

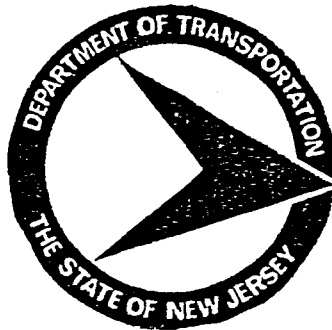
PREMATURE DETERIORATION
OF
WHITE CONCRETE CURB

FINAL REPORT

APRIL 1981

BY

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New Jersey Department of Transportation
Task Force on Concrete Durability

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16. Abstract <p>White concrete curbing constructed on a number of recent Department projects has displayed a significant lack of freeze-thaw resistance. Both cast-in-place and pre-cast curbing have manifested distress in the form of severe surface scaling and occasional cracking, flaking, and popouts within several years of opening to traffic. This report presents the results of a study undertaken to determine the causes of the curb durability problem and the nature of any needed improvements in Department specifications and related construction/inspection procedures.</p> <p>The primary focus of this study was on cast-in-place concrete. Three Department projects containing several miles of deteriorated C-I-P curbing were investigated. The results of curb condition surveys and laboratory tests performed on the hardened concrete indicate that the primary cause for the lack of curb durability was an inadequate air void system. This was evidenced by a generally low level of total air, as well as, deficiencies in bubble size and distribution as indicated by the specific surface of the air voids and the void spacing factor. It appears that this situation was occasionally aggravated by use of high water/cement ratio concrete and/or poor curing practices. Within particular projects, curb performance was observed to differ markedly with exposure conditions.</p> <p>The lack of durability exhibited on two precast curb projects was variously attributed to inadequate air content and premature exposure to an adverse environment. Recommended specification changes, training needs, and measures for restoration of the deteriorated curb are presented.</p>					
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CONCLUSIONS

1. The fundamental cause of the premature scaling of the cast-in-place concrete curbing on the studied projects was insufficient total air content.

The specified air content on the projects differed, being 3 to 6% on one project and $6 \pm 1\frac{1}{2}\%$ on two more recent jobs. Linear traverse analysis indicated that on an overall basis, total air content of the curb averaged only 3.4%. On the project having a specified air content of 3-6%, the average observed value for the hardened concrete was 3.8%. On the other two projects, the air level of test samples averaged below the specified minimum (3.6 and 1.5% versus 4.5%).

This situation of generally marginal-to-poor total air content was rendered even more critical by the fact that an average of nearly half of the measured total air volume consisted of large, entrapped (vs. entrained) air voids which are of dubious value in protecting against frost action.

As a consequence of the low air content and high ratio of entrapped to entrained air, the quality of the air void system in the tested concretes compared unfavorably with established criteria in the literature. The two important indicator parameters specific surface, α , and void spacing factor, \bar{L} , -- respectively averaged $408 \text{ in}^2/\text{in}^3$ and 0.0266 inches. These are extremely poor values when compared to the minimum α of $600 \text{ in}^2/\text{in}^3$ and the maximum \bar{L} of 0.008 inches generally considered necessary for frost resistant concrete.

2. The following factors further detracted from the frost-resistance of the studied concrete:

- a. The apparent occasional use of high water/cement ratio concrete and/or poor curing techniques, as evidenced by:
 - . the compressive strength of core samples from one project being significantly lower than that of project cylinders representing corresponding curb locations;
 - . the unusual, granular appearance of the cement paste in several test cores; and
 - . the extensive shrinkage cracking observed in curb surfaces.
- b. The distressed curb possessed a slightly higher capacity for absorbing water than similarly tested sound concretes. Given the inherently low frost resistance of the studied concretes (i.e., poor air void systems), these somewhat higher absorption levels might well have been critical in triggering distress.

3. The severity and extent of surface distress displayed by the white barrier curb on one studied project was markedly influenced by exposure conditions. That is, while tests performed on cores obtained from opposite curb faces at the same location indicated virtually identical (marginal-to-poor) air void systems, the performance of the concrete was distinctly different: deterioration was exclusively

confined to the north curb face, with almost the entire length of curb being affected. This differential performance is attributed to the fact that the shaded (north) curb face would not be expected to receive the beneficial heating and drying effects of the sun to the same degree as the south face. Thus, the former might retain more freezable water and/or be subjected to freezing cycles of longer duration. Similar, but less pronounced, differences in durability between curb faces were also observed on another study project.

4. Construction records for the studied projects often lacked proper documentation of curb construction operations. This deficient documentation could simply reflect poor reporting practices, or inadequate construction and testing procedures, or both.

Observations from ongoing projects indicate that curb is occasionally constructed with concrete not complying with specified requirements (e.g., slump or air content) and/or inadequate curing procedures.

5. On two study projects, the severity of the scaling condition at certain locations has greatly reduced the appearance and reflective properties of the barrier curb, thereby significantly diminishing its effectiveness as a traffic delineator.

6. The detrimental effect of early exposure of concrete to freeze-thaw cycles and de-icers is well known. The Portland Cement Association and others have suggested that permitting the concrete to air dry for a 30 day period prior to being subjected to an adverse environment will enhance durability. Since some of the deteriorated

cast-in-place and precast barrier curbing evaluated in this study was placed/manufactured during the fall and winter seasons, it would appear that adherence to such a provision would be beneficial.

7. Apart from performance, the barrier curb on a number of recent Department projects has required extensive finishing work to repair voids or pockets immediately after form stripping to achieve an acceptable surface. Several days experimentation on an ongoing project using concrete designed in accordance with ACI criteria failed to produce an improvement in the finish of the as-constructed curb. That is, use of a relatively sandy mix compared to the Department's did not eliminate the problem.

RECOMMENDATIONS

A. Specifications: Based on the recognized field problems in achieving an adequate level of air in curb concretes, as well as the initial findings of this study, the Department has recently implemented a change in specification provisions intended to improve curb durability. The amount of entrained air specified for white concrete has been increased from $6 \pm 1\frac{1}{2}$ to $7 \pm 2\%$. The Committee supports this change and recommends that a strong effort be made to comply with this requirement in the field.

It is recommended that Department specifications governing the construction of white concrete curb be further modified by the addition of the following requirements:

- . Curing Procedures - When final finishing work delays the application of white pigmented curing compound, the concrete shall be covered with wet burlap immediately upon form removal. The concrete curb shall remain covered with wet burlap until such time that its removal is necessary to permit final finishing to an even, smooth, and dense surface. Finishing shall be immediately followed by the application of white pigmented curing compound. At no time shall more curb be exposed to the atmosphere than necessary to accomplish the required finishing work.
- . Drying Time - Construction of concrete curb shall not be permitted between October 1 and February 28 except with the

approval of the Engineer. Such approval will not be routinely granted. The Contractor shall schedule curb construction operations in accordance with this provision.

B. Training: It is recommended that Department inspection forces receive training (or retraining) as to the need for the various specification provisions governing concreting operations, the importance of good concrete construction and control testing procedures and their ultimate influence on concrete quality.

C. Quality Awareness: The success of the recommended training effort would unquestionably be enhanced if a quality conscious atmosphere is established at the outset of instruction. As a first step toward accomplishing this, it is recommended that a high level administrator reaffirm the Department's commitment to achieving quality concrete on our projects. In line with this, an expressed appreciation for the tedious nature of concrete inspection should have a salutary effect on the morale of field personnel. Finally, inspection forces assigned to concreting operations should have a clear understanding as to the action Central Headquarters expects when non-compliance with specifications is encountered and assurance that such action will be supported by every level of supervision.

D. Evaluation of Air Void System: To provide a good verification mechanism to support field measurements of air content levels in plastic curb concrete, the central laboratory should begin compiling data necessary to evaluate the air void system in such concretes. This

can be accomplished by modifying the requirements of the proposed statistically based concrete strength specifications to include two additional cylinders for verification testing by the Department.

The additional specimens should be subjected to linear traverse analysis to determine the various characteristics of the air void system in curb concretes proposed for use. Core specimens (two) should also be obtained from curb constructed on Department projects representing each supplier of white concrete for similar testing.

To assist the evaluation process certain information relative to each test specimen should also be compiled. That is, the central laboratory should obtain a copy of the mix design including aggregate gradations, bulk specific gravities and loose unit weights, the particular air-entraining admixture (brand name) used and the quantity added, as well as, the slump and air content of the plastic mix.

The estimated annual cost of such a testing program is approximately \$11,000. This is only about one-half the anticipated cost for repairing a mile of deteriorated barrier curb with some type special surface coating.

The lab should acquire the capability (through the purchase of additional equipment or the modification of the existing apparatus) to perform linear traverse tests in complete accord with ASTM C457. The present equipment is somewhat limited in that it does not permit measurement of the smaller entrained air bubbles (i.e., their chord intercepts) necessary to precisely determine the distribution of

void sizes. Such data could prove most useful in those instances when a more comprehensive evaluation of air void system quality is warranted.

Based on the results of this study and literature reports, the minimum criteria for an effective air void system is an air content within specified limits (e.g., $7 \pm 2\%$ for curb concrete), specific surface area of air voids of at least $600 \text{ in}^2/\text{in}^3$, and a uniform distribution of air bubbles characterized by a void spacing factor equal to or less than 0.008 inches.

E. Restoration of Deteriorated Curb: It is recommended that the Department repair the surface of the barrier curb on two studied projects in an effort to arrest further deterioration and to restore adequate reflectance. The Department's Materials Committee should be consulted for guidance in the selection of a promising material for this purpose. One such material ("Thoroseal"), applied to a severely scaled barrier curb member in 1979 and currently under evaluation, has performed satisfactorily through one winter. At that time the estimated cost for applying two coats of this material to one mile of our standard barrier curb ranged from \$13,000 to \$21,000. The total quantity of curb on the involved projects is about three miles. Thus, the anticipated total costs for the indicated surface treatment are expected to exceed \$60,000. One possible means of reducing the latter expenditure is to select only the most severely scaled curb areas on these projects for repair. Should the Department decide to perform this curb repair work, the manufacturer of the coating material selected should be requested to provide more current cost data.

PART ONE: INTRODUCTION

1.1 OBJECTIVES

The basic objectives of this study were to determine the cause(s) of the unsatisfactory durability performance of certain recently constructed white concrete curb and the nature of any needed improvements in specifications and related construction/inspection procedures.

1.2 BACKGROUND

White portland cement concrete curbing on a number of Department projects constructed within about the last nine years has exhibited unsatisfactory freeze-thaw resistance. Projects have displayed premature distress in the form of severe scaling, cracking (or crazing), flaking, and pop-outs within relatively short periods after construction.

Scaling and allied forms of surface deterioration obviously pose a particularly acute problem in the case of white curb. As the deterioration process continues, the larger aggregate particles -- often dark-colored broken stone -- become exposed and make the curb increasingly unsightly. More importantly, such deterioration can result in rapid losses in the curb's reflectivity, thereby significantly diminishing its effectiveness as a traffic delineator. Simply, this progressive deterioration defeats the Department's design objective in specifying (premium priced) white rather than grey concrete for curbing. Another obviously important factor in this regard is the burden of re-construction or repair costs. Depending on the severity of the surface distress and traffic conditions, the Department may have to fund some type of rehabilitation measure to

prevent continued deterioration and/or improve the curb's reflectivity.

In 1977, the Department was confronted with several particularly pronounced cases of poor curb durability. On one precast job, for example, the curb displayed severe surface crazing and scaling within weeks of installation. Premature curb deterioration thus became a major topic of discussion and concern within the Department. Consequently, at the request of the Chief Engineer of Construction and Maintenance, the Department formed a committee to investigate the problem.

While premature freeze-thaw distress has been observed on both precast and cast-in-place New Jersey curbing, the committee elected to make only a minor evaluation of precast curb, due to the relatively small quantity of such curbing exhibiting distress and the Department's recent elimination of certain questionable equipment and curing practices employed in precasting. The thrust of this report is thus directed almost exclusively at cast-in-place construction.

The findings of an investigation of precast curb conducted by staff of the Bureau of Plant and Project Inspection are summarized in a report presented as Appendix A. Basically, the appended report indicates that the poor durability performance of precast members on one project -- fabricated on outside casting beds during mid-winter -- resulted from super-heating of steel forms and thus the near surface concrete, outdoor storage of these units in sub-freezing conditions, and premature exposure to de-icers. On another project, the durability problem was ascribed to the woefully inadequate air content (about 0.5%) of the hardened concrete.

It should be mentioned that the Department has experienced problems with white concrete curb durability in the past. In fact, at least one other Department task group was organized in 1971 to investigate premature deterioration of white portland cement concrete curbing. In summary fashion, that task group recommended⁽¹⁾ improvements in the Department's level of control relative to materials and curb construction procedures, as well as, increases in the curb concrete sampling and testing rate, and the specified air content level.

1.3 METHOD OF STUDY

Five completed construction projects having severely and/or extensive distressed curb were selected for investigation. These consisted of four barrier curb projects -- two constructed by cast-in-place methods and two precast installations -- and one vertical curb contract. The two cast-in-place barrier curb projects were subjected to in-depth study due to the quantity of curb involved and the pronounced severity and extent of the surface distress.

Since numerous factors can influence the scaling resistance of concrete, an effort was made to develop a plan of study that would address at least the most fundamental of these factors. The degree to which the plan was applied to each curb project varied since in some cases it was either not possible (e.g., curb had received some type restorative coating) or not believed necessary to apply the complete plan. In addition to a literature survey on the subject of concrete durability, the basic program adopted for this study included the following:

1.3.1 Curb Condition Survey: A condition survey was made of the curbing on selected projects using an objective rating system developed by the committee. The rating system which takes into account both the relative severity and extent of distress is detailed in Appendix B.

This rating procedure entailed visual examination of the curb being investigated by at least two individuals who served as "raters". The system was applied in a three step procedure: first, the raters partitioned the curb into areas based on severity of scaling, next they estimated the percentage (to the nearest 5%) of curb face affected in that area and finally, the length of the given area was measured. Since it was necessary to obtain a single condition rating for each area, the raters reached a consensus on all rating items prior to recordation (i.e., agreed on the limits, severity of scaling, and percent of curb face affected).

1.3.2 Project Records: Curb records were reviewed to determine construction dates and limits of placement, construction methods employed (e.g., placement, consolidation, curing procedures, etc.), weather information, and the results of quality control tests such as concrete slumps, air contents and compressive strengths.

1.3.3 Sample Locations: Results of the condition survey were keyed to the information contained in the project records to locate two similarly constructed sections of curb, one with little or no distress and another with severe scaling. Samples of the hardened concrete were then acquired from each of the areas of contrasting performance and subjected to laboratory tests.

1.3.4 Testing Program: Curb specimens, obtained from projects under study, were subjected to numerous conventional concrete quality tests.

The test procedures yielding data focused on in subsequent report sections are as follows:

- a. Compressive Strength - AASHTO T-24, "Standard Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete".
- b. Air Content - Modified ASTM C457, "Recommended Practice for Microscopic Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete". The procedure used was the same as that employed by the Pennsylvania D.O.T. (PTM 623); a copy of which is presented in Appendix C. In addition to measuring the air content of the total core, some specimens were subjected to a special test procedure to gain additional information about the air level and other important parameters of the bubble system at the surface of the concrete and at depths of 1/2, 1, 2 and 3 inches therefrom.
- c. Chloride Content - The level of chlorides at various depths from the concrete curb surface was determined from drilled powder type samples. These samples were tested in accordance with the procedure reported by H. A. Berman "Determination of Chloride in Hardened Portland Cement Paste, Mortar, and Concrete", Journal of Materials, JMLSA, Vol. 7, No. 3, September 1972, pp. 330-335.
- d. Absorption - Modified ASTM C642, "Specific Gravity, Absorption, and Voids in Hardened Concrete". The principle purpose of performing this test was to determine if concretes displaying differing durability levels also varied in their capacity for absorbing water.

1.3.5 Active Curb Projects: During the course of this study, committee members visited a number of active projects to observe concrete curb construction. Basically, this was done to determine the general adequacy of current quality control procedures employed in the field with regard to construction practices and sampling and testing methods.

PART TWO: FINDINGS AND ANALYSIS

2.1 CONDITION SURVEYS

The appearance of the curb on three study projects is shown in Figures 1, 2, and 3. The full length of the barrier curb on two large projects (shown in Figures 1 and 2) was evaluated in accordance with the rating system developed by the Committee.* The results of that effort are presented in the following two report sections.

2.1.1 Project A: Records indicated that the construction of approximately two miles of barrier curb on this project was performed by cast-in-place methods in the fall of 1972 and the spring and summer of 1973.

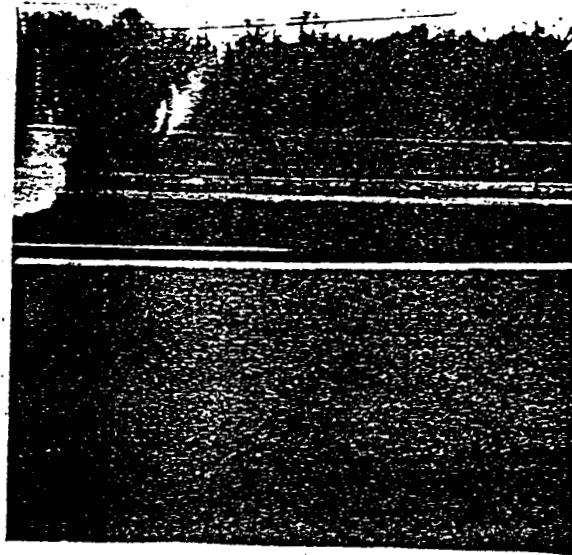
Table 1 shows the total length and overall percentage of each curb face displaying scaling of a given severity. As indicated, both sides of the project curbing displayed at least some distress; 63 and 82%, respectively for the southeast and northwest curb faces. The deterioration exhibited by the northwest curb face is considerably more severe than observed for the southwest face. Specifically, more than half of the northwest face was severely scaled, compared to only 15% for the southwest face.

Figure 4 shows the extent of scaling within each category -- that is, the total amount of curb surface affected with a given degree of distress. This data presentation further underscores the relatively greater extent of distress for the northwest curb. Where severe scaling occurred (i.e., condition 3), on the northwest curb face it covered more than twice the area of the similarly distressed curb on the southwest face.

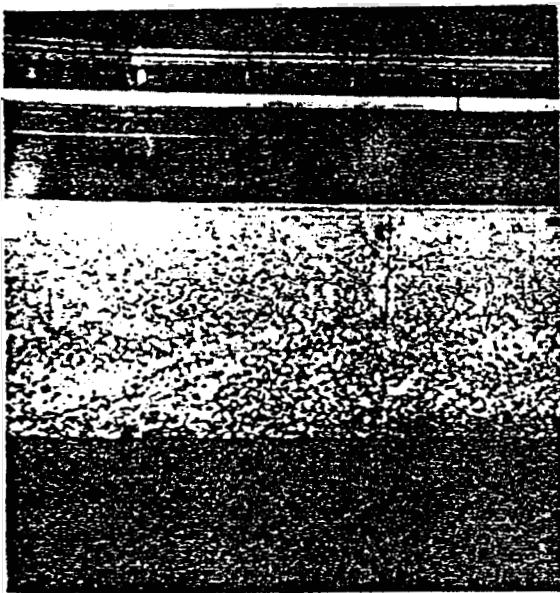
*Application of some type remedial surface repairs precluded making an accurate assessment of the surface condition on the remaining projects.

FIGURE 1. WHITE CONCRETE BARRIER CURB

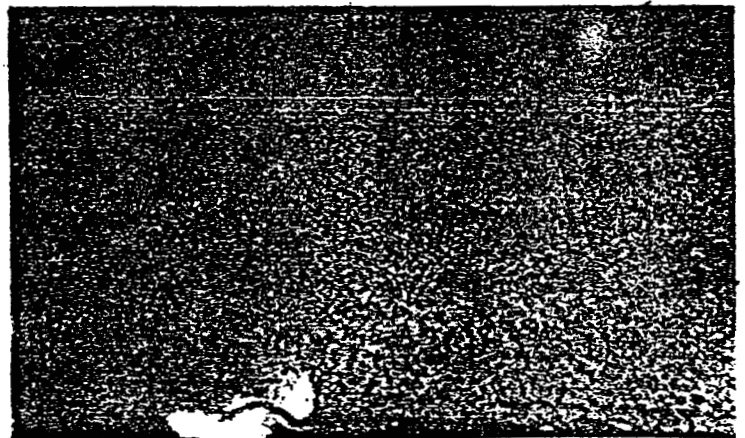
Approximately 5 years after construction (Project A)



1A. Unscaled (southeast) curb face.



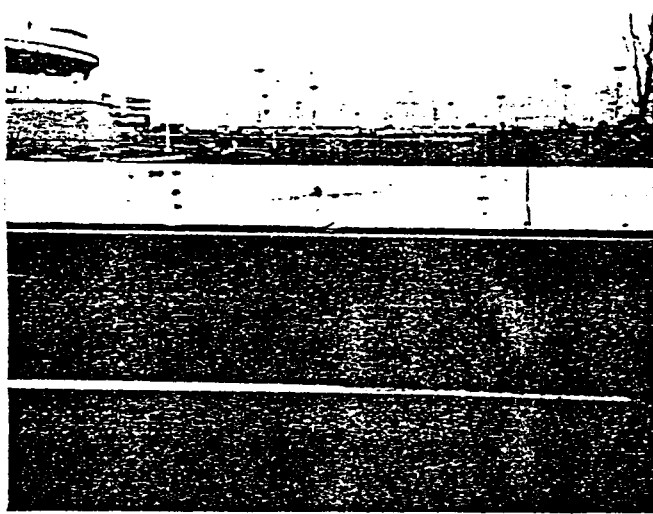
1B. Scaled (northwest) curb face.



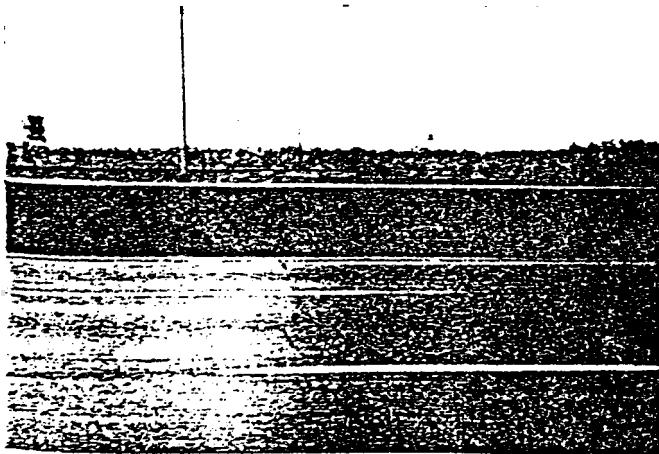
1C. Close-up of scaled (northwest) curb face.

FIGURE 2. WHITE CONCRETE BARRIER CURB

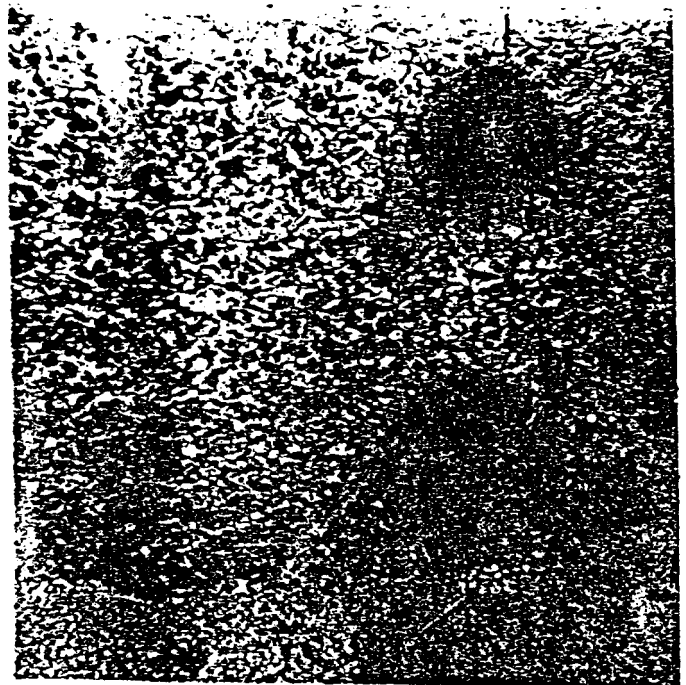
Approximately 7 years after construction (Project B)



2A. Unscaled (south) curb face.



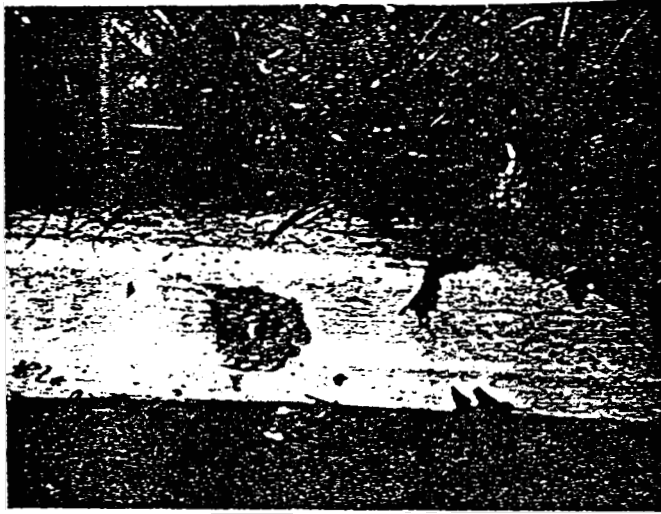
2B. Scaled (north) curb face.



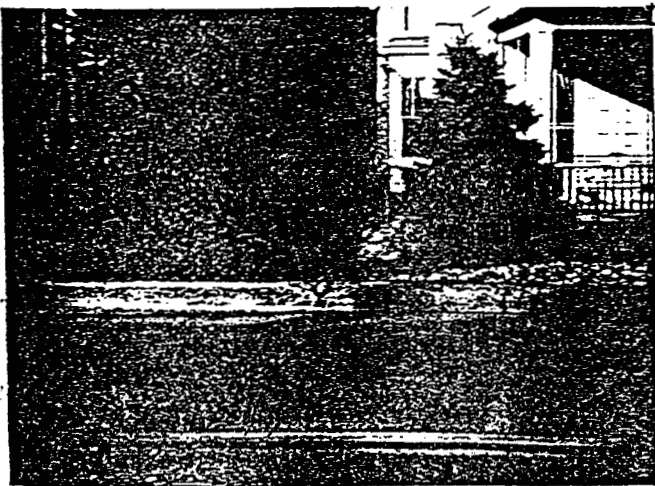
2C. Close-up of scaled (north) curb

FIGURE 3. WHITE CONCRETE VERTICAL CURB

Approximately 4 years after construction (Project C)



3A. Close-up of unscaled curb.



3B. Scaled curb.



TABLE 1: BARRIER CURB CONDITION SURVEY (PROJECT A)

Northbound Roadway
Southeast Curb Face

<u>Condition Rating</u> <u>Scaling Severity</u>	<u>Length</u> <u>(ft.)</u>	<u>Percent of Total</u> <u>Surveyed Length</u>	
0 (none)	3,479	37	
1 (slight)	1,616	17	} 63%
2 (moderate)	2,944	31	
3 (severe)	1,452	15	

Total Length Surveyed = 9,491 ft.

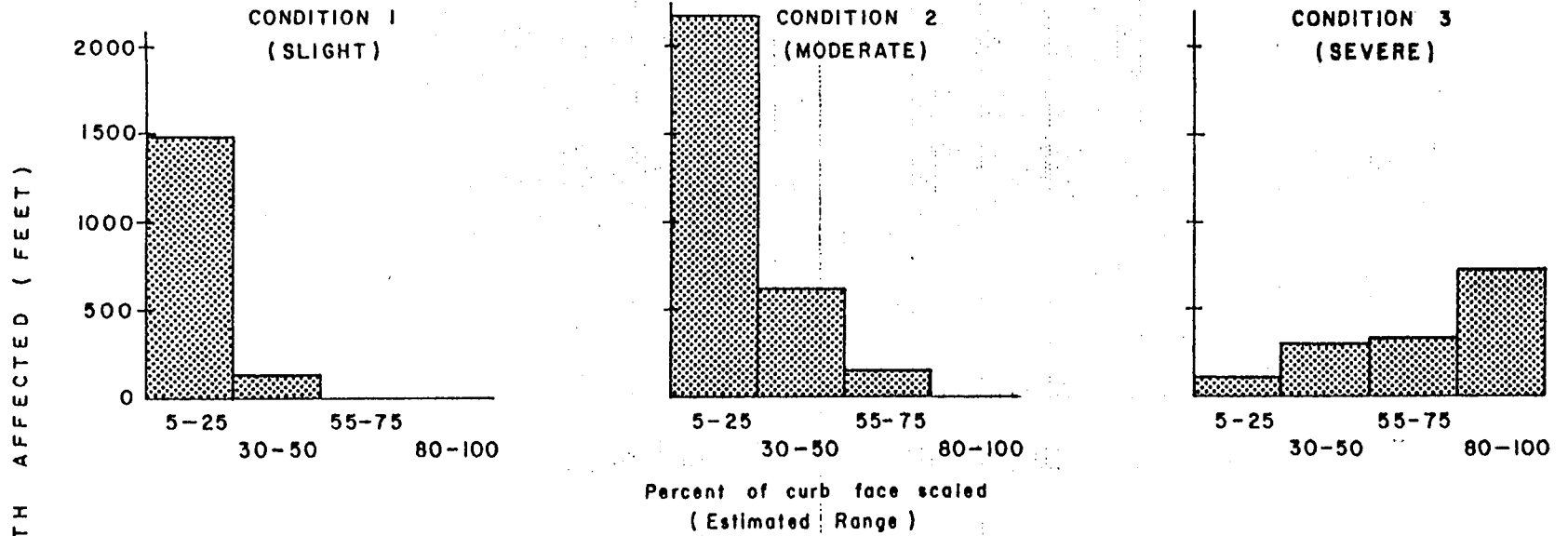
Southbound Roadway
Northwest Curb Face

<u>Condition Rating</u> <u>Scaling Severity</u>	<u>Length</u> <u>(ft.)</u>	<u>Percent of Total</u> <u>Surveyed Length</u>	
0 (none)	1,755	18	
1 (slight)	820	9	} 82%
2 (moderate)	2,038	22	
3 (severe)	4,878	51	

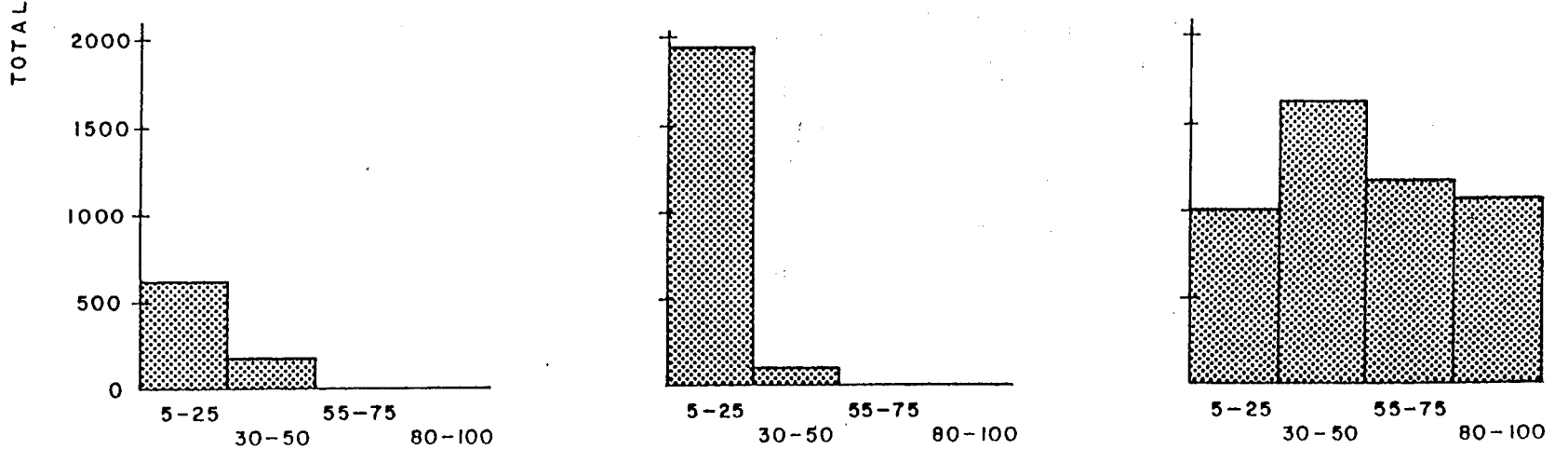
Total Length Surveyed = 9,491 ft.

Figure 4. PERCENTAGE OF CURB FACE AFFECTED BY VARIOUS DEGREES OF SCALING (PROJECT A).

NORTHBOUND ROADWAY (SOUTH EAST CURB FACE)



SOUTHBOUND ROADWAY (NORTH WEST CURB FACE)



2.1.2 Project B: Records show that about one mile of barrier curb was constructed on this project in the spring and summer of 1971, also by cast-in-place methods.

As indicated in Table 2, 95% or essentially the entire 5,100 feet of north curb face exhibited some degree of scaling with the largest amount (45%) being in the moderate category (see Figure 5). In marked contrast, the raters indicated no significant deterioration for the south curb face.

In summary, the barrier curb on both projects exhibited a good deal of surface distress. The data from these two projects strongly suggests the orientation of the curb with respect to the sun may influence the degree of scaling. That is, in both cases the face of curb exposed to the most sun was in better condition than the shaded side. The effect of exposure conditions is discussed in more detail in a later report section.

2.2 PROJECT RECORDS

Construction records for the studied projects often lacked proper documentation of curb construction operations. That is, reports generally did not indicate one or more of the following: results of concrete slump and air tests (or notes indicating such tests were run by others) consolidation procedures, the times forms were stripped, the type, rate and time of applying curing material, etc. Whether this deficient documentation simply reflects poor reporting practices or inadequate construction and testing procedures or both is generally not known. However, on Project "B" the records indicated curb concrete was tested for air content on only one of some thirty

TABLE 2: BARRIER CURB CONDITION SURVEY (PROJECT B)

Westbound Roadway
North Curb Face

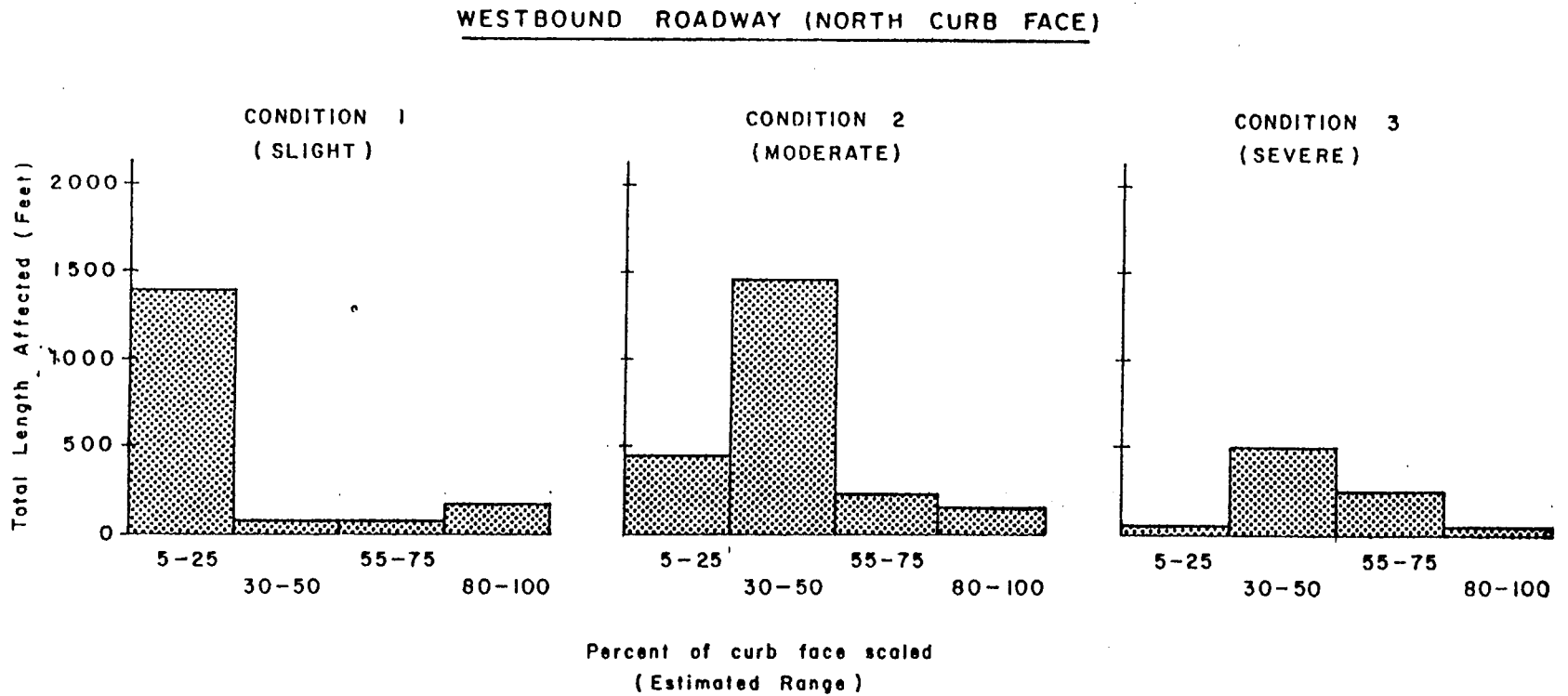
<u>Condition Rating</u> <u>Scaling Severity</u>	<u>Length</u> <u>(ft.)</u>	<u>Percent of Total</u> <u>Surveyed Length</u>	
0 (none)	274	5	
1 (slight)	1,661	33	} 95%
2 (moderate)	2,305	45	
3 (severe)	851	17	

Total Length Surveyed = 5,091 ft.

Eastbound Roadway
South Curb Face

(No significant deterioration noted)

Figure 5. PERCENTAGE OF CURB FACE AFFECTED BY VARIOUS DEGREES OF SCALING (PROJECT B).



construction days -- involving about one mile of our standard barrier curb -- and these (two) air tests were performed by the record sampling group rather than regularly assigned project personnel. It is recognized that this work was performed during an adverse period (budget restrictions imposed in early 1970s) in which there was a shortage of field personnel. Further, additional air tests would not in themselves guarantee durable concrete. Nonetheless, more frequent air tests may have revealed deficiencies in the air content level, thus affording field personnel the opportunity to take corrective action. The fact is, without such quality control test data, inspection personnel were severely handicapped since they had no means of assessing the concrete's potential freeze-thaw resistance.

2.3 EXAMINATION OF CORE SPECIMENS

Both visual and microscopic examination of core samples provided qualitative information about concrete quality. Some observations pertinent to studied specimens are presented in summary fashion as follows:

1. The amount of distress varied from hairline cracks (or crazing) indicative of rapid moisture loss resulting from inadequate curing to severe and extensive surface scaling. In at least one case, the surface mortar had completely scaled away.
2. Several cores displayed segregation and/or poor bond between the coarse aggregate and the mortar matrix. Some appeared to contain a disproportionately small amount of coarse aggregate.
3. The coarse and fine aggregate were free of cracks and fractures when examined microscopically.

4. The cement paste of severely scaled samples often had a chalky appearance suggesting extreme weathering and the possibility of a wet mix.

5. Several cores from the deteriorated concrete on Project A displayed a unique feature. Under magnification, the cement paste was seen to contain a voluminous number of extremely small spaces or voids which were termed micro-holes. The latter were rough and gritty without well defined perimeters as opposed to entrained air voids (see Figures 6, 7 and 8). Thus, the cement paste for these specimens can be characterized as being granular in appearance. Others² have indicated this condition may result from a variety of factors, including the poor curing of high water cement ratio paste.

2.4 TESTS OF HARDENED CONCRETE

2.4.1 Desired Air-Void System: The fundamental cause for the physical deterioration of concrete subjected to a freeze-thaw environment is the expansive forces developed during freezing of internal water. It is a universally accepted fact that when sound materials and proper mix design and construction practices are employed, an adequate amount (about 9 to 10% of the mortar phase) of purposely entrained air voids can protect concrete from such destructive forces. An equally important factor with regard to durability of the concrete -- although perhaps not so well recognized -- is the necessity that the air void system possess certain characteristics with regard to the size and distribution of the entrained air bubbles. The need for such an air void system to protect the paste is the subject of the following discussion.

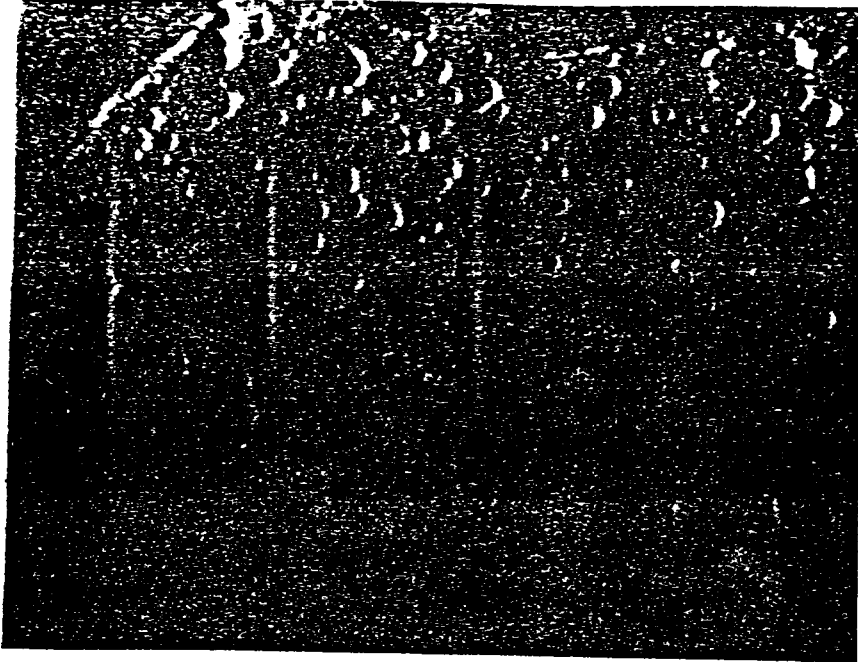


FIGURE 6. Magnified Photo (20x) of Concrete with about 6% Air Content.



FIGURE 7. Magnified Photo (20x) Illustrating Typical Differences in Size Between Entrapped (Center of Photo) and Entrained Air Voids.



FIGURE 8. Magnified Photo (20x) of Concrete
With Unusual Granular Texture.

A good deal of the knowledge on the mechanisms that cause damage during freezing is the result of investigative efforts by Powers^{3,4}, Helmuth⁵, Backstrom⁶, and others in studies conducted on hardened portland cement paste. Although no attempt will be made here to present a detailed account of these numerous and extensive studies, a synopsis of certain research bearing on the current work will be presented.

The overall objectives of the cited research was to study the behavior of water during freezing, the mechanisms causing damage, and the nature of the air bubble system needed to prevent the formation of destructive forces. The major findings from these and subsequent studies conducted on both laboratory and field concretes was that maximum protection from frost action is provided by an adequate volume of intentionally entrained air consisting of small discrete, closely-spaced air voids, uniformly distributed throughout the paste.

As a first step in understanding the need for an adequate system of air voids it is necessary to have at least a general appreciation of the pore structure in cement paste and the freezing process by which potentially damaging expansive pressures develop. As described by Powers and Helmuth³⁻⁵, hardened cement paste contains two types of submicroscopic space, classified as capillary and gel pores. Both vary in shape and size, the capillaries being considerably larger. During the hydration process "cement gel" is formed in a portion of the space originally occupied by mix water. The capillaries are that part of the previously water-filled space not containing hydration products. The capillary void system is randomly distributed and its volume is dependent on water cement

ratio. That is, the number and size of capillary cavities in the paste increases with water cement ratio.* The gel itself is porous, containing extremely small pores, with an estimated average diameter on the order of 18 angstrom units (about 0.0000007 inches). Although both types of pores are capable of containing water, the freezing of water in gel pores is essentially precluded for reasons related to their exceedingly small size.

With the onset of the freezing process, ice first begins to form in the larger capillary cavities of the paste, causing a volume increase. If these capillaries are full or nearly full of water,** the excess water tends to be expelled through the paste into the available intentionally entrained air voids. If the air voids (or other escape boundary) are sufficiently close to the capillaries, the pressure developed during expulsion of water will be maintained within safe limits; if not, permanent damage will occur. The development of expansion forces is further complicated by the occurrence of osmotic pressure. While an explanation of this additional factor is beyond the scope of this discussion, suffice it to say that because the water in gel and capillary pores contains differing concentrations of solutes (alkalis), additional stresses are super-imposed on the concrete. The purposely entrained air bubbles relieve both types of pressure by serving as a type of reservoir wherein displaced water can freeze without causing permanent damage to the concrete.

*Thus, concretes of high w/c ratio are generally capable of containing more freezable water than those with lower w/c ratio, and hence have a greater potential for distress.

**The water is usually in the form of a mild alkali solution.

Microscopic methods provide the means for evaluating the effectiveness of the air void system to protect the concrete. Application of one such technique, linear traverse, to hardened concrete specimens permits determination of the important characteristics of the air void system. These include the air content (A), the average number of voids per inch (n), the specific surface area of air voids (α), and the void spacing factor (\bar{L}) which is one-half the average distance between air bubbles. Based on the literature, an air void system is considered adequate when it possesses characteristics complying with the following criteria:

- Total air content (A) - sufficient to provide about 9 to 10% in the mortar phase.
- Average number of voids per inch (n) - significantly greater than the numerical air content. (In this study (n) values of 60%* greater than the numerical air content (A) will be considered adequate.)
- Specific surface area of air voids (α) - at least 600 sq. in. per cubic inch of air void volume.
- Spacing factor (\bar{L}) - no more than 0.008 inches.

Although each of these parameters influences the quality of the air void system to some extent, other investigators^{3,5} have shown that the spacing factor is probably the most significant with regard to durability. The calculated spacing factor provides a measure of the maximum distance water must travel between any point in the paste and an air void.

*Unfortunately, the literature surveyed did not define the term "significantly greater". While other investigators have used higher values (e.g., 75%) a lower value was selected here (60%), based on some data obtained from good quality New Jersey concretes.

The significance of the spacing factor can be appreciated from the fact that the destructive expansive forces in the concrete increase in approximate proportion to the square of the distance from the void⁵. In other words, the hydraulic pressure that exists in the paste during the freezing process increases appreciably the further a given point in the paste is from an escape boundary (i.e., an air void or concrete surface). As will be subsequently shown, a significant fraction of the studied curb concretes were deficient with respect to one or more characteristics of the air void system, (e.g., level of air content, and/or spacing factor, etc.).

As previously noted, a determination of air void characteristics can, as yet, only be made by microscopic analysis of the hardened concrete. However, the field engineer must judge the quality of the air void system solely on the basis of total air content measured in the plastic concrete. Fortunately, in practice, this apparent problem does not present a real difficulty since a satisfactory spacing factor will usually be obtained if appropriate materials, mix design, and construction procedures are employed. Further, the magnitude of the spacing factor is not detrimentally affected by normal conditions of handling, placement, and consolidation. Simply, if the total air content of the plastic concrete is adequate, the hardened concrete will usually possess a spacing factor of the magnitude necessary for a high level of durability.

The quality of the air void system can be affected by numerous factors. Backstrom et al⁶ have concluded that two factors -- proper vibration and low water cement ratio -- are particularly beneficial to durability. Apart from their importance with regard to other quality

parameters -- strength, density, and resistance to abrasion and shrinkage -- both enhance durability in that they facilitate achieving an air void system possessing the necessary properties; that is, numerous small voids having a relatively large specific surface with a small spacing factor.

Other factors being equal, the influence these two important variables have on the effectiveness of the air void system to protect the concrete against frost action are as follows:

Vibration: While consolidation decreases the total air content of the concrete, the specific surface of the air voids tends to increase (i.e., smaller bubbles). More importantly, vibration has no significant influence on bubble distribution (i.e., the computed spacing factor, \bar{L}). The loss in total air volume accompanying vibration is not considered to be of any great moment since the air lost is predominantly in the form of large, entrapped (vs. entrained) air bubbles which are of little, if any, benefit to durability. As previously alluded to, elimination of entrapped air also minimizes strength loss.

Water Cement Ratio: All else being equal, a concrete with a low water-cement ratio will possess a more satisfactory air void system than a concrete with a higher water-cement ratio and thus, will be more durable. The reason for this is that while an increase in water cement ratio will generally increase the total air content (in itself a positive factor), the air bubbles will be larger and more widely spaced (a negative factor), with the net effect being less freeze-thaw resistance.

This seeming anomaly for high water-cement ratio concrete (more air but less durability) has some important ramifications for field control

personnel. Suppose, for example, that sometime during the construction day concrete begins to be delivered with air contents on the high side of the desired range. If the instinctive response is to lower the level of air by reducing the quantity of air entraining admixture, this "control" measure may in fact reduce the quality of the product. That is, for given conditions, if the cause for increased air is too much water, an already inherently less durable mix will be rendered even more so.

2.4.2 Measured Properties of the Air Void System (Deteriorated Curb Projects):

The various characteristics of the air void system for the studied concretes are presented in Table 3.

Influence of Test Depth: As shown in the tabulation, specimens from Projects A and B were subjected to special testing which yielded the air content and other parameters of the bubble system at the surface of the concrete and at various depths. This rather extensive testing was performed to determine if the air void system in the near surface concrete was of poorer quality than that of the interior concrete.

On its face, the data from this study suggests the surface concrete is of slightly higher quality. That is, for four of five test specimens, the values listed for two important parameters, entrained air, A_e and spacing factor, Γ , indicate the surface concrete is somewhat superior* to interior test levels. However, in most instances, the magnitude of the indicated differences are not statistically significant. Simply, there is no meaningful difference in the quality of the air void system in the studied concretes at the various depths tested.

*Higher entrained air contents and smaller spacing factors.

TABLE 3: PROPERTIES OF THE AIR-VOID SYSTEM IN HARDENED CONCRETE (Projects Displaying Surface Deterioration)

(1) PROJECT	CORE NO.	CONCRETE SURFACE CONDITION	DEPTH IN.	n	AIR VOLUME, %				NO. VOIDS PER INCH, n	(3) PASTE AIR RATIO P/A	SPECIFIC SURFACE $\alpha = 400n/A$ in ² /in ³	(4) SPACING FACTOR \bar{L} , in.
					ENTR. A _e	ENTR.PD. A _t	TOTAL A	MORTAR FRACTION				
A (Barrier Curb)	H-24 thru H-26	Scaled	Surf.	3	<1mm 0.72	>1mm 0.94	1.7	3.1	1.27	18.2	299	0.0276
			½	3	0.57	0.55	1.1	2.0	0.96	28.2	349	0.0285
			1	2	0.48	0.44	0.9	1.6	0.82	34.4	364	0.0296
			2	2	0.39	1.58	2.0	3.6	0.78	15.5	156	0.0493
			3	2	0.42	0.66	1.1	2.0	0.80	28.2	291	0.0341
					$\bar{x} =$ $\sigma =$		0.52 0.133	0.83 0.457	1.4 0.47	2.5 0.85	0.93 0.205	24.9 7.83
	H-31 thru H-33	(2) Unscaled	Surf.	3	8.21	1.96	10.2	15.9	15.33	3.0	601	0.0051
			½	1	5.85	1.30	7.2	11.8	10.52	4.3	584	0.0074
			1	1	5.88	0.75	6.6	10.9	10.49	4.7	636	0.0071
			2	1	5.18	1.18	6.4	10.6	9.19	4.8	574	0.0079
			3	1	5.45	0.34	5.8	9.7	9.56	5.3	659	0.0072
					$\bar{x} =$ $\sigma =$		6.11 1.207	1.11 0.609	7.2 1.73	11.8 2.42	11.0 2.479	4.4 0.87
	H-38	Scaled	Surf.	1	2.10	0.28	2.4	4.3	3.55	12.9	592	0.0120
			½	1	1.30	0.53	1.8	3.2	2.19	17.2	487	0.0165
			1	1	1.35	0.53	1.9	3.4	2.21	16.3	465	0.0169
2			1	1.48	0.54	2.0	3.6	2.52	15.5	504	0.0153	
3			1	1.72	0.53	2.2	3.9	2.90	14.1	527	0.0140	
				$\bar{x} =$ $\sigma =$		1.59 0.328	0.48 0.113	2.1 0.24	3.7 0.43	2.67 0.568	15.2 1.72	515 48.7

(1) Specified air content was $6 \pm 1\frac{1}{2}\%$.

(2) Unscaled category may include some fine surface cracking or checking but not significant scaling.

(3) Volume of cement paste (P) in concrete calculated from mix design proportions and equal to 31%.

(4) When $P/A > 4.33$, $\bar{L} = \frac{3}{\alpha} \left[1.4 \left(\frac{P}{A} + 1 \right)^{1/3} - 1 \right]$; when $P/A < 4.33$, $\bar{L} = \frac{P}{\alpha A} = \frac{P}{400n}$

TABLE 3: PROPERTIES OF THE AIR-VOID SYSTEM IN HARDENED CONCRETE (Projects Displaying Surface Deterioration) CONTINUED

(1) PROJECT	CORE NO.	CONCRETE SURFACE CONDITION	DEPTH IN.	n	AIR VOLUME, %				NO. VOIDS PER INCH, n	(3) PASTE AIR RATIO P/A	SPECIFIC SURFACE $\alpha = 400n/A$ in ² /in ³	(4) SPACING FACTOR \bar{L} , in.
					ENTR. Ae	ENTRPD. At	TOTAL A	MORTAR FRACTION				
B (Barrier Curb)	H-1 thru H-3	Scaled	Surf. $\frac{1}{2}$	3	<1mm 2.07	>1mm 1.10	3.2	5.5	3.62	9.4	452	0.0136
				3	1.99	1.74	3.7	6.4	3.61	8.1	390	0.0148
				1	1.82	1.43	3.2	5.5	3.30	9.4	412	0.0150
				2	2.25	2.76	5.0	8.4	4.10	6.0	328	0.0154
				3	2.03	2.16	4.2	7.2	3.70	7.1	352	0.0154
				$\bar{x} =$	2.03	1.84	3.9	6.6	3.67	8.0	387	0.0148
	$\sigma =$	0.155	0.647	0.76	1.23	0.287	1.48	48.9	0.0007			
	H-12 thru H-14	(2) Unscaled	Surf. $\frac{1}{2}$	3	2.81	3.59	6.4	10.5	5.08	4.7	318	0.0142
				3	1.87	1.57	3.4	5.9	3.31	8.8	389	0.0154
				1	1.88	1.56	3.4	5.9	3.19	8.8	375	0.0160
				2	1.66	1.59	3.2	5.5	2.95	9.4	369	0.0167
				3	1.56	1.24	2.8	4.9	2.74	10.7	391	0.0167
				$\bar{x} =$	1.96	1.91	3.8	6.5	3.45	8.5	368	0.0158
	$\sigma =$	0.497	0.950	1.45	2.25	0.935	2.25	29.7	0.0010			
C (Vertical Curb)	X179 X181	Scaled	Entire Core	1	0.04	0.56	0.60	1.1	0.13	53.2	86	0.1500
				1	0.05	0.96	1.00	1.9	0.18	31.9	72	0.1452
	$\bar{x} =$	0.04	0.76	0.8	1.5	0.16	42.6	79	0.1476			
	$\sigma =$	0.007	0.283	0.28	0.57	0.035	15.06	9.9	0.0034			
X177	(2) Unscaled	Entire Core	1	1.70	1.12	2.8	5.1	2.87	11.4	410	0.0164	
All Data				$\bar{x} =$	2.24	1.20	3.4	5.8	4.00	14.3	408	0.0266
				$\sigma =$	2.018	.769	2.30	3.62	3.677	11.45	150.5	0.0354
All Data Excluding H-31 thru H-33				$\bar{x} =$	1.40	1.22	2.6	4.5	2.47	16.5	364	0.0308
				$\sigma =$	0.768	.810	1.40	2.29	1.353	11.56	127.4	0.0378

(1) Specified air content on Projects B and C was, 3 - 6% and $6 \pm 1\frac{1}{2}\%$, respectively.

(2) Unscaled category may include some fine surface cracking or checking but not significant scaling.

(3) Volume of cement paste (P) in concrete (calculated from mix design proportions) and equal to 30 and 31.9% for Projects B and C, respectively.

(4) When $P/A > 4.33$, $\bar{L} = \frac{3}{\alpha} \left[1.4 \left(\frac{P}{A} + 1 \right)^{1/3} - 1 \right]$; when $P/A < 4.33$, $\bar{L} = \frac{P}{\alpha A} = \frac{P}{400n}$

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Quality of Air Bubble System: A general review of the data in Table 3 reveals that with one exception*, these concretes do not possess the type of air void system necessary for adequate protection against frost-action. This statement applies whether analysis is based on the averages for given data sets or individual test values.

The listed data indicates a basic or general deficiency in the total air volume (A) and/or poor spacing factors (\bar{L}). Air contents are shown to range from an average of 0.8 percent (Project C) to 3.9 percent (Project B) with a grand average for all projects of only 2.6 percent. This average is considerably lower than the level of air currently considered needed and specified by the Department ($7 \pm 2\%$). Further, and very importantly, the indicated total air contents (A) include a relatively high proportion of larger, entrapped air voids (A_t) which, as previously noted, contribute little to frost resistance. Based on the overall averages for the listed projects, entrapped air (voids > 1mm) accounts for nearly half of the total air volume. Further, the volume of air in the mortar fraction averages only about one-half of the desired value (i.e., 4.5 vs. 9-10%).

About fifty percent of all the test results indicate the number of voids per inch (n) values are smaller than their matching percent air volume (A) rather than being significantly greater; the latter being the

*The exception is the unscaled concrete from Project A (Cores H-31 through H-33), which will be discussed later and is excluded from the above commentary.

general case for quality air void systems. Finally, the magnitude of the specific surface and spacing factor parameters (α and \bar{L}) -- which are indicative of bubble size and how the given air volume is distributed within the concrete -- are more representative of non-air than air-entrained concretes. That is, the average specific surface (α) values range from 79 to 515 in²/in³ (Projects C and A, respectively) or only about one-tenth to some 85 percent of the minimum desired value of 600 in²/in³. The inadequacy of the bubble distribution is apparent from the important spacing factor (\bar{L}) parameter which ranges from 0.0148 in. (mean for scaled concrete from Project B) to 0.1476 in. (mean for scaled concrete from Project C) with an overall average of 0.0308 in. On an overall basis then, the observed spacing factor is some 4 times larger than the spacing factor recommended for adequate freeze-thaw resistance. Importantly, since the destructive stresses developed in concrete vary with the square of the spacing factor, internal disruptive forces in these concretes might be expected to be on the order of 16 times greater than that associated with an appropriate spacing factor.

As noted earlier, the exception to the general pattern of unsatisfactory results is the unscaled concrete from Project A (cores H-31 thru H-33). These specimens exhibit characteristics that are in general conformance with the minimum requirements for an effective air void system. This data is considered to represent a reasonably adequate air void system since the magnitude of two important parameters ($\alpha = 611$ in²/in³ and $\bar{L} = 0.0071$ in.) which are indicators of average bubble size and distribution,

on the average, comply with the necessary criteria (i.e., $\alpha \geq 600 \text{ in}^2/\text{in}^3$ and $L \leq 0.008 \text{ in.}$, respectively). Note that the average amount of air in the mortar phase for this data set is also in accord with the desired 9 to 10 percent level.

Test Variability: A brief mention about the effect of test variability seems appropriate here. A measure of the variability (sample standard deviations) associated with each parameter presented in Table 3 is provided both by project (condition of concrete surface) and for the combined data from all projects. Of particular interest here is how well the indicated average values for the specific surface (α) and spacing factor (\bar{L}) parameters were defined. Using all test results and a two-tailed, t-score test at the 95% confidence level, the sample averages for these characteristics ($\alpha = 408 \text{ in}^2/\text{in}^3$ and $\bar{L} = 0.0266 \text{ in.}$) appear to have been established with reasonable precision*. That is, a 95% confidence interval for the true mean specific surface (α) is 351 to 465 in^2/in^3 while the interval for the true spacing factor \bar{L} is 0.0132 to 0.0400 in. Excluding the data for the scaled concrete from Project C (cores x179 and x181) whose values differ considerably from the remaining data, the interval estimates** for α and \bar{L} are 386 to 482 in^2/in^3 and 0.0135 to 0.0211 in., respectively. In neither of the preceding cases is the variability associated with the true mean value of these parameters

*Interval estimates (all data):

$$\text{Specific surface } \alpha = 408 \text{ in}^2/\text{in}^3 \pm 2\left(\frac{150.5}{\sqrt{28}}\right) = 408 \text{ in}^2/\text{in}^3 \pm 57 \text{ in}^2/\text{in}^3$$

$$\text{Spacing factor } \bar{L} = 0.0266 \text{ in.} \pm 2\left(\frac{0.0354}{\sqrt{28}}\right) = 0.0266 \text{ in} \pm 0.0134 \text{ in.}$$

**Interval estimates (excluding cores x179 and x181):

$$\text{Specific surface } \alpha = 434 \text{ in}^2/\text{in}^3 \pm 2\left(\frac{123.0}{\sqrt{26}}\right) = 434 \text{ in}^2/\text{in}^3 \pm 48 \text{ in}^2/\text{in}^3$$

$$\text{Spacing factor } \bar{L} = 0.0173 \text{ in} \pm 2\left(\frac{0.0096}{\sqrt{26}}\right) = 0.0173 \text{ in} \pm 0.0038 \text{ in.}$$

sufficient to permit their conformance with the previously described criteria for an adequate air voids system (i.e., $600 \text{ in}^2/\text{in}^3$ for α and 0.008 in. for \bar{L}). Thus, the data clearly indicates that, on the average, the air void systems of the white concrete on deteriorated curbing projects was "inadequate" from a durability standpoint.

2.4.3 Measured Properties of the Air Void System (Durable Curb Projects):

Linear traverse tests were also performed on specimens obtained from two barrier curb projects (D and E) for which there was no premature surface deterioration. These particular projects -- selected at random -- were constructed in the early sixties with white and grey concrete, respectively. As shown in Figure 9, the concrete curb on both of these older projects displayed good durability. The coarse aggregates utilized here differed from that of the other studied concretes in that gravel rather than a broken stone was used. Except for Project E, all of the studied concretes utilized a calcite sand as a fine aggregate.

The purpose of the linear test work was twofold; first, to evaluate the air void system of these sound concretes and second, to compare these systems to those of the concrete exhibiting surface distress as listed in Table 3. The air void characteristics for the samples from Projects D and E are presented in Table 4.

Based on the overall sound condition of the curb on these two projects, after some 20 years of roadside exposure, the results of linear traverse tests were expected to confirm that both curbs possessed an effective air bubble system.

FIGURE 9. BARRIER CURB CONCRETE DISPLAYING GOOD DURABILITY
AFTER ABOUT 20 YEARS SERVICE
(Projects D and E)



9A. Project D - White Barrier Curb.



9B. Project E - Grey Barrier Curb.

TABLE 4: PROPERTIES OF THE AIR-VOID SYSTEM IN HARDENED CONCRETE (Durable Curb Projects)

(1) PROJECT	CORE NO.	CONCRETE SURFACE CONDITION	DEPTH IN.	AIR VOLUME, %				NO. VOIDS PER INCH, n	(2) PASTE AIR RATIO P/A	SPECIFIC SURFACE $\alpha = 400n^3/A$ in ² /in ³	(3) SPACING FACTOR \bar{L} , in.
				ENTR. Ae	ENTR PD. At	TOTAL A	MORTAR FRACTION				
D (Barrier Curb)	H-338	Sound	Entire Core	<1mm 5.10	>1mm 0.32	5.4	9.9	8.70	5.4	642	0.0074
	H-339	"	"	5.55	0.57	6.1	11.1	9.69	4.7	633	0.0071
				$\bar{x} = 5.33$	0.44	5.8	10.5	9.20	5.0	638	0.0072
				$\sigma = 0.318$	0.177	0.49	0.85	0.700	0.49	6.4	0.0002
E ⁽⁴⁾ (Barrier Curb)	H-335	Sound	Entire Core	2.79	0.14	2.9	5.6	4.54	10.0	620	0.0102
	H-337	"	"	3.35	0.32	3.7	7.0	5.62	7.8	612	0.0092
				$\bar{x} = 3.07$	0.23	3.3	6.3	5.08	8.9	616	0.0097
				$\sigma = 0.396$	0.127	0.57	0.99	0.764	1.56	5.7	0.0007
All Data				$\bar{x} = 4.20$	0.34	4.5	8.4	7.14	7.0	627	0.0085
				$\bar{\sigma} = 1.335$	0.177	1.48	2.54	2.450	2.41	13.4	0.0015

(1) Specified air content on Projects D and E was, 3 - 6%.

(2) Volume of cement paste (P) in concrete (calculated from mix design proportions) and equal to 29% for both projects.

(3) When $P/A > 4.33$, $\bar{L} = \frac{3}{\alpha} \left[1.4 \left(\frac{P}{A} + 1 \right)^{1/3} \right] - 1$; when $P/A < 4.33$, $\bar{L} = \frac{P}{\alpha A} = \frac{P}{400n}$

(4) Barrier curb on Project E constructed with grey concrete mix.

As it turns out, this is indeed the case. As shown in Table 4, the various air void characteristics for Project D satisfy the criteria previously outlined (in report section 2.4.1) for adequate freeze-thaw protection. The data for Project E is also in substantial compliance, although the amount of air in the mortar phase and the spacing factors are somewhat borderline. As might be expected, comparison of air void properties for these sound concretes from Projects D and E to those for the scaled concrete in Table 3 strongly favor the former. More specifically, the average values for important parameters such as entrained air (A_e), air in the mortar phase, number of voids per inch (n), specific surface (α), and spacing factor (\bar{L}) for the specimens representing the durable concrete (all data from Projects D and E) are superior to those shown for the scaled concretes in Table 3.

2.4.4 Effect of Exposure Conditions: One aspect of concrete performance on Project B warrants further discussion. On that project, both sets of samples were obtained from the same location in the center barrier, but from opposite curb faces (north and south). In view of the close proximity of the sample locations, it's not surprising that the data for Project B (see Table 3) indicates virtually the same (relatively poor) air voids system for the concrete from both curb faces. Based on the near identical quality of the air bubble system for both sides of the center barrier, each face would be expected to exhibit similar durability levels. However, the concrete behaved markedly different, with deterioration exclusively confined to one side, the north curb face. That the observed behavioral difference was not isolated to the sample location but rather is representative for the job is clearly demonstrated by the condition

survey data presented in Table 2. The results for Project B indicate 95% or nearly the entire north curb face displayed some degree of scaling. In contrast, no significant deterioration was observed on the south curb face.

The cause of the performance anomaly as between the two curb faces is apparently related to some extent to exposure conditions. One possibility here is that since the shaded (north) curb face does not receive the beneficial heating and drying effects of the sun to the same degree as the south face, the former may retain more freezable water and/or be subjected to freezing cycles of longer duration.

Whether the marginal effect of such differences in exposure is, in fact, instrumental in causing a differential in durability performance is undoubtedly dependent on the quality of the given concrete. Since there are considerable quantities of concrete curb serving satisfactorily in similar environmental conditions, it is apparent that concrete of good quality will generally not be affected by such exposure differences. On the other hand, when -- as on Project B -- the concrete has a relatively poor air void system and hence an inherent marginal ability to resist frost action, a difference in exposure may be just sufficient to trigger deterioration.

It is interesting to note that the barrier curb on another project displayed similar differences in durability between curb faces. On Project A, one-half of the northwest (shady) curb face was severely scaled as compared to only 15% for the southeast curb face (see Table 1).

In summary, it is recognized that other factors may have played a part in the observed differential distress. Nonetheless, the marked difference in performance associated with concrete subjected to different exposure conditions within Project B, combined with the similar experience on Project A, yields a strong inference that exposure conditions influenced performance.

2.4.5 Concrete Strength: The compressive strength of the core specimens removed from concrete curbing on Projects A and B are shown in Table 5. These samples were obtained from the same test locations as the linear traverse analysis samples. This sampling procedure was adopted to permit strength comparisons of specimens removed from scaled and unscaled concrete within a given project.

The results of the testing on these two projects followed different patterns. That is, while on Project B, the mean compressive strength of specimens representing the unscaled concrete exceeds that of the scaled specimens, the situation is reversed for Project A. However, a two-tailed, t-score test applied at the 95% confidence level indicates these within project differences (scaled vs. unscaled concrete) are not significant for either Project A or B. Therefore, the apparent strength differences are most likely attributable to chance variation and/or the rather small sample sizes.

A review of project records indicates the average cylinder strength for the studied curb concretes -- placement dates corresponding to core sample locations -- is higher than that shown in Table 5 for the in-place concrete (combined core data) by some 1700 and 700 psi for Project A and B,

TABLE 5: SUMMARY OF CONCRETE COMPRESSIVE STRENGTHS

Project	Core Specimens		Project	
	Scaled	Unscaled	Cylinders*	
	Strength, PSI	Strength, PSI	Strength, PSI	
A	4070	3500	4950	
	3360	3410	4950	
	4620	<u>2920</u>	4950	
	3350	$\bar{x} = 3280$	5480	
	3730	$\sigma = 310$	5770	
	<u>3640</u>		<u>5660</u>	
	$\bar{x} = 3800$ $\sigma = 480$		$\bar{x} = 5290$ $\sigma = 390$	
Combined core data, $\bar{x} = 3620, \bar{\sigma} = 490$				
B	4780	4260	5340	
	3320	4330	5240	
	<u>5100</u>	<u>5570</u>	<u>5310</u>	
	$\bar{x} = 4400$	$\bar{x} = 4720$	$\bar{x} = 5300$	
	$\sigma = 940$	$\sigma = 740$	$\sigma = 51$	
	Combined core data, $\bar{x} = 4560, \bar{\sigma} = 780$			

*Cylinder strengths are for placement dates corresponding to core sample locations.

respectively. Applying the same statistical technique reveals that this difference in mean strength levels between the cylinders and cores is significant for Project A only.

The cause for the observed strength differential between project cylinders and the in-place concrete for Project A is not known. Nonetheless, if the cylinder strengths are considered representative of the concrete for the involved placement date, it would appear the in-place strength was adversely affected by construction operations. Possibilities include a lack of, or improper curing techniques and/or an increase in water cement ratio resulting from the addition of water during concrete placement, after molding cylinders for strength tests.

2.4.6 Absorption and Chloride Content: The amount of water absorbed by concrete provides at least an indirect measure of the potential for destructive stresses to develop during freezing. Further, since absorption reflects factors such as water cement ratio, curing history and aggregate properties, absorption results provide a generalized basis for judging the overall quality of concrete. However, since the laboratory test for absorption is relatively severe -- indicating saturation levels which would probably not be achieved under normal field conditions -- such test results are used here strictly on a relative basis to make comparisons among different concrete specimens.

Chloride test results are principally used to evaluate reinforced concrete to determine the potential for corrosion of the steel and spalling. For example, based on FHWA bridge deck criteria, the intrusion of chlorides resulting in concentrations above 2 lbs/cu. yd. are considered detrimental

and restorative action warranted. Apart from the characteristics of the concrete itself, the amount of entrapped chlorides in concrete is dependent on factors such as rate and frequency of deicer application, orientation of concrete surface, washing effect of rains, etc. Thus, chloride levels might be expected to be only roughly correlated to any trend indicated by absorption test results.

The results of absorption and chloride tests performed in this work are presented in Table 6. A general review of the individual absorption data for Projects A, B and C reveals no clear pattern with regard to the capacity of specimens displaying different durability levels (i.e., scaled vs. unscaled) to take on water. To illustrate, on Project A the scaled specimen absorbed more water during the immersion period than its corresponding unscaled sample. The situation is reversed for Project B, while the absorption values for specimens from Project C are about equal. On an overall basis, the average absorption level for the scaled and unscaled specimens from these three projects is identical (5.4%).

As shown in Table 6, the chloride results for each project are (as was expected) only roughly correlated to absorption values (i.e., higher chloride concentrations accompany higher absorption values and vice versa). Surprisingly, the average chloride content for each of the sound and distressed concretes tested is the same (about 0.055%).

Probably the most significant point in connection with Table 6 is that the average absorption level for projects exhibiting deterioration (A, B, C) is higher than that for the sound concretes from Projects D and E (5.4 vs. 4.0%).

TABLE 6: SUMMARY OF ABSORPTION AND CHLORIDE TEST RESULTS

6A. DETERIORATED CURB PROJECTS

Project	Unscaled Concrete			Scaled Concrete		
	Absorption, %	Chlorides*		Absorption, %	Chlorides*	
		%	lbs/cu.yd		%	lbs/cu.yd
A	6.3	0.056	2.18	7.1	0.081	3.16
B	5.2	0.068	2.65	4.3	0.035	1.36
C	4.6	0.043	1.68	4.8	0.042	1.64
	$\bar{x} = 5.4$	0.056	2.17	$\bar{x} = 5.4$	0.053	2.05
	$\sigma = 0.86$	0.0125	0.485	$\sigma = 1.49$	0.0248	0.969

6B. DURABLE CURB PROJECTS

Project	Sound Concrete		
	Absorption, %	Chlorides*	
		%	lbs/cu.yd
D	3.9(n=2)	0.073	2.85
E	4.1(n=3)	0.037	1.44
	$\bar{x} = 4.0$	0.055	2.14
	$\sigma = 0.141$	0.0255	0.997

*Test sample: outermost 3 inches of curb concrete.

In particular, assuming the absorption data is at least an indirect measure of the actual amount of freezable water a given concrete must accommodate during freezing periods, a potential source of the durability problem becomes evident. That is, as discussed earlier, the curb from Projects D and E -- which have displayed no distress after 20 years service -- have effective air void systems and, therefore, the inherent ability to provide for the orderly transfer of water during freezing. In contrast, the concretes from Projects A, B, and C, with one exception*, do not have this ability due to their deficient air void systems characterized by insufficient entrained air and/or large spacing factors (see Table 3). Given this situation, the slightly higher absorption level for the concretes on Projects A, B, and C might well be critical.

The fact that not all the concrete on Projects B and C scaled may be attributed to differences in factors other than the air void system (see, e.g., discussion of apparent effect of differences in exposure conditions in report section 2.4.4.

2.5 OBSERVATIONS FROM ONGOING PROJECTS

During the course of this study, committee members visited a number of projects to observe concrete curb construction. Concreting operations observed included mixing and placing, consolidation, form stripping, final

*The exception is the specimen representing the unscaled concrete from Project A which also had a reasonably effective air bubble system.

finishing, curing techniques, and sampling and testing methods.

Although the degree of specification compliance varied somewhat from project-to-project, on most an effort was made to employ generally adequate quality control procedures. However, certain of the deficiencies cited in the 1971 report¹ by the previous Department task force assigned to investigate premature deterioration of white concrete curbing still persist. In some instances, concrete not complying with slump or air content requirements is used in construction of curbing. Another deficiency worthy of note involves curing procedures.

On one project, curing compound was not applied until final finishing (rubbing) of most or all of the barrier was completed. The latter operation generally required most of the work day following concrete placement. Thus, the concrete was exposed to atmospheric conditions for a prolonged period without the benefit of curing. When the curing material was applied the rate was only about one-half that specified. When the resident engineer was advised of this situation, he directed the contractor to correct both deficiencies; that is, apply the curing material at the specified rate and in a timely fashion. It's particularly unfortunate that the strength and/or durability of the involved concrete may be impaired due to a lapse in the last activity necessary to the achievement of quality concrete as the construction practices employed prior to that point appeared adequate. An alternate procedure was suggested which field personnel advised would be adopted for subsequent curb construction. This procedure entailed removal of curb forms in groups of several curb sections (as opposed to the prior practice of removing most or all forms

the morning following concrete placement), finishing, and the immediate application of curing compound. It is recognized that such a procedure might negatively impact on the curb contractor's schedule as the early removal of forms facilitates their being set for subsequent production. In such cases, alternate means of protecting the curb concrete from rapid moisture loss should be employed. For example, placement of wet burlap could be used and removed in stages so as to permit final finishing to be followed by the immediate application of curing compound.

Field personnel have indicated that when deficiencies occur, they are often the result of insufficient project manpower. Whether this assertion is valid should be determined by the Department unit responsible for monitoring construction projects for compliance with specifications and operating procedures. In this connection, it should be mentioned that the Department's proposed concrete specifications -- which are scheduled for implementation in the near future -- contain increased sampling and testing provisions which can be expected to increase present manpower requirements.

The observations on ongoing projects, combined with the frequent inadequate documentation of curb construction operations in the records for studied projects, indicate that the Department has some deficiencies in the inspection area. Undoubtedly, some of the observed deficiencies resulted from a lack of awareness by assigned inspection forces as to the requirements for achieving quality concrete. In any event, it is believed there is a general need to improve communications between supervisory and inspection field forces. That is, supervisory project personnel should

provide the guidance, direction, and support necessary to assist assigned inspection forces in their daily endeavors to achieve a quality product. In addition to this instructive effort, formal training (or retraining) sessions should be included in the Department's ongoing winter training program. The fundamentals relating to plant equipment, proportioning, mixing, slump, air content, placement, curing, and quality control testing, and their ultimate influence on concrete quality should obviously be emphasized.

Finally, apart from the technical aspects, the success of any such training effort is largely dependent on establishing at the outset of instruction, an atmosphere of quality consciousness. Probably, the most effective means of accomplishing this is for those in high authority to reaffirm their commitment to achieving quality concrete on Department projects. The occasional reiteration of this general commitment by a Department administrator seems to have a most beneficial effect on both the field and staff forces of the various units involved in construction operations. More specifically, those forces assigned to construction activities on a continuous basis should have a clear understanding as to the action central headquarters expects when non-compliance with specification requirements is encountered and assurance that such action will be supported at every level of supervision.

2.6 USE OF ACI MIX DESIGN

The barrier curb constructed on a number of recent Department projects has required extensive patching or repair work after form stripping to achieve

an acceptable surface, due to varying amounts and sizes of surface voids. Trial use of different placement and consolidation procedures have failed to satisfactorily resolve this problem. Some industry and Department personnel have expressed the opinion that the use of ACI mix design criteria would provide a denser finished surface and possibly eliminate the repair work typically required after form removal. Basically, this improvement was expected from the relative increase in sand content for ACI mixes compared to those currently used for curb construction by the Department. In order to evaluate this supposed beneficial surface effect, concrete designed in accordance with ACI procedures was used to construct several days work on an ongoing barrier curb project.

Limited experimentation with placement and consolidation methods were also given trial application to permit evaluation of their potential to eliminate surface voids. Unfortunately, neither the use of concrete design by the ACI method nor the other indicated construction modifications proved beneficial in eliminating the surface void condition. In fact, use of this relatively sandy concrete mixture produced virtually the same surface as that observed with the Department's standard mix. Based on this trial installation then, it is likely that the cause of the surface voids is related to characteristics of the particular aggregates (i.e., broken stone and calcite sand) used in the mixture and/or the type and size of vibration equipment available for use.

2.7 ADDITIONAL FACTORS INFLUENCING CURB CONCRETE PERFORMANCE

The following subsections delineate additional factors that bear on concrete quality in general, and durability in particular. Although some of these matters were not addressed directly in this study, they were considered in the course of the committee's investigation and thus warrant general discussion.

2.7.1 Drying Time: Many literature studies deal with the premature deterioration of concrete. One factor that has been identified as having a significant negative effect on concrete durability is the exposure of concrete to freeze-thaw cycles and de-icing agents at an early age.⁷ The problem here is predominantly one of not having provided concrete placed in the late fall with a sufficient period to air dry subsequent to curing and prior to being exposed to an adverse environment. It should be noted here that a portion of the studied curb concrete (on project A and a precast job) was constructed during the fall and winter months. Recommendations as to the amount of drying time necessary have been offered by a number of researchers. The P.C.A.⁸ and others have suggested that when possible, a 30 day drying period be provided following curing and prior to application of de-icers to enhance durability. Another means of protecting the concrete under such conditions is the application of a water repellent surface treatment⁹ (e.g., linseed oil). However, conflicting results have been reported¹⁰ as to the effectiveness of various surface coatings used for this purpose to prevent scaling.

2.7.2 Air-Entraining Admixtures: The importance of using an air-entraining admixture capable of producing an effective air void system

which enhances durability without any deleterious effects on other concrete properties is obvious.

The Department of Transportation currently specifies that all* air-entraining admixtures comply with various requirements of AASHTO M154 "Air Entraining Admixtures for Concrete". However, certain of the cited AASHTO specification requirements considered necessary to insure adequate performance of the admixture are not included in the Department's provisions (e.g., those governing uniformity). Further, once an air-entraining agent has been approved for a Department project, usage on subsequent projects requires only certification that the material is the same as previously submitted. Thus, it is entirely possible that on a given project, an air-entraining admixture may be used that was not actually tested.

In an effort to improve this situation, the Department's Bureau of Quality Control has informally broadened its approval testing program. Air-entraining admixtures new to the Department are being subjected to more extensive testing while those on the existing approved list are to be tested at least every two years. Hopefully, the added requirements and more frequent quality testing will provide increased assurance that only effective air-entraining admixtures are approved for use on Department projects. A soon to be released version of Department specifications, reportedly will include the necessary additional quality provisions for admixtures.

*Excluding neutralized vinsol resin admixtures which are approved on the basis of certification compliance.

2.7.3 Variations in Air Content: Industry has reported experiencing control problems, particularly with white concrete, at the higher air content levels ($6 \pm 1\frac{1}{2}\%$) specified by the Department in recent years. Although air content is affected by many variables, part of the control problem may occur from the relatively high cement content (about seven bags/c.y.) typically used in Department curb mixes and the fineness of white cement. Since both factors tend to diminish the air-entraining potential of an admixture, achieving the required target level often necessitates substantial increases in the amount of air-entraining agent. The interaction of mix water and air-entraining agent at higher dosage levels can create another problem. That is, in the critical slump range (2-3 inches), addition of mix water sufficient to increase slump $\frac{1}{2}$ to 1 inch has been reported to cause substantial increases in air content. The principal concerns here are of decreases in concrete strength and the possibility of rejection for exceeding air content limits. Thus, the general tendency for producers is to aim for the low side of the specified range for air content rather than the target value. The latter can have a detrimental effect on durability.* Hopefully, the recently changed air content requirements for white concrete ($7 \pm 2\%$) will alleviate this situation and be beneficial to curb durability.

*Although the air content of the hardened concrete can vary (i.e., be higher or lower) from that measured in the plastic state, study test data from an ongoing project indicated the air content of in-place concrete was typically lower (i.e., from $1\frac{1}{2}$ to 3%). Based on this data then, it's likely that the tendency to maintain air content of the plastic mix on the low side of the specified range increases the potential for the as-constructed concrete to lack durability.

An industry response to these difficulties has been a request for permission to add additional dosages of air-entraining agent to the plastic concrete at the job site. A procedure governing the field addition of air-entraining agents has been developed by Plant and Project Inspection personnel and some successful field trials carried out with regard to increasing the total air content in the plastic concrete. However, there is a need to confirm that this seemingly desirable modification (i.e., the introduction of air-entraining agent at different mixing stages) does indeed yield a satisfactory air void system in the hardened concrete. Linear traverse analysis of the hardened concrete produced during such field trials should verify whether or not the increases in total air content obtained by this procedure are accompanied by satisfactory air void characteristics.

Because of the Department's current difficulties with the control of air contents in concrete, a study proposal (copy presented in Appendix D) was submitted and subsequently adopted for inclusion in the FY 1981 National Cooperative Highway Research Program. The proposal states the need for development of practical means to control air content in concrete at the relatively higher levels (5 to 8%) now considered necessary for long-term durability of bridge superstructures. This includes an evaluation of interactions between water reducing and retarding admixtures and typical portland cement concrete ingredients. The NCHRP study should be completed in about 1½ years and the results with regard to control of air content are expected to be applicable to concrete mixtures used for curb construction.

2.7.4 Workability: The amount of mix water required to achieve a given consistency is influenced by several factors, including aggregate particle shape and surface texture. The use of calcite sand in curb concrete to help achieve the desired white color (i.e., reflectance) tends to create mixtures requiring additional amounts of water for workability. This is because the calcite sand is angular and of a rougher texture than smooth well-rounded natural aggregate. The situation has been further aggravated in recent years as the Department has permitted the use of broken stone in lieu of gravel as coarse aggregate in curb mixes. Thus, the aggregates used in white concrete may promote improper construction practices (use of excessive mix water to obtain the desired workability) and reduced durability. The trend towards blending of natural and calcite sands while maintaining the specified reflectance value may reduce water requirements for a given level of workability. Alternate means of reducing mix water requirements include specifying gravel coarse aggregate and/or natural sands or use of grey rather than white cement in curb applications. Use of special admixtures (e.g., water reducers) appears attractive, however, they might increase the severity of current control problems. For example, they generally require separate introduction into the mix and may increase air content. In any event, their use would require some type of testing to verify the compatibility of admixtures and any needed adjustment in the dosage of air-entraining agent. Lastly, it would seem desirable to evaluate their effect on air void characteristics in the hardened concrete by the linear traverse technique. The NCHRP study cited earlier is expected to consider

the compatibility and interaction characteristics of admixtures and, hopefully, will provide answers to the questions just raised.

2.7.5 Concrete Plants: The equipment and procedures employed in the production and transport of concrete to the job site obviously have a significant effect on the quality of the concrete achieved in curbing installations. The mixer at the batch plant, the aggregate storage bins, the devices for dispensing water, and air-entraining and other admixtures should be maintained in good working order. Admixture dispensers should be of good quality, calibrated and serviced at appropriate intervals, and must be capable of accurately and uniformly dispensing design quantities. The scale system on the plant also must be accurate if appropriate proportions of material are to be placed in a concrete mixture. The trucks that transport material to the job site in transit and truck mix processes must be of adequate capacity and have satisfactory mixing devices (e.g., blades) to achieve consistent and uniform concrete quality at the job site. With truck or transit mix operations, it is also necessary that the mechanisms for introducing water into the mix be accurate and adequately controlled. In particular, there is a need for these devices to be checked to insure that they provide an accurate indication of the quantity of water introduced into the mix.

The Department's normal practice is to inspect the equipment used in manufacturing and transporting concrete for curbing operations. However, since this function is extremely important, there is a need for field inspection forces to be re-alerted to the necessity for

insuring that all equipment used in the production process is inspected and complies with specified requirements. This inspection effort is necessary both at the beginning of a project and periodically throughout the conduct of the construction work.

2.7.6 Construction Methods: If quality materials have been incorporated into a concrete curb mix in accordance with design proportions and the mixing equipment used during production is adequate, highly durable concrete curb can be expected to result in the field. However, in reality, this end result is only achieved if sound construction practices are employed for final mixing, placement, consolidation, and curing of the concrete. In truck or transit mix operations, the final mixing process also has a significant effect on the durability of the concrete. In particular, if in order to achieve workability, excessive water is added to the mix, the quality of the mix achieved to that point can be significantly impaired. Also, excessive or variable mixing speeds, particularly for extended periods, can have a detrimental effect on quality.

The construction practices employed in the placement and consolidation of concrete is another factor that can influence the final performance of curb concrete. Procedures should be used which avoid excessive handling and segregation of the mix. Adequate vibration should be used to insure that the mix is properly consolidated. The beneficial effects of achieving as dense a surface against restraining forms as possible are obvious.

The final construction activity which has a significant effect on durability of curbing is the curing operation. If a concrete is not cured in a timely fashion and with appropriate methods than premature drying resulting in reduced strengths and surface checking or crazing are apt to occur. The surface of such a concrete may subsequently scale since it's also susceptible to premature breakdown from weathering effects (i.e., intrusion of water and de-icer chemicals).

The Department's current specifications governing the construction of concrete curbing can be improved by the addition of certain detailed requirements, particularly with regard to curing procedures and drying time. They contain the basic criteria necessary to the achievement of durable concrete. The Department conducts periodic training and re-training seminars for its inspection forces as to the application of these requirements and their effect on concrete quality.

The field inspection efforts by the Department also rely heavily on the use of various quality control tests to monitor construction operations. Tests on the plastic concrete that are of greatest value during concrete placement are the slump and air content tests. If these tests are to be of any value in controlling field operations, they must be performed in accordance with standard procedures.

The measure of strength achieved in a concrete curb is normally obtained from cylinders molded at the job site. While strength is not as critical in curbing applications as in structural applications, it is still an important factor in the performance of concrete curbing. Therefore, there is a need in the inspection efforts to insure that

the molding of cylinders is being performed properly so that resultant strength test results are true indicators of the in-place concrete's load-bearing characteristics. Adherence to proper procedures when performing quality control tests often requires a re-training of inspection personnel which the Department attempts to accomplish as part of its winter training program. It is apparent that the training efforts relative to testing procedures and specification requirements should be continued and perhaps maybe even extended.

In order for the various quality control tests applicable at the time of construction to be of value, the tests must be performed in a frequent and timely fashion. The Department in recent years has recognized a need to increase the frequency of these tests. The pending new standard specifications for concrete will require a greater number of slump, air, and cylinder tests be performed on all classes of concrete. It appears that this increased testing frequency will indeed be beneficial to curbing operations as one of the areas of deficiency established in this study was a lack of sufficient air measurements during concrete placement operations. On one project (B), involving about one mile of our standard barrier curb only two air tests were performed, both on the same day.

2.7.7 Supplemental Concrete Testing: One of the evaluation tools used in this study to determine the quality of curb concrete was the linear traverse testing procedure. This particular evaluative technique permitted the task force to rather thoroughly assess the

adequacy of the air void system achieved in the hardened concrete. In essence, it was possible with this technique to establish the success or failure of the mix design, mix production, and construction procedures to achieve concrete of good durability characteristics.

Based on the results of this and other studies, the Department will soon be making a number of changes in the manner in which we specify and monitor the construction of concrete on our projects. It is anticipated that these changes will be indeed most beneficial to concrete durability, however, this requires verification. Also, there will be a periodic need to establish that the state-of-the-art of construction operations and concrete production are continuing to provide high quality concretes in our structures and pavements. For this reason, it is believed that a mechanism should be established whereby the air void system in hardened concretes from our construction projects are evaluated periodically, possibly through the record sampling program. The linear traverse procedure is considered an excellent means for determining whether or not this adequacy exists. Accordingly, core samples should be taken for microscopic analysis from concrete used for specific applications (e.g., curbs) to identify the characteristics of the void system achieved. The analysis information resulting from these tests should be provided to the Chiefs of the Bureaus of Quality Control, Construction Practices, and Plant and Project Inspection as an aid in identifying potential durability problems. Awareness as to the existence of such a problem should facilitate their timely resolution through modifications to construction control procedures or possibly construction specifications.

2.8 RESTORATION OF DETERIORATED CURB SURFACES

As shown in an earlier report section, large areas of curb concrete have deteriorated on certain of the studied projects (A and B). In such areas, the existing curb surface is unsightly and of dark color due to the scaling off of surface mortar and exposure of the broken stone used as coarse aggregate. Some type surface repairs are needed in order to forestall further deterioration and restore reflectance.

In recent years, the Department has experimented with a few products designed to seal and/or restore concrete surfaces. In 1976, two such coating products "Stanlus Pliolite" and "Tex-Cote" were applied to new barrier curbing constructed of grey concrete on a Department project (Route 1, Section 1H). Each coating product was applied by spraying techniques -- with the addition of "mica flakes" at some locations to enhance reflectance -- to test areas consisting of about 250 linear feet. Subsequent evaluation by the Bureau of Construction and Compliance Practices¹¹ indicates that although high initial reflectance (78 units) was provided by these products, both had a dirty brownish appearance after only six months exposure to the elements. At that time, it was concluded that these products might be beneficial as a protective coating only.

In 1979, another material ("Thoroseal") was applied to three barrier curb members (one severely deteriorated and two recently constructed) on adjacent sections of Route 1 in the vicinity of Trenton. This product, applied by brush and spray methods to the

scaled and new curbing, respectively, is currently under evaluation for the Interagency Committee on Specifications. This material -- which vastly improved the appearance of the scaled concrete and brightened the new curb -- has performed satisfactorily through one winter. Unfortunately, its long-term durability performance in a curbing application remains to be determined.

The cost of surface repairs are expected to be relatively high. For example, in 1979, the estimated total costs for applying two coats of "Thoroseal" to our standard barrier curb ranged from about \$0.40 to \$0.65 ¢/sq. ft. or some \$2.50 to \$4.00 per linear foot. Thus, the estimated total repair costs (material, equipment and labor) for one mile of our standard barrier curb could range from about \$13,000 to \$21,000.

Nonetheless, due to the progressive nature of the observed deterioration, some type repair work, in an effort to curtail further scaling and restore the desired brightness warrants consideration. If it's decided to repair the affected curb surfaces the Department's Materials Committee should be consulted with regard to the material to be specified. They may be able to provide guidance in selection of a promising material.

REFERENCES

- ¹ Andres, C. J., "Interim Report on White Concrete Curb", NJDOT Memorandum Report to Mr. J. Freidenrich, (December 2, 1971).
- ² Mielenz, R. C., "Diagnosing Concrete Failures", Stanton Walker Lecture No. 2, National Sand and Gravel Association/National Ready Mixed Concrete Association, University of Maryland, (1964) p. 14.
- ³ Powers, T. C., "The Air Requirement of Frost Resistant Concrete", Highway Research Board Proc. Vol. 29 (1949) pp. 184-202.
- ⁴ Powers, T. C., "The Mechanism of Frost Action in Concrete", Stanton Walker Lecture No. 3, National Sand and Gravel Association/National Ready Mixed Concrete Association, Silver Spring, Maryland, (1965) 35 pp.
- ⁵ Powers, T. C. and Helmuth, R. A., "Theory of Volume Changes in Hardened Portland Cement Paste During Freezing", HRB Proc. Vol. 32, (1953), pp. 285-297.
- ⁶ Backstrom, J. E., et al, "Origin, Evaluation, and Effects of the Air Void System in Concrete", Proc. American Concrete Institute, Vol. 55, Part 1, pp. 95-121, Part 2, pp. 261-272, Part 3, pp. 359-376, Part 4, pp. 507-517, (1958).
- ⁷ Grieb, W. E., et al, "Resistance of Concrete Surfaces to Scaling by De-Icing Agents", TRB Bulletin 323, (1962), p. 43.
- ⁸ PCA, "Design and Control of Concrete Mixtures", (1968), p. 71.
- ⁹ ACI Manual of Concrete Practice, Part 1, "Guide to Durable Concrete", (1979), pp. 201-208.
- ¹⁰ Arni, H. T., "Resistance to Weathering-Hardened Concrete", Significance of Tests and Properties of Concrete and Concrete-Making Materials, STP-169A, American Society for Testing and Materials, Philadelphia, (1966), pp. 261-272.
- ¹¹ Isler, Jr., J. P., "Special Reflective Coatings for Barrier Curb", NJDOT Memorandum of Record, (May 23, 1977).

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APPENDIX A: PRECAST CONCRETE CURB DISTRESS

Form AD-40 5/77

NEW JERSEY DEPARTMENT OF TRANSPORTATION

MEMORANDUM

TO R. Santora

FROM F. Palise

Research

Project Engineer, Materials

Region 3

SUBJECT Premature Deterioration of White Concrete Curb - Precast DATE 1-28-81 TELEPHONE NO. 201-431-4500 x 345

In conjunction with the task force investigation into the causes of premature deterioration of cast-in-place white concrete barrier curb, similar deterioration of precast curb was looked into. The following is a summary of our findings.

Problem - Immediately after placement of Precast curb two projects exhibited premature deterioration.

The curb on the first project was approximately two to six weeks old when surface scaling was first observed.

The curb on the second project was also only a few weeks old when six pieces deteriorated.

Investigation

(A) First Project

In April of 1975 five cores were taken from the affected curb for determination of chlorides content. Also four cores were taken for determination of compressive strength and air content. The Department's Bureau of Quality Control performed the compressive strength and chlorides testing and the Pennsylvania Department of Transportation performed the air content test by the Linear Traverse method. See Frank Wegel's memorandum to the Resident Engineer dated July 14, 1976. This report concluded that;

1. The curb contained higher amounts of chlorides in the "bad" areas as compared to the "good" areas,
2. Air contents and compressive strengths were satisfactory,
3. Proper construction techniques were utilized during manufacture,
4. Some units may have been over-vibrated causing extreme segregation on the surface areas,
5. The concrete was too green when it was shipped and placed

Mr. Wegel concluded that a laboratory investigation was necessary to further narrow the possibilities.

This investigation was initiated in July 1976, by Mr. H. Justus. See his memorandum to F. Wegel dated July 8, 1976, re: L.I. 1976-3. The results of this investigation, on file with the Bureau of Quality Control, were not conclusive enough to shed light on the problem.

Records indicate that these curb sections were fabricated on outside casting beds during the winter months of December 1975 and January 1976. Because of the cold weather conditions, the forms were preheated by playing live steam over them prior to concrete placement. It is suspected that the forms became superheated (approximately 230° to 240°F), resulting in a superheating of the surface concrete due to heat transfer from the heated steel forms. It was also determined that these pieces were stored outside and shipped to the project site in late January and February.

It is believed that the combination of excessive heating of the forms and subsequent storage of the curb section out-of-doors under subfreezing weather conditions caused the early and rapid deterioration experienced. This is confirmed by the emphasis the Portland Cement Association places on proper drying time during the curing of concrete. In their, "Design and Control of Concrete Mixtures" publication they state the following:

"The minimum curing period for adequate scale resistance to chemical de-icers generally corresponds to the time required to develop the design strength of the concrete. A period of air drying, which enhances resistance to scaling, should then elapse before application of de-icing salts. This drying period should be at least one month if possible."

(B) Second Project

In April of 1974 four cores were taken from deteriorated curbs for compressive strength. The strengths obtained were all in excess of 6,000 psi confirming the 6,000 + psi strengths obtained with 6" x 12" cylinders made at the time of batching. However the air contents measured on the plastic concrete did not exceed 4.3%. In order to determine whether the curb had sufficient air entrainment the Department took two more cores for Linear Traverse testing by the Pennsylvania Department of Transportation. Their results indicated that the "barrier contained essentially no entrained air. The air content of the near-surface concrete is just as low as the interior concrete. Thus, this concrete has no protection from frost action." The values of air entrainment were in the area of 1/2 percent. It was concluded this low amount of air entrainment caused the premature failure of this curb.

Investigation revealed the concrete for this curb was batched from a "Continuous Mix Type Truck Mixer. It was concluded that this type mixer could not consistently entrain specification air because of the nature of white concrete and the auger type mixing method used.

Solution

The Department's precast inspection procedure now requires careful monitoring of the preheating of forms and also requires that members that are not steam cured to be stored at temperatures above 60° F for a seven day period after pouring. Also, "Continuous Mix Type Truck Mixers" are no longer allowed to be used in the fabrication of precast barrier curb.



F. Palise

FP/acc

CC: R. E. Leahey
H. Justus
File

APPENDIX B: RATING SYSTEM EMPLOYED FOR CURB CONDITION SURVEYS

DEVELOPED BY

TASK FORCE ON PREMATURE DETERIORATION OF WHITE CONCRETE CURB

RATING SYSTEM

In order to obtain a numerical deterioration index for white concrete curb, the rating system shown below which takes into account both the "severity and extent" of distress shall be used.

RATING SCALE

<u>Condition</u>	<u>Surface Appearance (Severity)</u>
0	No scaling. Includes surface cracks, pop-outs, and surface voids.
1	Slight scaling, approximately 1/8" deep or less, virtually no coarse aggregate visible.
2	Moderate scaling, approximately 1/8" to 1/4" deep, some coarse aggregate visible.
3	Severe scaling, approximately 1/4" deep or deeper. Most or all of the coarse aggregate is visible.

Note 1: Estimate the percent of curb face area between recorded limits (Stations) that is affected in increments of 5%. For example, if the length of curb between stations X and Y is rated as condition 2 and the estimated area affected is 60%, record as condition 2, 60%.

Note 2: When the area affected is predominantly in the top, middle or lower 1/3 portion of the curb face it shall be recorded. For the example given in Note 1 above, if the deterioration was predominantly in the lower section of the curb face, record as condition 2, 50%,L. If both the middle and lower sections are predominantly affected, record as condition 2, 60%, ML. If the top, middle, and lower sections are similarly affected no subscript designation is necessary (i.e., record as condition 2, 60%.

APPENDIX C: METHOD OF TEST FOR DETERMINING PROPERTIES OF
THE AIR VOID SYSTEM IN HARDENED CONCRETE

Commonwealth of Pennsylvania
Department of Transportation

Pa. Test Method No. 623
Revised November, 1972
4 Pages

Bureau of Materials, Testing & Research

Method of Test for

AIR CONTENT OF HARDENED CONCRETE
BY LINEAR TRAVERSE ANALYSIS

1. Scope and Purpose

1.1 This method of test describes the procedure for determining the volumetric percentage of entrained air voids in hardened concrete. In this procedure, polished sections of concrete are examined and measurements are made with a stereoscopic microscope and a traversing stage. This method is a modification of ASTM Designation: C-457, Recommended Practice for the Microscopical Determination of Air-Void Content, Specific Surface, and Spacing Factor of the Air-Void System in Hardened Concrete.

1.2 The geometric characteristics of the air void system, the entrained air content especially, are indicative of the resistance to scaling of moist concrete when subjected to freezing temperatures, particularly in the presence of the commonly used de-icing chemicals.

2. Definitions

2.1 Air Void—a small space enclosed by cement paste and occupied by air. (NOTE 1) This term does not refer to capillary or other openings of submicroscopical dimensions or to voids within particles of aggregate.

NOTE 1: For special purposes, void systems of satisfactory size distribution and spacing may be produced by the evolution of hydrogen resulting from the chemical reaction of metallic aluminum with cement and water.

2.2 Entrained Air Void—an air void less than one millimeter and greater than 0.005 millimeters in diameter. Entrained air voids are typically spherical or nearly spherical in shape.

2.3 Entrapped Air Void—an air void equal to or greater than one millimeter in its smallest dimension. Entrapped air voids are typically irregular in shape. Entrapped air voids are considered to make no significant contribution to the durability of concrete when subjected to freezing temperatures.

3. Apparatus

3.1 The apparatus and materials for sample preparation and for measuring the geometrical characteristics of the air-void system shall meet or exceed the minimum requirements set forth in Sections 4 and 6 of ASTM Designation C-457. The apparatus and materials required for sample preparation consists of power saws, polishing laps, and various abrasive compounds for grinding and polishing the sawed sections of the concrete. The measuring apparatus is essentially a stereoscopic microscope mounted above a movable stage which has electrical and mechanical accessories that permit counting and measuring portions of the intervals traversed as the stage is moved back and forth under the microscope. See Figure 1.

4. Samples

4.1 When the concrete in a pavement or a structure is to be tested by this method, obtain the sample of hardened concrete in accordance with PTM 606.

4.2 When a molded specimen of concrete is to be tested by this method, the entire specimen shall be submitted.

4.3 When unusual circumstances do not permit samples to be obtained in accordance with Sections 4.1 and 4.2, above, samples should be obtained as prescribed by the Petrographer, to ensure that samples suitable for testing will be obtained.

4.4 The samples shall be prepared in reasonable conformity to the procedure described in Section 5 of ASTM Designation C-457. The sample preparation consists essentially of sawing a slab of concrete, usually about 4 x 6 x 1 inches, from the sample submitted; one side of the slab is then ground and polished on laps and mounted horizontally on the traversing stage.

5. Procedure

5.1 **Total Traverse Length.** The total length of traverse required, which depends on the size of the coarse aggregate, is taken from the following table (ASTM C-457) and the number of traverses necessary to provide the required total length are plotted uniformly along one edge of the polished surface of the slab.

Minimum Length of Traverse

Nominal or Observed Max. Size of Aggregate (in.)	Minimum Length of Traverse (in.)
3	120
1½	100
1	95
¾	90
½	80

5.2 **Measurements--Short Method.** Under 100x magnification and oblique illumination, the number of entrained and entrapped air voids intercepted by the traverses are counted, the intercepted intervals of entrapped air voids and the total distance traversed are determined. The relationship between the entrained air content and the number of entrained voids per inch is shown in Figure 2. The entrapped air content (%) is calculated from the number and average chord length of the entrapped air voids.

$$A_E = 1 \times n \times 100$$

The total air content is the sum of the entrained and entrapped air void contents, expressed as percentages.

5.3 **Measurements--Long Method.** This is the referee method. Also, it is required when the size distribution of entrained air voids is abnormal, such as occurs when the voids are caused by the evolution of hydrogen in the mortar due to the presence of aluminum. In this method, under 100x magnification and oblique illumination, the intervals intercepted by each entrained and entrapped air void (their chord lengths) are determined, as well as the number of voids of each type and the total distance traversed. The volumetric percentage of each type of air void is a function of its average chord length and number of voids.

$$A = 1 \times n \times 100$$

6. **Report.** Form TR-459, Air Content of Hardened Concrete by Linear Traverse Analysis.

6.1 **Report Voids Per Inch, Total Traverse Length, Entrained Air, Entrapped Air, and Total Air.** (NOTE 2).

NOTE 2: This same report form includes additional information obtained at the same time that the entrained air content is determined and is provided to permit an evaluation of the quality of the concrete.

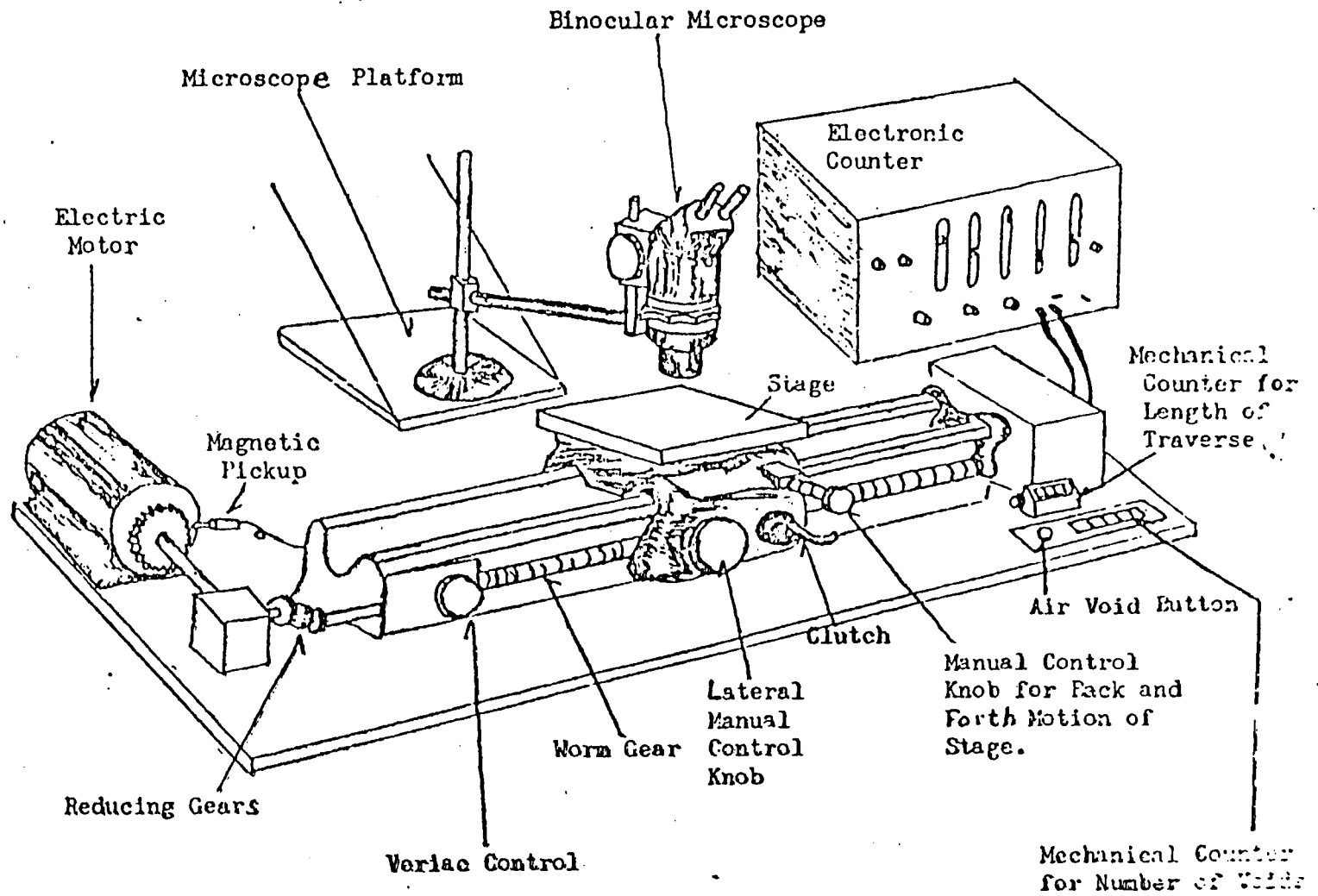


FIGURE 1

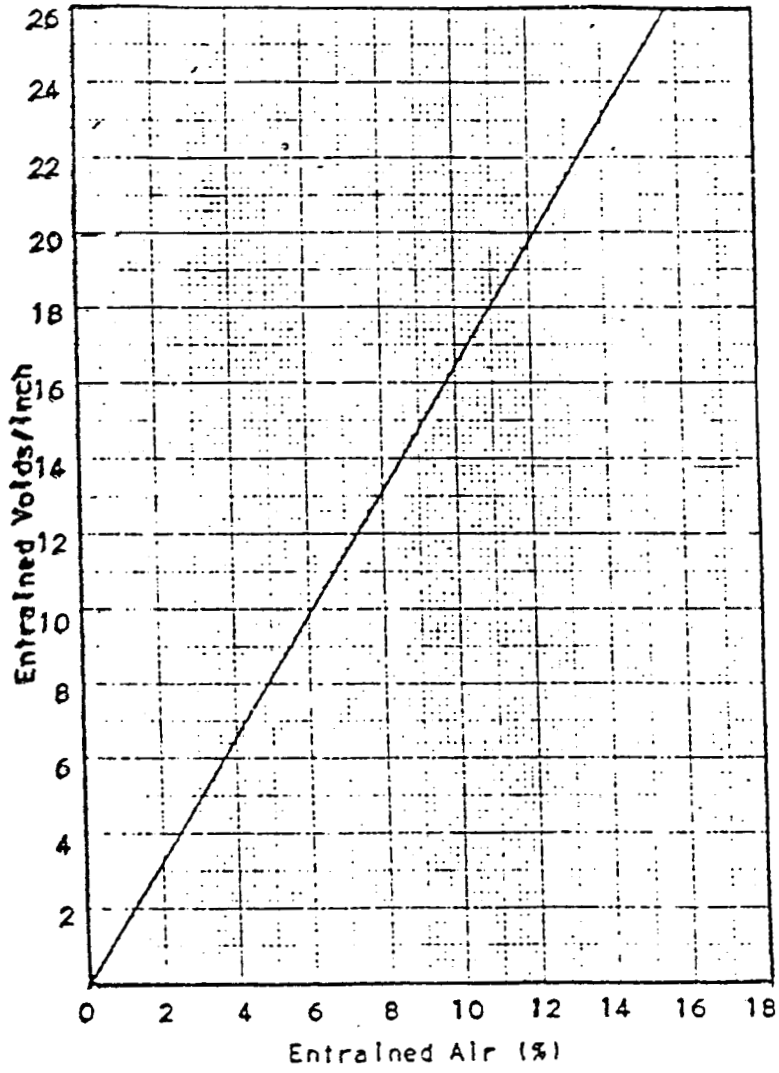


FIGURE 2

Mechanical Section:

The mechanical section shall consist of an XY stage made up of a manually operated Y stage and a motor-driven X-axis stage.

The Y-axis slide shall provide 5 inches of travel with a drum dial for reading to .001 inch and a mechanical counter for reading to .01 inch.

The X-axis shall provide 15 inches of travel and is driven at a rate adjustable from .25 to 0.6 inches per minute.

A Hall Effect Pulse Generator attached to the X-axis motor provides a pulse for each revolution of the motor armature, or .00025 inches of slider travel.

Counter/Display:

The output of the Pulse Generator shall feed a divide-by-4 circuit so that new pulses are generated for each .001 inch of slider travel (25.4 microns). These pulses are used for operation of the electronic counters.

The following displays shall be provided:

Total stage travel (5 digits) to 99.999 inches

Total void chord lengths (5 digits) for voids greater than 1 mm (to 99.999 inches)

Total void chord lengths (5 digits) for voids less than 1 mm (to 99.999 inches)

Number of intercepts (6 digits) greater than 1 mm, to 999,999

Number of intercepts (6 digits) less than 1mm, to 999,999

A RESET button shall be provided for individual counters, with an additional button for simultaneous reset of all counters.

The displays shall be of the LED type of size adequate for convenient viewing.

A regulated power supply shall be used to minimize effects of line voltage or load variation.

Control Box:

Control of the system shall be from a separate control box providing the following functions:

Chord-length Select - greater than or less than 1 mm.

Pulse Generator Deactivate.

FWD-STOP-REV Switch for control of the X-axis.

Two-speed control with switch for selection of appropriate X-axis translation speed.

APPENDIX D: NCHRP PROJECT STATEMENT "CONTROL OF ENTRAINED AIR IN CONCRETE"
NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Transportation Research Board

National Research Council

F.Y. 1981

Project Statement

- I. Project Number: 81-D-7
- II. Research Project Title: Control of Entrained Air in Concrete
- III. Research Problem Statement: •

The inclusion of entrained air within the matrix of portland cement concrete has long been recognized as an effective means for improving the durability of concrete exposed to the highway type environment. However, in recent years there has been a trend toward requiring higher air contents, nearly twice those levels previously considered adequate. This action has primarily been in response to the nationwide problem of premature bridge deck distress, as well as to an increased understanding of the quality variations that occur in concrete.

Control of air entrainment at these new target values (5, 6, 7 and even 8 percent entrained air content) has proven to be very difficult. The higher dosages of air entraining admixtures required to achieve the desired new levels apparently interact with other concrete ingredients (water, water reducing admixture, retarding admixture) in a non-uniform and frequently unpredictable fashion. This has been particularly true of the interaction between the air entraining agent and mix water. At concrete slumps in the 2 to 3 inch range, only small increases in slump (additional water) of 1/2 to 1 inch have been noted to cause almost a doubling of the entrained air level. Excessive variability in concrete quality and noncompliance with both air entrainment and strength requirements have resulted. Recommendations to return to the previous low air levels have been voiced by industry as a solution to this

new problem.¹ It is hoped that such measures will not be necessary.

A study is needed to develop practical means for control of air entrainment in structural concrete at the 5 to 8 percent levels now considered necessary for long-term durability of bridge superstructures.

IV. Research Proposed:

The objectives of this project are:

1. Determine the effects in concrete quality of interactions between typical portland cement concrete ingredients and admixtures at air entrainment levels between 5 and 8 percent.
2. Develop practical means for control of air entrainment in structural concrete at the 5 to 8 percent level without significant reduction in a concrete's other quality measures.

The study should quantify the effects of varying dosages of typical air entraining admixtures on the entrained air content, air bubble spacing, bubble size, compressive strength and slump of structural concretes containing typical ranges of coarse and fine aggregate, cement contents, water cement ratio and of other admixtures. The information gained from this effort should then be used to develop potential methods for controlling air contents at desired levels without jeopardizing other quality requirements. As part of the study, the potential control methods should receive trial applications and the most effective means selected based on the results of those trials. The final study report should provide guidance for implementing use of the selected control method.

V. Estimate of Problem Funding and Research Period:

Recommended Funding: \$75,000
Research Period: 18 months

VI. Urgency:

The use of air entrainment in concrete still serves as the single most effective measure for achieving adequate durability in structural concrete.

The entrainment levels currently being prescribed throughout the country may not be practically achievable without significantly impairing other quality factors associated with concrete. A study must be undertaken immediately to determine what quality effects will occur and means for attaining the desired air levels that minimize the negative effects.

VII. Persons Developing the Problem:

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VIII. Problem Monitor:

Robert E. Leahey

IX. Date and Submitted by:

March, 1979
Louis J. Gambaccini
Commissioner of Transportation
New Jersey Department of Transportation

X. References:

1. Gaynor, R. D., "Additional Comments on Air Entrainment," National Ready Mix Concrete Association Technical Information Letter No. 333 and Concrete Construction Magazine, March, 1976 and October, 1976 issues.