FINAL REPORT

EFFECTIVE FIELD USE OF HIGH-RANGE, WATER-REDUCED CONCRETE

by

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(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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SUMMARY

This report describes the experience of the Virginia Department of Highways and Transportation with the use of high range, water reduced (HRWR) concrete. A description of the installation of the HRWR concrete in two pavements and four bridge decks, along with the results of evaluative tests, is given in Appendix A. Appendix B details the evaluations of HRWR concretes prepared in the laboratory at the Research Council. Based on the field and laboratory experience, recommendations concerning the further use of HRWR concrete by the Virginia Department of Highways and Transportation were formulated.

As noted in Appendix A, on the average the HRWR concrete placed in the field with conventional equipment was properly consolidated and controlled. However, because of the unanticipated variability of the concrete, portions of the concrete exhibited inadequate consolidation, segregated mixture components, improperly entrained air, shrinkage cracks, and poor finishes. Also, specimens subjected to cycles of freezing and thawing showed low durability factors that were attributed to an unsatisfactory air void system.

As noted in Appendix B, subsequent laboratory work revealed that HRWR admixtures satisfied the requirements of ASTM C494. On the basis of the results of the laboratory work, explanations were developed for the problems that occurred in the field.

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INTRODUCTION

Superplasticizers may be grouped into four generic classes as follows: (1) sulphonated melamine formaldehyde condensates, (2) sulphonated naphthalene formaldehyde condensates, (3) modified ligno sulphonates, and (4) others.[1] The napthalene formaldehyde condensates have been used in Japan for approximately 13 years and the other three classes have been used in Germany during the past 10 years. Their use has spread to other parts of Europe, to Canada, and to the United States during the past 8 years.

The superplasticizing admixtures are typically used for one or more of three purposes. First, they may be used to produce high-range, water-reduced (HRWR) concrete, which is best described as concrete exhibiting conventional workability (slump = 0 to 5 in.)* but having a water to cement (w/c) ratio at least 12% less than that of a conventional mixture.[2] The cost of the admixture is usually justified on the basis of improvements in the early or long-term strength or reductions in permeability. A second application for the admixtures is in the production of flowing concrete, i.e., concrete having a conventional w/c and strength but a slump in excess of 7¼ in.[1] The cost of the admixture is justified on the basis of a reduction in labor costs, since the concrete is reported to be self-leveling. This concrete also lends itself to good consolidation in heavily reinforced members. A third application is in the production of concrete having conventional workability and strength but a lower than conventional cement content. In this case, the cost of the admixture is offset by a reduction in the cost of cement.

The early experiences in Japan emphasized HRWR concrete, whereas the early experiences in Germany concentrated on flowing concrete.[1] The predominant application for HRWR concrete in the United States has been in the precast, prestressed concrete industry, where energy consumption can be reduced through a reduction in accelerated curing time and production rates can be increased.

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*For metric conversions, see Notations on page 23.

Most highway applications have been for pavement or bridge deck repairs. The ASTM classified the admixtures as Type F, Water Reducing High Range, and Type G, Water Reducing High Range and Retarding.(2) Information on superplasticizing admixtures continues to surface but the best current sources are the proceedings of the two international symposiums on Superplasticizers in Concrete held in Ottawa, Canada, in May 1978 and June 1981,(3,4) and reports by the U. S. Department of Transportation,(5) the Portland Cement Association,(6) and the Federal Highway Administration.(7) The sources of information generally support expanding the use of HRWR admixtures.

REPORT FORMAT

The body of this report gives a general discussion of Virginia's experience with HRWR concrete and focuses on the development of conclusions and recommendations on its use.

A description of the installation of HRWR concrete on two pavements and four bridge decks, along with the results of evaluative tests, is given in Appendix A.

Appendix B details the evaluations of HRWR concretes prepared in the laboratory at the Research Council.

BACKGROUND

HRWR concrete was used experimentally by the Virginia Department of Highways and Transportation on five construction jobs between May 1974 and June 1977. Melamine (M) and naphthalene (N) sulfonate polymer admixtures were used to produce concrete having a w/c in the range of 0.34 to 0.37, which was a 20% to 25% reduction in water content. On these jobs an effort was made to maintain a workability that would allow the concrete to be placed with conventional equipment; that is, to use concrete with a slump $\geq$ 2 in.

State maintenance forces installed the first HRWR concrete in Virginia in the form of 15 small, partial-depth pavement patches on the Norfolk and Virginia Beach Expressway.(8) No problems were encountered, and the maximum time required to batch, place, consolidate, finish, and apply the liquid membrane curing compound for any one patch was about 15 minutes. The patches appear to be in good condition after being subjected to seven years of heavy traffic and a very modest number of cycles of freezing and thawing.

Maintenance forces next used HRWR concrete to construct a full-depth, 9-in. turning lane approximately 200 ft. long and 11 ft. wide on Rte. 29 near Lynchburg. The ready-mix concrete, which was batched at a plant located 5 minutes from the job site, was placed and finished in a few minutes without any noticeable problems. This pavement appears to be in satisfactory condition after being subjected to 6.5 years of moderate traffic and a fair number of cycles of freezing and thawing. Several major transverse cracks are visible and much of the surface has scaled moderately, with coarse aggregate being visible in many areas. An examination of cores removed from the pavement indicated that some of the concrete was poorly consolidated.

As with the full-depth pavement installation, for the first deck overlay with HRWR concrete, which was placed on a bridge (B616) at Charlottesville, the HRWR admixture (FX-32) was blended in powdered form with the fine aggregate prior to being placed in the ready-mix truck at the batch plant, which was located 25 minutes from the job site. A rapid loss in workability during transit and placement was not anticipated and therefore not properly accommodated. Petrographic examinations of cores removed from the 4 in. thick overlay showed that the concrete was much too permeable because of inadequate consolidation. Following one winter of freezing and thawing and heavy traffic, the concrete deteriorated to the point that it had to be replaced. Obviously, the concrete was inferior because the contractor failed to place, consolidate, and finish it before it lost its workability.

See Appendix A for additional details on these three installations.

PURPOSE AND SCOPE

The consolidation problems resulting from the rapid loss in workability during the construction of B616 in Charlottesville suggested a need for an evaluation of HRWR concrete. The need was urgent because HRWR concrete was scheduled to be used on two new bridge decks at Norton, one new deck in Roanoke, and on one deck on a repair project in South Hill.

The work plan was to monitor the batching and placing of the HRWR concrete on these bridges and to conduct laboratory research to gain information on which to base recommendations to the Virginia Department of Highways and Transportation on the effective use of HRWR concrete.

The specific objectives were to:

1. Establish guidelines for adding superplasticizers and for mixing, placing, consolidating, and finishing superplasticized concrete for bridge decks.

2. Establish field acceptance procedures for superplasticized concrete.

3. Examine the freeze-thaw durability of superplasticized concrete.

4. Identify factors which contribute to rapid slump loss.

Because the field installations in Norton were under way at the time the working plan was approved,(9) it was necessary to complete the monitoring of the field installations prior to initiating the work in the laboratory.

DISCUSSION OF RESULTS

ASTM C494 Requirements

The laboratory results indicated that when used in typical highway concretes, either alone or in combination with type D water-reducing, retarding admixtures, HRWR admixtures satisfied the requirements of ASTM C494 for type F or type G admixtures. Failures were limited to the following: (a) a failure to meet the early strength requirements when the water reduction was only 12%, (b) a failure to meet the setting time requirements when the dosage of HRWR admixture or HRWR admixture plus type D admixture was very high, and (c) a failure to satisfy the freeze-thaw requirements when the air content was below 6.5%.

Cylinder Strength

The greatest obvious benefit to be achieved from the use of HRWR concrete is an improvement in the strength of concrete cylinders. In the work discussed here, the twenty-eight day cylinder strengths and flexural strengths appeared to increase, as would be expected based on the water reduction that is achieved. The strength of the HRWR concrete relative to that of the control concrete was usually greatest at early ages. The improvements in cylinder strengths were noted in both the laboratory and field prepared specimens.

Permeability

The laboratory results indicated that another potential benefit to be derived from the use of HRWR concrete is a reduction in permeability proportional to the water reduction. No permeability tests were performed on the field specimens, but it is believed that as long as proper consolidation was achieved the expected permeability was also obtained. Because of problems in achieving proper consolidation in the field, due to a loss in slump, much of the concrete was probably more permeable than indicated by the laboratory specimens. The risk that proper consolidation will not be achieved tends to offset the potential benefit in permeability to be gained from using HRWR concrete.

Drying Shrinkage

HRWR concrete specimens prepared in the laboratory (no specimens were prepared in the field) exhibited a shrinkage similar to that of the control concrete. It is believed that shrinkage was negligible in both the HRWR concrete and the conventional control concretes because they were both of very high quality. The only shrinkage problem noted in the field was a limited amount of plastic shrinkage that resulted from a failure to apply the curing compound before all the excess surface moisture was lost.

Setting Time

The laboratory work indicated that the use of HRWR admixtures usually retarded the setting time slightly, but occasionally set was accelerated, particularly with the use of melamine admixtures, and quite frequently the setting time was extended two hours or more. Extended retardation was usually limited to the concretes containing type D retarders or to concretes given very high dosages of admixtures.

Freeze-Thaw Performance

The specimens prepared in the laboratory exhibited improved resistance to damage from cycles of freezing and thawing over that of the specimens prepared in the field. The likely cause of the high percentage of failures of the freeze-thaw specimens prepared in the field was their low air content. The specifications called for an air content of 5% to 8% or 5% to 9%, and on the average the specifications were satisfied. However, because of the variability of the field concrete, some specimens had lower than prescribed air contents and a majority of the specimens had an air content lower than the 6.5% found to be the typical minimum amount for satisfactory performance based on the laboratory work. Also, the laboratory work revealed that the transition between unacceptable and acceptable freeze-thaw performance occurs when the air content is between 5% and 6.5%.

Air Void Characteristics

Concretes prepared in the laboratory exhibited air void characteristics similar to those of the concretes prepared in the field. Typically, the HRWR highway concretes exhibited a spacing factor between 0.008 and 0.014 in., and most of these concretes passed the freeze-thaw test conducted in accordance with ASTM C666, Procedure A. A plot of the relationship between durability factor and spacing factor indicated that it is reasonable to expect acceptable durability when the spacing factor is less than 0.012 in.

On the average, the HRWR highway concretes having a w/c = 0.34 exhibited a specific surface of 388 $in.^{-1}$ The specific surface appears to be a function of the w/c; as the w/c increases the specific surface increases. No relation was found between the durability factor and specific surface.

Slump Loss

On the average, the HRWR concretes lost slump about twice as fast as the control concretes. The rate of slump loss varied from batch to batch, but no definite trends could be established.

It appeared that HRWR concrete prepared in a ready-mix truck lost slump faster than the same mixture proportions combined with a pan-type mixer in the laboratory. Evidently the efficiency of the mixer, mixing time, and the degree of control over the relative quantities of ingredients can affect the slump as well as the loss of slump. In general, the rapid slump loss appears to be a natural characteristic of HRWR concrete. The literature indicates that some combinations of cement and admixtures lose slump faster than others. More study of slump loss is needed.

Air Loss

Some HRWR concretes lost air twice as fast as conventional highway concretes, and this must be taken into account when accepting concrete.

Type D Admixtures

Based on the laboratory work it appears that, in general, the use of the type D admixtures in combination with the HRWR admixtures did not significantly change the freeze-thaw performance, the air void characteristics, or the rate of slump loss. Early strength was less only when the set was retarded considerably. There was no field experience with type D admixtures.

Sequence of Addition of Admixtures

Based on the laboratory work it is believed that the sequence of the addition of the HRWR admixture and the air-entraining admixture (AEA) has only a marginal effect on the properties of the concrete. When the AEA is added last, the specific surface tends to be slightly higher and the slump lower than when it is added first. The delayed addition of the HRWR admixture retards the set and produces concrete with a lower air content, because air is lost during the delay. This behavior would be expected, since it is generally accepted that admixtures are the most effective the later they are added to the concrete.

Segregation

Segregation of the mixture was noted in the field and the laboratory concretes when slumps exceeded 7 in. This happened only when unanticipated moisture was present in the mixture or when the dosage of HRWR admixtures was intentionally high enough to produce the high slump. It was also observed that concretes exhibiting unacceptably low air contents tended to bleed and segregate. It is believed that segregation can be prevented by maintaining an acceptable air content in the concrete, by maintaining a slump of 7 in. or less, and by using the correct dosage of HRWR admixture for the moisture content, air content, and mixture proportions.

Trial Batching

One or more trial batches were made prior to placing the HRWR concrete in the field. However, these were not extensively monitored so as to identify problems that could arise during all phases of the field installations. Based on the work in the laboratory, it is believed that problems with HRWR concrete can be held to a minimum with adequate trial batching and preliminary planning.

Significance of Laboratory Work

As a result of the laboratory work, see Appendix B, suitable explanations were derived for the problems encountered when HRWR admixtures were used in the field. For example, the laboratory work indicated that the freeze-thaw failures were a result of air contents lower than 6.5%. It also revealed that the large spacing factors are typical of HRWR concretes having a w/c = 0.34 and are not necessarily related to field activities. The consolidation and finishing problems noted in the field were a result of a failure to properly anticipate and appropriately deal with the rate of slump loss typical of HRWR concretes. The segregation was a result of placing HRWR concrete with a slump in excess of 7 in. The bleeding was caused by a combination of low air contents and high concentrations of the HRWR admixture resulting from a failure to get the admixture properly distributed throughout the ready-mix truck. In some instances, inadequate mixing may have magnified all of the cited problems, because a ready-mix truck cannot be expected to disperse an admixture in low-slump concrete as effectively as the pan-type mixer used in the laboratory.

GUIDELINES FOR EFFECTIVE USE OF HRWR CONCRETE

Batching and Placing

One of the objectives of this project was to establish guidelines for adding HRWR admixtures and for mixing, placing, consolidating, and finishing HRWR concrete.

Trial Batches

It is believed that the first step is to become familiar with the cement, admixtures, and mixture proportions proposed for the work at hand. If the HRWR admixture is not specified, the initial selection can be based on cost, since there appears to be little difference between most of the admixtures when considered on a percentage-solids basis. Batches of paste or mortar should be prepared and the slump loss, setting time, and bleeding characteristics observed. A mini slump cone can be used to identify any problem with slump loss.(10) If problems are noted, a change should be made in the cement or combination of admixtures.

Once any problems with the pastes or mortars have been solved, a concrete mixture should be proportioned in accordance with ACI recommended practice and a trial batch should be made simulating the conditions, equipment, manpower, and procedures anticipated for the proposed project. A successful trial batch should enhance the chances for a successful installation. If problems are noted during the trial batch, the mixture proportions, equipment, or installation plans should be changed as necessary to eliminate them.

Batch Size

The quantity of concrete batched should be no greater than the quantity that can be placed, consolidated, screeded, and finished while maintaining acceptable properties of the concrete. It has been shown that the time required to install a given quantity of concrete is a function of many variables, including the length of the screed span. For typical bridge decks in Virginia, only about 1.5 to 3.5 $yd.^3$ can be placed and screeded in the 15 minutes that is typical of the time required for HRWR concrete to lose half its slump. Much larger volumes of HRWR concrete could be properly placed in the same amount of time in structural members such as bridge beams that have a much smaller screed surface to volume ratio than bridge decks.

Addition of HRWR Admixtures

When feasible, the HRWR admixture should be batched with the other ingredients. This procedure provides the best opportunity to disperse the admixture throughout the concrete mixture and is particularly important when the slump of the concrete would be below 2 in. without the admixture. Delaying the addition of the HRWR admixture appears to be an acceptable practice but is certainly more likely to cause quality control problems than adding it during the batching of the concrete. When addition of the admixture must be delayed, the slump of the concrete should be $\geq$ 2 in. if possible prior to the addition so that proper mixing and distribution of the admixture can be reasonably assured. Multiple additions of the admixture are acceptable as long as proper distribution is achieved and the specified plastic properties of the concrete are maintained. Multiple additions of the AEA can also be tolerated but should be avoided if possible because of the increased potential for quality control problems.

Mixing

Proper mixing of the concrete is a prerequisite for satisfactory performance. Ready-mix trucks are not particularly suitable for mixing concrete having a slump of less than 2 in. If they are to be used to mix HRWR concrete, steps should be taken to ensure that the initial slump of the concrete is at least 2 in. Appropriate steps could include specifying a higher than usual w/c or adding a type B or D admixture or partial dose of HRWR admixture during the initial batching. High efficiency mixers such as the pan-type mixer used in the laboratory should be used to mix HRWR concrete that is to have a slump of less than 2 in. prior to the addition of the HRWR admixture.

Placing

HRWR concrete should be placed as quickly as possible, with a direct discharge from the mixer into the forms being used when feasible. Methods such as the use of baggies or wheelbarrows that require a prolonged transport time between the mixer and the forms should be avoided.

Consolidation

Equipment must be available to properly consolidate the concrete while it has acceptable workability. Concrete that exhibits a high slump should be vibrated carefully to prevent segregation, with the amount of vibration being inversely proportional to the slump. Internal vibrators should not be used to consolidate concrete having a slump of less than 2 in. External vibrators such as vibrating screeds have been found to provide acceptable consolidation for such concrete.

Finishing

With the exception of trowel finishes, which are seldom used in highway applications, finishing operations must be completed while the concrete has acceptable workability. HRWR concrete tends to stiffen prematurely at the surface, so a screed finish is the easiest type to achieve. Special finishes such as are imparted with a burlap drag, rake, or tines will not be satisfactory unless applied immediately after the screeding operation. An acceptable grooved finish for skid resistance is probably best achieved by sawing the hardened concrete surface.

Curing

To prevent plastic shrinkage cracking, the curing compound or curing material should be applied to the surface of the concrete as the sheen disappears. There is usually little excess bleed water on the surface of HRWR concrete, so the curing compound or material will usually have to be applied at a very early age, such as immediately after the screeding or other finishing operation.

Acceptance Procedures

The second specific objective of this project was to establish acceptance procedures for HRWR concrete.

ASTM C494 Requirements

Initially, it must be determined that when used in the mixture proportions proposed for a job the admixture will satisfy the requirements of ASTM C494. The laboratory work has demonstrated that when used alone or in combination with type D admixtures the typical HRWR admixtures can satisfy the requirements of ASTM C494. Any HRWR admixtures found to be significantly different from those that have been evaluated would have to be tested for conformance. Also, the HRWR admixtures would have to be tested for conformance when used in concrete mixtures in which the cements or mixture proportions are significantly different from those used in the study.

Slump

As in conventional practice, the slump (ASTM C143) of the concrete should be checked prior to placement. Unless otherwise specified, the slump should be from 2 to 7 in. throughout the installation. Because of slump loss, the inspector should predetermine the time that will be required to install the concrete and should reject concrete that will have a slump of less than 2 in. before the installation is complete. In most instances concrete that exhibits a slump in excess of 7 in. initially can be used once the slump is $\leq$ 7 in. The same requirements apply if additional HRWR admixture is added to the concrete to increase the slump.

Air Content

As in conventional practice the air content (ASTM C231) should be checked prior to placing the concrete. Because of the possibility of a sizeable change in air content taking place during the installation, the inspector should be prepared to make as many tests as necessary to ensure that all the concrete has the specified air content at the time it is placed in the forms.

Where resistance to damage from cycles of freezing and thawing is of major importance as in bridge decks, the air content should be between 6% and 10% and preferably on the higher side of the specified range. Where such resistance is of lesser importance as with most precast concrete members, the air content should be between 5% and 9%. An acceptable specification for pavement repairs is 5% to 9%.

Appearance

Concrete that is bleeding excessively or otherwise segregating should be rejected. Excessive bleeding and segregation are good indicators that the air content is too low, that the HRWR admixture dosage, the w/c, or the slump is too high, or that mixing is incomplete.

Strength

Again as in conventional practice, the strength of the concrete should be determined by subjecting specimens prepared at the job site to compression or flexural tests. Because of the water reductions usually achieved with HRWR admixtures, there is little chance that properly prepared specimens will fail 28-day strength tests. Failures at very early ages may occur if the w/c was not as low as anticipated or if the set of the concrete was accidently delayed for a considerable time.

Final Acceptance

In most instances, compliance with the previously mentioned specifications will ensure that the concrete is acceptable. Final decisions as to the quality of the concrete that did not satisfy the previously mentioned specifications should be based on petrographic examinations, permeability tests, or compression tests of cores removed from the structure. The petrographic examination can verify if the air content was adequate and if consolidation was satisfactory, the permeability tests can provide an indication of the w/c and the degree of consolidation of the concrete, and the compression tests can provide a good indication of the strength of the concrete.

Freeze-Thaw Durability

A third objective of this study was to examine the freeze-thaw durability of HRWR concrete. The study indicated that HRWR concrete can satisfy the requirements of ASTM C666, Procedure A when the air content exceeds 6.5%. Typically, the HRWR concrete exhibited a spacing factor between 0.008 in. and 0.014 in., and most of the concrete passed the freeze-thaw test when the spacing factor was less than 0.012 in. The average specific surface for HRWR concrete having a w/c of 0.34 was 388 in.$^{-1}$, which is much lower than that found in conventional highway concretes. The low specific surface was found to be caused by the low w/c and the presence of the HRWR admixture.

Slump Loss

A fourth objective of this project was to identify factors that contribute to rapid slump loss. The study found that, on the average, the HRWR concretes lost slump about twice as fast as the control concretes. The rate of slump loss varied from batch to batch but no definite trends could be established. It appeared that HRWR concrete prepared in a ready-mix truck would lose slump faster than the same mixture proportions combined with a pan-type mixer in the laboratory. Evidently the efficiency of the mixer, mixing time, and the degree of control over the relative quantities of ingredients can affect slump as well as slump loss. In general, the rapid slump loss noted in Virginia appears to be a natural characteristic of HRWR concrete. More study of slump loss is needed.

The literature indicates that some combinations of cements and admixtures lose slump faster than others. For example, a report by the FHWA indicates that "slump loss is a function of cement and admixture composition, dosage of admixture, time of addition of admixture, concrete paste contents, and temperature."(7) The interested reader should refer to this work. It is worth noting, however, that the effect of some of these variables on slump loss is of academic interest only since the effects are either minor or the desired effects are impractical to implement. For the time being it is believed that the best way to handle slump loss is to determine ahead of time the rate of slump loss for the locally available cements and admixtures and to organize the installation operations to deal with it. If slump loss continues to be a problem, an effort can be made to find a combination of cement and admixture that will be more acceptable.

Recommended Applications for HRWR Concrete

(A) HRWR concrete is best suited for use in precast, prestressed concrete work because of the advantages to be gained from the high early strength and the potential for reducing the accelerated curing time. Furthermore, slump loss can be handled more easily in the plant. Finally, it is believed that with proper knowledge of HRWR admixtures, conventional precast plant concreting practices, with minor modifications, can be used to batch, place, consolidate, finish, and accept HRWR concrete. Two major precast concrete producers in Virginia are routinely using HRWR concretes in nonhighway applications. Unfortunately, the higher air content which is required for satisfactory freeze-thaw performance will cause some reduction in strength but the reduction should not be a problem.

(B) HRWR concrete is second best suited for pavement repairs and other general concrete construction. The high early strength offers significant advantages but slump loss can present a problem if the user is not prepared to accommodate it. Conventional concrete practice must be modified slightly when HRWR concrete is used for pavement repairs, since care must be taken to ensure that proper mixing is achieved when ready-mix trucks are used and to ensure that the concrete is placed and finished before the slump drops below the acceptable level. The higher air content which is required for frost protection should not be a problem.

(C) Primarily because of the rapid loss in slump, HRWR concrete does not lend itself to use in bridge deck construction. Although it is probably true that a properly organized contractor could construct a good quality HRWR concrete deck, there is little chance that HRWR concrete decks could be properly constructed by the average contractor on a regular basis. Assuming that adequate consolidation were achieved, an HRWR concrete deck would be less susceptible to chloride intrusion than a conventional deck, and adequate freeze-thaw durability could be achieved by maintaining the air content above 6.5%. However, weighing the benefits against the risks, HRWR concrete decks do not appear to be an attractive alternative at this time. The use of HRWR concrete in other parts of the bridge superstructure would be acceptable but not necessarily advantageous. An air content of 6% to 10% should be the minimum specified for HRWR concrete used in bridge decks.

Concluding Remarks

The use of HRWR admixtures to produce concrete having a slump in excess of 7 in. or concrete with a water reduction less than 12% should not be permitted until further study is made of these types of concrete. Similarly, the use of cement reduced concrete containing HRWR admixtures should not be permitted until an adequate study can be made of these concretes.

It is believed at this point that the greatest risks associated with the use of HRWR admixtures in typical highway concretes include segregation, rapid loss in slump, extended setting time, and poor freeze-thaw durability. Since a contractor who is familiar with HRWR concrete can probably minimize these risks, in some situations the benefits to be gained from using HRWR concrete will justify the risks.

In most situations conventional concrete acceptance procedures and concreting practices, particularly those which are rapid, can be used to handle HRWR concrete. Because of slump loss and air loss special care must be taken to ensure that the concrete has the proper air content and workability at the final stages of the installation. Satisfactory freeze-thaw durability can be achieved by maintaining a proper air content. Slump loss appears to be a natural characteristic of HRWR concrete related to the properties of the concrete and for the present will have to be dealt with rather than eliminated. Perhaps in the future special blends of cement will be developed that will provide for extended working time and special equipment will be devised to minimize the problems associated with placing HRWR concrete.

CONCLUSIONS

1. When used in typical highway concretes, either alone or in combination with type D water-reducing, retarding admixtures, HRWR admixtures can satisfy the requirements of ASTM C494 for type F or type G admixtures.

2. The obvious benefits achieved by using HRWR admixtures in typical highway concrete include an increase in the early and the 28-day compressive and flexural strengths, and a decrease in permeability.

3. The use of HRWR admixtures in typical highway concrete appears to have little effect on drying shrinkage.

4. The greatest risks associated with the use of HRWR admixtures in typical highway concretes include segregation, rapid loss in slump, extended setting time, and poor freeze-thaw durability.

5. Segregation can usually be prevented by preparing a properly proportioned and properly air-entrained mixture with a slump of 7 in. or less.

6. On the average, HRWR concretes tested in this study lost slump about twice as fast as typical highway concretes.

7. The use of HRWR admixtures in typical highway concretes usually retards the setting time slightly, but occasionally set may be accelerated, particularly with the use of melamine admixtures, and quite frequently setting time may be extended two hours or more.

8. HRWR highway concretes having an air content of 6.5% or greater as determined by ASTM C231 can pass the freeze-thaw test prescribed by Procedure A of ASTM C666. Similar concretes with an air content less than 5.0% can't pass the test.

9. Typically, HRWR highway concretes exhibit a spacing factor between 0.008 in. and 0.014 in. It is reasonable to expect acceptable freeze-thaw performance when the spacing factor is less than 0.012 in.

10. On the average, HRWR highway concretes having a w/c = 0.34, exhibit a specific surface of 388 $in.^{-1}$. The specific surface appears to be a function of the w/c;as the w/c increases the specific surface increases.

11. Some HRWR concretes lose air twice as fast as conventional highway concretes and this must be taken into account when accepting the concrete.

12. The sequence of the addition of the HRWR admixture and the AEA has only a marginal effect on the properties of the concrete.

13. In general, the use of type D admixtures in combination with HRWR admixtures did not produce significant improvements in the freeze-thaw performance, the air void characteristics, or the rate of slump loss. Early strength was less only when set was retarded considerably.

14. The laboratory work reported here provided suitable explanations for the problems encountered when HRWR admixtures were used in the field.

15. Problems with HRWR concrete can be held to a minimum with adequate trial batching and preliminary planning.

16. HRWR concrete is best suited for use in precast, prestressed concrete work because of the advantages to be gained from the high early strength and the potential for reducing the accelerated curing time. Furthermore, slump loss can be handled more easily in the plant.

17. HRWR concrete is second best suited for pavement repairs and other general concrete construction. The high early strength offers significant advantages but slump loss can present a problem if the user is not prepared to accommodate it.

18. Primarily because of the rapid loss in slump, HRWR concrete does not lend itself to use in bridge deck construction. The use of HRWR concrete in other parts of the bridge superstructure would be acceptable but not necessarily advantageous.

19. The use of HRWR admixtures to produce concrete having a slump in excess of 7 in. or concrete with a water reduction less than 12% should not be permitted until further study is made of these types of concretes.

RECOMMENDATIONS

1. Permission to use HRWR admixtures that conform to the requirements of ASTM C494, Type F or Type G should be granted on a case-by-case basis, so long as the user demonstrates he can use the admixtures without producing segregated concrete or concrete that otherwise does not meet specifications.

2. The Department should prepare a specification to cover the requirements for HRWR concrete. The requirements should be the same as those contained in Table II-15 of the <u>Road and Bridge Specification</u> with the exception that the upper limit on slump should be increased to 7 in. and the average acceptable air content should be increased by from 1% to 3%, depending upon the class of concrete.

3. A laboratory research project should be conducted to evaluate flowing concretes, more specifically concretes with slumps in excess of 7 in. or concrete in which the water reduction is less than 12%.

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4. A laboratory research project should be undertaken to evaluate the suitability of HRWR admixtures for reducing the cement content of typical highway concretes.

5. The Department should keep abreast of developments pertaining to HRWR admixtures.

ACKNOWLEDGEMENTS

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METRIC CONVERSIONS

1 inch	= 2.54 cm
1 ft.	= 30.5 cm
1 lb./ft.^{3}	= 16.02 kg/m^3
1 lb./yd.^{3}	= 432.5 kg/m^3
1 yd.^{3}	= 0.765 m^3
1 ft.^{3}	= 28.3 dm^3
1 lb./in.^{2}	= 6.895 kPa

APPENDIX A

FIELD INSTALLATIONS

Installation Designations

Prior to the initiation of this research project, HRWR concrete had been used on three construction projects in Virginia. These installations are designated as follows:

Partial-depth pavement repair	—	R-44
Full-depth turning lane	—	R-29
Barracks Road Bridge deck overlay	—	B616

Limited details of these installations are given along with the more detailed and planned evaluations of the HRWR concrete used at Norton and South Hill. Although only two contractors were involved, the use of HRWR concrete at Norton and South Hill is best described as five installations designated as follows:

Fourth deck overlay in Norton	—	B602-C
Fifth and sixth deck overlays, in Norton	—	B602
Seventh, eighth, and ninth deck overlays in Norton	—	B603
First, second and third deck overlays in South Hill	—	I85-A
Fourth and fifth deck overlays in South Hill	—	I85-B

For comparison, evaluations were made of the two conventional installations by the contractors in Norton and South Hill and a third conventional installation in Floyd County that involved similar construction circumstances. These control installations are denoted as follows:

First, second, and third deck overlays in Norton	B604
Sixth deck overlay in South Hill	I85-C
First and second deck overlays in Floyd County	B639

Comparison of Mixture Proportions and Plastic Properties of Concrete

Mixture Proportions

As can be seen from Table A-1 the mixture proportions were not significantly different for any of the installations. The cement content was 6-3/4 to 7-1/2 bags/yd.^{3} for all the installations. One-inch maximum size crushed stone was used on many of the installations; half-inch maximum size crushed stone or gravel was used on the others. The water content was 20% to 25% lower for the HRWR concrete than that for the control installations. The concentration of HRWR admixture was 1.0% solids by weight of cement for the installations in which FX32 was used and varied from 0.5% to 1.0% for the installations in which M150 was used.

Plastic Properties of Concrete

The ASTM C231 pressure method was used to measure the air contents of all the study concretes, and the consistency was determined in accordance with ASTM C143. As can be seen from Table A-2, on the average the properties of none of the concretes were significantly different at the plastic stage, with the exception that the slump at discharge was generally higher for the HRWR concrete. However, because of the higher rate of slump loss of the HRWR concrete (see figure A-1), the slump was not always higher during the placing, consolidation, and screeding of the concrete. It was common for the slump to decrease by 50% in 20 minutes. The sawtooth effect exhibited in Figure A-1 by the curves for B603, I85-A, and I85-B was caused by interrupting the discharge to inject additional HRWR admixture.

It is immediately apparent from the magnitudes of the standard deviations in Table A-2 that a significant difference between HRWR concrete and conventional concrete is the variability in their properties at the plastic stage. Assuming a normal distribution of data, approximately 35% of the HRWR concrete had an air content and 40% a slump outside of the design range at the time of discharge as compared to only approximately 5% and 15%, respectively, for the conventional concrete. It is believed that the large variability in the measured properties of the HRWR concrete was caused by (1) the rapid change in the slump, (2) the retempering efforts to achieve a more uniform slump, (3) incomplete mixing, and (4) between-batch fluctuations in the gradations and moisture content of the fine aggregate. These fluctuations were handled in the conventional installations by withholding one gallon of water per yard of concrete and adding it at the job site as needed to get the desired slump. The fluctuations could not be handled in the HRWR concrete because the slump prior to the addition of the admixture was zero, regardless of whether or not the water was withheld. The fluctuations were magnified in the high slumps occurring following the addition of the HRWR admixture.

Table A-1

Mixture Proportions

Installation	HRWR Type	HRWR Dosage, % Solids by Wt. Cement	Vinsol Resin, Oz./yd.	Cement, lb./yd.^{3}	Aggregate (lb./yd.^{3}) Coarse	Aggregate (lb./yd.^{3}) Fine	Nominal Max. Coarse Agg. Size, in.	Type Coarse Agg.	Maximum w/c
R-44	FX-32	1.0					0.5	Gravel	0.35
R-29	FX-32	1.0		658			1.0	Crushed stone	0.35
B616	FX-32	1.0	4.3	658	1401	1623	0.5	Crushed stone	0.37
B602	M150	0.5	5.5-7.5	635	1838	1256	1.0	Crushed stone	0.34
B603	M150	0.5+	7.5-10.0	635	1746	1350	1.0	Crushed stone	0.34
I85-A	M150	0.6+	8.0-10.0	705	1657	1214	0.5	Gravel	0.35
I85-B	M150	0.6+	10.0	658	1657	1296	0.5	Gravel	0.35
B604	None	0	6.3-7.0	635	1792	1136	1.0	Crushed stone	0.43
I85-C	None	0	6.4	705	1465	1293	0.5	Crushed stone	0.42
B639	None	0	7.0	635	1809	1178	1.0	Crushed stone	0.44

Table A-2

Properties of Plastic Concrete

Installation	Air Content, Percent				Slump, in.			
	Design	Avg.	Std. Dev.	Z[a]	Design	Avg.	Std. Dev.	Z[a]
B602	5.0-8.0	5.4	1.9	50	4.0-8.0	5.7	2.8	48
B603	5.0-8.0	6.1	1.4	30	4.0-8.0	4.8	2.3	45
I85-A	5.0-9.0	6.5	1.6	23	≥6.0	8.2	1.4	11
I85-B	5.0-9.0	5.5	1.7	41	≥6.0	8.2	2.8	42
B604	5.0-8.0	6.8	0.9	11	2.0-4.0	2.8	0.6	11
I85-C	5.0-9.0	6.7	0.4	0	2.0-5.0	4.7	0.2	6
B639	5.0-8.0	6.8	0.8	8	2.0-4.0	3.8	0.5	34

[a] Z = Percent of data falling outside of design range assuming a normal distribution.

Obviously, uniform concrete is difficult to achieve when admixtures are added to ready-mix trucks at the job site. The problems are compounded when the slump prior to the addition of the admixtures at the job site is less than 2 in. Hewlett suggests that to avoid the mixing problems that occur when low-slump concrete is mixed in a ready-mix truck, an initial dose of HRWR admixture, or a dose of conventional admixture or additional water, should be added at the batch plant so that the slump is 2 in. when the ready-mix truck reaches the job site.[A-1]

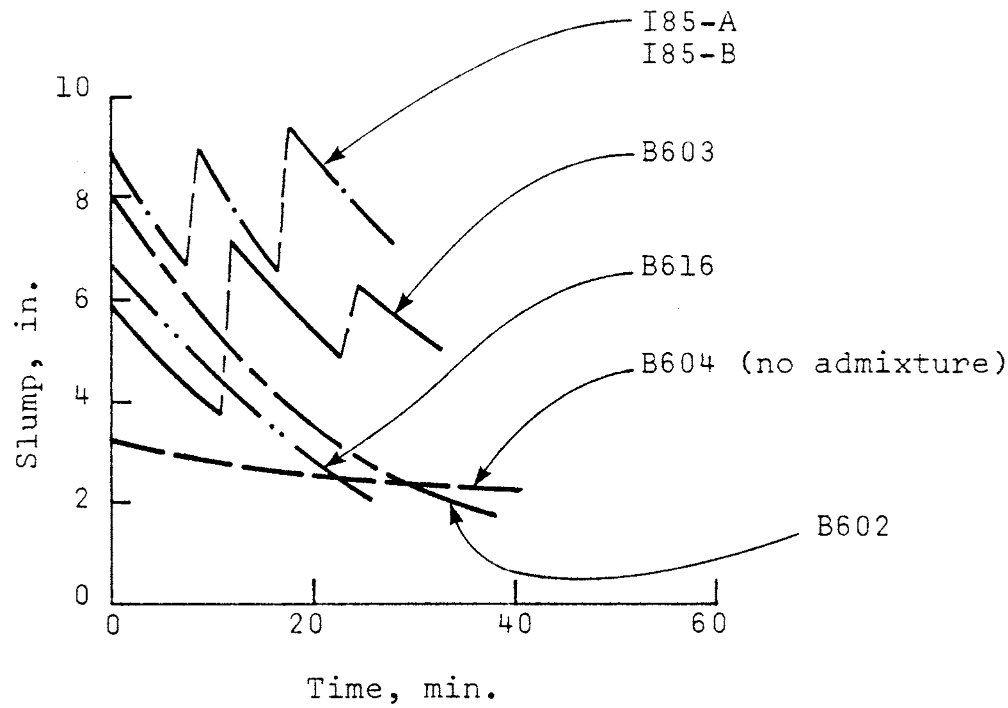

Figure A-1. Typical curves for slump versus time after mixing initial quantity of HRWR admixture.

Comparison of Batching and Placing Conditions and Equipment

Table A-3 shows the batching and placing conditions and equipment and Table A-4 relates the conditions and equipment to the success of an installation and to the development of problems. There are some clear differences between the installations from the standpoint of types of equipment and method of concrete placement. Some combinations were obviously better suited than others to handle the high rate of slump loss exhibited by HRWR concrete. For example, installation R-44 was the best suited to handle HRWR concrete because the installation was similar to what would be found in the laboratory. The ingredients were pre-weighed and bagged, the batch size was small, the screed span was short, the admixture was added during the mixing, and the mixing of the ingredients took place just prior to discharge at the job site. The concrete for a patch could be mixed, placed, consolidated, and screeded in less than 15 minutes.

Table A-3

Batching and Placing Conditions and Equipment

Installation	Date	HRWR Admixture Addition Time	Mixing Equipment	Batch Size, (yd.^{3})	Haul Time, (min.)	Placing Method	Vibration	Screed Type	Screed Span, (ft.)	Depth of Concrete, (in.)	On Site Mixing and Deposit Time, (min. per batch)
R-44	May 74	A	2 ft.^{3} paddle type mixer	< 0.1	0	Direct Discharge	One Internal Vibrator	Wooden Straight-edge	≤ 3'	2-4	10
R-29	Nov. 74	A	8 yd.^{3} capacity Ready-mix trucks	8	5	Direct Discharge	One Internal Vibrator	Wooden Straight-edge	11'	9	20
B616	July 76	A	8 yd.^{3} capacity Ready-mix trucks	6	25	Direct Discharge	Two Internal Vibrators	Oscillating longitudinal	36'	4	25
B602-C	Sept. 76	A	8 yd.^{3} capacity Ready-mix trucks	8	19	Crane and 1 yd.^{3} bucket	Two Internal Vibrators	Oscillating longitudinal	42'	4-6	40
B602	Oct. 76	B	8 yd.^{3} capacity Ready-mix trucks	8	19	Crane and 1 yd.^{3} bucket	Two Internal Vibrators	Oscillating longitudinal	42'	4-6	39
B603	Mar. 77	C	8 yd.^{3} capacity Ready-mix trucks	6	20	Crane and 1 yd.^{3} bucket	Two Internal Vibrators	Oscillating longitudinal	42'	4-6	40
I85-A	April 77	C	7 yd.^{3} capacity Ready-mix trucks	6	30	Pump	Two Internal Vibrators	Oscillating transverse	30'	2-4	27
I85-B	May 77	C	7 yd.^{3} capacity Ready-mix trucks	6	30	Buggies	Vibrating Screed	Vibrating transverse	15'	2-4	40
B604	Sept. 76	N.A.	8 yd.^{3} capacity Ready-mix trucks	8	21	Crane and 1 yd.^{3} bucket	Two Internal Vibrators	Oscillating longitudinal	42'	4-6	23
I85-C	June 77	N.A.	7 yd.^{3} capacity Ready-mix trucks	7	30	Buggies	Two Internal Vibrators	Oscillating transverse	30'	2-4	45
B639	Oct. 76	N.A.	8 yd.^{3} capacity Ready-mix trucks	8	75	Buggies	Two Internal Vibrators	Oscillating longitudinal	40'	4-6	45

A) HRWR admixture added during batching of concrete
B) HRWR admixture added at job site just prior to discharge
C) HRWR admixture added at job site just prior to discharge and added again one or two times during the discharge.

Table A-4

Successful and Problem Features of Installations

Installation	Successful Features	Obvious Installation Problems	Likely Cause of Problems
R-44	Uniform mixing Rapid installation Small batch size, short screed span	None	N.A.
R-29	Uniform mixing Rapid installation Short screed span	None	N.A.
B616	None	Poor consolidation Poor finish	Loss of slump during transit
B602-C	None	Poor consolidation Poor finish	Loss of slump during transit
B602	Majority of concrete was properly placed and consolidated	Areas of bridge decks exhibited segregation, poor consolidation and poor finish	Poor mixing, slump loss, between-batch fluctuations in gradation and moisture content of aggregate, failure to consolidate and screed concrete before slump was lost
B603	Multiple additions of admixture helped maintain uniform slump	Poor consolidation Poor finish	Poor mixing, slump loss, between-batch fluctuations in gradation and moisture content of aggregate, failure to consolidate and screed concrete before slump was lost
I85-A	Multiple additions of admixture helped maintain uniform slump. Pump provided rapid placement	Poor consolidation Poor finish	Slump loss and failure to consolidate and screed concrete before slump was lost
I85-B	Short screed span, multiple additions of admixture helped maintain uniform slump, vibrating screed provided satisfactory finish	Areas exhibited segregation	Between-batch fluctuations in gradation and moisture content of aggregate
B604	No problems	None	N.A.
I85-C	No problems	None	N.A.
B639	No problems	None	N.A.

On the other hand, installations B616 and B602-C were clearly not suitable for HRWR concrete. The admixture was added at the batch plant and the concrete lost most of its slump before it reached the job site. Efforts to restore the slump of the concrete by adding water at the bridge site were unsuccessful.

The other installations deserve various ratings as to their suitability for HRWR concrete. Installation R-29 was successful because the concrete was batched at a ready-mix plant located only 5 minutes from the job site. Also, the installation was successful because the concrete was discharged directly into the forms; the installation depth was 9 in., which was 2 to 3 times greater than for the other installations; and the screed span was 11 ft., which is considerably shorter than those on the other installations. The direct discharge and greater installation depth allowed for a rapid discharge and quick consolidation. The short screed span allowed the screed to move onto the concrete within a short time. The plant batching eliminated the quality control problems associated with the on-site addition of admixtures. The installation was successful because the concrete could be properly batched, deposited, consolidated, and screeded within 30 minutes.

Unfortunately, R-29 was an unusual installation in a number of respects. For example, as is obvious from Table A-3 the typical ready-mix concrete installation requires a 20 to 30 minute or longer haul time. The typical overlay situation requires 30 to 40 minutes to deposit the concrete because the concrete can seldom be deposited directly into the forms from the truck and because the installation depth is shallow. In addition, the typically long screed spans do not allow all the concrete to be screeded immediately after it is placed. Figure A-2 shows the relationship between the screed span and the time required to place, consolidate, and screed 1 $yd.^3$ of concrete on typical bridge decks. The data for the figure were collected during bridge deck construction projects at Berryville, Norton, and South Hill. It can be seen that the longer the screed span, the longer it takes to complete installation operations on the concrete. The slow nature of the typical overlay installation does not lend itself to the use of HRWR ready-mix concrete.

The on-site addition of the HRWR admixture was initiated with installation B602 to eliminate the problem of slump loss in transit. Unfortunately, the HRWR concrete used in Virginia had a slump of zero prior to the addition of the admixture and it was difficult to get the admixture properly dispersed throughout the 8 $yd.^3$ of concrete in the ready-mix truck. Probably because of mixing problems and a slow placement operation, portions of the HRWR concrete on B602 were soupy enough to segregate and bleed and other portions were too stiff to properly consolidate and finish with the screed. (See Figures A-3 and A-4.)

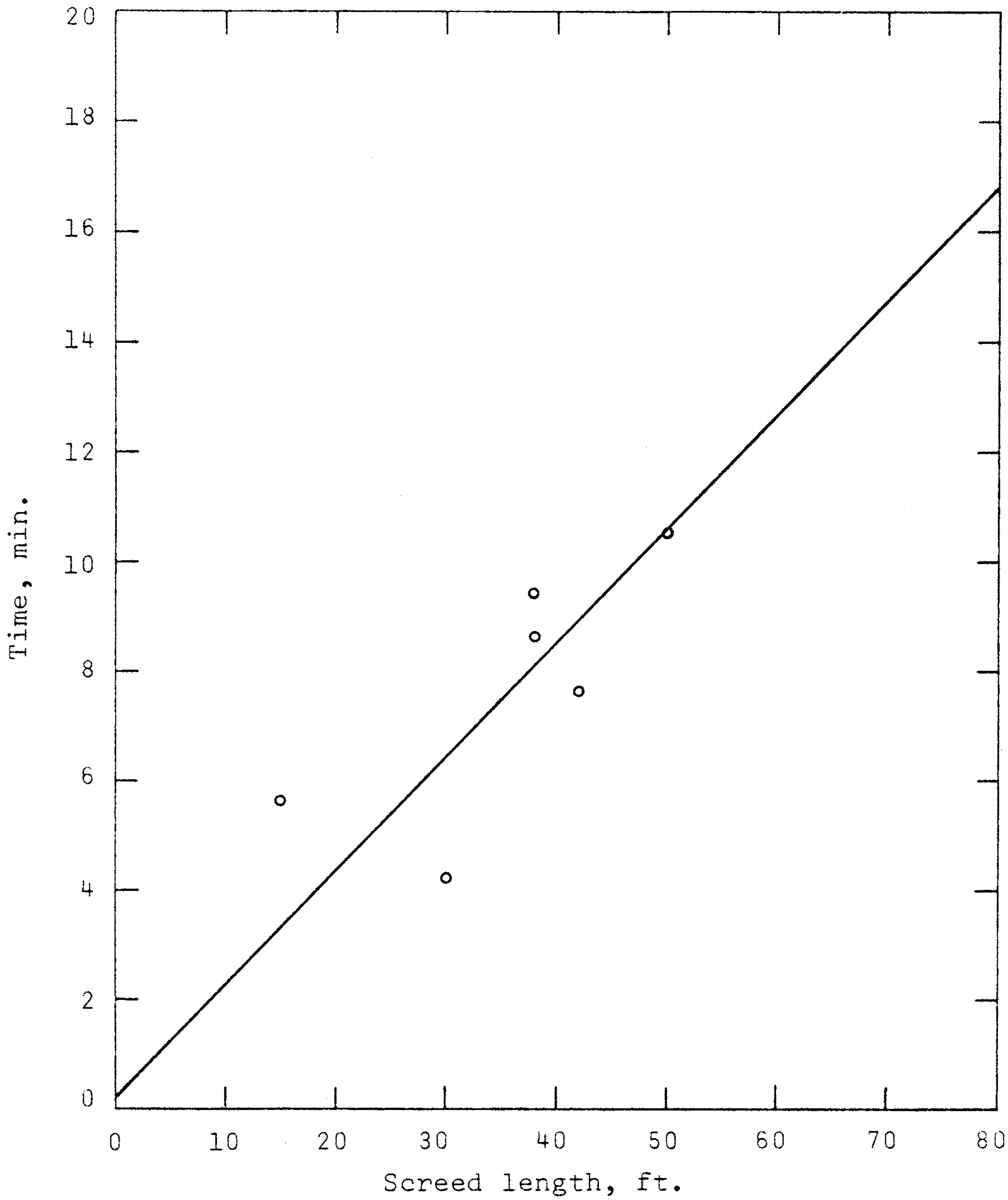

Figure A-2. Relationship between screed length and the time required to place, consolidate, and screed 1 yd.[3] of concrete on typical bridge decks in Virginia.

Figure A-3. Each cubic yard of HRWR concrete used on B602 differed in appearance and slump.

Figure A-4. Core showing segregation of fluid concrete used on B602.

As a result of the problems on B602 the manufacturer of the HRWR admixture recommended that changes in the mix design be made for B603. To prevent bleeding and segregation, the fine aggregate content was increased 7.5% by weight and the coarse aggregate content decreased proportionately. To provide for more complete mixing and a shorter discharge time, the batch size was reduced to 6 yd.^{3} To help maintain a uniform slump, the addition of the HRWR admixture one or two times during the discharge was initiated.

Unfortunately, the modifications did not eliminate most of the problems. Segregation did not occur on B603, but the slump did not exceed 8 in. since for the same dosage of HRWR admixture the slump was generally lower than on B602 due to the higher fine aggregate content on B603. Because each mixing of the additional admixture required several minutes, as much time was required to mix and deposit the 6-yd. batches used on B603 as for the 8-yd. batches on B602. Multiple additions of the HRWR admixture helped maintain a more uniform slump on B603, but it was obvious that proper mixing was not always achieved. Occasionally, after the addition of the admixture the consistency of the concrete did not change, and at other times the first concrete discharged after mixing was very soupy but was followed by concrete that was very stiff. Also, it was obvious that the multiple additions of the HRWR admixture did not eliminate the variability in the concrete caused by between-batch fluctuations in gradation and moisture content of the aggregate. For example, one span of B603 was covered with bleed water following the screeding operation and another span was stiff enough to walk on before the screeding operation was complete. Hewlett has indicated that an overdose of HRWR admixture will cause bleeding.[(A-2)]

The technique of plant batching and site mixing with multiple additions of HRWR admixture as used on B603 was continued on I85-A and I85-B. The installations were similar with the following exceptions. The average slump of the concrete was slightly higher on I85-A and I85-B than on B603 because the w/c was higher and because a gravel was used instead of a crushed stone. On I85-A the concrete was pumped into place so rapidly that the ready-mix producer had difficulty keeping the pump supplied.

A double-rotating-drum type transverse screed that rolled over the 30-ft. wide deck surface between the parapets was used to level the concrete, which previously had been consolidated with internal vibrators as it was discharged from the pump. Operating from the work bridge that was kept about 15 ft. behind the screed, laborers applied a hand finish, broom texture, and membrane curing compound. The entire operation was well-organized and moved in a very systematic manner (see Figure A-5), but the finished product appeared to be less than desirable. More than half of the surface area was very rough and there were numerous highly porous areas in the top 0.25 in. of the overlay, both of which may be attributed to the inability of the contractor to properly level and finish the concrete before it lost its workability (see Figure A-6). The overlay also had numerous shrinkage cracks that probably formed because the contractor did not apply the curing compound as soon as the sheen disappeared. The fluid concrete was virtually self-leveling and self-consolidating, but to obtain a satisfactory finish and to prevent shrinkage cracks it was probably necessary to screed, texture, and apply the curing compound within about 20 minutes after the concrete was placed. The contractor decided that he could not speed up his operation sufficiently to provide a satisfactory finish and chose to abandon the pumping operation.

On the subsequent HRWR deck installations on I85 (I85-B), the contractor chose to bring his placement operations under control by dividing the 30-ft. roadway width into two 15-ft. wide sections and replacing the drum type screed with a custom-made vibrating screed. The screed consisted of a vibrator attached to the midspan of several 2 in. x 10 in. timbers and two metal angles attached to the bottom of the timbers.

The concrete was mixed at the site as with the pumping operation and buggies were used to transport the concrete from the trucks to the deck. Since the screed spanned a distance of only 15 ft. the contractor was able to consolidate, screed, finish, and apply the curing compound in a very short time after the concrete was placed (see Figure A-7). Also, the forward travel of the vibrating screed could be adjusted to suit the consistency of the concrete and thereby impart a satisfactory finish whether the concrete was fluid or very stiff. Considerable vibration is needed to consolidate and finish stiff concrete, whereas very little vibration can be tolerated when consolidating and finishing a fluid concrete. Although buggies do not provide for a rapid placement operation, the short span vibrating screed provided a satisfactory finish. Two spans were overlaid with HRWR concrete using this technique.

It has been apparent that between-batch fluctuations in gradation and moisture content of the fine aggregate can cause sizeable between-batch fluctuations in slump when a standard dosage of HRWR admixture is added to concrete. Nowhere was this phenomenon more pronounced that on I85-B, where concrete of desired workability was delivered on one day and a soupy mixture, as shown in Figure A-8, was delivered on another day. If the slump of the concrete had been something other than zero prior to the on-site addition of the HRWR admixture, the slump could have been measured and the dosage of HRWR admixture adjusted to prevent creating the soupy concrete. LaFraugh reports that he has successfully used the "Vebe" apparatus to detect differences in workability between batches of concrete having a slump of zero.(A-3) Perhaps this apparatus should have been put to use during the field installations in Virginia.

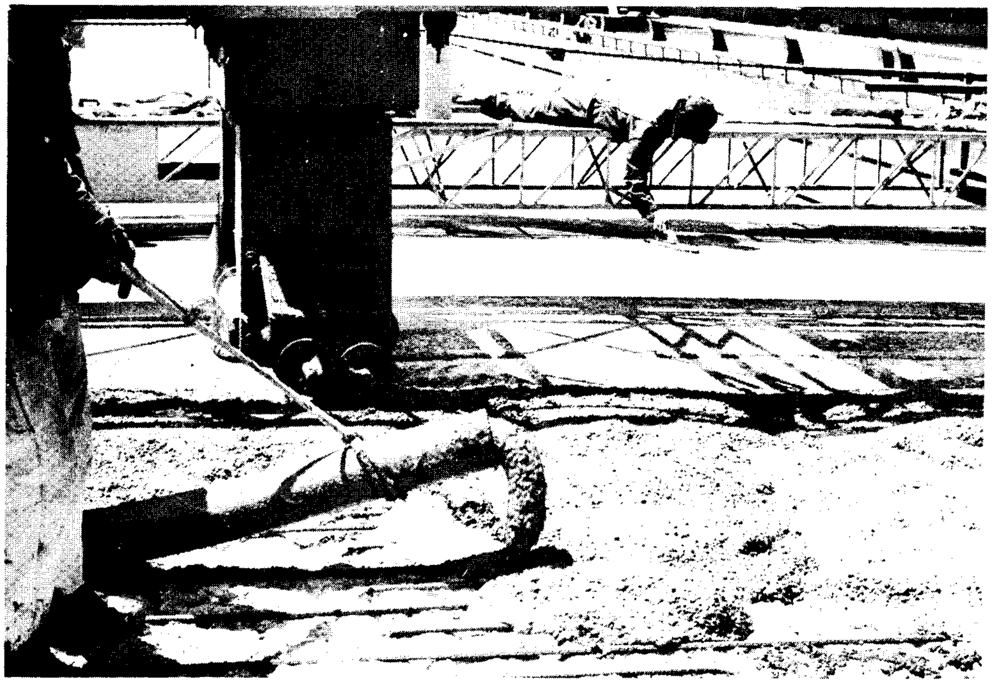

Figure A-5. HRWR concrete being pumped into place, I85-A.

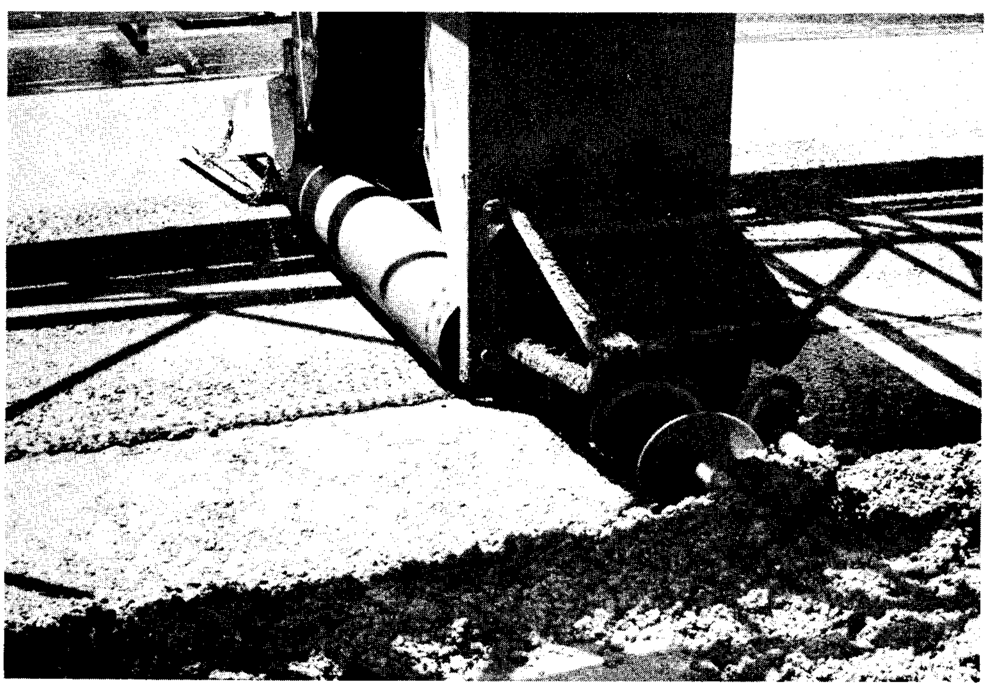

Figure A-6. Poor finish resulting from a rapid loss in workability.

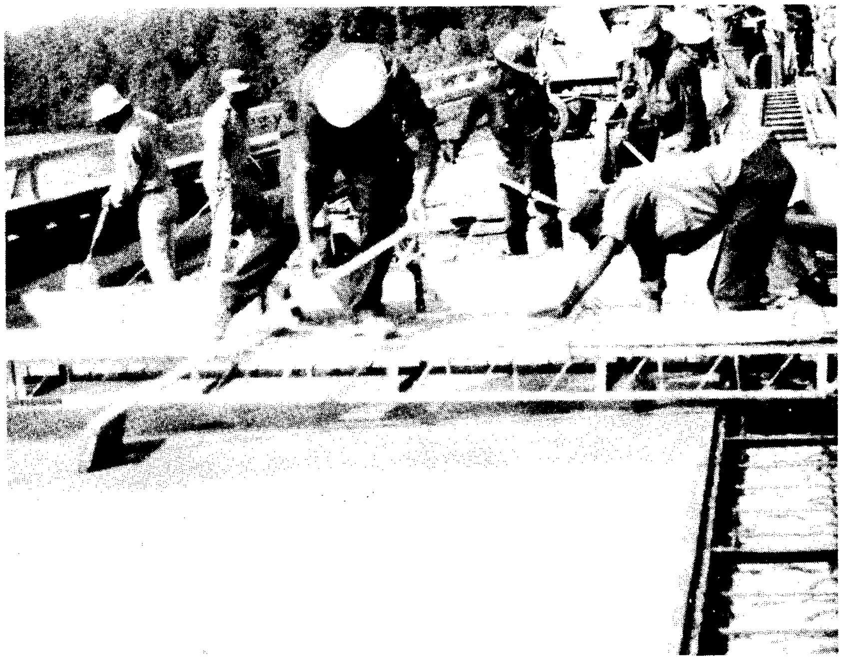

Figure A-7. Satisfactory finish obtained with a vibrating straightedge and rapid placement operation.

Figure A-8. HRWR concrete flowing out of control on I85-B.

It is obvious from the field installations in Virginia that the ready-mix producers and the contractors were capable of batching and installing the conventional concrete used on the control bridges B604, I85-C, and B639. A variety of reasons have been cited to explain why the same personnel experienced considerable difficulty when using the same equipment to batch and install HRWR concrete in similar installations. Obviously, the primary cause of the problems was slump loss and a failure on the part of the personnel involved to properly deal with the high rate of slump loss. In installations where the concrete could be batched and placed in a short time, slump loss was not a problem. The simplest of equipment, such as a wooden straightedge, could be used to screed the concrete when the screeding was done while the concrete was workable. On the other hand, it was difficult to achieve adequate consolidation and a satisfactory finish with a vibrating screed when the screeding was done after the concrete had lost most of its slump.

Secondary problems with mixing, bleeding, and segregation resulted from unsatisfactory attempts to deal with slump loss. It probably is not reasonable to expect to get a uniform, reproducible concrete of acceptable plastic characteristics when an HRWR admixture is added to a ready-mix truck containing poorly mixed concrete having a slump of zero.

Properties and Performance of the Hardened Concrete Specimens

Cylinder Strengths

Standard 6 in. x 12 in. specimens made from random samples of the concretes were tested in accordance with ASTM C39. As indicated by Table A-5, the HRWR concrete attained significantly higher early and 28-day strengths than the concrete without the admixture, but also exhibited the largest variation in strength between cylinders.

Freezing and Thawing Tests

Standard 3 in. x 4 in. x 16 in. freeze-thaw beams made from random samples of the concrete were subjected to 300 cycles of freezing and thawing in accordance with ASTM C666 Procedure A, modified by using 2% NaCl by weight in the water, and the results are shown in Table A-6. Prior to testing, the beams were field-cured or moist-cured as indicated in Table A-6. Beams cured in a similar manner are grouped together. The results of tests on three sets of A4 concrete beams made in the laboratory are included in Table A-6 for comparison.

Table A-5

Cylinder Strengths, psi

Installation	3-Day[a] Avg.	3-Day[a] Std. Dev.	14-Day Avg.	14-Day Std. Dev.	28-Day Avg.	28-Day Std. Dev.
R-29	5100	—	—	—	—	—
B602	3460	160	5880	650	7020	830
B603	2240	650	8080	170	8910	410
I85-A	—	—	—	—	7960	290
I85-B	4680	600	—	—	6290	450
B604	2530	170	4210	160	5990	280
I85-C	—	—	—	—	5610	260
B639	—	—	3200	—	3690	250

(a) Field-cured specimens.

Table A-6

Freezing and Thawing Performance for 300 Cycles

Location	Date Cast	HRWR Admixture	No. Spec.	W/C	Type Care	Surface Rating Avg.	Surface Rating Std. Dev.	Percent Weight Loss Avg.	Percent Weight Loss Std. Dev.	RDF Avg.	RDF Std. Dev.	RDF Percent of Control
Matls. Lab.	11/20/75	None	2	0.42	2 wks. moist 1 wk. lab	1.5	---	1.1	---	100	---	100
Matls. Lab	2/7/74	FX-32	3	0.32	2 wks. moist 1 yr. lab	2.1	0.1	3.0	0.2	77	15	77
Matls. Lab	8/10/76	Mighty RD2	3	0.35	2 wks. moist 3 wks. lab	2.1	0.1	0.4	0.5	94	9	94
B604	8/30 & 9/11/76	None	8	0.43	3-7 mos. field	1.9	0.4	1.1	0.5	90	7	100
B602	10/11 & 15/76	Mighty 150	13	0.34	2-6 mos. field	2.1	0.9	1.6	1.6	70	23	78
B639	10/27 & 28/76	None	4	0.43	1 mo. field	2.3	0.2	3.2	0.9	98	1	100
I85-A	4/29/77	Mighty 150	3	0.35	1 mo. field	2.5	1.4	4.7	3.3	62	42	63
I85-B	5/27/77	Mighty 150	3	0.35	1 mo. field	4.8	2.3	19.8	17.8	47	38	48
I85-C	6/14/77	None	3	0.42	2 wks. moist	2.3	0.1	5.1	1.6	97	2	100
I85-A	4/29/77	Mighty 150	3	0.35	2 wks. moist	5.3	1.2	2.3	4.0	8	6	8
I85-B	5/20/77	Mighty 150	4	0.35	1 mo. moist	4.4	1.5	10.1	4.4	19	8	20
B603	3/8 & 10/77	Mighty 150	9	0.34	1 mo. moist	2.7	0.9	1.3	2.5	44	19	45

From the table it is apparent that, on the average, most of the field specimens performed satisfactorily with respect to surface rating and weight loss. A few of the HRWR specimens scaled severely and lost a considerable amount of weight, but most others performed as well as the conventional concrete specimens with respect to scaling and weight loss. The durability factors were significantly lower for the HRWR concrete. Low durability factors for this type concrete have been reported by Tynes.[A-4]

It appears that the durability factors were influenced by the curing method and the curing period, with the lowest values being found for moist-cured beams tested 2 weeks after batching. But regardless of the curing method and curing period, in no case was the durability factor better for the HRWR concrete than for the conventional concrete when both were cured in like manner. Assuming the conventional A4 concrete specimens have a durability of 100, Table A-6 clearly shows the low relative durability factors for the similarly cured HRWR specimens. It is anticipated that the results in Table A-6 are representative of the relative freeze-thaw performance to be expected of the concretes in the study structures. However, despite the low durability factors, the HRWR concrete decks are in excellent condition after 4 years of service life. Periodic evaluations of these structures would be desirable to shed some light on the relationship between freeze-thaw performance in the field and performance based on the ASTM C666 freeze-thaw test.

Petrographic Examinations

Petrographic examinations were conducted to determine the quantity, size, and spacing of voids in 4-in. diameter cores removed from the overlays and in 6 in. x 12 in. cylindrical specimens made from random samples of the study concretes. The voids data are shown in Table A-7.

From Table A-7 it can be seen that there is agreement, within the range of 1 standard deviation, between the average of the measured air contents and the average of the total void contents of the cores and the 6 in. x 12 in. specimens for all the concretes except the mixture pumped into place on I85-A. Thus, it is reasonable to assume that, on the average, the HRWR concrete was properly batched and consolidated. However, because the magnitudes of the standard deviations are much greater for the HRWR concrete than for the conventional concrete, it is apparent that more than 50% of the HRWR concrete was either inadequately consolidated or extremely over or under entrained with air. The void data for the cores suggest that, in general, the concrete in B602 has a low entrained air content, the concrete in B603 has a high entrapped air content, and the concrete in I85-A has a high entrained air content. Note the marked increase in the entrained air content of the cores as compared to the specimens for I85-A. The specimens were prepared from concrete which was not pumped and therefore it appears that the agitation provided by the pumping operation increased the air content. The high entrained air contents may have been caused by the combined entraining effect of the air-entraining admixture and the HRWR admixture. The low entrained air contents were probably caused by a loss of air during the highly fluid state and during the mixing and the placing of the concrete. The relatively high fine aggregate content specified for B603 likely hindered consolidation efforts and resulted in a high entrapped air content.

Air Void Spacing Factor

An air void spacing factor, $\bar{L}$, of 0.008 in. or less has heretofore been considered needed for satisfactory freeze-thaw durability in conventional bridge deck concrete.(A-5) Values of $\bar{L}$ were calculated for the study concretes and are reported in Table A-8. From the table it can be seen that there is good agreement between the $\bar{L}$ values as determined from the cores and those as determined from the 6 in. x 12 in. specimens made of fresh concrete. The greatest difference is associated with the HRWR concrete, with the higher values for the cores probably reflecting a problem with consolidation.

Satisfactory spacing factors were obtained for the conventional overlay concretes. Values of $\bar{L}$ for the HRWR overlays were about twice as large on the average as for the conventional concrete. The large values of $\bar{L}$ are associated with low air contents and low specific surfaces. The air content of some of the HRWR concrete was lower than specified, but sufficiently high to provide a satisfactory $\bar{L}$ in conventional concrete. Unfortunately, some specimens of HRWR concrete which had the specified air content also failed the freeze-thaw test. Petrographic examinations indicated that, in general, the entrained voids were larger in the HRWR concrete than in conventional concrete. The large diameter of the entrained voids provided the poor air void distribution that was probably responsible for the poor freeze-thaw durability.

Table A-7

Void Contents of Cores and Field Specimens

Installation	Design	Measured Air Content, Percent			Voids in Cores, Percent							Voids in Specimens, Percent						
					> 1 mm		< 1 mm		Total			> 1 mm		< 1 mm		Total		
		$\bar{x}$	s	z	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	z	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	z
R-44	4-8	—	—	—	2.2	—	2.8	—	5.0	—	—	—	—	—	—	—	—	—
R-29	4-8	—	—	—	1.8	—	3.0	—	4.8	—	—	—	—	—	—	—	—	—
B616	5-9	—	—	—	2.9	1.0	1.7	1.1	4.6	1.8	60	—	—	—	—	—	—	—
B602	5-8	5.4	1.9	50	2.5	1.2	2.9	1.6	5.3	2.2	55	2.2	0.8	5.3	2.9	7.5	3.4	67
B603	5-8	6.1	1.4	30	3.4	1.2	4.2	1.4	7.5	2.4	57	2.0	0.7	4.4	1.0	6.3	1.6	35
I85-A	5-9	6.5	1.6	23	2.3	1.3	8.7	3.0	11.0	2.0	84	2.1	1.1	3.0	1.0	5.2	1.9	48
I85-B	5-9	5.5	1.7	41	3.0	—	1.5	—	4.5	—	—	1.6	—	2.5	—	4.1	—	—
B604	5-8	6.8	0.9	11	2.8	0.7	3.7	0.3	6.5	0.5	0	1.5	0.5	4.6	1.5	6.1	1.4	30

$\bar{x}$ average

s 1 standard deviation

z percent of data falling outside of design range

Table A-8

Air Void Spacing Factors, in.

Installation	Cores Avg.	Cores Std. Dev.	Field Specimens Avg.	Field Specimens Std. Dev.
R-44	0.0091	—	—	—
R-29	0.0134	—	—	—
B616	0.0205	0.0087	—	—
B602	0.0134	0.0039	0.0102	0.0031
B603	0.0110	0.0043	0.0098	0.0020
I85-A	0.0063	0.0028	0.0122	0.0012
I85-B	0.0217	0.0039	0.0142	0.0004
B604	0.0075	0.0004	0.0079	0.0024
B639	—	—	0.0047	0.0020

Discussion of Field Installations

The rapid slump loss associated with HRWR concrete is an extablished phenomenon.(A-6) Data recorded during the field installations in Virginia clearly indicate that the workability of the HRWR concrete decreased by about 50% in 15 to 20 minutes. If conventional equipment is to be used with HRWR concrete, the placement operations must be completed before the workability of the concrete falls below 2 in. A batch of concrete having an initial slump of 4 in. must be consolidated and screeded within a 15 to 20 minute interval immediately following this initial slump measurement. Likewise, a batch having an initial slump of 8 in. must be screeded within 30 to 40 minutes.

It is believed that HRWR concrete can be satisfactorily placed by properly coordinating the batch size to the site conditions, the construction personnel and equipment, the geometry of the form, and the consistency of the mix. Batches of 8 $yd.^3$ or more could probably be properly placed in the forms for bridge beams or similar structural members having a low surface area to volume ratio in 15 to 20 minutes. On the other hand, data collected on numerous conventional bridge deck installations in Virginia show that the installation time is a function of screed span, and that on typical bridges only about 1.5 to 3.5 $yd.^3$ can be placed, consolidated, and screeded in 15 minutes (see Figure A-2). Additional HRWR admixture must be added periodically to larger size batches to maintain a satisfactory consistency. Because of the rapidly changing consistency of the HRWR concrete and the problems associated with adding additional admixture to a large batch, conventional field acceptance practices are often impractical. For example, slump and air content determinations made at the beginning of the discharge are not representative of the plastic properties of the concrete at the end of the discharge.

Although it has been reported that with experience a contractor can properly install HRWR concrete in deck overlays,(A-7) the experience in Virginia indicates that it is extremely difficult for the average contractor, when using conventional equipment, to consistently install durable HRWR concrete in flatwork such as a bridge deck overlay where the plastic concrete is typically subjected to long haul distances and prolonged installation time, and where a majority of the concrete is readily exposed to fluctuations in wind velocity, humidity, and temperature. The potential for poor consolidation, poor finish, and poor freeze-thaw performance tends to offset the benefits that could be achieved from higher strength and reduced permeability. It is felt at this time that HRWR concrete is best suited for special applications that can be carefully supervised.(A-8)

Ways to minimize slump loss have been cited in the literature. For example, Hewlett has indicated that slump loss is greatest when a medium dosage of HRWR admixture is used.(A-9) A medium dosage was used in Virginia. Kasami has reported that the initial slump is greatest when the HRWR admixture is added 15 to 60 minutes after the initial mixing of the concrete.(A-10) Although in Virginia subsequent dosages were added 15 or more minutes later, the first dosage was usually added within 2 minutes after the initial mixing. Mailvaganam has reported that slump loss is less when a hydroxcarboxylic acid retarder is used in combination with an HRWR admixture.(A-11) No type B or D retarders were used in the HRWR concrete placed in Virginia. The implementation of the above suggestions may have minimized the placement problems encountered.

Preliminary Conclusions from Field Evaluations

On the average, the HRWR concrete placed in Virginia was adequately batched and consolidated using conventional equipment. Also, compression test specimens provided extremely high early and 28-day strengths. However, because of the variability of the concrete, portions of the overlays exhibited inadequate consolidation, segregation, improperly entrained air, shrinkage cracks, and poor finishes. Furthermore, freeze-thaw specimens provided low durability factors because of an unsatisfactory air void system.

The rapid slump loss associated with HRWR concrete can be accommodated by anticipating the amount of slump loss and properly matching the batch size to the placement rate and by adding the HRWR admixture immediately prior to discharging the concrete. For the rate of slump loss experienced in Virginia, it is believed that quality control can be maintained by specifying a batch size equal to the quantity of concrete that can be batched, placed, and finished in a 20-minute interval. Mixture proportions should be specified to provide a slump of approximately 2 in. or more prior to the addition of the HRWR admixture, if the fluctuations in gradation and moisture content are to be detected by the slump cone and accommodated by adjusting the dosage of the admixture. Also the field data suggest that the concrete should be used with caution where freeze-thaw durability is extremely important. Unfortunately, the field data were useful only in identifying problem areas, because the multitude of variables that affect field data allowed only general conclusions to be drawn. Further research was needed to explain the problems to allow for further review of the literature, and to aid in the development of guidelines for batching, placing, and accepting HRWR concrete.

REFERENCES — APPENDIX A

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A-4 . Tynes, W. O., "Investigation of Proprietary Admixtures," USAE WES TR C-77-1, April 1977 (NTIS AD A039612).

A-5 . Mielenz, Richard C. et al., "The Air Void System in Job Concrete," Journal of the American Concrete Institute, October 1958.

A-6 . LaFraugh, op. cit.

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A-10. Kasami, H. et al., "Workability and Pumpability of Superplasticized Concrete — Experience in Japan," First International Symposium on Superplasticizers, May 1978, p. 125.

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APPENDIX B

LABORATORY RESEARCH

The laboratory work was directed at gaining an insight into the problems that had occurred in the field and arriving at reasonable solutions to them. For example, because many of the specimens prepared in the field had failed the freeze-thaw test, additional information was needed on the freeze-thaw durability of HRWR concrete. It had been noted that the cores and specimens of the field concrete contained many coarse voids and exhibited high spacing factors, and these suggested that all the specimens should have failed the freeze-thaw test. Accordingly, more information was needed on the relationship between the freeze-thaw durability and the void characteristics of the HRWR concrete. Slump loss also had been a major problem and it was hoped that the laboratory work would result in the development of ways to reduce the rate of slump loss. When some people suggested that the problem with slump loss had been caused by an incompatibility between the cement and the admixture, it was decided to use 3 cements and 6 brands of HRWR admixtures in the laboratory work. One of the cements was a type I because some of the manufacturers of the HRWR admixtures believed that the problems in Virginia had resulted from the use of type II cement. Also, two type D water-reducing admixtures were used in combination with some of the HRWR admixtures in an effort to reduce the dosage of HRWR admixture required, because it had been suggested that at lower dosages slump loss would be less, and the void characteristics and freeze-thaw durability would be better. On the other hand, some people believed that problems with compatibility could result from combining the various admixtures. Finally, it was hoped that some of the bleeding and segregation which had occurred in the field could be reproduced in the laboratory so that the underlying causes could be determined.

Materials

Cements

Three lots of cement were used in the concrete mixtures prepared in the laboratory. Lot II A, a type II cement, was obtained from Lone Star Industries in July 1977; lot I B, a type I cement, was obtained from the same source in February 1979; and lot II C, a type II cement, was obtained from Lehigh in August 1978. The chemical and physical characteristics of the cements are shown in Table B-1. Approximately 70% of the batches were prepared with cement II A, 20% with II C, and 10% with I B. There does not appear to be much difference between the cements, and the type I and type II obtained from Lone Star are probably more similar than the two

Table B-1

Chemical and Physical Characteristics of Cements

Cement Type	II A	II C	I B
SiO_2	21.3	21.9	20.9
Al_2O_3	4.4	3.9	5.3
Fe_2O_3	4.3	3.2	2.2
CaO	63.7	60.6	62.9
MgO	3.0	3.1	4.0
SO_3	2.7	3.4	3.1
Insoluble residue	0.08	0.52	0.21
Ignition loss	0.5	1.4	1.2
Alkalies (as Na_2O)%	0.73	0.60	0.76
C_3S %	54.0	39.8	49.8
C_2S %	20.3	32.8	22.4
C_3A %	4.0	4.9	10.3
C_4AF %	13.1	9.7	6.7
Fineness (Blaine)	3646	4100	3560

type II cements obtained from Lone Star and Lehigh. Cement II C is the finest, has the lowest alkali content and the highest SO_3 content. Cement IB has the highest C_3A content.

Fine Aggregate

Natural siliceous sand obtained from Lone Star Industries, Inc. was used in the study. Although two lots were used, one from Kinglands Reach and one from Willis Road, they were similar in characteristics and performance. The properties of the sands were as follows:

Specific gravity	2.62
Absorption	0.7% to 0.9%
Fineness modulus	2.7 to 2.8
Percent voids	48.8 — 51.0

Coarse Aggregate

The coarse aggregate was a siliceous gneiss obtained from the Martin Marietta Plant at Red Hill, Virginia. The aggregate has a specific gravity of 2.78 and an absorption of 0.6%. It was screened so as to provide a 1/2-in. maximum nominal size, 50% retained on the 3/8-in. screen, and 50% retained on the no. 4 screen.

Admixtures

Six brands of HRWR admixtures were used. A majority of the concrete mixtures were prepared with two naphthalene sulfonate polymer admixtures, Mighty 150 and Sikament, and one melamine sulfonate polymer admixture, Melment L10. A limited number of mixes were prepared with WRDA-19 and FX-34, both naphthalene sulfonate polymer admixtures, and Mighty RD2, a retarding version of Mighty 150. The admixtures are described in Table B-2.

In addition to the HRWR admixtures, two type D water-reducing retarders, Plastimate, a salt of hydroxylated carboxylic acid manufactured by the Sika Chemical Company, and Pozzolith 122-R, a hydroxylated polymer manufactured by Master Builders, were used in some of the concrete mixtures, at dosages of 17.5 oz./yd. and 29.5 oz./yd., respectively.

The AEA was a neutralized vinsol resin manufactured by Protex Industries, with the exception that at the request of the manufacturer Daravair, another neutralized vinsol resin, was used in the batches containing WRDA-19.

Table B-2

Properties of Admixtures

Admixture	Specific	Percent Solids
Mighty 150	1.19	42
Sikament	1.17	40
Melment L10	1.10	20
WRDA 19	1.2	33
FX-34	Powder	100
Mighty RD2	1.2	45

Mixture Proportions

The concrete mixtures prepared for the study conformed to one of three basic mixture proportions shown in Table B-3, with the exception that the control batches containing the type D retarders had a w/c = 0.40, which represented a 7% reduction in the w/c. The cement content was 658 lb./yd.^{3} and the coarse aggregate content 1,509 lb./yd.^{3} The mixture proportions differ in that the sand content was adjusted upward as the water content was decreased. Typically, the slump was 2 in. to 5 in. and the air content was 5% to 9% immediately following completion of the mixing of the concrete. Typically, three duplicate batches were prepared to evaluate each combination of admixtures and mixture proportions.

Table B-3

Mixture Proportions

w/c	Water reduction, percent	Fine aggregate content, lb./yd.^{3}
0.43	0	1,416
0.38	12	1,503
0.34	21	1,572

Mixing Procedures

All concretes were mixed in a 2-ft.^{3} capacity open pan-type mixer. The majority of the mixtures were prepared using the following procedure, which is here designated procedure A.

1. Add cement and fine aggregate and mix 1/2 minute.
2. Add water and AEA (and retarder) and mix 1 minute.
3. Add coarse aggregate and mix 3 minutes.
4. Wait 3 minutes.
5. Add HRWR and mix 3 minutes.

Since it is usually necessary, because of slump loss, to add the HRWR admixture at the job site just prior to discharge, a number of batches were prepared using a modified version of procedure A here designated procedure A-1. This mixing procedure was developed to simulate a field condition in which a ready-mix truck is travelling to a job site, and differs from procedure A in that step 4 lasts 30 minutes rather than 3.

A number of batches were also prepared using a third procedure, designated B, which differs from procedure A in that the HRWR is added in step 3 rather than step 5 after mixing the CA for 1 minute, and the AEA is added at the beginning of step 5 rather than step 2. It was hoped that procedure B might produce a better air void system than could be achieved with procedures A and A-1.

Properties of the Plastic Concrete

Immediately following completion of the mixing of the concrete, three portions of the mixture were removed from the mixer and checked for slump, air content, unit weight, and temperature. Once the tests were complete, which usually required approximately 5 minutes, part of the concrete used in the tests was returned to the mixer and blended with the remaining concrete by turning the mixer several revolutions. Specimens were immediately prepared and usually consisted of the following: three 6 in. x 12 in. and three 3 in. x 6 in. cylindrical specimens for compression tests; one 3 in. x 3 in. x 11¼ in. specimen used to measure drying shrinkage and absorption; and five 3 in. x 4 in. x 16 in. specimens, two for freeze-thaw tests, and three for flexural tests, one of which was later cut and polished and subjected to petrographic examination. More often than not following fabrication of the specimens, which usually required approximately 15 minutes, the remaining portion of the concrete was tested for slump, unit weight, and air content. The slump and air content were usually determined prior to preparing the specimens and again after the specimens were prepared to provide an indication of the loss in slump and air. The results of the slump and air content determinations are shown in Tables B-4 and B-5. The majority of the data are based on the average of three duplicate batches of concrete.

The percentage change in slump and air content shown in these tables are based on an assumed linear relationship between these characteristics and time, and they were computed from the measurements made before and after the specimens were prepared. Although the relationships between these characteristics and time are not necessarily linear, they are reasonably linear in the interval defined by 20 minutes ± 5 minutes, which accounts for the majority of the measurements. Specifically, the percentage change in slump (air) in 20 minutes is

$$100 \left[1 - \frac{\text{final slump (air)}}{\text{initial slump (air)}} \right] \frac{20}{\Delta_t} .$$

Table B-4

Plastic Properties of Experimental Concretes

Mix No.	Cement Type	HRWR Type	HRWR Dosage, S/S	Type D Admix.	Slump, in. Before Spec.	Slump, in. After Spec.	Percent Slump Loss in 20 Min.	Percent Air Content Before Spec.	Percent Air Content After Spec.	Percent Air Loss in 20 Min.
w/c = 0.34										
M1	II A	Mighty 150	0.46	—	3.1	2.3	32	7.3	—	—
M2	II A	Mighty 150	0.42	Plastimate	3.4	2.1	48	7.0	5.6	12
M3	II A	Mighty 150	0.42	122-R	4.0	2.8	32	7.4	—	—
M4	II A	Mighty 150	0.59*	—	5.0	2.6	39	6.6	5.5	13
M5	II A	Mighty 150	0.63	—	6.2	3.7	24	8.7	6.7	15
M6	II A	Mighty 150	0.63**	—	2.9	2.3	18	7.2	6.0	8
M7	II A	Mighty 150	0.67*	—	7.8	5.6	24	5.8	5.0	13
M8	II A	Mighty 150	0.92	—	1.5	—	—	4.3	—	—
L1	II A	Melment	0.54	—	2.6	1.1	36	6.2	—	—
L2	II A	Melment	0.68	Plastimate	5.7	3.5	26	7.0	4.9	20
L3	II A	Melment	0.44	122-R	3.0	2.0	19	7.1	5.4	14
L4	II A	Melment	0.62	122-R	5.2	2.0	34	3.0	—	—
L5	I B	Melment	0.78	122-R	3.8	2.8	18	9.0	5.0	30
L6	I B	Melment	0.78	—	3.0	—	—	2.8	—	—
L7	II A	Melment	0.58**	—	3.4	2.2	38	6.6	—	—
S1	II A	Sikament	0.60	—	3.4	2.5	31	7.3	6.5	19
S2	II A	Sikament	0.48	Plastimate	3.8	3.2	20	7.6	—	—
S3	II A	Sikament	0.44	122-R	4.6	2.9	22	7.3	5.8	14
S4	I B	Sikament	0.60	—	5.1	2.2	39	10.6	8.0	23
S5	I B	Sikament	0.84	Plastimate	7.5	5.1	18	8.5	6.0	18
S6	I B	Sikament	0.84	122-R	4.7	2.5	26	5.5	3.8	18
W1	II C	WRDA-19	0.62	—	2.1	1.0	31	8.1	—	—
R1	II A	Mighty RD2	0.41	—	2.8	2.7	3	8.0	—	—
F1	II A	FX 34	1.0	—	2.8	2.2	24	5.7	—	—

*Mix Procedure A-1
**Mix Procedure B

Table B-4 continued

Mix No.	Cement Type	HRWR Type	HRWR Dosage, S/S	Slump, in. Before Spec.	Slump, in. After Spec.	Percent Slump Loss in 20 Min.	Percent Air Content Before Spec.	Percent Air Content After Spec.	Percent Air Loss in 20 Min.
w/c = 0.38									
M10	II A	Mighty 150	0.29	3.6	2.8	24	6.4	5.1	28
L10	II A	Melment	0.30	3.0	2.3	29	6.5	5.8	10
L11	II C	Melment	0.58	1.5	—	—	6.9	—	—
L12	II C	Melment	0.58	1.5	—	—	3.6	—	—
W10	II C	WRDA-19	0.36	4.6	2.0	32	8.8	—	—
W11	I B	WRDA-19	0.36	1.5	0.4	48	5.1	—	—
R10	II A	Mighty RD2	0.27	5.5	4.7	14	8.1	—	—
F10	II A	FX 34 Powder	0.80	3.3	2.4	28	6.7	—	—
S10	II C	Sikament	0.36*	6.9	3.0	25	6.2	—	—
w/c = 0.43									
M20	II A	Mighty 150	0.21	4.6	3.0	28	7.0	6.1	8
L20	II A	Melment	0.22	4.8	3.9	16	7.2	5.4	22
W20	II C	WRDA-19	0.20	3.3	2.0	23	6.0	—	—
W21	I B	WRDA-19	0.20	2.7	1.8	20	5.9	—	—
S20	II C	Sikament	0.20*	5.3	3.1	18	5.5	—	—

*Mix Procedure A-1

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Table B-5

Plastic Properties of Control Concrete

Mix No.	Cement Type	Type D Admix.	Slump, in. Before Spec.	Slump, in. After Spec.	Percent Slump Loss in 20 Min.	Percent Air Content Before Spec.	Percent Air Content After Spec.	Percent Air Loss in 20 Min.
C1	II A	—	2.4	2.1	14	6.7	5.9	8
C2	II C	—	2.0	—	—	6.1	—	—
C3	II A	Plastimate	1.5	—	—	6.4	—	—
C4	II A	122-R	1.5	—	—	7.0	—	—

It is obvious from Table B-4 that all of the admixtures, with the exception of Mighty RD2, exhibited a significant loss in slump in 20 minutes, typically from 20% to 35%. In Table B-4, the average slump losses in 20 minutes for the batches with different w/c values were: w/c = 0.34 — 27%, w/c = 0.38 — 29%, and w/c = 0.43 — 21%. By comparison that for control concrete shown in Table B-5 was only 14%. Therefore, it can be concluded that, on the average, the HRWR concrete lost slump about twice as fast as the control concrete. Also, it appears from the data in Tables B-4 and B-5 that the rate of slump loss was somewhat affected by the mixture proportions and the combinations of admixtures and cement.

The average for air losses in 20 minutes, shown in Tables B-4 and B-5, were as follows: w/c = 0.34 — 17%, w/c = 0.38 — 19%, and w/c = 0.43 — 15%. Therefore, it can be concluded that the concrete containing the HRWR admixtures also lost air about twice as fast as the control concrete shown in Table B-5, which exhibited an 8% loss.

Figure B-1 shows the relationship between slump and time and air content and time for HRWR concretes having a w/c = 0.34 and prepared by mixing procedure A. There are no major differences between the various admixtures with the exception that Mighty RD2 lost very little slump. The curves in Figure B-1 can be used as standards for comparing the curves in Figures B-2 through B-4.

Figure B-2 shows the relationships between slump and air content and time for the various admixtures used in combination with the type D water-reducing retarders Plastimate and 122R. In general, the addition of the type D retarders did not significantly affect the loss in slump or air, which is unusual considering that the retarding version of Mighty 150 exhibits very little slump loss. Evidently the type and dosage of the type D admixture were factors.

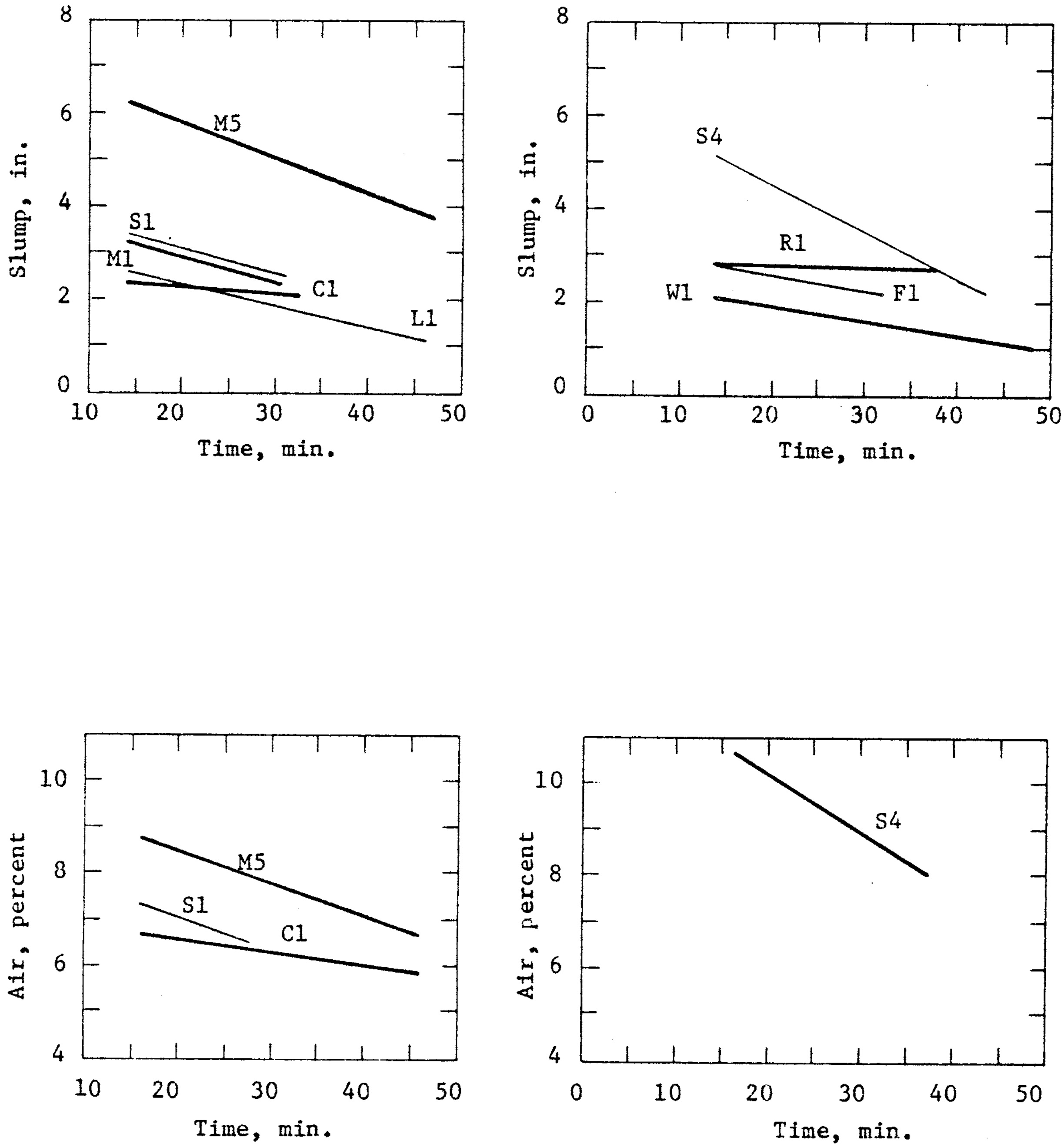


Figure B-1. Slump vs. time and air content vs. time for HRWR concrete mixtures.

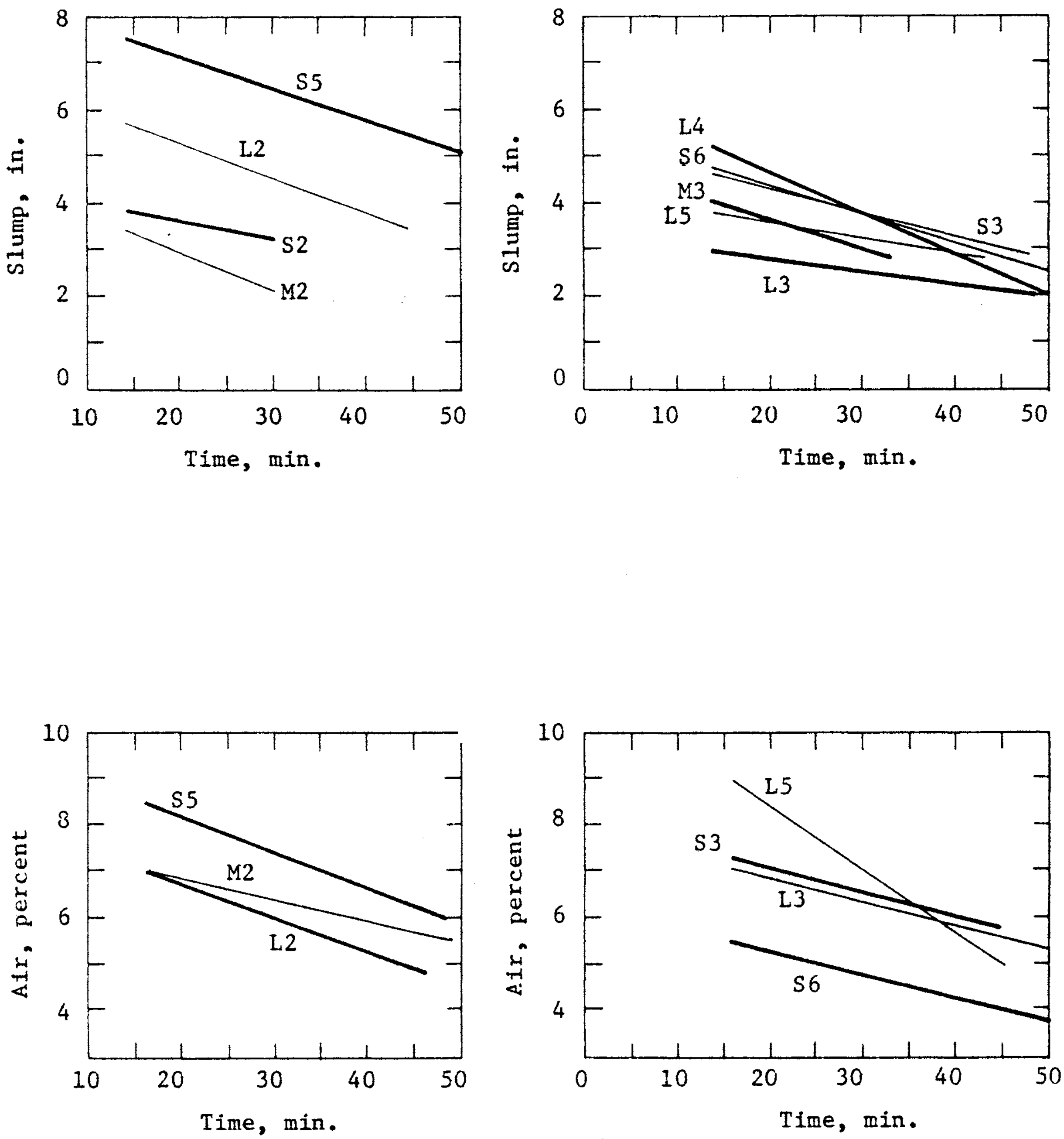
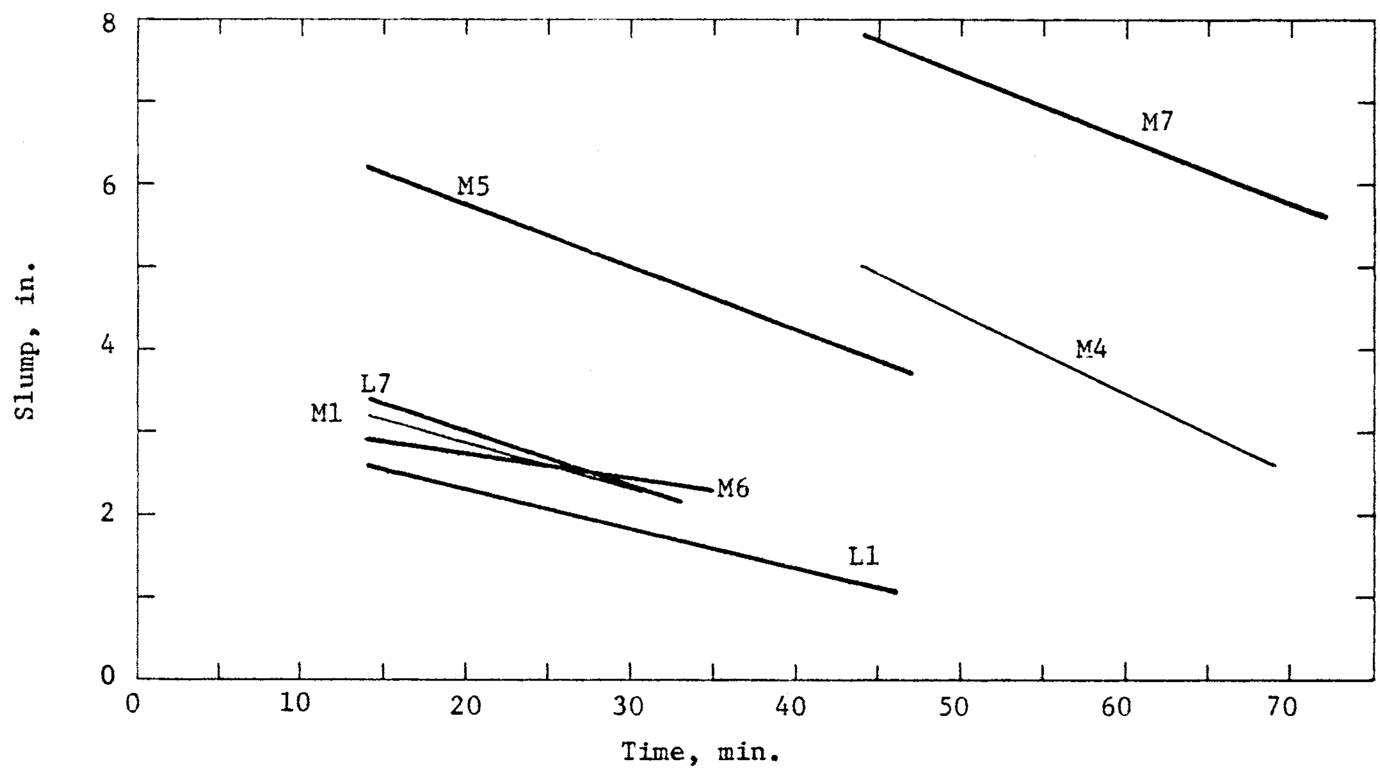


Figure B-2. Slump vs. time and air content vs. time for HRWR concrete mixtures containing Type D admixtures Plastimate (left) and 122R.



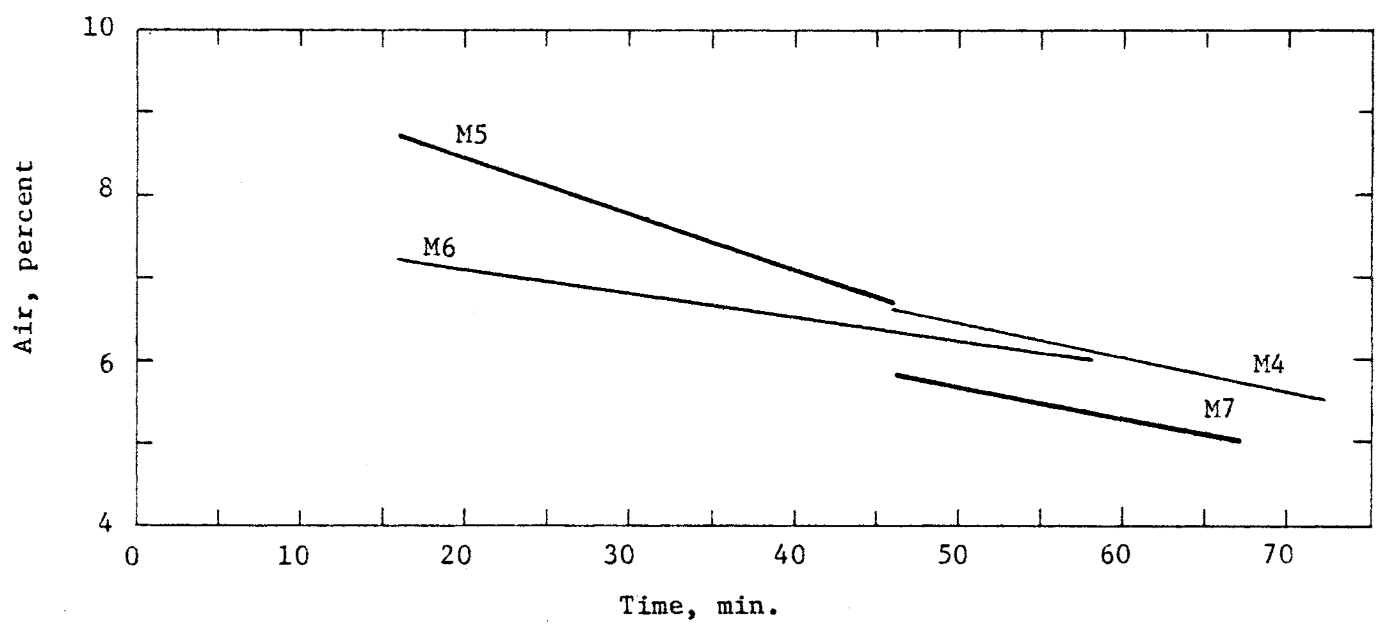


Figure B-3. Slump vs. time and air content vs. time for HRWR concrete mixtures prepared with different mixing procedures.

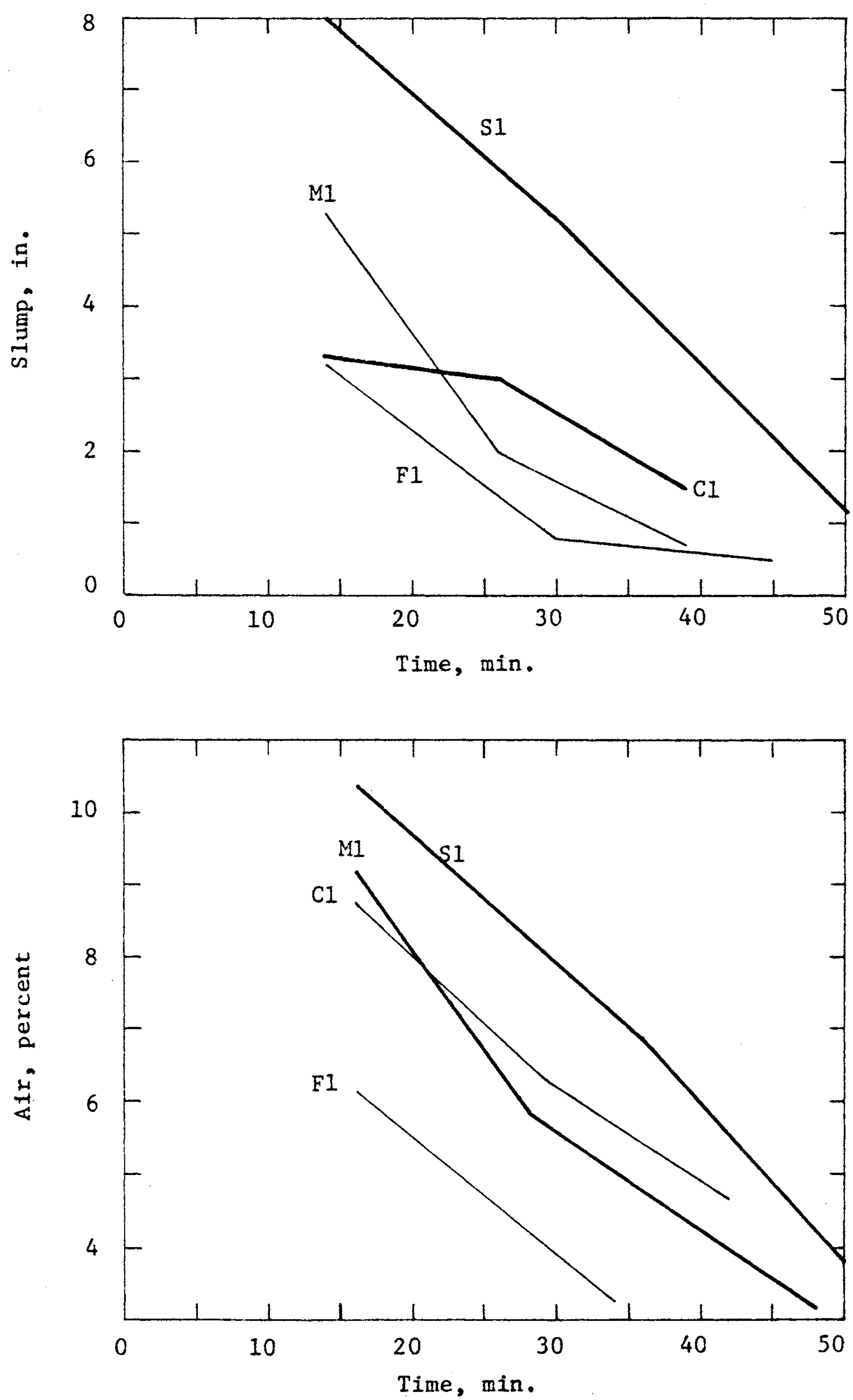


Figure B-4. Slump vs. time and air content vs. time for HRWR concrete mixtures subjected to 10-minute intervals of continuous mixing.

Figure B-3 is a plot of the relationships between slump and air content and time for HRWR concrete prepared by different mixing procedures. When compared with mixing procedure A, the delayed-addition procedure (A-1), seemed to have little effect on the initial slump, the rate of slump loss, or the rate of air loss. However, the air content following the delayed addition of the HRWR admixture was lower, as would be expected due to a loss of air prior to the addition of the HRWR admixture. It is interesting to note that it is possible to start with sufficient air-entraining admixture to have an air content of over 8% if the HRWR admixture is added as in procedure A, and have an air content approaching only 5% — by adding the HRWR admixture 30 minutes later.

When compared with mixing procedure A, mixing procedure B, in which the air-entraining admixture is added after the HRWR admixture, tended to produce concrete with a slightly lower initial slump and lower rate of air loss, but in general there were no major differences. Evidently, the HRWR admixture is slightly less effective when added at the early stages of mixing.

Figure B-4 shows the relationships between slump and air content and time for concrete mixed continuously for 10 minutes prior to making each of the slump and air content determinations. The initial dosage of air-entraining admixture was 25% higher than that used for the concretes shown in Tables B-4 and B-5 so that higher initial air contents could be achieved. It is obvious from Figure B-4 that continuous mixing significantly increases the rate of loss in slump and air. In Figure B-4 there is no major difference in the rates of loss of slump and air between the HRWR concretes and the control concretes, whereas in Figure B-1, which represents undisturbed samples, loss in the slump and air for the HRWR concrete is twice as fast as that of the control concrete. It can be theorized that in the undisturbed samples the internal agitation (and the increase in the surface area of the cement that can be hydrated) provided by the dispersing action of the HRWR admixture caused an increase in the loss of slump and air over that of the control batches. On the other hand, the agitation of both types of concretes mechanically was sufficient to cause similar losses in slump and air in the control and HRWR concretes.

In general, the HRWR concretes used in the field installations in Virginia lost slump at twice as fast a rate as did the undisturbed concretes represented in Figure B-1 but not quite as fast as the continuously mixed concretes represented in Figure B-4. One can speculate that the differences in the rates of slump loss are due to the differences in the amount of agitation provided by the mixers. The ready-mix trucks probably provided less efficient mixing than the pan-type laboratory mixer but tended to provide a broken form of continuous mixing in that the concrete was agitated some each time a cubic foot was discharged from the ready-mix truck. The loss in slump also was probably greater in the field because there was less control over the moisture content of the concrete and because of difficulties in getting the admixture dispersed throughout the ready-mix truck.

Figure B-5 shows some relationships between slump and time for Mighty 150 used at three dosages in mixtures having three w/c's. Figure B-5 illustrates that, within certain limits, the same slump behavior can be produced in mixtures having different w/c's by using appropriate dosages of admixture.

Figure B-6 shows that there is a relationship between the rate of slump loss, setting time, and dosage of HRWR admixture. The rate of slump loss tends to increase as the dosage of admixture is increased, up to a point, and then it tends to decrease. Similarly, the time to final set tends to decrease up to a similar point and then increases as the dosage of HRWR admixture increases. It seems that at the dosage of 0.4% to 0.6% solids, which is usually recommended by the manufacturers for use in HRWR concrete, the time of set is at a minimum, but the slump loss is at a maximum. Efforts to reduce slump loss by changing the dosage of HRWR admixture can cause delays in set.

No relationship could be found for the rate of air loss and dosage of HRWR admixture.

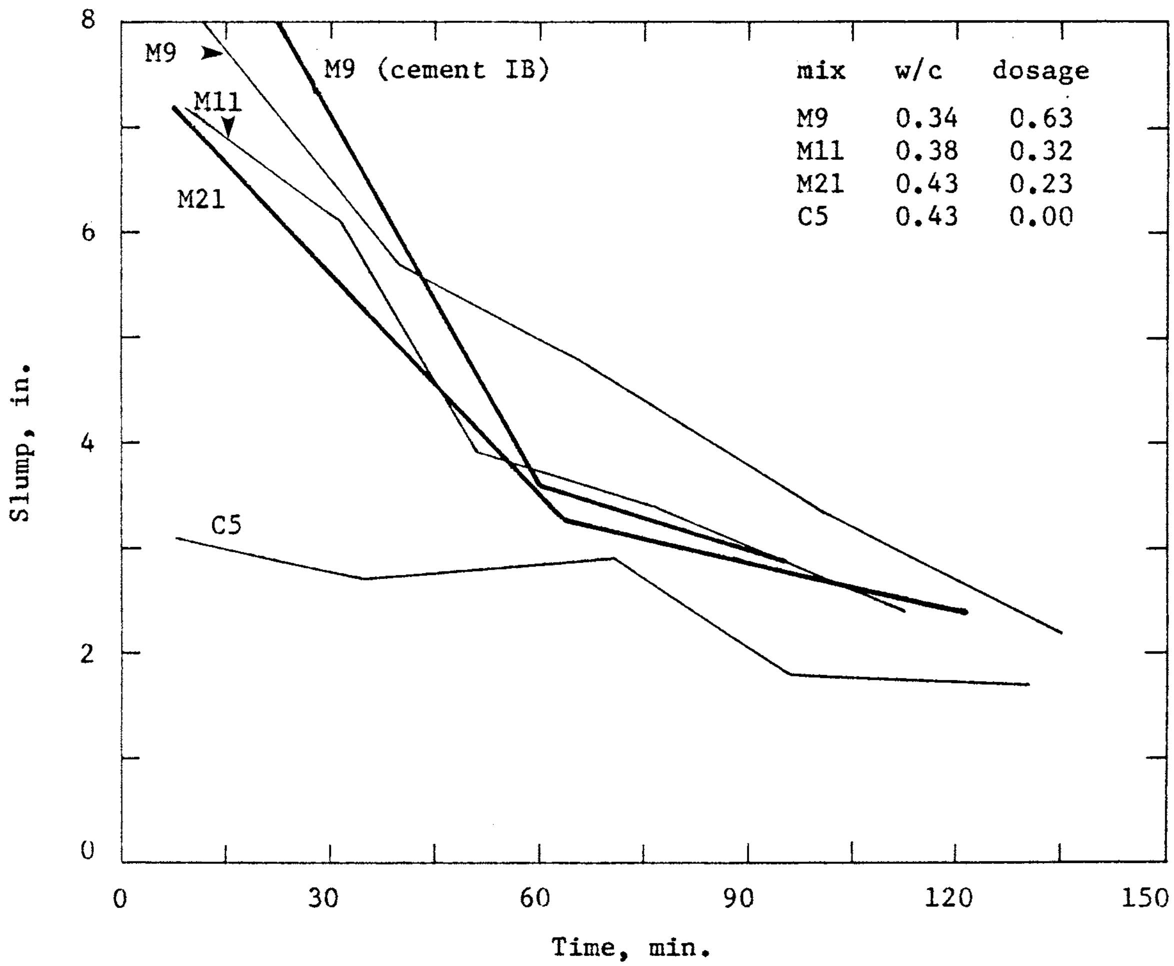


Figure B-5. Slump vs. time for concretes with different dosages of M150 and different w/c.

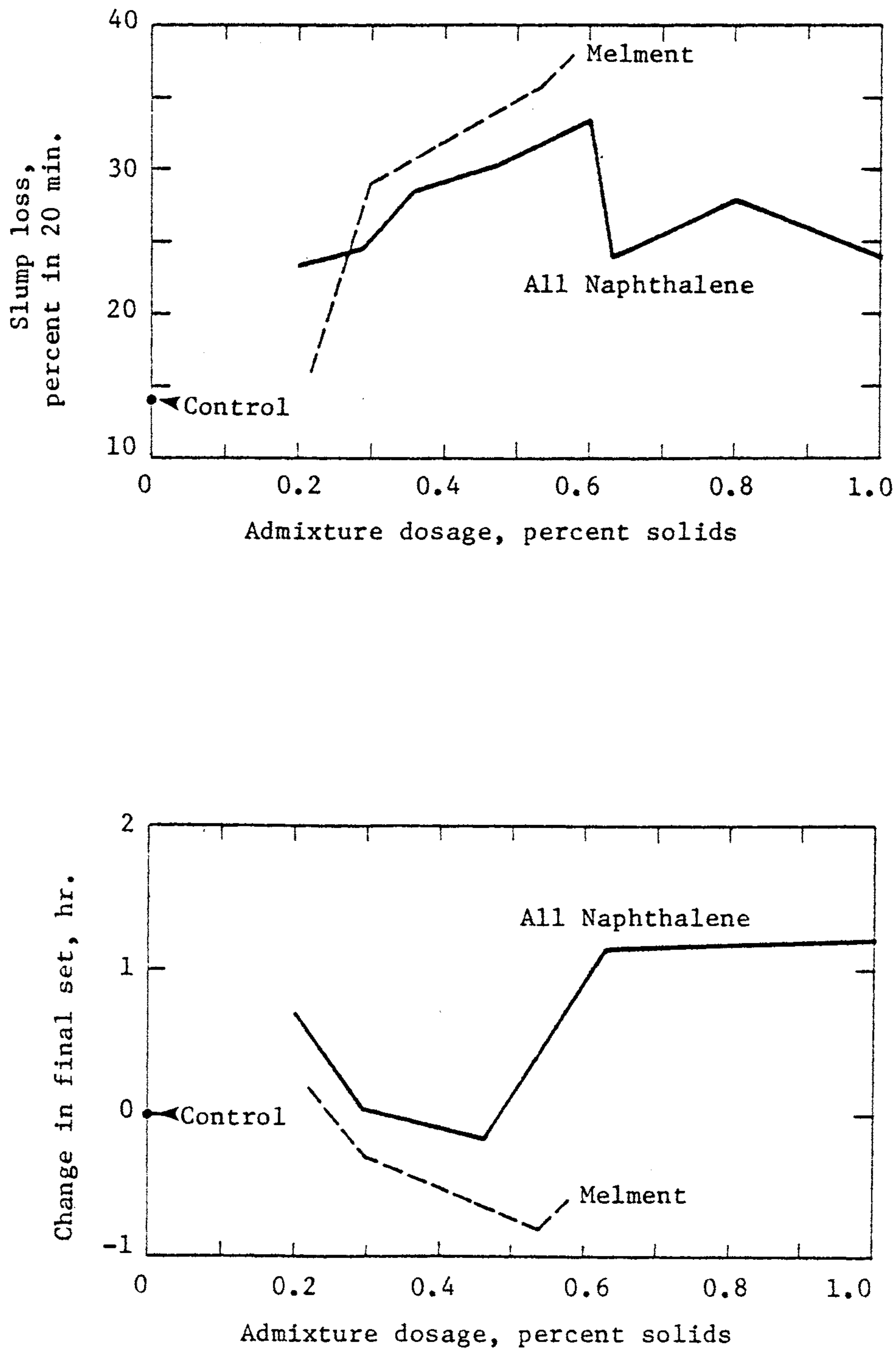


Figure B-6. Relationship between slump loss, final set, and dosage of HRWR admixture.

Setting Time

The setting times determined by Proctor penetration, ASTM C403 are shown in Tables B-6 and B-7. Since the purpose of the study was to examine the performance of HRWR admixtures used in combination with type D admixtures as well as when used alone, control batches containing 17.5 oz. plastimate per cubic yard and 29.5 oz. 122 R were also prepared. When appropriate, the retardation reported in these tables is based on comparisons with control batches containing the same dosage and kind of type D admixture.

To meet the requirements of ASTM C494 for a type F water reducer high range, the initial and final sets shall be between 1 hour earlier and 1.5 hours later than for a mixture that does not contain the admixture. To meet the requirements for a type G water reducer high range retarding, the concrete must reach initial set between 1 hour and 3.5 hours later and final set no more than 3.5 hours later.

Based on the data shown in Tables B-6 and B-7, most of the admixtures tested satisfied the time of set requirements for a type F admixture as specified by ASTM C494. Exceptions were the Sikament and Mighty RD2. Mighty 150 also failed when used with mix procedure A-1, which requires the delayed addition of HRWR. All three HRWR admixtures — Mighty 150, Melment, and Sikament — failed the type F requirements but passed the type G requirements when used in combination with plastimate and 122 R with the exception that Sikament failed when used with 122 R. Unfortunately, no control batches were prepared with cement IB, the type I cement, so the retardation could not be determined. However, the results with the type I cement are reported so that they might be compared with the batches containing the type II cements. In general, there appears to be little difference in setting time between the type I cement and the type II cement IIA. However, it should be noted that in general a higher dosage of HRWR admixture was used in the batches containing type I cement.

The data suggest that the melamine admixtures as represented by Melment had the greatest accelerating effect on set and that the naphathalene admixtures either had little effect or tended to retard set. The setting time seemed to increase as the w/c increased, as was demonstrated by all three admixtures — Mighty 150, Melment, and WRDA-19 — tested at three w/c's. The use of mix procedure A-1 with Mighty 150 retarded the set, which was expected since the accelerating effect of the admixture enters the hydration process at a later time. The use of mix procedure B with Melment had little effect on setting time, which also would be expected since with both procedure A and procedure B the AEA and the HRWR admixture were added within several minutes of each other and within several minutes of the time the water was added to the cement.

Table B-6

Time of Set of Air-Entrained Mortar for Experimental Mixes

Mix No.	Cement Type	HRWR Type	HRWR Dosage, S/S	Type D Admix.	Time of Set (Hr.) Initial	Time of Set (Hr.) Final	Retardation (Hr.) Initial	Retardation (Hr.) Final
w/c = 0.34								
M1	II A	Mighty 150	0.46	—	4.7	5.8	0.0	- 0.4
M2	II A	Mighty 150	0.42	Plastimate	7.7	9.2	1.6	1.4
M3	II A	Mighty 150	0.42	122-R	10.1	11.7	2.6	2.7
M7	II A	Mighty 150	0.67*	—	6.7	8.0	2.0	1.8
M8	II A	Mighty 150	0.92	—	6.3	7.7	1.6	1.5
L1	II A	Melment	0.54	—	4.2	5.4	- 0.5	- 0.8
L2	II A	Melment	0.68	Plastimate	7.5	9.1	1.4	1.3
L3	II A	Melment	0.44	122-R	9.2	10.8	1.7	1.8
L4	II A	Melment	0.62	122-R	[illegible].8	9.3	0.3	0.3
L5	I B	Melment	0.78	122-R	9.2	10.8	—	—
L6	I B	Melment	0.78	—	4.3	5.6	—	—
L7	II A	Melment	0.58**	—	4.5	5.6	- 0.2	- 0.6
S1	II A	Sikament	0.60	—	6.8	8.1	2.1	1.9
S2	II A	Sikament	0.48	Plastimate	8.1	9.7	2.0	1.9
S3	II A	Sikament	0.44	122-R	12.0	13.8	4.5	4.8
S4	I B	Sikament	0.60	—	6.6	8.1	—	—
S5	I B	Sikament	0.84	Plastimate	9.2	10.6	—	—
S6	I B	Sikament	0.84	122-R	12.0	13.9	—	—
W1	II C	WRDA-19	0.62	—	4.2	5.3	0.2	- 0.2
R1	II A	Mighty RD2	0.41	—	24.3	27.1	19.6	20.9
F1	II A	FX 34	1.0	—	6.1	7.4	1.4	1.2

*Mix procedure A-1

**Mix procedure B

Table B-6 continued

Mix No.	Cement Type	HRWR Type	HRWR Dosage, S/S	Time of Set, Hr. Initial	Time of Set, Hr. Final	Retardation, Hr. Initial	Retardation, Hr. Final
w/c = 0.38							
M10	II A	Mighty 150	0.29	4.7	6.0	0.0	-0.2
L10	II A	Melment	0.30	4.4	5.9	-0.3	-0.3
L11	II C	Melment	0.58	4.1	5.4	0.1	-0.1
L12	II C	Melment	0.58	3.7	5.0	-0.3	-0.5
W10	II C	WRDA-19	0.36	4.3	5.7	0.3	0.2
W11	I B	WRDA-19	0.36	3.0	4.1	—	—
R10	II A	Mighty RD2	0.27	13.0	15.0	8.3	8.8
w/c = 0.43							
M20	II A	Mighty 150	0.21	5.5	7.2	0.8	1.0
L20	II A	Melment	0.22	4.8	6.4	0.1	0.2
W20	II C	WRDA-19	0.20	4.7	5.9	0.7	0.4
W21	I B	WRDA-19	0.20	3.8	4.7	—	—

Table B-7

Time of Set of Air-Entrained Control Mixes

Mix No.	Cement Type	Type D Water Reducer	Time of Set, Hr.		Retardation, Hr.	
			Initial	Final	Initial	Final
C1	II A	—	4.7	6.2	Control	—
C2	II C	—	4.0	5.5	Control	—
C3	II A	Plastimate	6.1	7.8	1.4	1.6
C4	II A	122-R	7.5	9.0	2.8	2.8

Drying Shrinkage

One specimen 3 in. x 3 in. x 11¼ in. was prepared from each batch of concrete for determining the drying shrinkage as prescribed by ASTM C157. The specimens were moist cured for 2 weeks and air dried for the third and fourth weeks after batching. The change in length of the specimens during the four-week period is a measure of the drying shrinkage. The length change expressed as a percentage of the original lengths are shown in Tables B-8 and B-9. ASTM C494 requires that when the length change of the specimens made from the control concrete is less than 0.030%, the specimens made from the concrete containing the admixture should not decrease in length more than 0.010% more than the control. As can be seen from the data in Tables B-8 and B-9, all of the specimens prepared with the type II cements satisfied the requirements of ASTM C494. Also, the shrinkage of the specimens prepared with the type I cement, for which no control batches were prepared, was similar to that of the specimens prepared with the type II cements. Also, based on the limited data available, the mixing procedure appeared to have no effect on drying shrinkage.

Table B-8

28-Day Drying Shrinkage for Experimental Concretes

Mix No.	Cement Type	HRWR Type	HRWR Dosage, S/S	Type D Admixture	Percent Length Change at 28 Days	Pass or Fail
w/c = 0.34						
M1	II A	Mighty 150	0.46	—	0.021	Pass
M2	II A	Mighty 150	0.42	Plastimate	0.034	Pass
M3	II A	Mighty 150	0.42	122-R	0.020	Pass
M4	II A	Mighty 150	0.59*	—	0.020	Pass
M7	II A	Mighty 150	0.67*	—	0.018	Pass
M8	II A	Mighty 150	0.92	—	0.024	Pass
L1	II A	Melment	0.54	—	0.027	Pass
L2	II A	Melment	0.68	Plastimate	0.039	Pass
L3	II A	Melment	0.44	122-R	0.024	Pass
L4	II A	Melment	0.62	122-R	0.030	Pass
L5	I B	Melment	0.78	122-R	0.020	No controls
L6	I B	Melment	0.78	—	0.026	No controls
L7	II A	Melment	0.58**	—	0.016	Pass
S1	II A	Sikament	0.60	—	0.019	Pass
S2	II A	Sikament	0.48	Plastimate	0.035	Pass
S3	II A	Sikament	0.44	122-R	0.018	Pass
S4	I B	Sikament	0.60	—	0.027	No controls
S5	I B	Sikament	0.84	Plastimate	0.036	No controls
S6	I B	Sikament	0.84	122-R	0.021	No controls
W1	II C	WRDA-19	0.62	—	0.024	Pass
R1	II A	Mighty RD2	0.41	—	0.013	Pass
F1	II A	FX 34 Powder	1.0	—	0.026	Pass

*Mix procedure A-1 **Mix procedure B

Table B-8 continued

Mix No.	Cement Type	HRWR Type	HRWR Dosage, S/S	Percent Length Change at 28 Days	Pass or Fail
w/c = 0.38					
M10	II A	Mighty 150	0.29	0.018	Pass
L10	II A	Melment	0.30	0.018	Pass
W10	II C	WRDA-19	0.36	0.030	Pass
W11	I B	WRDA-19	0.36	0.026	No controls
R10	II A	Mighty RD2	0.27	0.018	Pass
F10	II A	FX-34 Powder	0.80	0.028	Pass
S10	II C	Sikament	0.36*	0.018	Pass
w/c = 0.43					
M20	II A	Mighty 150	0.21	0.004	Pass
L20	II A	Melment	0.22	0.016	Pass
W20	II C	WRDA-19	0.20	0.021	Pass
W21	I B	WRDA-19	0.20	0.022	No controls
S20	II C	Sikament	0.20*	0.014	Pass

*Mix procedure A-1

Table B-9

28-Day Drying Shrinkage for Control Concretes

Mix No.	Cement Type	Type D Water Reducer	Percent Length Change at 28 Days
C1	II A	None	0.020
C2	II C	None	0.028
C3	II A	Plastimate	0.029
C4	II A	122-R	0.020

Bleeding Characteristics

In the early stages of the project, samples were prepared from several batches of the concretes containing Mighty 150 to determine their bleeding characteristics in accordance with ASTM C232. Because the concretes were air-entrained and because the w/c's were low, no measurable amount of bleed water could be obtained from the samples. Therefore, it was concluded that for the mixture proportions used in the project bleeding was not a problem, and further efforts to measure bleed water were discontinued.

Compressive and Flexural Strength

Figures B-7 through B-10 show the relationships between compressive strength and flexural strength and age for the majority of the concrete mixtures. Most of the data points are based on the average of the strengths of three specimens, one from each of three duplicate batches of concrete. The cylinders for compressive strength tests were prepared and tested in accordance with ASTM C39. Approximately one-half were the standard 6 in. x 12 in. size and, for convenience, the other half were 3 in. x 6 in. The flexural strength specimens were prepared and tested in accordance with ASTM C78 and were 3 in. x 4 in. x 16 in. Unless otherwise noted, the concrete mixtures from which the specimens were prepared had a cement content of 658 lb./yd.^{3}, a slump of from 2 in. to 5 in., and an air content of from 5% to 9% in the plastic state.

Figure B-7 shows the relationship between compressive strength and flexural strength and age for specimens prepared from concretes having different w/c's. Figure B-7 confirms the generally accepted principle that as the w/c decreases, the strength of the concrete increases. It can be seen from this figure that none of the HRWR admixtures offered any significant advantages over the others from the standpoint of strength.

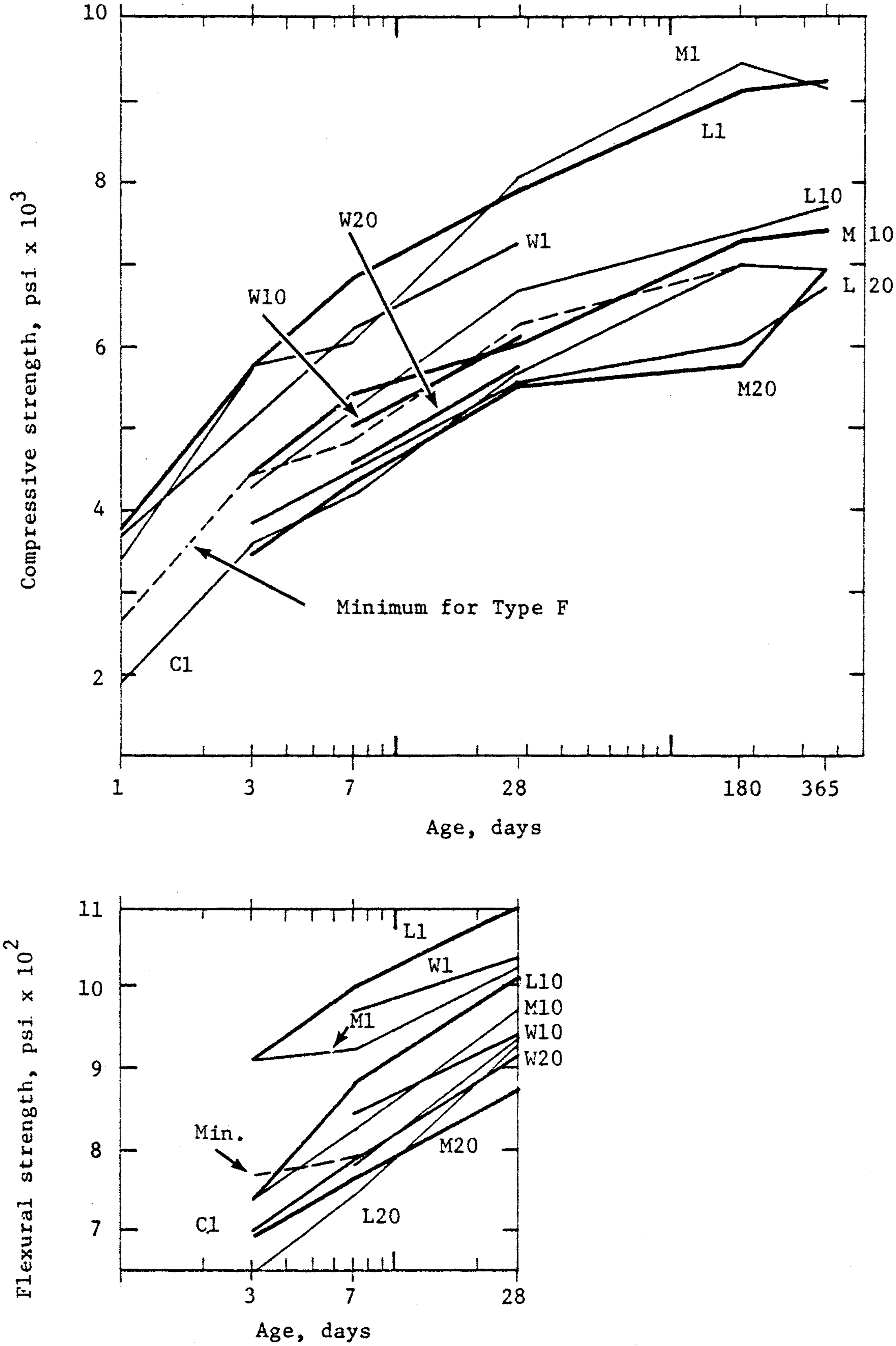


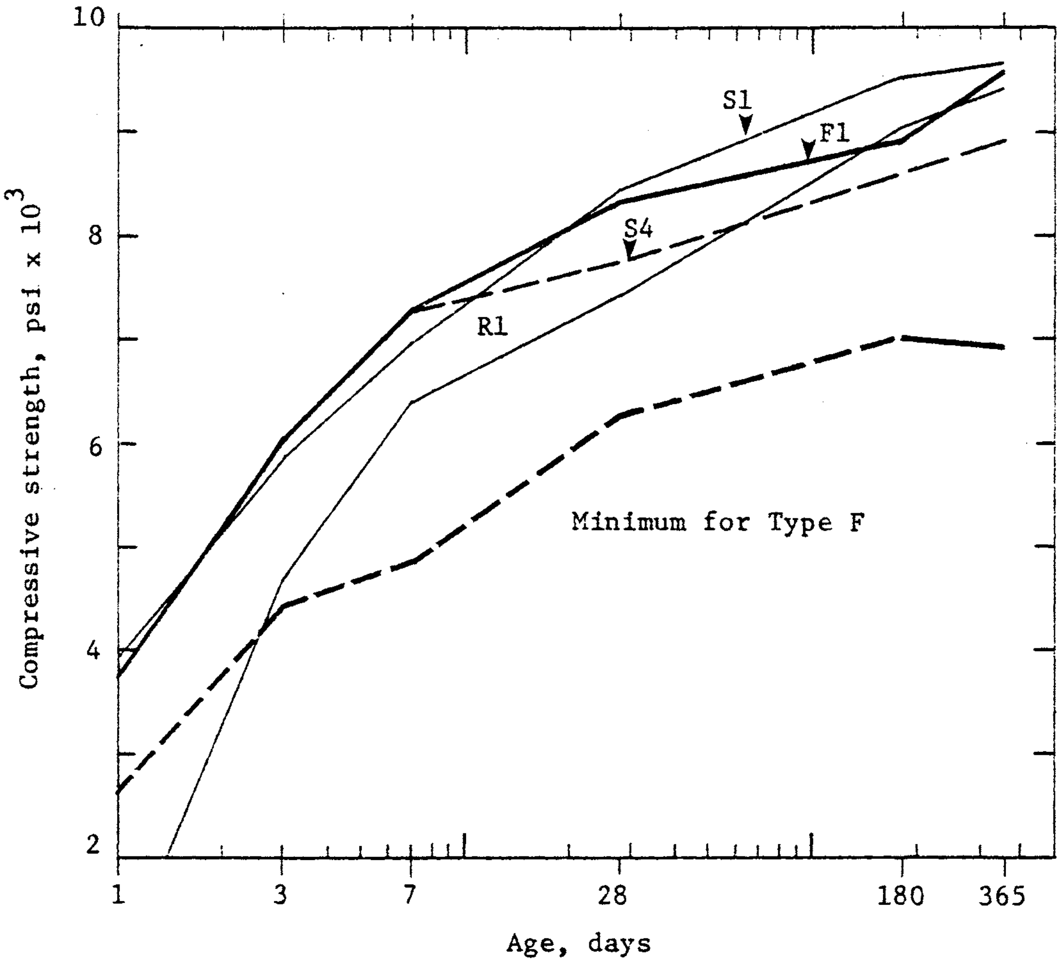
Figure B-7. Relationship between compressive and flexural strength and age for three w/c's.

It also can be seen from Figure B-7 that, on the average, when the HRWR admixtures were added to concrete without changing the w/c the strength was the same as for the control concrete that contained no water-reducing admixture. For this application, the admixtures were being used as plasticizers rather than water reducers; therefore, as would be expected, the admixtures did not satisfy the compressive and flexural strength requirements specified by ASTM C494. On the other hand, when the admixtures were added so as to produce a workable mixture having 12% less water than the control mix, the compressive strengths increased approximately 20% and the flexural strengths approximately 6% at 3 days. To satisfy the requirements of ASTM C494 for a type F admixture, compressive strengths must be 25% higher at 3 days and flexural strengths must be 10% higher. At the 12% minimum water reduction allowed by ASTM C494 to qualify type F and type G water reducers, it is obvious that many of the batches did not meet the strength requirements, particularly at early ages. But it is obvious that at slightly greater water reductions the admixtures would meet the requirements.

Figure B-7 shows that when the admixtures were added so as to produce a workable mixture having 21% less water than the control mixture, the compressive strength increased approximately 90% at 1 day and 50% at 3 days, and the flexural strength increased approximately 32% at 3 days. When the admixtures were used to provide a 21% water reduction, all the admixtures far exceeded the strength requirements of ASTM C494.

The data shown in Figure B-7 agree in pattern with the data presented by others, and they support the hypothesis that the strength of concrete containing HRWR admixtures at 28 days and later is a function of the w/c. The strength of the HRWR concrete relative to the control concrete is usually greatest at early ages, probably because the cement particles are dispersed by the admixtures and therefore are more quickly hydrated.[B-1] Evidently, when the admixtures were used to provide only a 12% water reduction, the dosage was too low to fully disperse all the cement particles and consequently there was some difficulty in meeting the early strength requirements of C494.

Figure B-8 shows the relationship between compressive strength and flexural strength and age for concretes containing 3 other HRWR admixtures and having a w/c of 0.34. The strength behavior of the concretes prepared with these HRWR admixtures was not noticeably different from the behavior of the concretes having a w/c of 0.34 and shown in Figure B-7. Of particular interest, however, is the fact that the concrete prepared with Mighty RD2 did not reach final set for 27 hours, so that no 1-day strengths could be determined, but the strengths at 3 days and later were not significantly different from those of the other concretes. Because of the delayed set, batches containing Mighty RD2 did not meet the 1-day strength requirements for a type G water reducer as specified by ASTM C494.



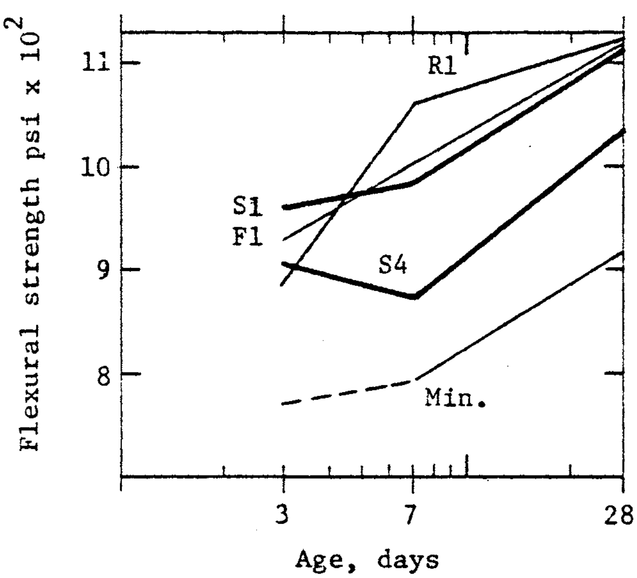
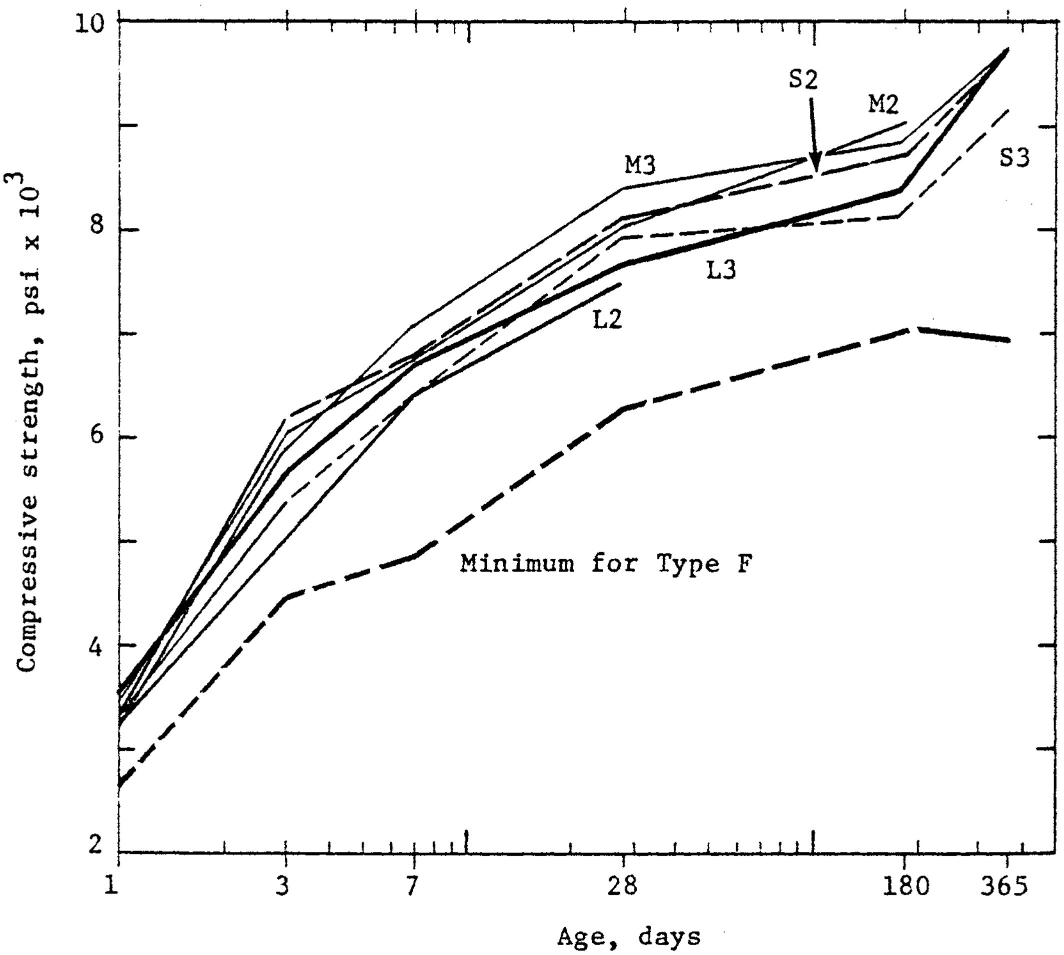


Figure B-8. Relationship between compressive and flexural strengths and age for other HRWR concrete (w/c = 0.34).

Also of interest in Figure B-8 is the fact that the strength behavior of the concrete prepared with the FX-34 admixture, which was added to the concrete mixture in powder form, was not signifi-cnatly different from that of concretes containing the other liquid admixtures. Also of interest, Sikament was used with both type I and type II cements but, unfortunately, the average air content of the batches prepared with the type I cement was 10.6%, which was 3.5% higher than those for the batches containing type II cement. Taking the difference in air content into account, it can be seen that the strengths of the concretes containing Sikament was as would be expected for the two types of cement.

Figure B-9 shows the relationships between compressive strength and flexural strength and age for specimens prepared from concrete having a w/c of 0.34 and containing one of three HRWR admixtures and one of two type D water-reducing retarding admixtures. Although the strengths at 1 day and 3 days may have been marginally less for the concretes containing the type D admixtures, as compared to those that didn't, the strengths at later ages were essentially the same for all the specimens. It's reasonable to say that at 7 days and older, no significant benefit, from the standpoint of strength, was derived from using any one of the HRWR admixtures or combinations of HRWR admixtures and type D admixtures tested. Batches prepared with all HRWR admixtures and combinations of HRWR admixtures and type D admixtures exhibited both flexural and compressive strengths far exceeding the requirements of ASTM C494.

Figure B-10 shows the effect of the delayed addition of the HRWR admixture (mix procedure A-1), the effect of adding the AEA last (mix procedure B), and the effect of slump on the compressive and flexural strengths of HRWR concrete having a w/c of 0.34 and containing M 150 and Melment. It can be seen that there was no difference in compressive strength that could be attributed to the delayed addition of the M 150 or to adding the AEA last when using Mighty 150 and Melment. Also, there was no basic difference between strengths of concrete having a slump of from 2 to 5 in. and that with a slump of from 5 to 7 in., but the strength appeared to be less for concrete having a slump greater than 7 in. For the batches prepared with a slump greater than 7 inches, the 3-, 7-, and 28-day compressive strengths were relatively low but higher than required by ASTM C494, but the flexural strengths at these ages were lower than required. It is believed that the lower strength at the high slump was due to some type of segregation that occurred during the preparation of the specimens or to the presence of water in the mixture that was not anticipated. Re-gardless of the reason, it is recommended that to maintain optimum strength, slumps be held to 7 in. or less.



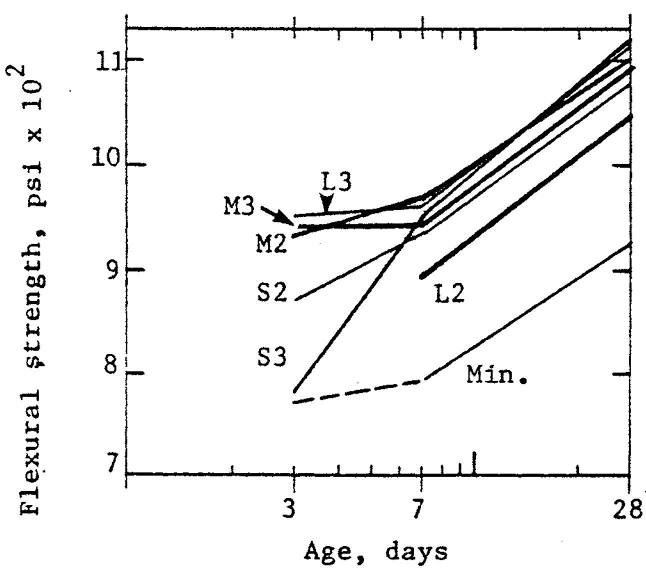


Figure B-9. Relationship between compressive and flexural strength and age for HRWR concretes containing Type D admixtures (w/c = 0.34).

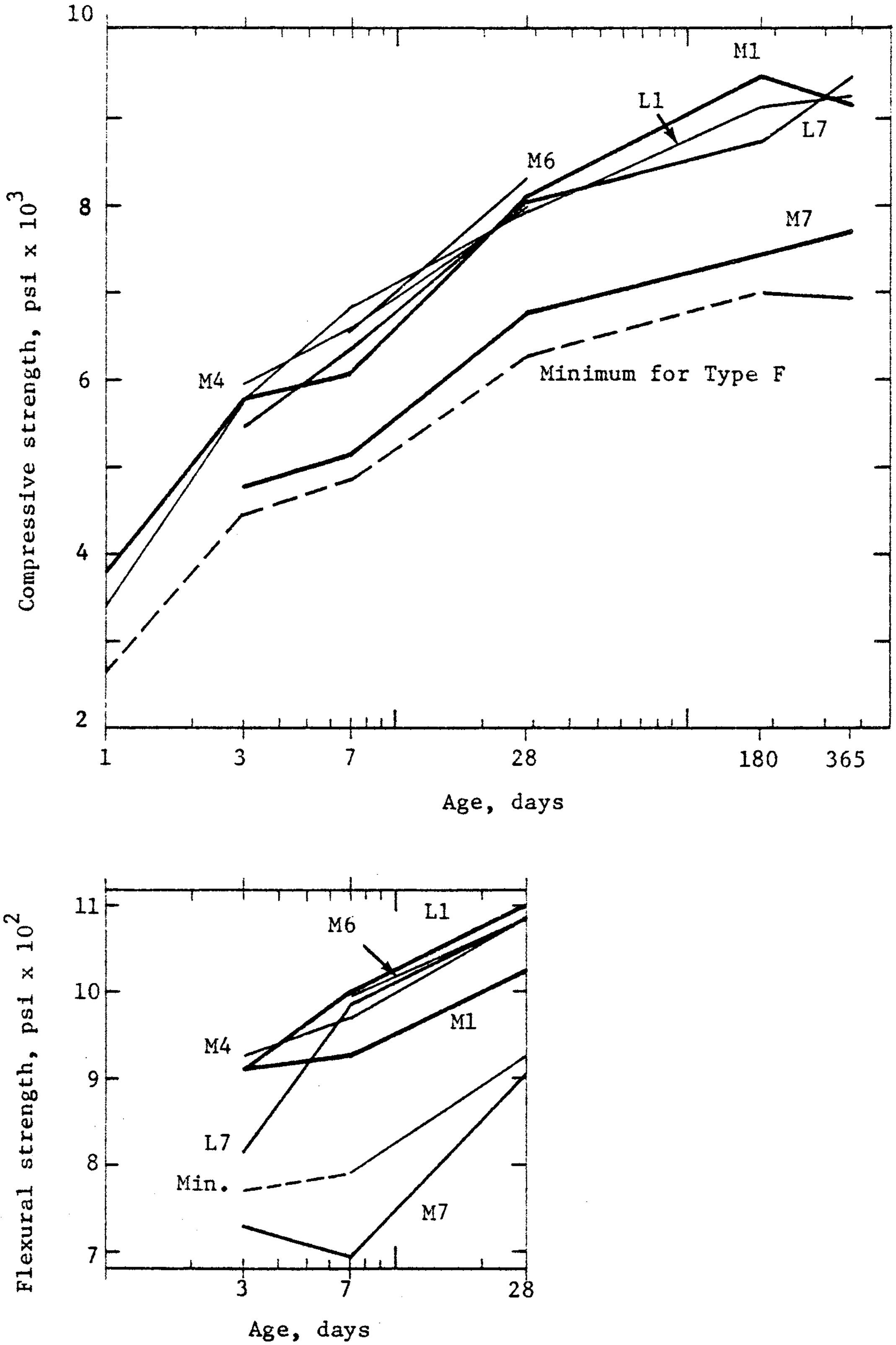


Figure B-10. Relationship between compressive and flexural strengths and age for HRWR concretes prepared with different mixing procedures (w/c = 0.34).

Absorption

To quantify the relationship between w/c and absorption in HRWR concrete, one 3 in. x 3 in. x 11 in. specimen from each of 81 batches was placed in a water bath for 60 days. The weights of the specimens were recorded at intervals of 1 day, 2 weeks, 1 month, and 2 months. Following the 60 days of soak, the specimens were oven-dried. Fifty-two of the specimens were prepared from concretes containing one of five brands of naphthalene sulphonated polymer admixtures, 18 were prepared from a concrete containing a melamine sulphonated polymer admixture, and 11 did not contain an SWR admixture. Table B-10 shows the average relations between w/c and absorption based on the linear regression of the data for specimens prepared with each of the HRWR admixtures and without any admixtures at the 1-day and 60-day soak periods.

Table B-10

Average Relationship Between w/c and Absorption Based on Linear Regression

Days in Soak	Admixture Type	No. of Specimens	Absorption at Indicated w/c		
			0.34	0.38	0.43
1	—	11	—	—	3.72
1	Melment	18	2.77	3.11	3.53
1	All Naphthalene	52	2.57	3.14	3.85
60	—	11	—	—	4.28
60	Mighty 150	17	3.03	3.61	4.33
60	Melment	18	3.20	3.60	4.10
60	Sikament	18	2.92	—	—
60	WRDA-19	9	3.66	4.11	4.68
60	Mighty RD2	3	2.84	4.34	—
60	FX-34	5	2.79	3.36	—
60	All Naphthalene	52	3.02	3.63	4.39

It is obvious from Table B-10 that, on the average, the lower the w/c the lower the absorption of the concrete. Differences between concretes prepared at the same w/c with different admixtures are believed to be related to the effect of the admixtures on the properties of the plastic concretes and the corresponding effect on consolidation. Unfortunately, the 95% confidence band width for the 60-day-soak data was wide, 1.62%. Therefore, it would be difficult to accurately predict a w/c in the range of 0.34 to 0.43 based on the results of soak tests.

Freeze-Thaw Durability

Standard 3 in. x 4 in. x 16 in. freeze-thaw beams were prepared, moist cured for 2 weeks, and subjected to 300 cycles of freezing and thawing in accordance with ASTM C666 Procedure A. The specimens were subjected to 8 freeze-thaw cycles a day, which allows completion of the test in 6 weeks. The specimens were evaluated periodically throughout the 300-cycle test with respect to surface rating (ASTM 672), weight loss, and dynamic modulus. Experience has indicated that good performance can be expected when the surface rating, an indication of scaling, is less than 3, the weight loss less than 7%, and the durability factor (DF), which is an indicator of internal cracking, greater than 60%. ASTM C494 simply requires that the DF of the test concrete be at least 80% that of the control concrete.

Clearly the freeze-thaw durability of concretes containing HRWR admixtures is one of the most interesting and most controversial issues considered in this report. The results of the freeze-thaw tests are shown in Tables B-11 and B-12. As can be seen from the tables, some concretes containing each of the six HRWR admixtures tested passed the freeze-thaw test. Therefore, each of the six admixtures can satisfy the freeze-thaw requirements of C494. However, of probably greater significance is the fact that concrete containing four of the six HRWR admixtures failed the freeze-thaw test. The exceptions were WRDA-19 and Mighty RD2. Therefore, it would seem that the use of HRWR admixtures does not guarantee that concrete will pass or fail the freeze-thaw test, but rather that the physical properties of the concrete that result from the use of the admixtures determine whether or not a concrete passes or fails.

In general, the use of mix procedure B and type D admixtures in combination with the HRWR admixtures, did not significantly improve the freeze-thaw performance, and the improvements noted for Melment were probably due to the higher air content.

Table B-11

Results of Freeze-Thaw Tests of Experimental Concretes

Mix No.	Cement Type	HRWR Type	HRWR Dosage, S/S	Type D Admix.	Surface Rating	Weight Loss, %	DF, %	Pass or Fail ASTM C494
w/c = 0.34								
M1	II A	Mighty 150	0.46	—	1.2	0.4	73	Pass
M2	II A	Mighty 150	0.42	Plastimate	0.9	0.1	86	Pass
M3	II A	Mighty 150	0.42	122-R	0.7	0.7	90	Pass
M4	II A	Mighty 150	0.59*	—	0.5	0.1	75	Pass
M5	II A	Mighty 150	0.63	—	0.5	0.0	89	Pass
M6	II A	Mighty 150	0.63**	—	0.4	0.0	79	Pass
M7	II A	Mighty 150	0.67*	—	0.5	0.6	54	Fail
M8	II A	Mighty 150	0.92	—	0.4	0.0	16	Fail
L1	II A	Melment	0.54	—	0.4	0.1	50	Fail
L2	II A	Melment	0.68	Plastimate	1.0	0.2	75	Pass
L3	II A	Melment	0.44	122-R	0.5	0.1	87	Pass
L4	II A	Melment	0.62	122-R	0.9	0.0	36	Fail
L5	I B	Melment	0.78	122-R	1.0	0.4	90	No control
L6	I B	Melment	0.78	—	1.0	0.1	41	No control
L7	II A	Melment	0.58**	—	0.8	0.5	94	Pass
S1	II A	Sikament	0.60	—	0.6	0.0	76	Pass
S2	II A	Sikament	0.48	Plastimate	0.8	0.2	84	Pass
S3	II A	Sikament	0.44	122-R	0.7	0.1	85	Pass
S4	I B	Sikament	0.60	—	0.6	0.1	99	No control
S5	I B	Sikament	0.84	Plastimate	1.0	0.1	91	No control
S6	I B	Sikament	0.84	122-R	0.9	0.1	94	No control
W1	II C	WRDA-19	0.62	—	0.5	0.2	86	Pass
R1	II A	Mighty RD2	0.41	—	0.2	0.1	96	Pass
F1	II A	FX 34	1.0	—	0.1	0.0	32	Fail

*Mix Procedure A-1

**Mix Procedure B

Table B-11 continued

Mix No.	Cement Type	HRWR Type	HRWR Dosage, S/S	Surface Rating	Weight Loss, %	DF, %	Pass or Fail ASTM C494
w/c = 0.38							
M10	II A	Mighty 150	0.29	0.8	0.2	95	Pass
L10	II A	Melment	0.30	0.7	0.1	71	Fail
L11	II C	Melment	0.58	0.7	0.3	89	Pass
L12	II C	Melment	0.58	1.2	2.1	20	Fail
W10	II C	WRDA-19	0.36	1.0	1.2	78	Pass
W11	I B	WRDA-19	0.36	0.7	0.4	81	No control
R10	II A	Mighty RD2	0.27	0.4	0.4	90	Pass
F10	II A	FX 34 Powder	0.80	0.2	0.1	98	Pass
S10	II C	Sikament	0.36*	0.5	0.4	72	Pass
w/c = 0.43							
M20	II A	Mighty 150	0.21	0.7	0.7	58	Fail
L20	II A	Melment	0.22	1.2	3.6	57	Fail
W20	II C	WRDA-19	0.20	0.9	1.5	80	Pass
W21	I B	WRDA-19	0.20	1.0	1.3	75	No control
S20	II C	Sikament	0.20*	1.4	1.4	89	Pass

*Mix Procedure A-1

Table B-12

Results of Freeze-Thaw Tests of Control Concretes

Mix No.	Cement Type	Type D Water Reducer	Surface Rating	Weight Loss, %	DF, %	80% of Control
C1	II A	—	0.9	0.4	91	73
C2	II C	—	0.9	0.9	85	68
C3	II A	Plastimate	2.0	1.4	89	71
C4	II A	122-R	0.4	0.2	98	78

Air Void Characteristics

Petrographic examinations were conducted in accordance with ASTM C457 (Rosiwal Method) to determine the quantity, size, and spacing of voids in the vertically cut faces of 3 in. x 4 in. x 16 in. flexural specimens prepared alongside the freeze-thaw specimens. The results of the examinations are shown in Tables B-13 and B-14, along with the results of measurements of the air content of the plastic concrete made in accordance with ASTM C231 prior to preparing the specimens and also, in many cases, after the specimens were prepared.

Until recently it was generally accepted that concrete must have an air void spacing factor ($\bar{L}$) of 0.008 in. or less to pass a freeze-thaw test conducted in accordance with ASTM C666 Procedure A. Although many still support this requirement, the results of recent tests conducted by others suggest that HRWR concrete with a higher $\bar{L}$, one in the neighborhood of 0.010 in., can pass various freeze-thaw tests. Of course, the large volume of recent evidence indicates that HRWR concrete with a higher $\bar{L}$ can pass a less severe freeze-thaw test such as procedure B of ASTM C666 or a modified version of Procedure A such as conducted by the Portland Cement Association in which the rate of freezing and thawing is only 2 cycles a day rather than the 6 to 12 cycles a day required by ASTM C666. It is obvious from Table B-13 that the HRWR concrete prepared for this study typically exhibited an $\bar{L}$ between 0.008 and 0.014 in.

A plot of the relationship between the durability factor and the spacing factor for 67 batches of HRWR concrete is shown in Figure B-11. The curve of best fit is based on a linear regression of the data. The curve of best fit indicates that, on the average, a DF of 60 can be achieved with an $\bar{L}$ of 0.0129 in. Unfortunately, the correlation coefficient for the data was low (only -0.56); therefore, at the 95% confidence level a concrete with an $\bar{L}$ of 0.0129 in. can have a DF between 0 and 100. A separate regression was made on the data obtained for each of the six HRWR admixtures but there were no significant differences in the relationships between DF and $\bar{L}$ for any of them.

Table B-13

Air Void Characteristics of Experimental Concretes

Mix No.	Cement Type	HRWR Type	HRWR Dosage, S/S	Type D Admix.	Plastic Air, % Before Spec.	Plastic Air, % After Spec.	Total Voids, %	Specific Surface	$\bar{L}$, in.
w/c = 0.34									
M1	II A	Mighty 150	0.46	—	7.3	—	6.0	383	0.011
M2	II A	Mighty 150	0.42	Plastimate	7.0	5.6	6.2	443	0.009
M3	II A	Mighty 150	0.42	122-R	7.4	—	6.9	376	0.010
M4	II A	Mighty 150	0.59*	—	6.6	5.5	5.3	361	0.014
M5	II A	Mighty 150	0.63	—	8.7	6.7	5.7	424	0.011
M6	II A	Mighty 150	0.63**	—	7.2	6.0	5.9	416	0.010
M7	II A	Mighty 150	0.67*	—	5.8	5.0	5.7	277	0.016
M8	II A	Mighty 150	0.92	—	4.3	—	3.7	208	0.026
L1	II A	Melment	0.54	—	6.2	—	6.2	336	0.012
L2	II A	Melment	0.68	Plastimate	7.0	4.9	5.8	491	0.010
L3	II A	Melment	0.44	122-R	7.1	5.4	4.9	345	0.016
L5	I B	Melment	0.78	122-R	9.0	5.0	7.4	507	0.007
L6	I B	Melment	0.78	—	2.8	—	4.9	487	0.010
L7	II A	Melment	0.58**	—	6.6	—	5.6	399	0.011
S1	II A	Sikament	0.60	—	7.3	6.5	5.9	334	0.013
S2	II A	Sikament	0.48	Plastimate	7.6	—	7.1	414	0.009
S3	II A	Sikament	0.44	122-R	7.3	5.8	6.6	418	0.010
S4	I B	Sikament	0.60	—	10.6	8.0	7.6	367	0.010
S5	I B	Sikament	0.84	Plastimate	8.5	6.0	8.0	509	0.006
S6	I B	Sikament	0.84	122-R	5.5	8.8	4.3	510	0.010
W1	II C	WRDA-19	0.62	—	8.1	—	8.4	448	0.007
R1	II A	Mighty RD2	0.41	—	8.0	—	6.9	401	0.009
F1	II A	FX 34	1.0	—	5.7	—	5.6	316	0.015

*Mix Procedure A-1
**Mix Procedure B

Table B-13 continued

Mix No.	Cement Type	HRWR Type	HRWR Dosage, S/S	Plastic Air, % Before Spec.	Plastic Air, % After Spec.	Total Voids, %	Specific Surface	$\bar{L}$, in.
w/c = 0.38								
M10	II A	Mighty 150	0.29	6.4	5.1	6.0	538	0.008
L10	II A	Melment	0.30	6.5	5.8	5.5	498	0.010
L11	II C	Melment	0.58**	6.9	—	6.5	739	0.004
L12	II C	Melment	0.58	3.6	—	4.5	265	0.025
W10	II C	WRDA-19	0.36	8.8	—	8.3	446	0.008
W11	I B	WRDA-19	0.36	5.1	—	6.3	389	0.011
R10	II A	Mighty RD2	0.27	8.1	—	8.8	349	0.009
F10	II A	FX 34 Powder	0.80	6.7	—	6.9	483	0.008
S10	II C	Sikament	0.36*	6.2	—	5.9	398	0.011
w/c = 0.43								
M20	II A	Mighty 150	0.21	7.0	6.1	5.7	519	0.009
L20	II A	Melment	0.22	7.2	5.4	6.6	463	0.010
W20	II C	WRDA-19	0.20	6.0	—	6.8	440	0.010
W21	I B	WRDA-19	0.20	5.9	—	6.0	468	0.010
S20	II C	Sikament	0.20*	5.5	—	4.5	590	0.009

*Mix Procedure A-1
**Mix Procedure B

Table B-14

Air Void Characteristics of Control Concretes

Mix No.	Cement Type	Type D Water Reducer	Plastic Air, % Before Spec.	Plastic Air, % After Spec.	Total Voids, %	Specific Surface	$\bar{L}$, in.
C1	II A	—	6.7	5.9	5.5	643	0.007
C2	II C	—	6.1	—	6.0	663	0.007
C3	II A	Plastimate	6.4	—	5.7	670	0.007
C4	II A	122-R	7.0	—	6.5	625	0.007

Another reasonable way to evaluate the data in Figure B-11 is to ignore the extreme data points, which represent 15% of the data, and to consider only those that are concentrated in the vicinity of the curve of best fit, as indicated by the dashed area in Figure B-11. This evaluation leads to the conclusion that it is reasonable to expect acceptable durability when $\bar{L}$ is less than 0.0115 in. and it is reasonable to expect unacceptable durability when $\bar{L}$ is greater than 0.0153 in.

In an effort to determine if some other property of HWRW concrete might correlate with DF better than $\bar{L}$, regressions were made of the data representing the relationship between DF and the air content of the plastic concrete, the void content of the hardened concrete, specific surface, dosage of HRWR admixture, w/c, 60-day absorption, and slump. A correlation coefficient of 0.62 was found for the relationship between DF and the air content based on data from 86 batches. This correlation is slightly better than the one between DF and $\bar{L}$. A correlation coefficient of 0.39 was found for the relationship between DF and total voids, and virtually no correlation was found for the relationships between DF and the other variables.

A plot of the relationship between DF and the air content is shown in Figure B-12. It can be seen from Figure B-12 that, on the average, a DF of 60% can be achieved with an air content of 6.2%. Individual correlations were made using the data for each of the six HWRW admixtures, and there were no significant differences in the results. If one ignores the linear regression and considers only the data points, it is reasonably safe to conclude

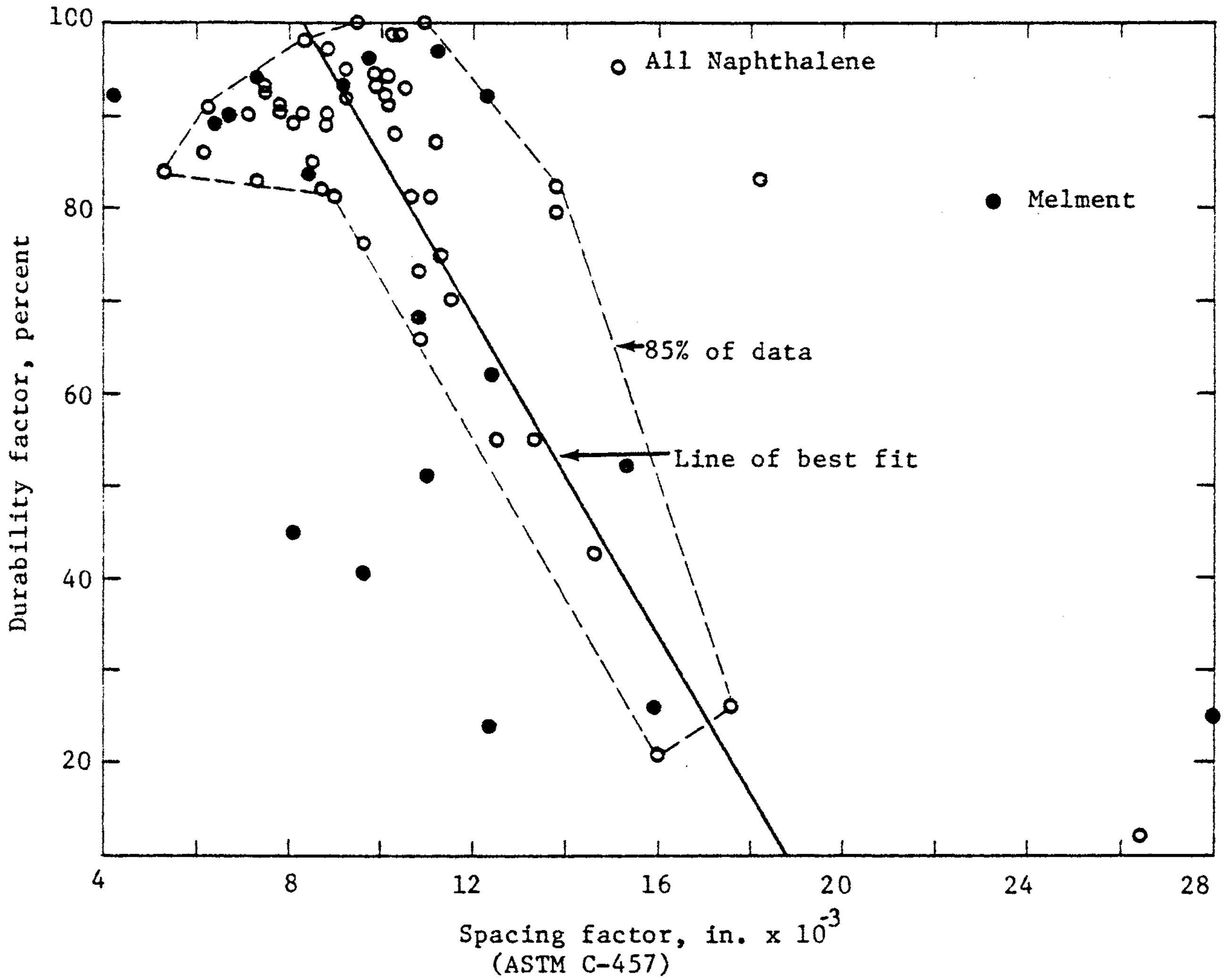


Figure B-11. Relationship between durability factor and spacing factor for HRWR concrete.

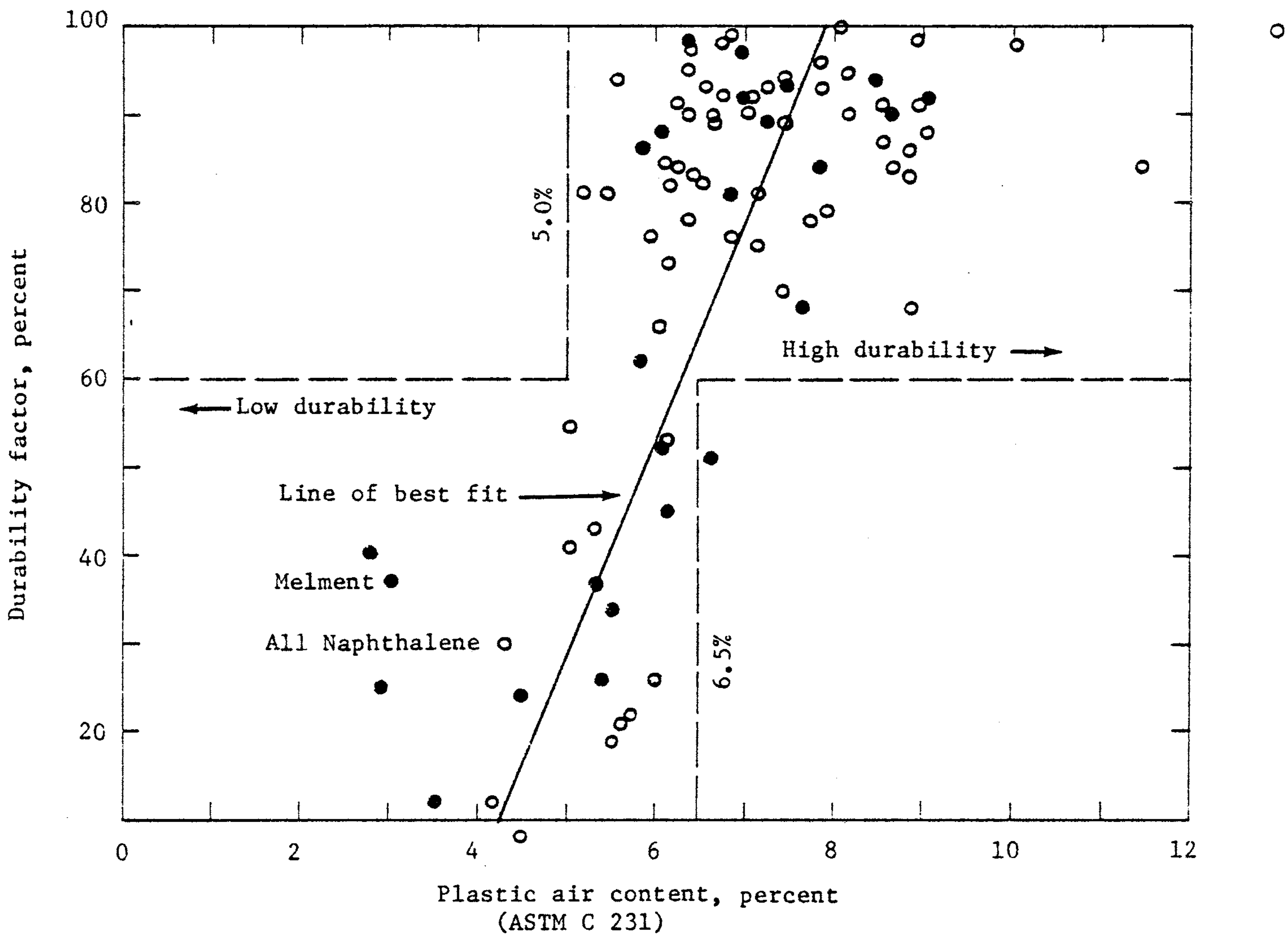


Figure B-12. Relationship between durability factor and plastic air content.

that satisfactory freeze-thaw durability can be achieved when the air content exceeds 6.5%, and that unacceptable durability can be expected when the air content is less than 5.0%. Typical bridge deck concretes that do not contain an HRWR admixture can pass the freeze-thaw test when the air content exceeds 4.5%. Evidently, more air is required in the HRWR concrete because the voids are much larger on the average and therefore less effective in providing protection against frost. For HRWR concrete the transition between unacceptable and acceptable freeze-thaw performance occurs when the air content is between 5% and 6.5%.

A linear regression of the relationship between DF and total voids (Figure B-13) indicated that, on the average, a DF of 60% could be achieved with a total void content of 5.8%. The 95% conficence band was about the same width as the band for the relationship between DF and air content. The 5.8% total void content is 0.4% lower than the 6.2% average air content of plastic concrete required to achieve a DF of 60%. It is believed that the void content is lower because the air content measurement was usually made at least 10 minutes before the petrographic specimens were fabricated and during this time the concrete lost some air. Also, the petrographic specimens had a larger surface area to volume ratio than the sample used for the pressure test, so there was a chance for a greater loss of air from the petrographic specimens than from the samples tested for air content. As was shown in Tables B-4 and B-5, typically measurements of the air content of plastic concrete made after the specimens were prepared indicated an air content that was less than the total void content.

If one ignores the linear regression and considers only the data points, it is reasonably safe to conclude that acceptable durability will be achieved when the total void content exceeds 6.0%. Separate regressions were made with the data for each of the six HRWR admixtures and the results were similar to those shown in Figure B-13. The relationships between DF and total void content are valid only when the consolidation is equivalent to that achieved in the laboratory.

Since it is obvious that for the same air content HRWR concrete typically exhibits a specific surface lower than that of the control concrete and a higher $\bar{L}$, an effort was made to find correlations between the specific surface and other properties of the concrete and the spacing factor and other properties.

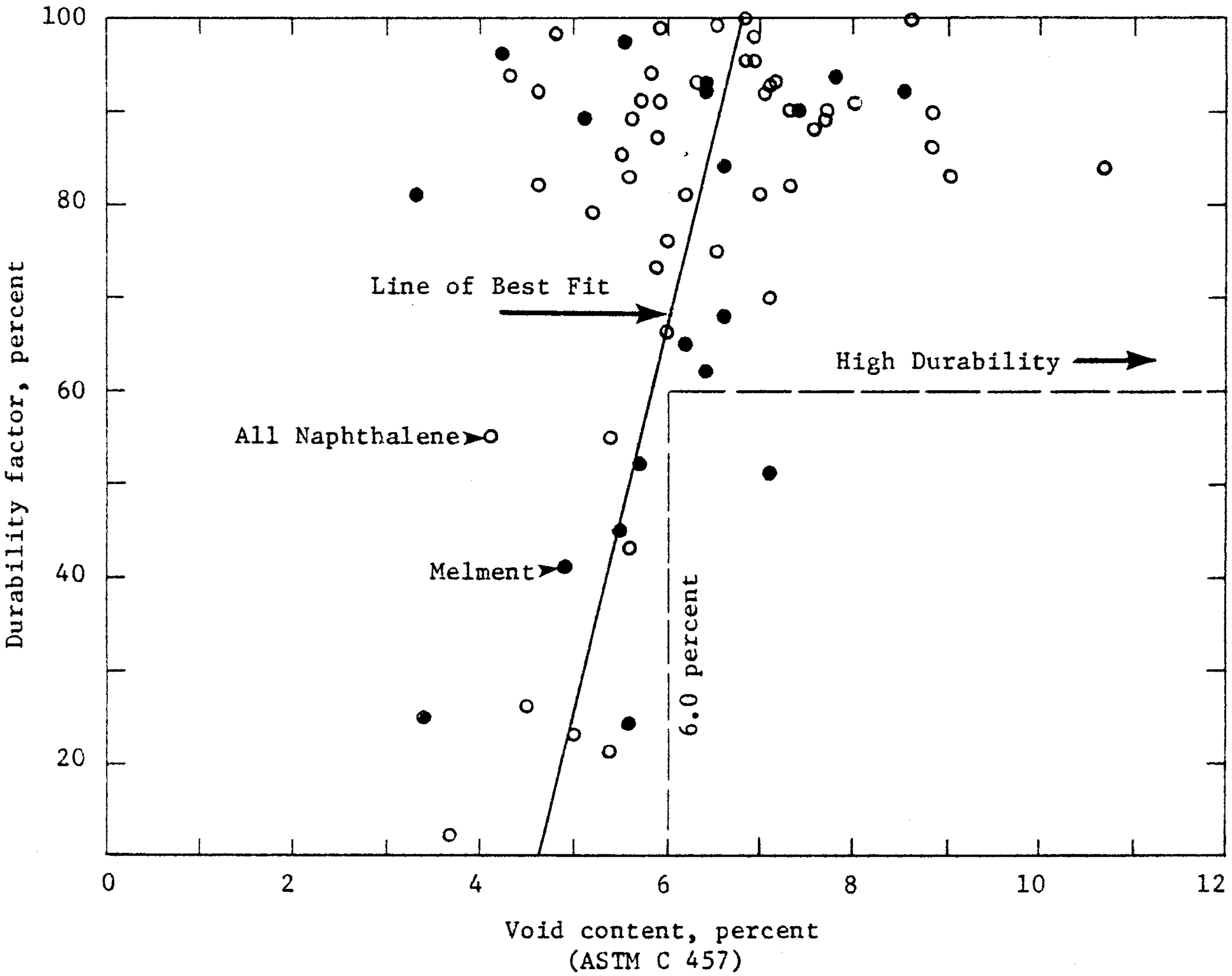


Figure B-13. Relationship between durability factor and void content.

No correlation was found between slump and the spacing factor and slump and specific surface. A very poor correlation was found between amount of HRWR admixture and the spacing factor, with a tendency for the spacing factor to increase as the dosage of HRWR admixture was increased. A better correlation was found between the specific surface and dosage of HRWR admixture, with a tendency for the specific surface to decrease as the dosage of HRWR admixture was increased. The correlation coefficient was low, only -0.19 , when a regression was made of the data for the 73 batches prepared with all three cements. However, when a regression was made of the data for the 54 batches prepared with cement IIA, the correlation coefficient increased to -0.56.

Although virtually no correlation was found between the spacing factor and w/c, even though there was a tendency for the spacing factor to increase as the w/c was decreased, it was encouraging to find a correlation coefficient of 0.50 for the relationship between w/c and the specific surface for the 73 batches prepared with all three cements. The correlation coefficient increased to 0.63 when a regression was made on the data from the 54 batches prepared with cement IIA.

Two pairs of curves are shown in Figure B-14. One shows the relationship between the specific surface and w/c for both control and HRWR concretes prepared with cement IIA as compared to just the HRWR concretes. The other pair shows the relationship between the specific surface and w/c for concretes prepared with cement IIC as compared to the relationship obtained when Sikament was added to these concretes. In both cases the presence of the HRWR admixtures caused the curves to rotate clockwise, verifying that the specific surface decreases both because of a decrease in w/c and because of the presence of an HRWR admixture. Therefore, it can be concluded that the low values for specific surface typically found for HRWR concrete are caused by the low w/c and the presence of the HRWR admixture. Based on the curve of best fit for the 54 data points for cement IIA shown in Figure B-14, specific surfaces of 618 and 388 respectively, can be expected for w/c = 0.43 and 0.34. Also, on the average, to obtain specific surfaces in excess of 600 requires a w/c in excess of 0.42.

It is believed that the relationship between w/c and the specific surface shown in Figure B-14 explains why the concrete used by the Virginia Department of Highways and Transportation, which typically has a w/c between 0.43 and 0.49, typically has a specific surface in the neighborhood of 600 to 800 rather than 1,000 or more as reported by Mielenz in 1958 as being typical.(B-2)

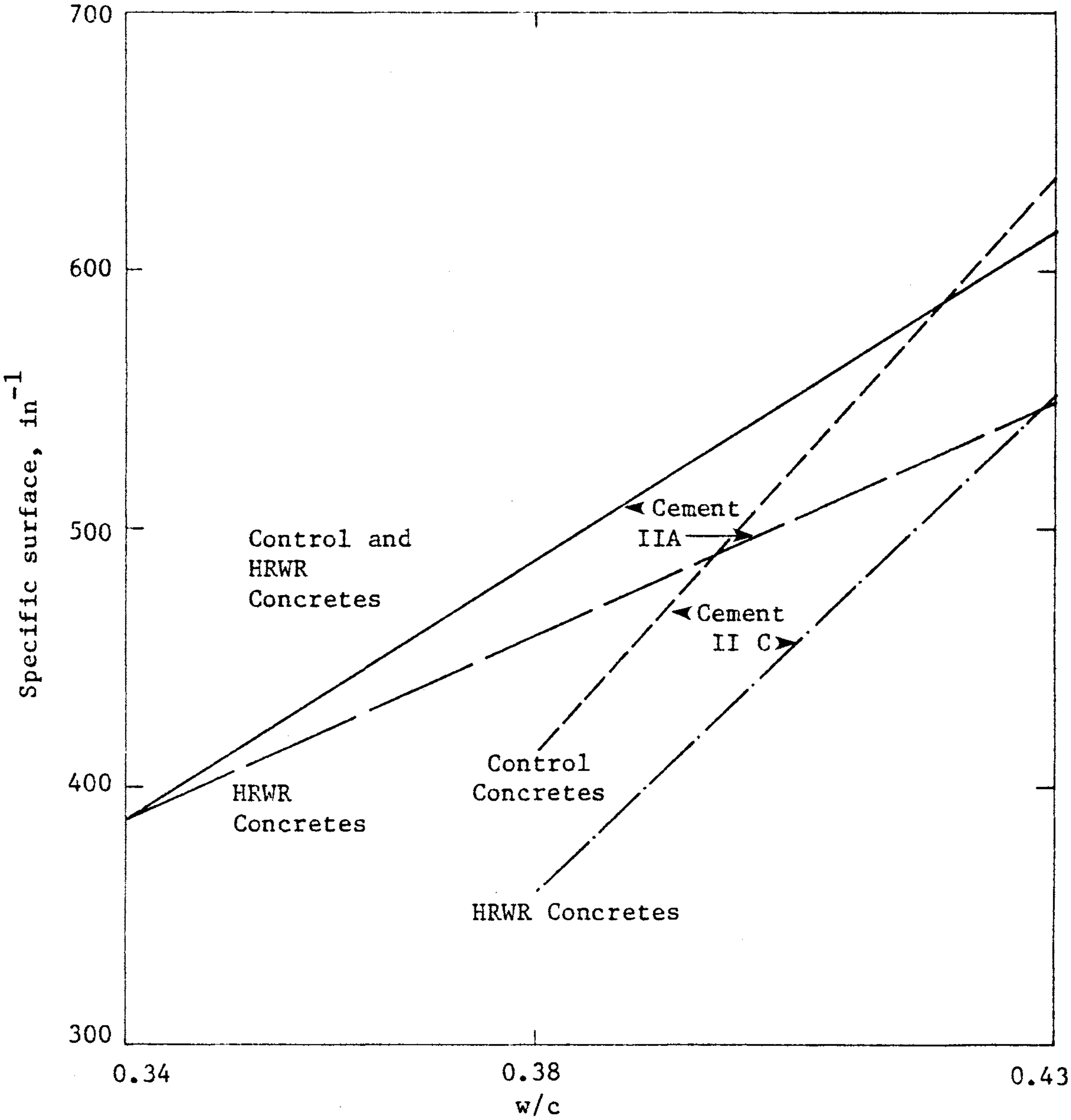


Figure B-14. Relationship between specific surface and w/c.

REFERENCES — APPENDIX B

B-1. Whiting, David, "Effects of High-Range Water Reducers on Some Properties of Fresh and Hardened Concretes," Portland Cement Association, 1979, p. 8.

B-2. Mielenz, Richard C. et al., "The Air Void System in Job Concrete," _Journal of the American Concrete Institute_, October 1958.