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PREVENTION OF SCALE ON CONCRETE PAVEMENT SURFACES BY AIR ENTRAINMENT

By

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SCALE PREVENTION ON CONCRETE HIGHWAYS BY MEANS OF AIR ENTRAINMENT

One form of concrete deterioration prevalent in Michigan, and in other states having similar climate, is surface scaling and subsequent disintegration from the surface downward. This condition has become more apparent as the use of chemical salts has increased for the removal of ice from pavements. The unsightliness of scaled areas, the necessary subsequent maintenance and the added possibility of further deterioration have been of vital concern to highway engineers for years and the subject of considerable research. This problem has led, within the last decade, to a concerted program of research in which many agencies have participated, including certain federal, state and municipal departments, as well as individual portland cement manufacturers and the Portland Cement Association. The most significant result of this research has been the discovery of the principle of air entrainment and the application of this principle to construction practice for the purpose of creating more durable concrete pavements.

The results of investigations by the several agencies have demonstrated conclusively that concrete having excellent durability and high scale resistance can be produced by introducing into the concrete mixture a definite quantity of air in excess of that normally found in ordinary concrete. The resulting product is commonly referred to as air-entrained concrete.

It is the purpose of this paper to present the significant facts pertaining to the manufacture and use of air-entrained concrete for scale prevention purposes based on the results of many studies on this subject and including the experiences of the Michigan State Highway Department.

Air Entrainment in Concrete

The principle of air entrainment in concrete consists of the incorporation into the concrete mixture of proper amounts of minute, uniformly distributed, but disconnected air bubbles. Since this introduced air functions differently than the air in ordinary concrete mixtures, it materially alters the physical properties of both the plastic and hardened concrete. Freshly mixed concrete containing entrained air is more plastic, possesses better workability and can be handled with less segregation than ordinary concrete. The hardened concrete has excellent durability with respect to freezing and thawing action and remarkable resistance to scaling caused by the chloride salts used in ice control. Furthermore, surface water or bleeding of the concrete during placing is practically eliminated, thus greatly reducing the time interval between mixing and finishing operations.

Although the entrained air has a definitely beneficial effect on workability and durability, data available at the present time indicate that for each percentage increase in the amount of air above the amount which exists in ordinary concrete there will be a reduction in flexural strength of two to three percent and in compressive strength three to four percent. The strength decreases in proportion to the increase in air content. It is generally accepted that satisfactory scale resistance and durability can be obtained without serious loss in strength if the total air content is maintained between three and five percent by volume computed on the basis of the theoretical weight of air free concrete of the same pro-

portions. A minimum total void content of three percent is sufficient to assure durability; more than five percent needlessly impairs strength without appreciable improvement in resistance to frost and salt action. Since the air content of ordinary concrete is normally around 1 to 1.5 percent the increase in void content brought about by the introduced air would correspond to a drop in unit weight of the concrete of from about three to six pounds per cubic foot. The best practice is to keep the air content as low as possible consistent with the results desired.

Air-Entraining Materials.

The air-entraining materials which have been investigated and tried experimentally in varying amounts may be grouped functionally into three general classes; (1) organic compounds whose inherent foaming action is independent of any subsequent chemical reaction with the cement; (2) other organic compounds which, when added to the cement, react with the alkalis present to produce foaming agents; and (3) gas generating agents. Some of these compounds may be either interground with the cement or added to the batch at the mixer, while others are of necessity restricted to only one of these two methods of incorporating the air-entraining agent in the concrete mixture.

The first group includes the sodium compounds of certain organic acids found in fats, oils and resins and the sodium salts of various sulfated or sulphonated organic compounds. These compounds are soapy in nature and rely for their effect on the property they possess of weakening the surface tension of water to cause foaming. Examples of this type are Orvus (sodium

lauryl sulfate), neutralized Vinsol resin (sodium salt of the resin acids), and Darex, the air-entraining ingredient of the latter being the sodium salt of a still different sulphonated organic compound.

The materials found in the second group are not in themselves air-entraining agents. In order to cause foaming they must be converted to the respective water-soluble soaps through their reaction with the hydroxides of the alkali metals present in the cement. Examples of this type are rosins, flake Vinsol resin, and the various animal and vegetable fats and oils. Here the actual amount of air-entraining material produced will depend not only upon the amounts of these substances added, but also on the amount and availability of the alkali oxides present in the cement. For this reason, air-entraining agents of the first group in general give more consistent and uniform results than those of the second and their effect is influenced less by the length of mixing time, since the soap forming reaction progresses as mixing continues.

Both of the above groups of air-entraining materials serve to entrap air as such in the mix. Materials of the third group, as their name implies, do not entrap air, but generate gas, usually hydrogen or oxygen, within the mix by the action of inorganic elements or compounds on certain constituents of the cement. The commonest examples of this type are aluminum powder, which produces hydrogen in contact with the alkali hydroxides, and hydrogen peroxide, which is completely decomposed in the presence of these hydroxides to liberate oxygen. The gases so formed seem to accomplish the same purpose as entrained air in promoting durability and in some cases the use of aluminum

powder is of definite advantage in preventing pockets underneath horizontal reinforcing steel caused by water gain, since a slow swelling of the concrete takes place for some time after placing.

At the present time the American Society for Testing Materials has issued tentative specifications concerning the use of Vinsol resin (a product of the Hercules Powder Company of Wilmington, Delaware) and Darex AEA (a product of the Dewey and Almy Chemical Company of Cambridge, Mass.) as air-entraining materials in the manufacture of air-entraining portland cements. The Vinsol resin may be added to the clinker as plain flake resin or sodium resinate in solution or powder form. The sodium resinate of Vinsol resin and Darex may either be added to the batch at the mixer as separate ingredients or interground with the cement at the mill.

There are many other materials available which have the property of entraining air in concrete and may prove satisfactory if properly used. However, these materials should not be used unless it can be demonstrated through research and experience that they entrain the specified amount of air without impairing the quality of the concrete.

The blending of plain portland cement with a natural cement which contains an interground air-entraining agent will produce a satisfactory air-entrained concrete. The blending is usually performed on the basis of one part natural cement to five parts portland cement.

The introduction of added air into a concrete mixture necessitates changes in mix design and careful control of production if optimum results are to be achieved. Almost every element in concrete making, whether of

materials or processes, must now be examined in the light of its effects on air content, and conversely, the effect of the air content on processing of the mix and the properties of the hardened concrete. For instance, in a given mix, air entrainment will be influenced by the water content, the effect being more pronounced in lean mixes than in rich ones. The amount, character and grading of both fine and coarse aggregate, the individual properties and amount of cement used, mixing time, method of mixing and amount and type of air-entraining agent all affect to varying degrees the quantity of air taken into the mix. In addition, there are encountered during the process of manufacturing air-entrained concrete in the field numerous factors which influence the quality and air content of the finished product. Each project becomes an individual problem in concrete mix design and control which requires much more supervision than is necessary when working with ordinary concrete in order to produce a uniform concrete mixture meeting specified design requirements.

The question of a choice between the use of an air-entraining cement or an air-entraining admixture at the mixer will depend almost entirely on how the Engineer wishes to control the work. Each method has its advantages and disadvantages. In either case proper control methods must be provided to insure a satisfactory end product at the mixer.

Design of Mix.

In the design of air-entrained concrete it has been customary only to make certain changes or adjustments in the ordinary concrete mix necessary to insure the specified air content and other desirable properties of the concrete with the least sacrifice in strength.

Methods of adjusting proportions of the mix vary among different users. Features common to all, however, are reduction in water and sand content. Other adjustments are possible under certain conditions and no hard and fast rule can be applied to these adjustments.

Mortar tests alone cannot be depended upon to give an accurate indication of the amount of air which will be entrapped in the finished concrete. The air content of a given concrete mix can be determined only on the basis of actual trials with all of the materials to be used. Major adjustments of these trial batches may require control of other factors than sand content alone for optimum results. Such tests may reveal a deficient or excessive air content which would involve too great an adjustment in sand content, and would therefore compel a change of air-entraining cement or the amount of air-entraining agent used as an admixture. Once the mix is designed on this basis, any additional changes could then safely be made by varying the sand content of the mix in the field at the beginning of the job and thereafter as may be necessary under conditions encountered during the progress of the work.

Characteristics of Air-Entrained Concrete.

The introduction of well distributed minute air bubbles into a concrete mix apparently decreases the particle interference of the aggregates, thereby greatly improving the workability of the treated concrete over that of normal concrete with the same aggregates and proportions. The resulting mixture has an extremely fatty appearance similar to that of an over-sanded

mixture. Segregation and bleeding are practically eliminated. As a result there is little free water on the surface to facilitate finishing operations and it is therefore imperative that finishing operations be started and completed with a minimum of delay or else drying of the surface will hinder proper finishing. Extreme fluctuations in temperature, relative humidity or wind velocity will influence the finishing characteristics of air-entrained concrete.

Air-entrained concrete is inherently more sticky than ordinary concrete. Consequently, steel shod floats and finishing tools have proven better than wooden ones. In some cases it may even be necessary to adjust the transverse oscillations of the screed to the forward motion to prevent torn surfaces. Experience has proven that the problems encountered are simply those involved in adjusting construction practice to the characteristics of the new concrete and require no more radical changes than might be necessary due to many other circumstances which are frequently encountered in job conditions.

Construction Practice.

Certain construction procedures must be closely observed in order to derive maximum benefit from the air-entraining materials. Caution must be exercised in handling of air-entraining cements during batching operations. These cements have a greater tendency to flow in the dry state than normal portland cements and special precautions should be taken to prevent batch losses due to leakage through cracks and opening of any kind. Handling and proportioning of the aggregates at the batching plant should be conducted in such a manner as not to alter too greatly their original grading character-

istics and batch weights. The water content of the mixture greatly influences the amount of entrained air and therefore must be carefully controlled within narrow limits. Since the time of mixing is generally fixed there remains the speed of rotation, the mixing characteristics and physical condition of the mixer drum to influence the properties of the mixed concrete. All of these factors may be successfully controlled on any project by rigid inspection and proper specifications based upon experience and research.

Calcium chloride in amounts up to two percent have been added successfully to air-entrained concrete to facilitate paving operations during periods of low air temperatures. Laboratory tests indicate that calcium chloride in amounts up to two percent, when added to the batch, either in solution or dry form, increase early strengths, without decreasing the effectiveness of the air-entraining material in entraining air and in providing a high degree of resistance to scaling and to disintegration caused by freezing and thawing action.

Experience also indicates that color pigments made from iron oxides can be used successfully with air-entraining materials without any sacrifice in the strength, durability or scale resistance characteristics of the concrete.

Michigan has been using air-entrained concrete for the past five years as a method to eliminate scale caused by ice control methods, and a brief description of our experience may be of some interest in connection with the general subject of this paper.

MICHIGAN'S EXPERIENCE WITH AIR-ENTRAINED CONCRETE

Michigan's experience in the use of air-entrained concrete dates back to the construction of the Michigan Test Road in 1940. A portion of this Test Road was devoted entirely to a study of the problem of scaling and methods for its control. Factors in the investigation to receive major consideration in relation to scaling were the addition of mineral fillers to supplement the fines in the aggregates, proprietary admixtures, air-entraining materials, natural cements with and without air-entraining materials, and finishing and curing methods. Subsequent durability studies revealed that by using air-entraining materials it was possible to obtain a concrete surface practically 100 percent scale resistant to chloride salts. (The other methods investigated were unsuccessful in this respect.)

When the Test Road was constructed two air-entraining materials were available for trial, flake Vinsol resin and a wetting agent called Orvus, manufactured by the Procter and Gamble Soap Company for industrial use. Two Michigan cement manufacturers furnished Vinsol resin portland cement milled from the same clinker respectively as was used in manufacturing the standard portland cements specified for comparative study on the same project. The cement was ground with 0.15 pounds ($\pm$ 20 percent) of pulverized Vinsol resin per barrel of cement added to the clinker at the time of grinding. The specific surface of the cement was specified to be within 1750 and 2100 square centimeters per gram. These requirements were furnished by the Portland

Cement Association. Measurements of drop in weight in the field showed that this specification gave the desired weight drop of approximately five pounds per cubic foot for the materials used on the project.

The Orvus, procured in paste form from the manufacturer, was dissolved in warm water to form a solution of known concentration. The required amount of the solution per batch of concrete was added to the dry materials at the skip. It was found by experiment that, for the particular materials used, 0.05 pounds of Orvus per barrel of cement gave the desired reduction in weight of approximately five pounds per cubic foot. The concrete mixtures resulting from the use of either of the two air-entraining materials, Orvus and Vinsol Resin, possessed similar physical properties characteristic of air-entrained concrete.

The reduction in strength of the air-entrained concrete as compared to the standard concrete was approximately 15 to 20 percent. This marked difference in strength values on the Test Load may be attributed to the high air content required in the concrete and lack of basic information in the design, control and handling of air-entrained concrete at that time.

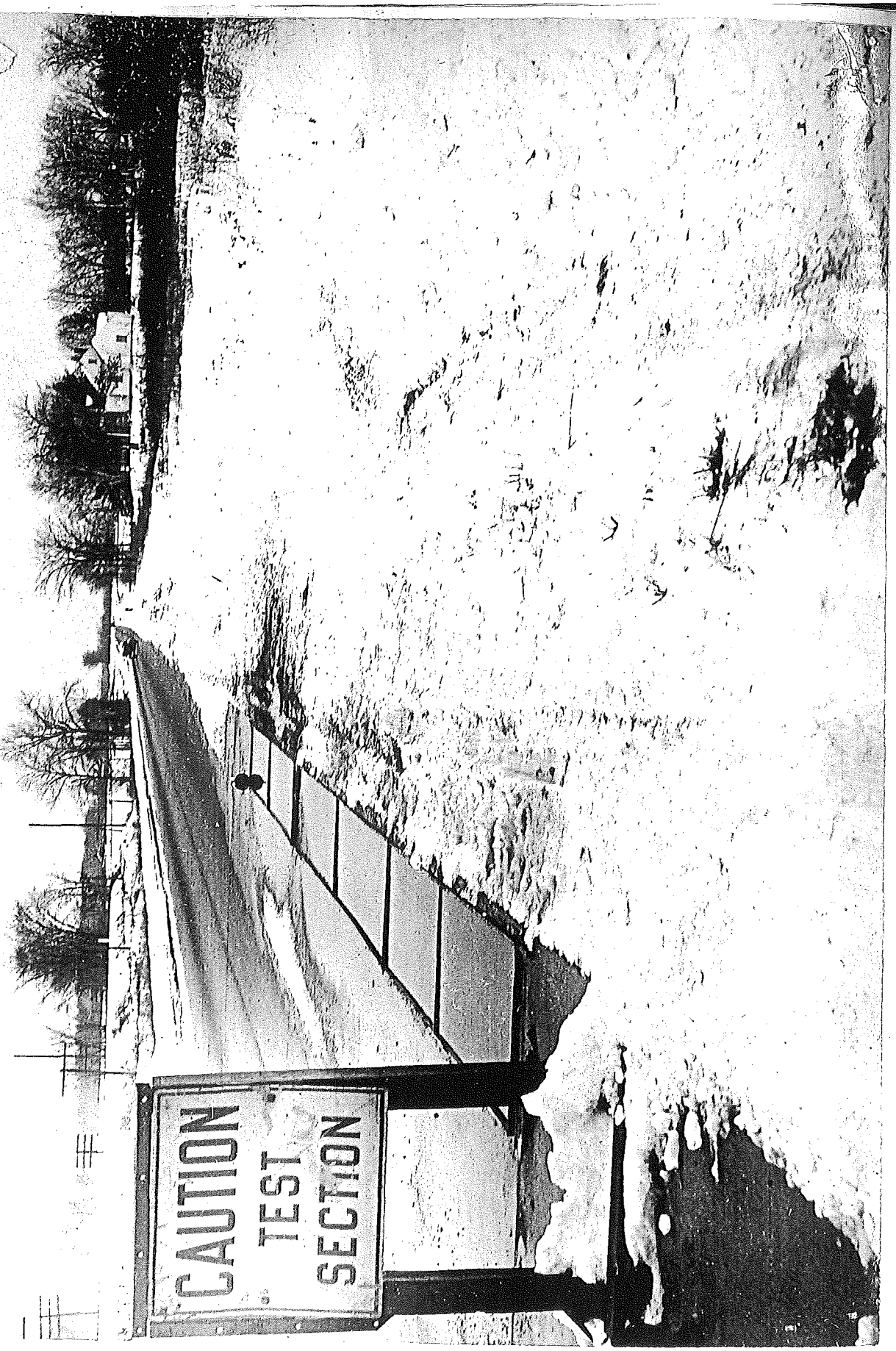
Accelerated Scaling Studies: The scale resistance properties of the respective concrete sections were subsequently evaluated by a series of accelerated scaling studies conducted during the winters of 1940-1941 and 1941-1942.

To accelerate the scaling action of chloride salts, test panels three feet wide and twelve feet long were located at selected spots on each concrete surface embodying the special feature under consideration. Water was

applied to the test area 1/4 inch deep and allowed to freeze over night. The following morning the ice was melted by distributing calcium chloride over the area at the rate of five pounds per area. When the ice was disintegrated the slush was removed and the surface flushed. Fresh water was again applied to the test area and the freezing and thawing cycle repeated. At the end of each freezing and thawing cycle the amount of scale developed during the cycle was determined by superimposing over the test area a grid mesh with twelve inch openings. Weather conditions permitted a complete freezing and thawing cycle practically every day throughout the duration of the tests. A typical installation of test panels used in accelerated scaling studies is shown in figure 1.

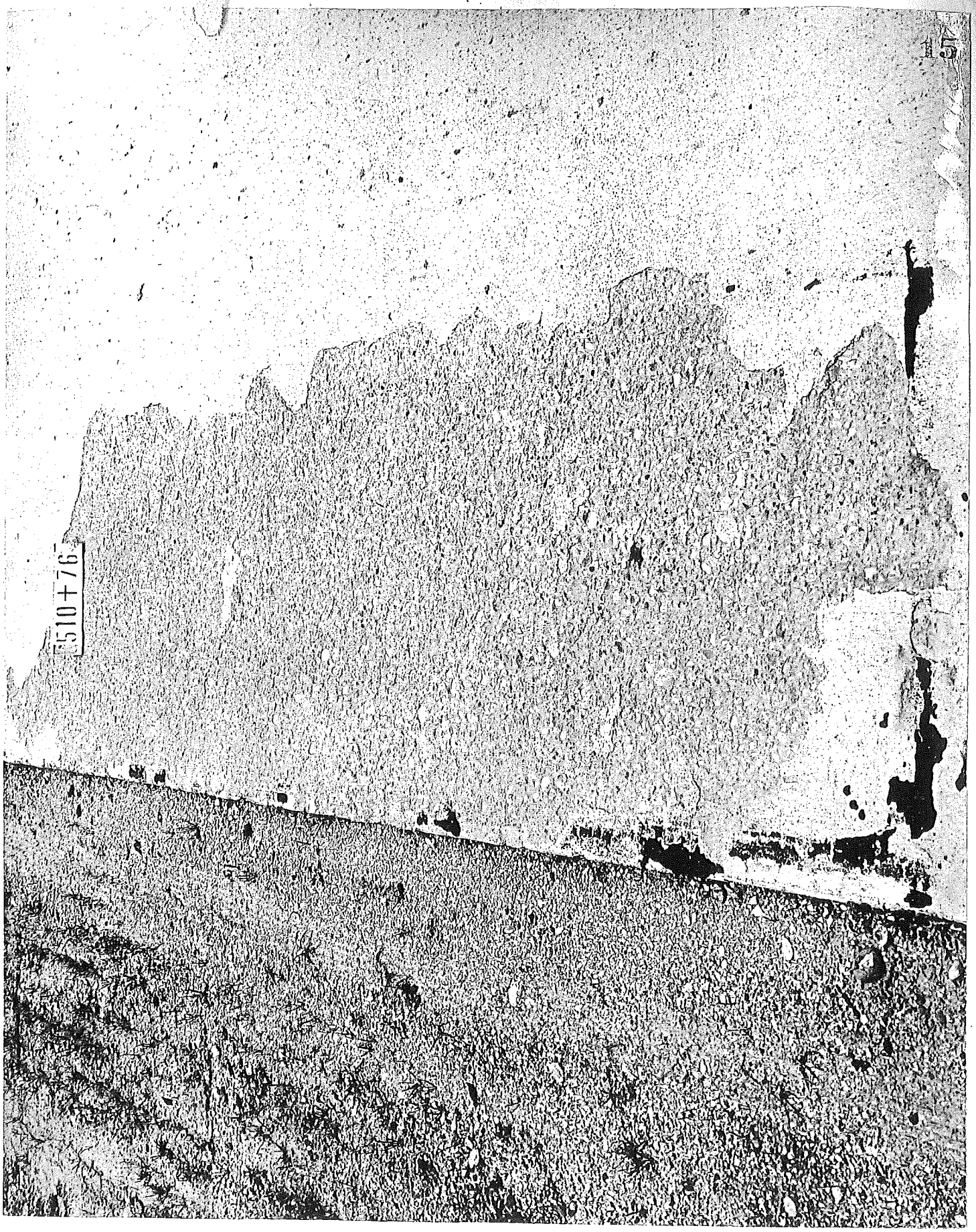
The air-entrained concretes containing Orvus or Vinsol resin did not scale under these tests, which were considered much more severe than would be experienced from normal de-icing operations. The data in Table I presents the relative resistance to scaling of the different concretes at conclusion of the tests. The air-entrained concrete panels did not scale after 95 cycles whereas 100 percent surface scale occurred on standard concrete after an average of 24 and 22 cycles. Figures 2, 3 and 4 illustrate the relative condition of the respective pavement surfaces after a definite number of freezing and thawing cycles.

Durability Studies. Additional freezing and thawing tests on core specimens obtained from the several concrete pavement sections containing air-entraining materials were performed in the laboratory.



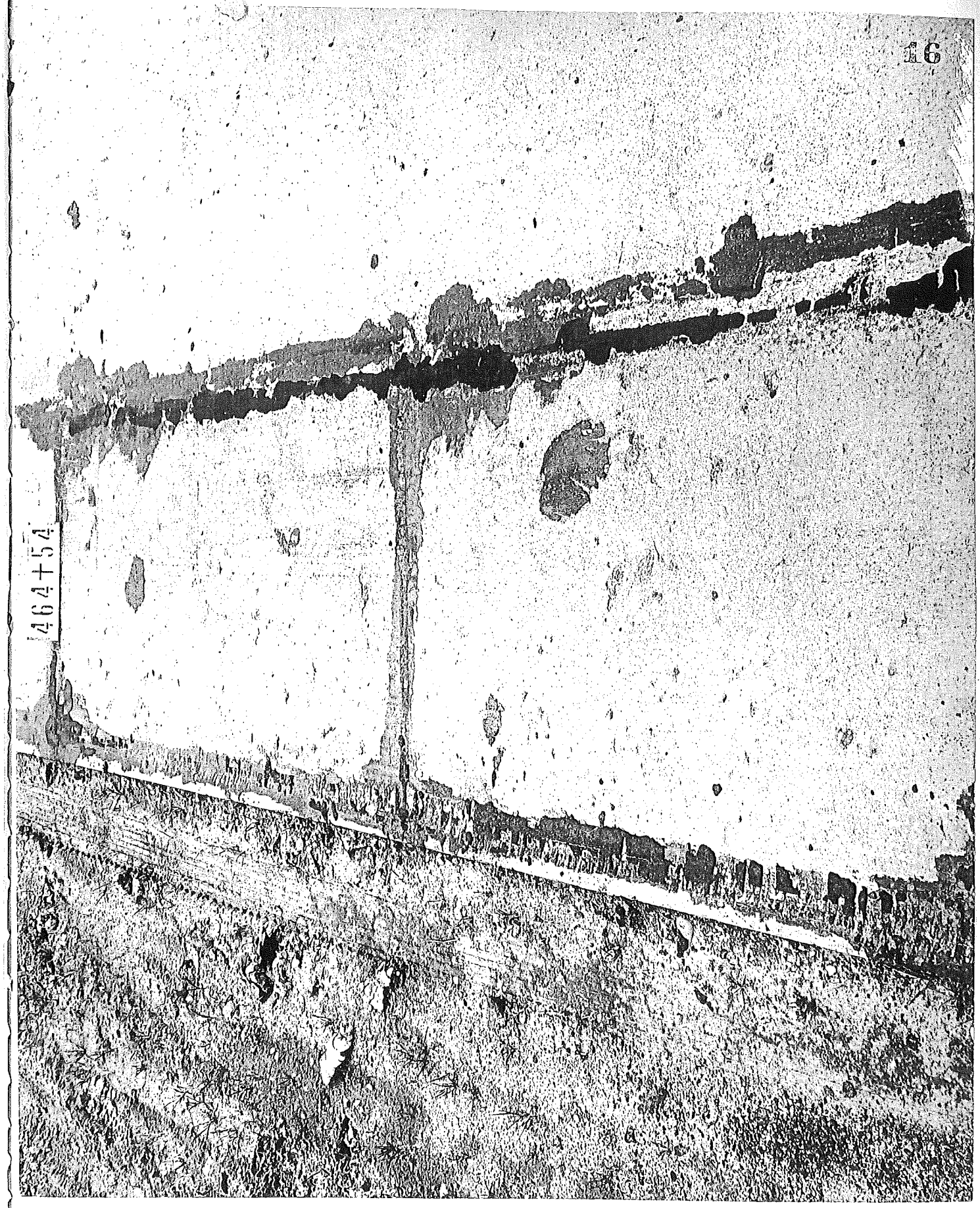
Typical installation of test panels used in accelerated scaling studies.

Figure 1



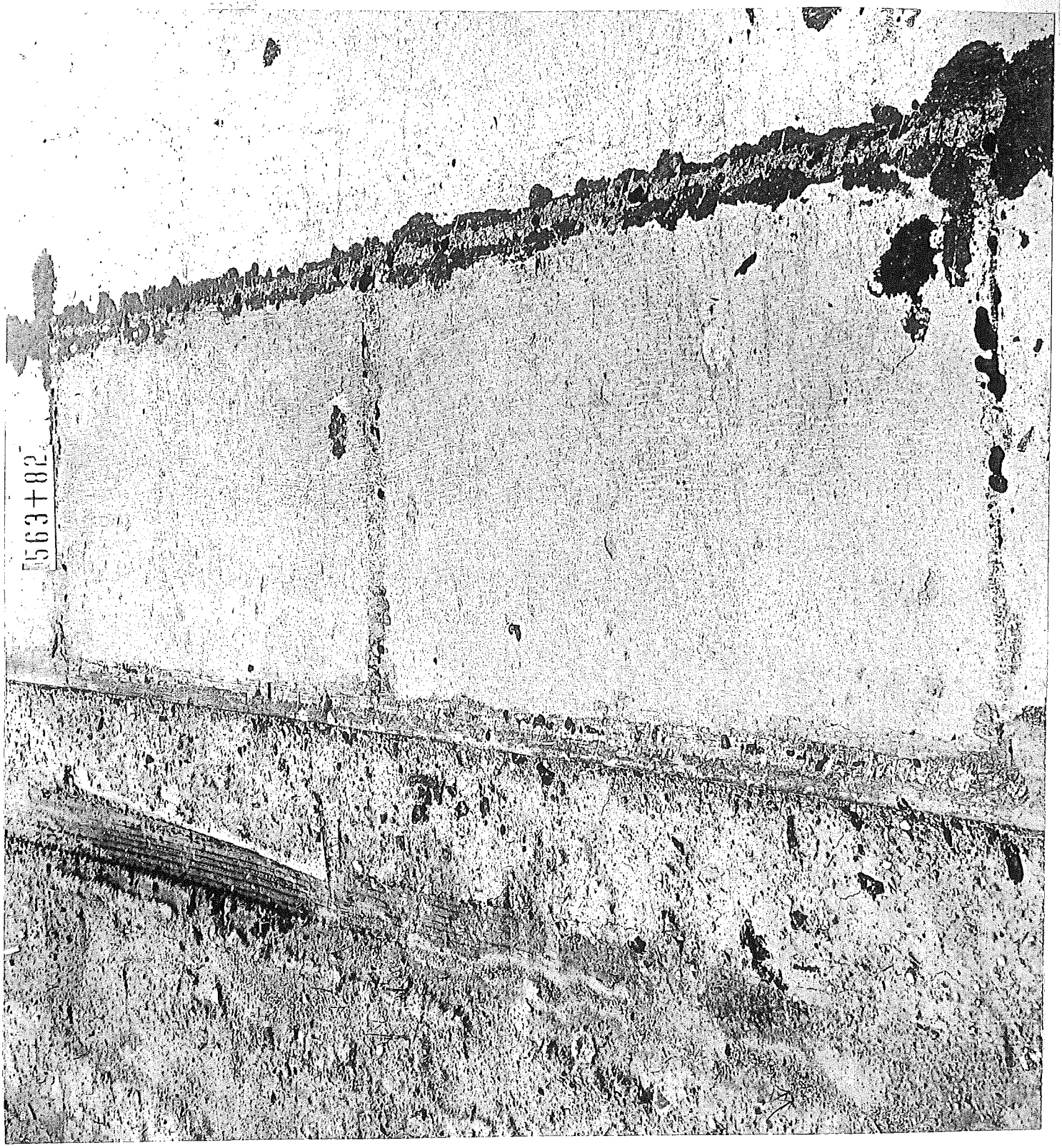
Typical condition of ordinary concrete after 9 cycles of freezing and thawing, 100 per cent scaled.

Figure 2.



Condition of concrete containing Orvus, after 93 cycles of freezing and thawing. No scale.

Figure 3.



Condition of concrete containing Vinsol Resin after 93 cycles of freezing and thawing. No scale.

Figure 4

TABLE I

COMPARATIVE RESULTS FROM SCALING STUDIES

Air-Entraining Material	Brand Cement	1940 - 1941 Cycle**	1940 - 1941 % Scale	1941 - 1942 Cycle**	1941 - 1942 % Scale
Orvus	1	33	0	*93	0
Orvus	2	33	0	*94	0
Vinsol Resin	1	33	0	*93	0
Vinsol Resin	2	33	0	*94	0
None	1	33	61	41	100
None	1	13	100	9	100
None	2	21	100	32	100
None	2	27	56	7	100

* 1942 Studies continued on panels tested in 1941

** Number of cycles at which scaling studies were discontinued due to weather conditions or when 100 percent scaling of test panel occurred.

At the time of the test the core specimens were 21 months old. The cores were frozen and thawed in water each day until complete disintegration had taken place. Two interesting facts were observed from these test data which are summarized in Table II. In the first place, cores drilled from the air-entrained concrete had with few exceptions considerably greater resistance to freezing and thawing than those taken from ordinary concrete and second, the air-entrained concrete resisted deterioration equally at top and bottom of the core, whereas the ordinary concrete was considerably weaker at the top than at the bottom. The latter phenomenon has for a long time been known to exist in normal concrete pavements. Apparently this inherent weakness can be corrected by the use of air-entraining materials.

Air-Entraining Materials with Limestone Aggregates.

Further experimentation was carried on using air-entraining materials with limestone aggregates as an attempt to improve the objectionable characteristics of stone sand in concrete such as bleeding, poor workability, difficult finishing and excessive scaling. This work was done on Project M 75-28, C2 located on M-94 in the City of Manistique, Schoolcraft County in 1941. Orvus was used as the air-entraining material and was added at the mixer in specified amounts of approximately 0.05 pounds per barrel of cement throughout the entire project. In part of the project mineral filler was added in addition to the air-entraining material.

It was observed that the introduced air reduced considerably the bleeding so typical of stone sand mixes and improved the workability of the con-

TABLE II

SUMMARY OF RESULTS FROM CORE STUDY

Air Entraining Material	Brand Cement	Cycles for Disintegration	
		Top	Bottom
Orvus	1	205	205
Orvus	2	110	200
Vinsol Resin	1	175	170
Vinsol Resin	1	200	200
Vinsol Resin	2	205	200
Vinsol Resin	2	215	200
Standard	1	120	135
Standard	1	120	195
Standard	2	80	110
Standard	2	70	135

Results are for individual cores, rather than an average of a group.

crete over that of regular stone sand concrete. The added fines in addition to the entrained air contributed materially to the reduction of bleeding and improvement in workability of the concrete mixture. Beam tests indicated that the concrete in all cases was up to specification requirements both for the seven day and twenty-eight day periods.

During the following winter, 1941-1942, this pavement was subjected to the same type of accelerated scaling tests described previously. At the completion of 75 cycles of freezing and thawing, there was no indication of scaling in either section. A recent inspection, in 1945, revealed that no surface scaling had taken place. Figure 5 shows the present relative condition of two different limestone aggregate projects abutting each other. The concrete on the left of the joint is that of the Manistique test project where air entrainment was used. No scaling is noted. The concrete to the right of the joint is badly scaled. This concrete contained no air-entraining agent.

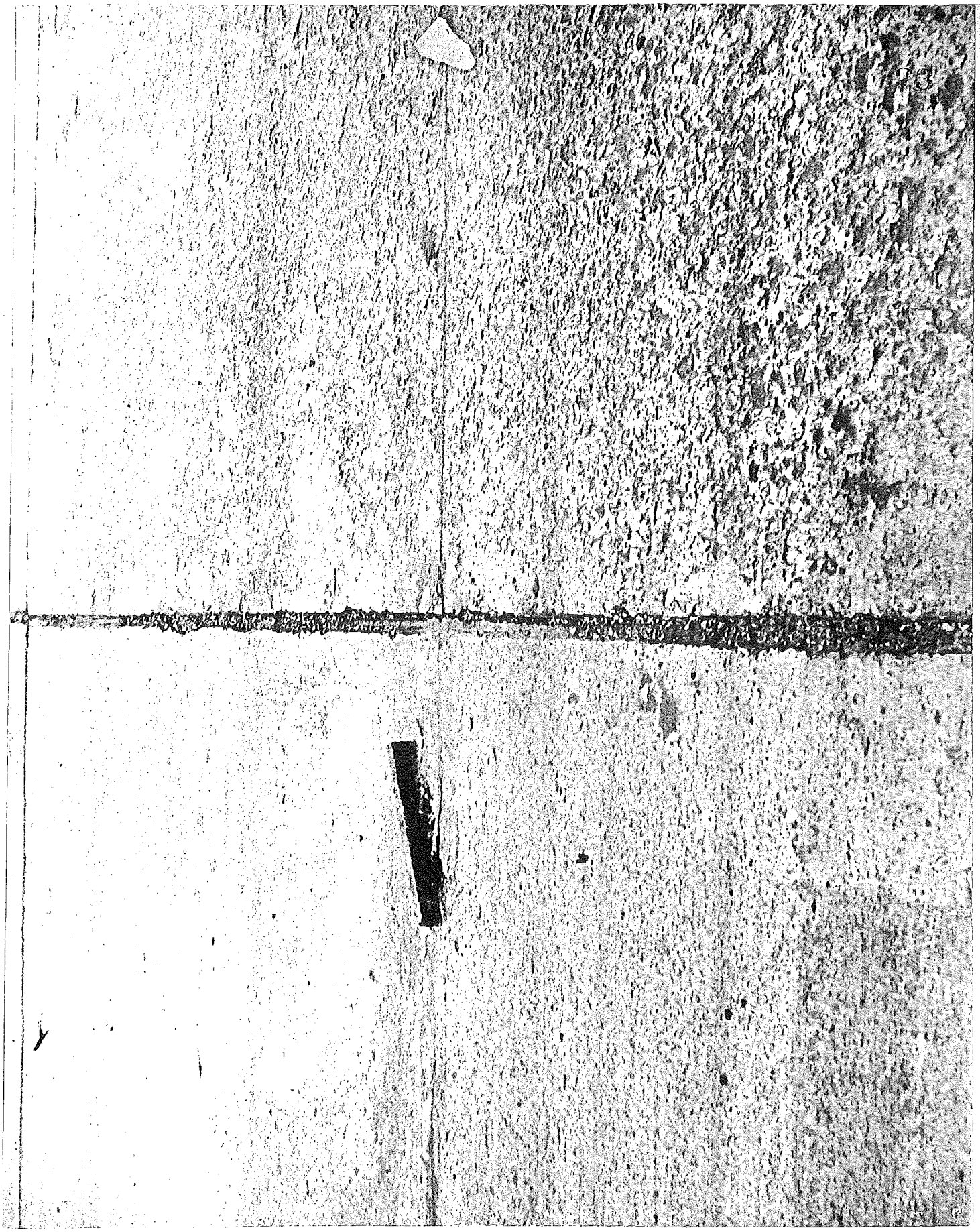
On the basis of the encouraging results obtained from the various test projects, the Department authorized in 1941 the use of air-entraining materials in several concrete pavement projects. From 1941 to 1943 approximately 100 miles of air-entrained concrete pavements were constructed. In all of this work the air-entraining material was added at the mixer.

The effectiveness of air entrainment in eliminating scale can be found in many cases where projects containing air-entrained concrete abut

projects constructed with ordinary concrete. The contrast in scale resistance is striking, as illustrated in Figures 6, 7 and 8. This example is typical of many others to be found throughout the state.

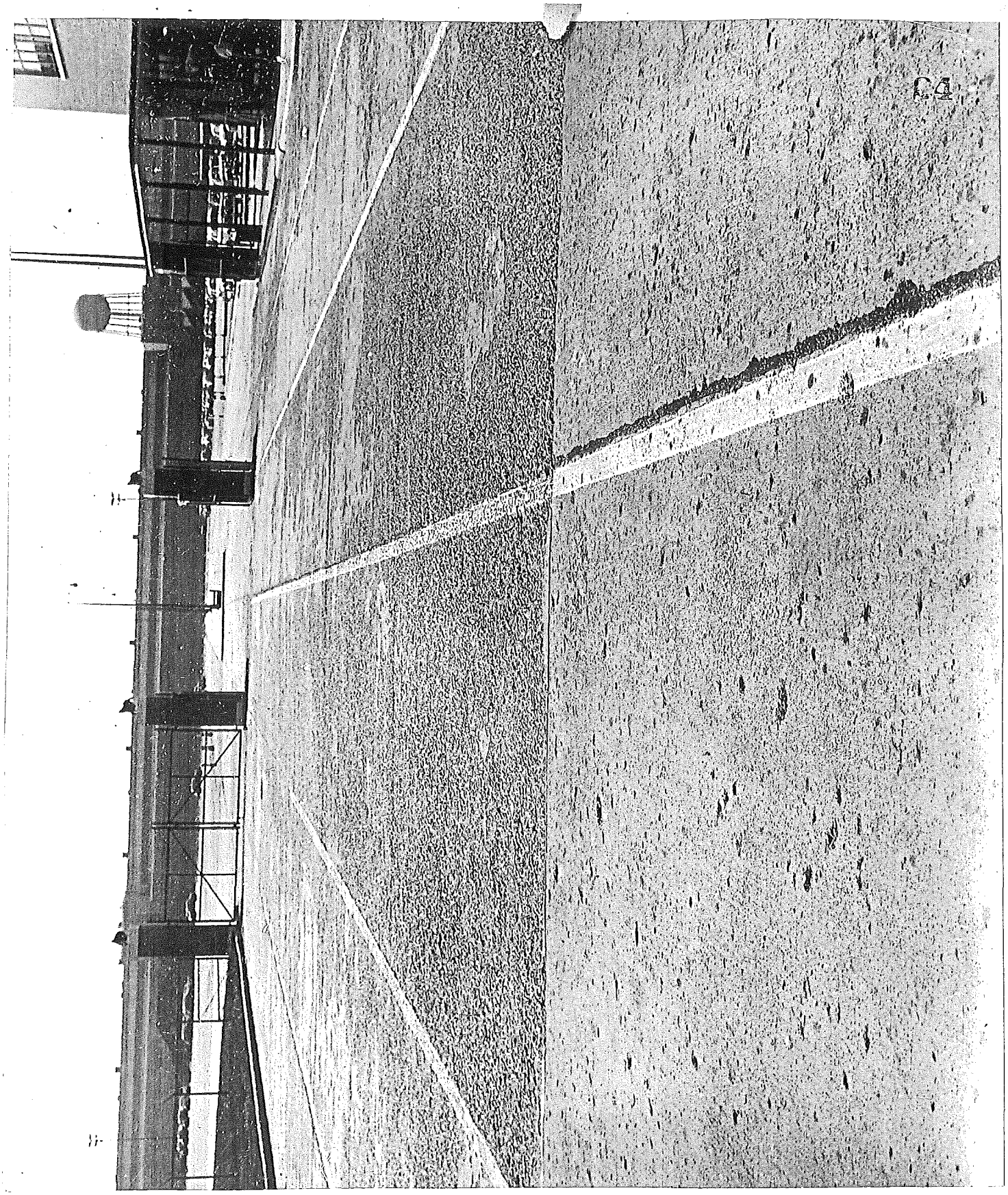
In 1943 specifications for Vinsol Resin air-entraining portland cement were officially recognized by the American Society for Testing Materials and by the Government. With the advent of air-entraining cement the practice of adding air-entraining materials at the mixer has practically ceased in Michigan. At the close of the construction season in 1945, Michigan had approximately 150 miles of two-lane pavement containing air-entrained concrete.

It is now generally acknowledged that the use of air-entraining materials in concrete pavements is a distinct step forward in the construction of better highways for the future and indicates the successful solution of just one of the many problems confronting highway administration today. The Department, recognizing the advantages to be gained by this new development, now requires that air-entraining materials be used on all concrete pavement projects constructed under its jurisdiction.



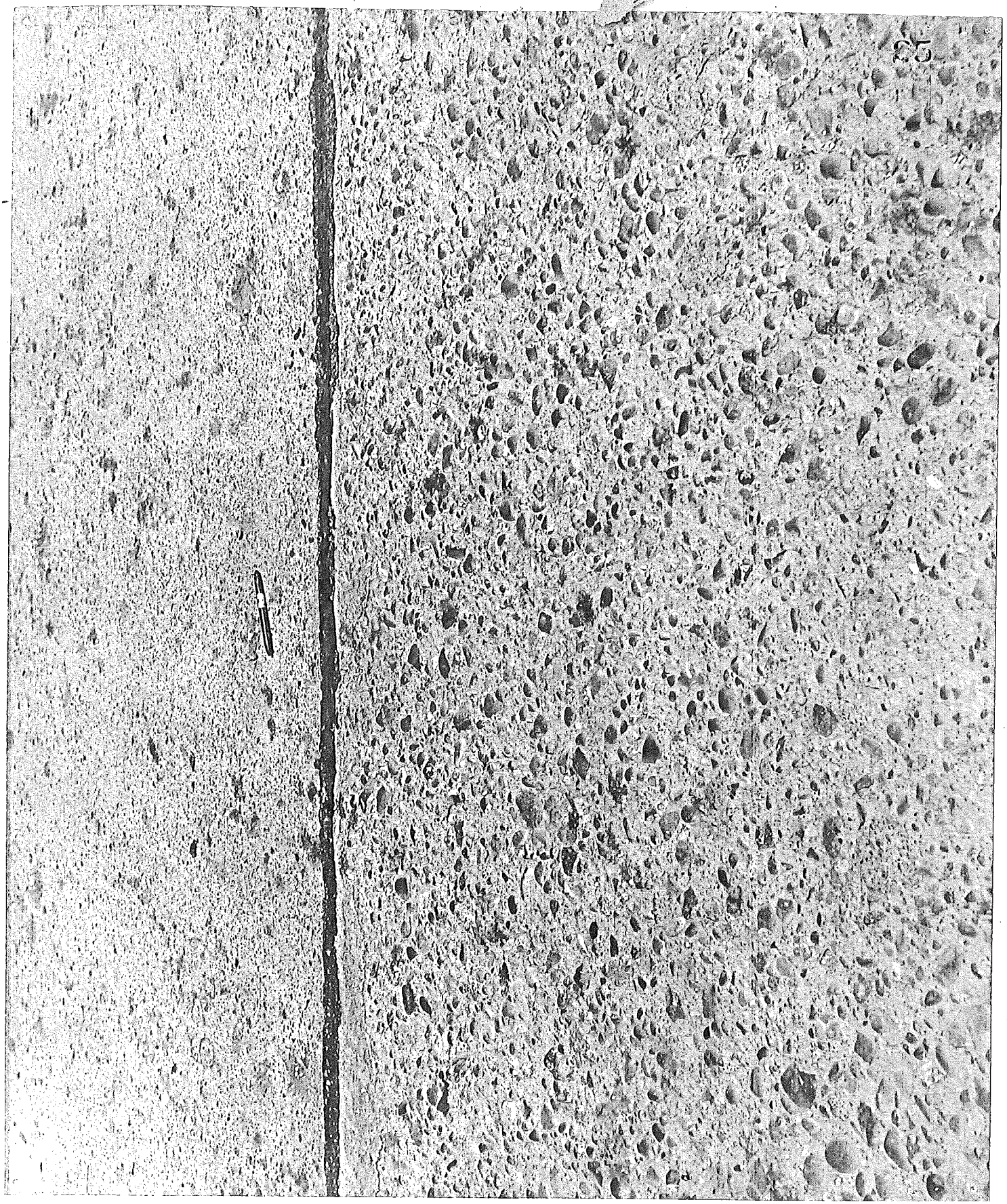
Manistique Limestone test project. Air-entrained concrete on left of joint. Ordinary limestone concrete on right.

Figure 5



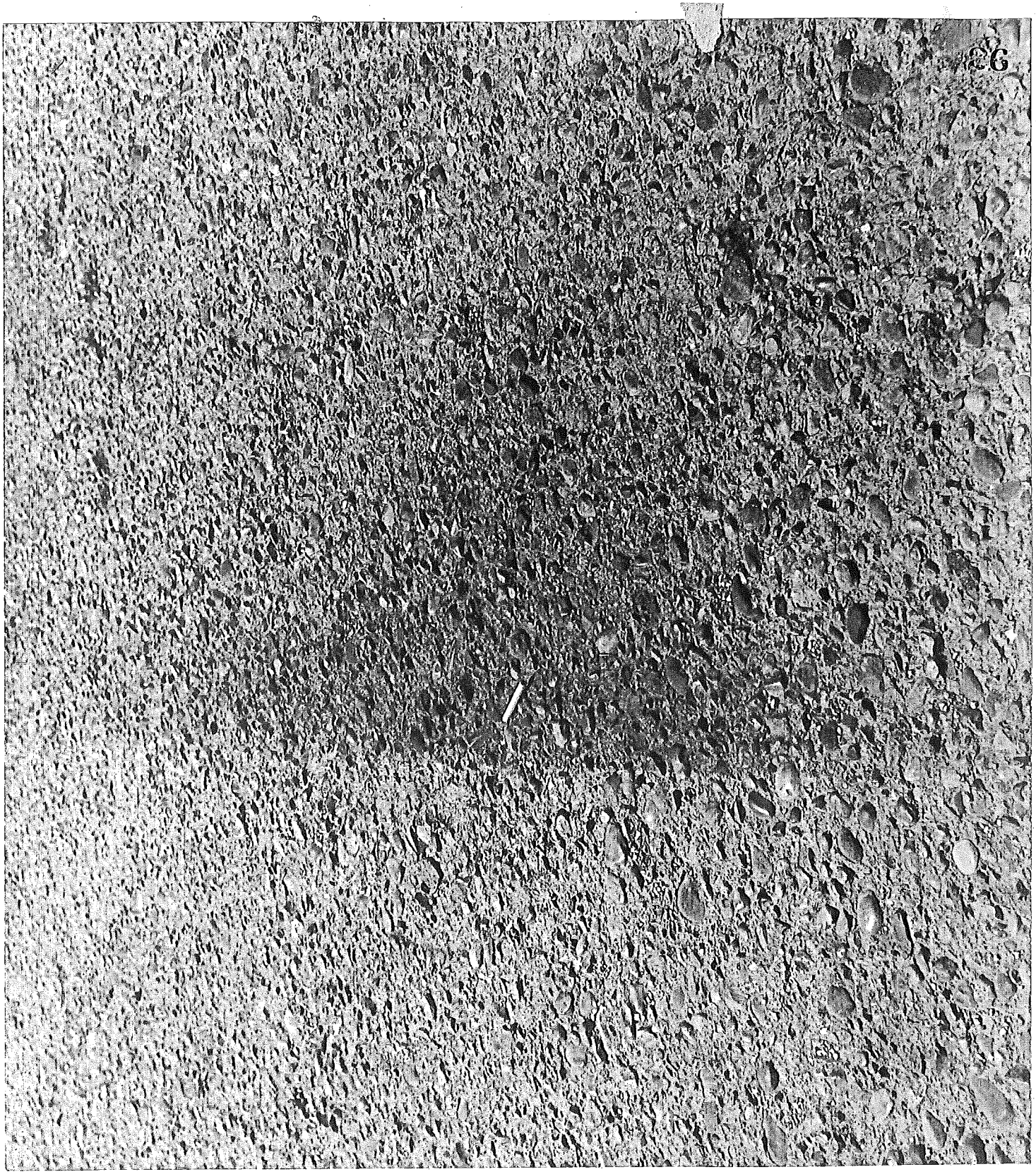
Entrance to Ford Bomber plant, Willow Run. Air-entrained concrete in foreground, end of State construction.

Figure 6



Entrance to Ford Bomber Plant, Willow Run. Close view of concrete surfaces in Figure 6 showing general condition of scaled and unscaled surfaces. Air-entrained concrete in background.

Figure 7



Entrance to Ford Bomber Plant, Willow Run. Close view of concrete surface in Figure 6 showing depth of scaling.

Figure 8

1. Typical Installation of Test Panels used in Accelerated Scaling Studies.

2. Table I - Comparative Results from Scaling Studies.

3. Typical condition of ordinary concrete after 9 cycles of Freezing and Thawing, 100 percent scaled.

4. Condition of Concrete containing Orvus, after 93 Cycles of Freezing and Thawing. No Scale.

5. Condition of Concrete containing Vinsol Resin after 93 Cycles of Freezing and Thawing. No scale.

6. Table II - Summary of Results from Core Study

7. Manistique Limestone Test Project. Air-entrained Concrete on left of joint. Ordinary Limestone Concrete on right.

8. Entrance to Ford Bomber Plant, Willow Run. Air-entrained Concrete in foreground, end of State Construction.

9. Entrance to Ford Bomber Plant, Willow Run. Close view of Concrete Surfaces in slide 8 showing general condition of Scaled and Unscaled Surfaces. Air-entrained Concrete in background.

10. Entrance to Ford Bomber Plant, Willow Run. Close view of Concrete surface in slide 8 showing depth of scaling.