces may vary between 20 and 35 percent of the absolute volume of the required amount of portland cement depending on the type of fly ash and specification requirements for the concrete.

Fly ash should not be used as a cement replacement in concrete containing less than five sacks of portland cement per cubic yard prior to such replacement. For mixes containing less than five sacks of cement, replacement of cement with fly ash may adversely affect the strength gain characteristics and fresh concrete properties significantly.

This guideline is proposed for use with normal weight aggregates consisting of gravel, crushed stone or combinations thereof and either natural or manufactured sand or combinations thereof.

The materials or ingredients used for determining a mix design should be the same materials or ingredients as those which will be used in actual construction.

The term "cement plus fly ash", (C+F), refers to the total combined weight of portland cement and fly ash in a concrete mix.

Only fly ash meeting the requirement of Departmental Material Specification D-9-8900, "Fly Ash" shall be used.

2. Mix Design

For designing concrete mixes with fly ash, a trial mix procedure, based on absolute volume, similar to that described in Construction Bulletin C-11 and supplement thereto, is used.

The specific gravity of fly ash must be known to calculate absolute volume for mix proportioning. The Materials and Tests

Division will furnish the specific gravity of fly ash from the approved sources to be used.

A Class A fly ash can replace 20 to 30 percent of the absolute volume of the portland cement and a Class B fly ash can replace 25 to 35 percent.

The first step in designing concrete mixes with fly ash is to design a mix which meets water:cement ratio and workability requirements without any fly ash. This will be considered the control design. An existing mix design which is satisfactory in every respect may be used; however, a trial mix should be made from this design. Make at least three test specimens for strength (flexural and compressive) and test them in accordance with Test Method Tex-418-A or 420-A.

The second step is to replace a portion of the absolute volume of portland cement with fly ash. In this case the absolute volume of portland cement, for the control design, is known. The amount of fly ash replacement should be the minimum recommended for the class of fly ash to be used - 20 percent for Class A fly ash or 25 percent for Class B. Make small trial mixes until a design is produced which meets all workability requirements. The mixes containing fly ash will generally require less water than the control design. Make at least three test specimens for strength (flexural and compressive) and test them in accordance with Test Method Tex-418-A or 420-A.

The water demand for the mixes containing fly ash may vary from the control design and should be adjusted as necessary, on an absolute volume basis, to produce the desired workability.

For each mix design, the water:(C+F) ratio should be determined on a weight basis - pounds of water per pound of (C+F). For the mixes with fly ash the water content per cubic yard shall not exceed the maximum water content per cubic yard allowed in the specifications for the control design.

Next plot the values of strength and water:(C+F) ratios as illustrated in Figure 1. If the strength is insufficient select a higher cement content (one sack higher) and repeat steps 1 through 3 and plot the resulting data as illustrated in Figure 1. From Figure 1 determine the optimum fly ash content, strength and W:(C+F) ratio. Make a trial batch for pilot test to prove all aspects of the design.

The selected design should have at least 110 percent of the minimum specified flexural strength (120 percent compressive strength). This overdesign is needed to compensate for variations in strength caused by variations in materials, equipment, job conditions and job procedures.

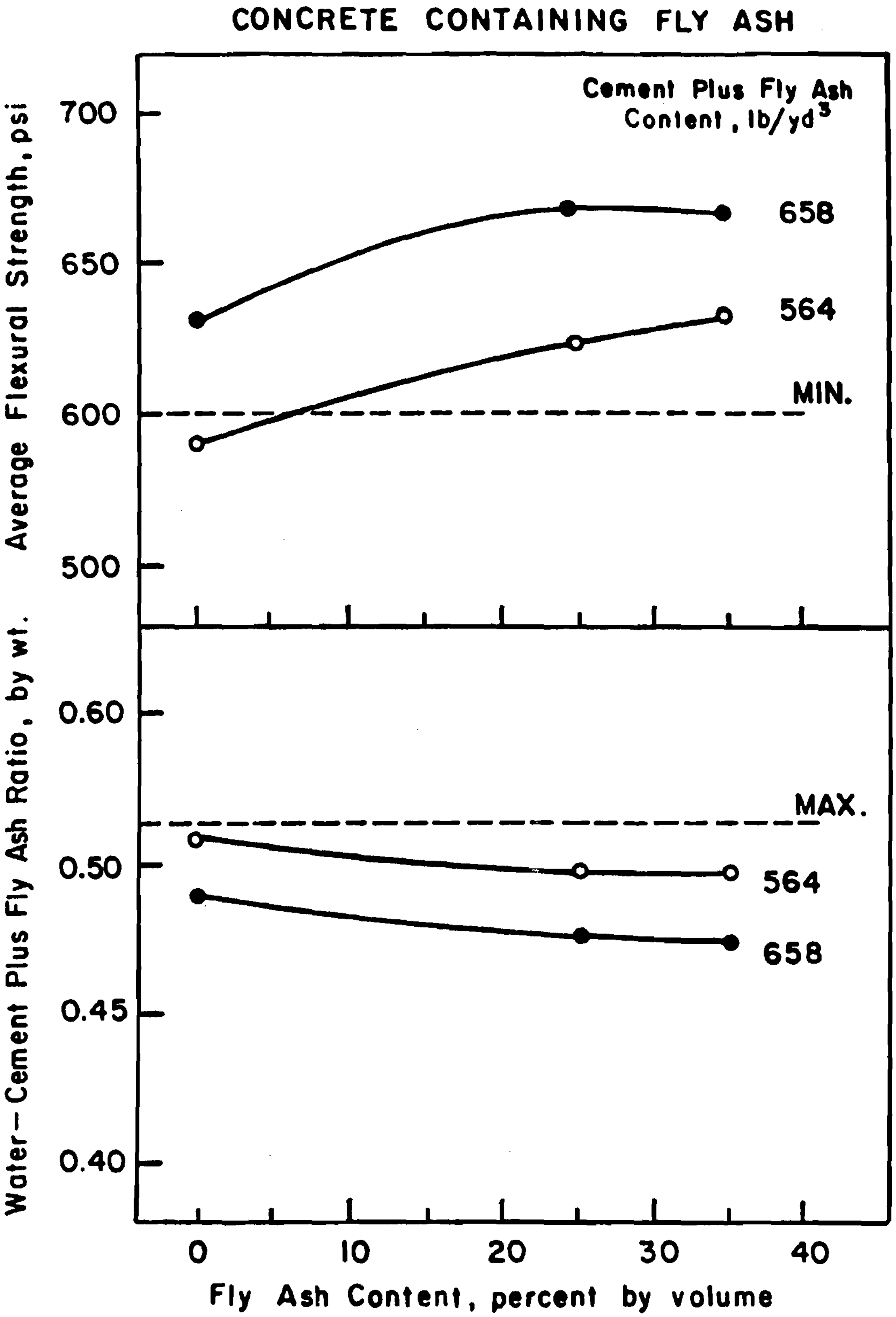


Figure E.1. Example of small trial mix design results.

3. High Strength Concrete

The following items and Table 1 should be used as a guide for design of high strength concrete (higher than 9000 psi compressive strength) with or without fly ash. Table 1 gives reasonable values from which to start a mix design. Some variations will occur depending on materials and their sources. An increase in the amount of water shown in the table will result in a drastic loss of strength.

1. The most important variable affecting the strength of high strength concrete is the water:C or (C+F) ratio. For a 28-day compressive strength of at least 9000 psi, the water:(C+F) ratio must be less than 0.35.

2. If no admixtures or fly ash are added to the mix, at least ten sacks of portland cement per cubic yard are needed to produce high strength concrete with a slump of three to four inches. A portland cement content of 9+1/2 sacks per cubic yard is near optimum for strength and workability when high range water reducer (HRWR) is used to produce a water:C ratio of 0.30 and a slump of at least four to five inches.

3. When HRWR is used in producing high strength concrete, the slump of the concrete prior to the addition of the HRWR must be in the range of one to two inches. This will result in concrete having adequate consistency and workability after HRWR is added.

4. Compressive strength increases as HRWR dosage rate increases, up to a dosage rate which causes the mix to segregate and become unworkable. Significant retardation may result from the addition of too much HRWR. Strength, workability and dosage rates may vary with the brand of HRWR.

5. High strength concrete can be produced from either natural gravel or crushed stone; however, crushed stone produces higher strength.

6. High strength can be produced with aggregate ranging in size up to one inch maximum. However, with or without HRWR, the highest concrete compressive strength results from using smaller maximum size aggregate.

7. For mixes containing no admixture, high strength concrete can be best produced using a sand with a fineness modulus of from 2.7 to 3.1. Fineness modulus as low as 2.4 are satisfactory for producing high strength concrete when HRWRs are used.

8. More compressive strength has resulted by adding Class B fly ash than by adding an equal weight of portland cement, if the absolute volume of fly ash is in the range of 20 to 35 pecent of the total absolute volume of portland cement and fly ash.

9. Generally, the one-day strength of high strength concrete is slightly reduced by the addition of fly ash; however, this loss of strength can be overcome by the reduction of the water content with the addition of HRWR.

10. The 28-day compressive strength of concrete ideally cured for seven days is not seriously affected by curing in hot dry conditions from 7 to 28 days after casting.

TABLE E.1. High Strength Concrete Mix Design Guidelines.

Min Comp. Str. 28-day psi	9,000 (a)	10,000 (a)	9,500 (a)	10,500 (a)
Sacks cement per cu yd	10.0	8.5	7.0	6.0
Max Water-Cement ratio (gal/sack)	3.9	3.4		
Crushed Coarse Aggr. Grade Number (b)	4, 5 or 6	4, 5 or 6	4, 5 or 6	4, 5 or 6
CA/FA Ratio (by weight)	2.0 (c)	2.0 (c)	2.0 (c)	2.0 (c)
Fly Ash (Class B) % of (C+F)	----------	----------	35 (f)	35 (f)
High Range Water Reducer	----------	Yes (d)	----------	Yes (d)
<u>General Usage</u>				
Prestressed Concrete	Yes	Yes	Yes	Yes
Cast in Place	Yes	Yes	Yes	Yes
<u>Other Notes</u>				
Good Formed Surfaces	Yes	Yes	Yes	Yes
Good Finished Surfaces	Yes	See Note	Yes	See Note

NOTES:

(a) Based on tests performed on 6-in. dia. X 12-in. cylinder of concrete made using a rigid steel mold.

(b) Crushed stone should have saturated surface-dry unit weight of at least 90 lb/cu ft., and a saturated surface-dry specific gravity of at least 2.50.

(c) Mixes containing no high-range water-reducer should be made using a coarse sand whose fineness modulus is at least 2.70

(d) Dosage of high-range water-reducer should be highest possible without causing segregation or excessive retardation of fresh concrete.

(e) Smoothly finished surface possible with motor-driven finishing tools. despite high fines content this mix is not easily finished by hand.

(f) Use of Class B fly ash at a rate of 35 percent by absolute volume of the total cement plus fly ash content is recommended for these mix proportions.

REFERENCES

1. ACI Committee 363, State-of-the-Art Report on High Strength Concrete (ACI 363R-84), American Concrete Institute, Detroit, 1984.

2. Blick, Ronald L. "Some Factors Influencing High-Strength Concrete," Modern Concrete, V. 36, No. 12, Apr. 1973, pp. 38-41.

3. Carpenter, James E. "Applications of High Strength Concrete for Highway Bridges," Public Roads, Vol. 44, No. 2, Sept. 1980, pp. 76-83.

4. Carrasquillo, R.L. Personal Communication, June 1985.

5. Carrasquillo, R.L., "Production of High Strength Pastes, Mortars and Concretes," Materials Research Society Symposia Proceedings, Vol. 42, Very High Strength Cement-Based Materials, Materials Research Society, Editor: J. Francis Young, 1985, pp. 151-168.

6. Cook, James E., "A Ready Mix Concrete Company's Experience with Fly Ash." Paper presented at the 1980 Fly Ash Conference, Texas A & M University, May 21, 1980.

7. Diamond, S., and Lopez-Flores, F. "Comparative Studies of the Effect of Lignitic and Bituminous Fly Ashes in Hydrated Cement Systems," Proceedings, Symposium on Fly Ash Incorporation in Cement and Concrete, Materials Research Society, Editor: S. Diamond, 1981, pp. 112-123.

8. Fisher, G.L., Prentice, B.A., Silberman, D., Ordov, J.M., Biermann, A.H., Ragaini, R.C., and McFarland, A.R. "Physical and Morphological Studies of Size-Classified Coal Fly Ash," Environmental Science and Technology, V. 12, No. 4, April 1978, pp. 447-451.

9. Hester, Weston T., "Microstructure as a Tool for Proportioning High Strength Concrete Mixes," Materials Research Society Symposia Proceedings, Vol. 42, Very High Strength Cement - Based Materials, Materials Research Society, Editor: J. Francis Young, 1985, pp. 193-200.

10. Hogan, F.J., and Meusel, J.W. "Evaluation for Durability and Strength Development of a Ground Granulated Blast Furnace Slag," Cement, Concrete and Aggregates, V. 3, No. 1, Summer 1981, pp. 40-52.

11. "How Super are Superplasticizers?" Concrete Construction Magazine, Concrete Construction Publications, Inc., Addison, Illinois, May 1982, pp. 409-415.

12. Jahren, P., "Use of Silica Fume in Concrete," Special Publication SP-79, Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, Vol. II, American Concrete Institute, Detroit, 1983, pp. 625-642.

13. Janak, Karl J., "Comparative Compressive Strength of 4 x 8-in. Versus 6 x 12-in. Concrete Cylinders Along with the Investigation of Concrete Compressive Strength at 56 Days," Report 3-I-4-116, Materials and Tests Division, Texas State Department of Highways and Public Transportation, March 1985.

14. Lauf, R.J., "Microstructure of Coal Fly Ash Particle," Ceramic Bulletin, V. 61, No. 4, April 1982, pp. 487-490.

15. Mailvaganam, Noel P., Bhagrath, R.S., and Shaw, K.L., "Effects of Admixtures on Portland Cement Concretes Incorporating Blast Furnace Slag and Fly Ash," Special Publication SP-79, Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, Vol. I, American Concrete Institute, Detroit, 1983, pp. 519-537.

16. Manz, Oscar E., "Review of International Specifications for Use of Fly Ash in Portland Cement Concrete," Special Publication SP-79, Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, Vol. I, American Concrete Institute, Detroit, 1983, pp. 187-200.

17. Mehta, P.K., "Pozzolanic and Cementitious By-Products as Mineral Admixtures for Concrete - A Critical Review," Special Publication SP-79, Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, Vol. I, American Concrete Institute, Detroit, 1983, pp. 1-46.

18. Mindess, Sidney, "Relationships Between Strength and Microstructure for Cement-Based Materials: An Overview," Materials Research Society Symposia Proceedings, Vol. 42, Very High Strength Cement-Based Materials, Materials Research Society, Editor: J. Francis Young, 1985, pp. 53-68.

19. Musser, Peggy L., "Bond Performance of Reinforcing Sttel Embedded in Concrete Made Using Superplasticizer," Master's Thesis, The University of Texas at Austin, April 1985.

20. Peterman, M.B., and Carrasquillo, R.L., "Production of High Strength Concrete," Research Report 315-1F, Center for Transportation Research, The University of Texas at Austin, October 1983.

21. Powers, T.C., in Proceedings of the Fourth International Symposium on the Chemistry of Cement (National Bureau of Standards, Washington, D.C., 1960), Vol. II, p. 577.

22. Radjy, Farrokh F., and Loeland, Kjell E., "Microsilica Concrete: A Technological Breakthrough Commercialized," Materials Research Society Symposia Proceedings, Vol. 42, Very High Strength Cement-Based Materials, Materials Research Society, 1985, pp. 305-312.

23. Sellevold, E.J. and Radjy, F.F., "Condensed Silica Fume (Microsilica) in Concrete: Water Demand and Strength Development," Special Publication SP-79, Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, Vol. II, American Concrete Institute, Detroit, 1983, pp. 677-694.

24. Sellevold, E.J., Bager, D.H., Jensen, E.K., and Knudsen, T., "Silica Fume Cement Pastes - Hydration and Pore Structure," Proceedings, Nordisk Mini Seminar on Silica in Concrete, December 1981, 32 pages.

25. Skrastins, J.I. and Zoldners, N.G., "Ready-Mixed Concrete Incorporating Condensed Silica Fume," Special Publication SP-79, Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, Vol. II, American Concrete Institute, Detroit, 1983, pp. 813-829.

26. "Standard Specifications for Construction of Highways, Streets and Bridges," Texas State Department of Highways and Public Transportation, September 1, 1982.

27. Texas State Department of Highways and Public Transportation, Departmental Material Specifications, Specification D-9-8900.

28. Yuan, Robert L., and Cook, J.E., "Study of a Class C Fly Ash," Special Publication SP-79, Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, Vol. I, American Concrete Institute, Detroit, 1983, pp. 307-319.