

MICHIGAN
STATE HIGHWAY DEPARTMENT
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AIR-ENTRAINED CONCRETE

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One form of concrete deterioration prevalent in Michigan, as well as in other states in corresponding climatic zones, 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 has been of vital concern to highway engineers for years and the subject of considerable research. This problem has led, within the last few years, to a concerted program of research in which many agencies have participated, including certain federal departments, several State Highway Departments, cities, portland cement manufacturers, as well as the Portland Cement Association.

The aim has been to develop a concrete more durable to frost action and which would have high resistance to the action of chloride salts as they are now used on our highways and streets.

Preliminary studies in air entrained concrete started in 1935 when New York State constructed several experimental pavements to determine methods of increasing the scale resistance of concrete pavements. Included in their studies were many different brands of Portland Cement used alone and blended with natural cements with and without fatty materials. Also they experimented with portland cement ground with beef tallow, fish oil stearate and Vinsol resin.

On the basis of the results obtained from their studies with air entraining materials from 1935 to 1939 there was started in 1940 considerable research work on this subject by different State Highway Departments, cement manufacturers and other interested agencies.

The results of investigations by the several agencies have demonstrated conclusively that concrete having excellent durability and high scale resistance can be produced by incorporating into the concrete mixture proper amounts of minute uniformly distributed, but disconnected air bubbles. In addition, the entrained air in the concrete produced better workability of the concrete and eliminated excess surface water or bleeding which materially reduced the time interval between mixing and finishing operations.

This paper presents the significant facts pertaining to the use of air entrained concrete in highway construction resulting from the many studies on this subject and including the experiences of the Michigan State Highway Department in the use of air entrained concrete during the last four years.

FACTS CONCERNING AIR-ENTRAINED CONCRETE

At the present time air is introduced into the plastic concrete in a practical way by means of certain organic materials which are either added directly to the concrete batch at the mixer or interground with the cement clinker during the process of cement manufacture. The product produced by the latter method is known as air-entraining portland cement.

1. Methods of Entraining Air in Concrete:

The air entraining materials which have been investigated and tried experimentally in varying amounts may be grouped into several classes: (1) mineral oils; (2) animal or vegetable fats or oils; (3) wetting agents and (4) natural resins.

Mineral Oils. Mineral oils were not added intentionally to increase air voids and thus durability of concrete. They were introduced into the cement by accident through leakage of bearing in some types of grinding machinery. The discovery of the fact that the presence of small amounts of this oil in the cement increased the durability of the concrete was greatly responsible for the trend of research in this field.

Animal or Vegetable Fats. Small additions of animal or vegetable fats or oils have been made to portland cement for years, for purposes of obtaining "waterproof products" and as grinding aids. They are more effective in producing air voids than the mineral oils. Beef tallow is the more common of these materials.

Wetting Agents. Wetting agents or foaming agents of which there are a great number, have been used with considerable success to entrain air in concrete. The most extensively used material of this group is a commercial and patented product called Orvus, manufactured by the Procter & Gamble Soap Co. This is a sulphated fatty alcohol containing sodium lauryl sulfate as

the material

the active ingredient. ~~Orvus~~ is procurable in paste or powder form and must be dissolved in water to form a solution of desired concentration. This solution is added at the mixer. X

Natural Resins. Natural resins products from wood have been used occasionally as grinding aids in cement mills, when added in proper amounts continuously, it resulted in a very effective air-entraining cement. The resin with which most experience has been had and from which results are most consistent is Vinsol resin. X

Vinsol resin is a hard, high melting, dark colored resinous commercial product manufactured by the Hercules Powder Company under patents which have been dedicated to the public use by the Company. It consists substantially of the petroleum-hydrocarbon insoluble fraction of a coal-tar hydrocarbon extract of pine wood.

It is available as a finely ground non-caking powder or in emulsion form. Chemically Vinsol resin is an impure abietic acid in powder form. When the acid comes in contact with the portland cement and water it forms a calcium salt of abietic acid which has the characteristics of soap, and as such, favors the entrainment of air in concrete during mixing operations.) R

Vinsol resin has been used in different forms for air-entraining purposes, first, it is most commonly obtained in powder form and as such, must be ground with the cement for best performance as an air-entraining material. This method is used more extensively than any other at the present time. Sodium Resinates made from Vinsol resin in combination with sodium hydroxide are available in powder form and when dissolved in water the solution is added at the mixer. An emulsion containing Vinsol resin is also available commercially for air-entraining purposes. This material is also added at the mixer.

Gas Generating Agents. In addition to the organic materials, certain gas generating agents as aluminum powder and hydrogen peroxide have been employed with considerable success to produce air voids in concrete.

The aluminum powder reacts with the calcium and alkali hydroxides produced during the hydrolysis of the cement to form hydrogen gas which is trapped in the concrete to form air voids. Hydrogen peroxide in the presence of metallic-oxide decomposes completely to water and oxygen. The liberated oxygen produces air voids in the concrete.

At the present time, Vinsol resin is the only air entraining material recognized in official specifications of the American Society for Testing Materials and of the Federal Government.

ENTRAINED AIR IN CONCRETE

Research and field experience at the present time indicate that for the best results for pavement concrete, taking into consideration, scale resistance, durability, and strength, are obtained when the reduction in weight is between the limits of 3 to 6 pounds per cubic foot, as compared with concrete of the same proportions and consistency made with the parent portland cement containing no air entraining material. This drop in weight per cubic foot is equivalent to approximately a 2 to 4 percent air content respectively. No appreciable improvement in durability is gained by going beyond the upper limit. In fact, a considerable reduction in strength is experienced as the air content is materially increased. The present trend is to keep the air content as low as possible.

Experience indicates that the optimum quantities of air entraining materials of the different classes which must be used per sack of cement to obtain the desired drop in weight or proper air content is approximately as

follows:

Mineral Oils	0.04 to .06 per cent
Animal Fats & Oils	0.01 to .03 per cent
Wetting Agents (Orvus Paste)	0.005 to 0.025 per cent
Vinsol Resin (In Portland Cement)	0.025 to 0.045 per cent

The amount of entrained air in a concrete mixture is reflected by a reduced weight per cubic foot. Therefore, it is possible to measure the air content of a concrete mixture by the simple unit weight determination. The unit weight determination provides a practical field method for checking the air content of the concrete as placed as well as the yield value. Other methods are being developed to facilitate easy and accurate determination of the air content of concrete mixture both in the laboratory and in the field.

The amount of entrained air in a concrete mixture increased with the quantity of air-entraining material, with the slump of the concrete, with the leanness of the mix and with the mixing time. Experience has shown that optimum results are obtained with the quantities of air entraining materials specified above when the cement content of a mixture is between 5 and 7 sacks per cubic yard, the slump approximately 2 inches and mixing time 1 minute. It is important to control concrete mixtures within these limits, in order to avoid unnecessary reduction in strength without gain in durability and possible construction difficulties.

The introduction of air into the concrete mixture results in an increased volume of mortar caused by the bulking effect of the entrained air. Moreover, the fatness of the mortar makes any additional volume of mortar unnecessary. Therefore, in designing air entrained concrete mixtures, the volume of mortar per unit volume of concrete should be maintained the same as for normal concrete mixtures. This can be done by adjusting the quantity of sand and water content. Thus it is possible to maintain standard cement

factors, avoid over sanded mixtures and alleviate the tendency towards reduction in strength.

CHARACTERISTICS OF AIR-ENTRAINED CONCRETE

The introduction of proper amounts of well distributed minute air bubbles into a concrete mix apparently decreases the particle interference of the concrete 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 extreme fatty appearance similar to an over sanded mixture. Segregation and bleeding are practically eliminated. As a result there is little free water on the surface to facilitate or delay the finishing operations. Therefore, it is necessary that finishing operations be completed with a minimum of delay or else drying of the surface will hinder proper finishing. Extreme fluctuations in temperature and relative humidity and wind velocity will influence the finishing characteristics of the air-entrained concrete.

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

Concrete strengths are decreased in proportion to the increase in air content. The decrease in flexural and compressive strengths corresponding to optimum air contents is between 5 percent and 20 percent. In the design

of air-entrained concrete mixes advantage may be taken of such factors as increased volume of the mortar and inherent workability resulting from fatness of the mortar to overcome excessive drop in strength values by increasing the cement to sand^d ratio and decreasing the water to cement ratio. In practice it is possible to reduce the sand 3 to 4 pounds per sack of cement and the water approximately 1/2 gal. for same amount of cement.

CONSTRUCTION PRACTICE

In the field, the proper air content in the mixture is determined by checking the unit weight. Any discrepancy between actual weight and design weight per cubic foot is corrected by adjusting the amount of air-entraining material added at the mixer or the quantity of the sand. In the case of Vinsol resin cement the only adjustment possible will be in the quantity of sand per batch.

Certain construction procedures must be closely observed in order to obtain maximum benefit from the use of air-entraining materials. In the first place it is important that the water content be controlled to very narrow limits. The water content of the mixture greatly influences the amount of entrained air which can be incorporated into the concrete. Also the mixing time should not exceed the normal time of approximately 1 minute. Prolonged mixing may cause excessive air entrainment.

The use of Vinsol resin cement requires special attention as to its handling at the batching plant, especially so when furnished in bulk form. Because it flows more freely than standard portland cement there can be considerable loss in handling at the plant or during the transportation of materials in the batch trucks. It has been found desirable to place the cement between layers of aggregates in the batch trucks.

Calcium chloride in amounts up to 2% have been added successfully

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to air entraining^{ed} concrete to facilitate paving operations during periods of low air temperatures. The presence of the calcium chloride in the mix tends to offset the inherent slow setting properties of air entraining^{ed} concrete at low air temperatures. In addition, laboratory test indicate that calcium chloride causes an increase in strength at early ages, over that of normal concrete poured under similar conditions. It has been observed from actual experience in the field that the water content of the concrete mixture must be held at a minimum in order to insure normal construction operations in cold weather, ^{especially} when calcium chloride is used with air entrained concrete.

PART II
MICHIGAN'S EXPERIENCES IN THE USE OF AIR ENTRAINING MATERIALS

Michigan's experience in the use of air entraining materials in concrete pavements dates back to the construction of the Michigan Test Road during the summer and fall of 1940. The Michigan Test Road was constructed in cooperation with the Federal Works Agency, Public Works Administration on M 115, between US 10 and M 66 in Clare and Osceola counties. Included in the test road was an investigation of sealing, to determine its causes and methods of prevention. The investigation was dedicated to the establishment of certain fundamental principles in concrete construction and to correlate certain laboratory studies with construction methods in order to develop more durable concrete pavements. To obtain this end, the investigation was divided into two separate studies: first, a laboratory study of concrete durability as related to scaling; and second, the construction of a special pavement for field observations which is widely known as the durability project of the Michigan Test Road.

The durability project was constructed to furnish a field laboratory for the purpose of observing, under service conditions, certain important

factors relevant to current highway construction practice which might be in some manner associated with scaling, or which might, when properly controlled, increase the resistance of the concrete to scaling. The factors receiving major consideration were proportioning and grading of aggregates with definite recognition of the material passing the 200 mech; the relative effect of additives, including both physical and chemical varieties; the effect of natural cement blends and cements produced with grinding aids as air-entraining materials; and the relationship of finishing operations and curing methods to scaling.

The durability project was constructed in conjunction with a complementary pavement project for the study of concrete pavement design. The two research projects constitute the Michigan Test Road. A map giving the general location of this project (in the State) is shown in Figure 2. The durability project is 7.7 miles in length. The location is ideal from a standpoint of average weather conditions in Michigan and the length is sufficient to reduce the variables of construction to a minimum for each factor investigated. The project was constructed under regular contract and construction procedure using the Michigan State Highway Department's 1940 plans and specifications with necessary supplementals.

The cements used on the durability project included two brands of regular portland cement as normally used in the construction of concrete pavements in Michigan. Admixtures included the use of certain proprietary materials known as Plastiment, Pozzolith, Orvus and Vinsol resin. Natural cement, ground with and without the use of calcium stearate was also included as a blend with standard portland cement. Mineral fillers and natural fines were added in certain instances to increase the density and workability of the mix and as a possible factor in the reduction of scaling.

Mix designs included the regular proportioning as determined by the material specifications and the mortar void design method in the Michigan State Highway Department. Short test sections 120 ft. in length were included to determine the relation of scaling ^T methods of curing. X

The two air entraining materials which were selected for study on the durability project are a wetting agent called Orvus and a grinding aid of the resinous type commonly known as Vinsol resin.

Sufficient Orvus was added to the Mix to produce a drop in weight of 4 to 6 pounds per cubic foot of concrete of the same consistency and cement content without the addition of Orvus. It was found that, for the particular materials used on the durability project, 0.06 pounds of Orvus per barrel of cement gave a reduction in weight of approximately 5 pounds per cubic foot. The Orvus paste 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.

On the durability project two cement manufacturers furnished Vinsol resin portland cement milled from the same clinker respectively as was used in manufacturing standard portland cement for the durability project. The Vinsol resin cement was manufactured under specifications furnished by the Portland Cement Association as follows: - "The cement shall be ground with 0.15 pounds (\pm 20 percent) of pulverized Vinsol resin per barrel which should be uniformly added to the clinker at time of grinding. The specific surface of the cement as determined in accordance with A.S.T.M. C 115-38T shall not be less than 1750 nor more than 2100 square centimeters ^{per} ^{gram} specification gave the proper weight drop of approximately 5 pounds per cubic foot for the materials used on the project. "

Measurements of drop in weight in the field showed that

Physical Characteristics of Plastic Concrete:

The concrete mixtures resulting from the use of either of the two air entraining materials (Orvus and Vinsol resin) were very similar in their physical characteristics during the plastic state. The workability of the concrete with entrained air was decidedly better than that of normal portland cement concrete. Practically no segregation or bleeding was experienced. Straight edging and floating of the plastic concrete containing entrained air was slightly more difficult than the standard portland cement concrete because it has an inherent characteristic of becoming somewhat sticky. The concrete mixture with entrained air has the appearance of being fatty or over sanded. It was also noted that its finishing characteristics were influenced somewhat by extreme fluctuations in temperature and relative humidity at time of pouring.

Strength Characteristics of Aged Concrete:

During the construction of the durability project 6"x12" compression cylinders and 6"x8"x24" beam specimens were prepared for subsequent strength test in order to determine the effect of the various admixtures on the strength characteristics of the concrete. Average results from these tests are shown in Table 1. The strength values are also compared on a percent basis with those of the concrete made with standard portland cement No. 1. This particular brand of cement was used as a reference throughout the project.

The data in Table I show a decided drop in strength characteristic if the concrete containing air entraining materials, as compared to normal portland cement concrete. The Vinsol resin cement on an average gave better strength characteristics than the Orvus material. Yet with but one exception the flexural strength of the concrete containing Orvus or Vinsol

TABLE I

SUMMARY OF CONCRETE STRENGTH DATA

Material	Cement	COMPRESSION STRENGTH						FLEXURAL STRENGTH**			
		6"x12" Cylinders				Cores 6"		Beams 6"x8"x24"			
		7 Days		28 Days		20 Months		7 Days		28 Days	
p.s.i.	% Var.*	p.s.i.	% Var.*	p.s.i.	% Var.*	Mod.of Rup. p.s.i.	% Var.*	Mod.of Rup. p.s.i.	% Var.*		
Orvus	1	2608	74	3728	81	3962	74	339	69	562	80
Orvus	2	2324	66	3857	84	3820	71	425	75	602	86
Vinsol Resin	1	2845	90	3867	84	4010	75	508	89	529	75
Vinsol Resin	2	3580	101	3991	87	5420	101	576	102	771	110
Standard	1	3543	100	4587	100	5375	100	567	100	702	100
Standard	2	2837	80	4597	100	6600	123	546	96	659	94
Specification Strength				2500				550		650	

* Percent Variations Based on Standard Cement No. 1

** By Three Point Loading Method A.S.T.M. Designation C 78-59

resin was below specification requirements by a considerable amount. This marked difference in strength values may be attributed to the high air content required in the concrete and to the inability of the engineer to consistently control within definite limits such factors as water content, uniform gradation and workmanship throughout the construction of the project.

In order to further evaluate the merits of the air-entraining materials incorporated in the test road and to judge the relative performance of the resultant concrete in service, certain durability studies were made, including accelerated scaling tests on the slab surface and the freezing and thawing of field specimens as well as core segments.

Accelerated Scaling Studies:

The accelerated scaling studies consisted of exposing test panels of the pavement surface on the durability project to the action of ice and calcium chloride under controlled conditions.

The first and second of the series of scaling studies were completed during the winter months of 1940-1941 and 1941-1942 respectively.

Originally two test methods were employed to ascertain the resistance of concrete pavement mixtures to calcium chloride attack. The methods have been designated as methods "A" and "B". Method "A" was discontinued after the first year's study because it was found that method "B" gave more accelerated results and was better adapted to control procedure. In test method "A" a 10 percent solution of calcium chloride of 1/4 inch minimum depth was applied and allowed to remain in place 5 days. At the end of this period the solution was removed, the panel flushed, and water applied to a depth of 1/4 inch. After the water had frozen, the ice was melted by an application of 5 pounds of flake calcium chloride per area.

When the ice was decomposed, the slush was removed from the test area, the surface was flushed and allowed to rest one day before beginning the next cycle.

Test area "B" received a different treatment. Water was applied to the test area and allowed to freeze over night. The following morning the ice was melted by distributing calcium chloride over the area at the rate of 5 pounds per area. When the ice was decomposed, the slush was removed from the test area and the surface was flushed. Fresh water was applied to the test area and the freezing and thawing cycle repeated. On the basis of the quantity of water resulting from the melted ice in each test area, it was calculated that 5 pounds of flake calcium chloride would be sufficient to produce approximately a 10 percent solution.

Each test area was constructed 3 feet wide and 12 feet long. A dyke was formed around the perimeter of this area of sufficient height to confine the water and calcium chloride solutions. The test panels are illustrated in Figure 3.

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 steel mesh grid with openings 12 inches square. By means of the grid the amount of scaled surface could be measured quickly and accurately.

During the first series of scaling studies in 1940-1941, two test panels were established for each factor studied. One test panel was subjected to test method "A" and the other to test method "B". In the second deason's studies condcuted in 1941-1942, test method "B" was repeated only on the test areas pertaining to those certain factors under comparative study where it seemed advisable to repeat the scaling observ-

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ations for two reasons: first, to verify or check the results of the first season's observations; and second, to correlate the age factor with the resistance of the concrete to scaling. Scaling tests were discontinued on those sections under observation which showed abnormal tendencies toward scaling during the first season's test, and on other sections which were believed to be of insignificant value to the research program.

The most significant fact brought out by the accelerated scaling studies was that the air entraining materials, Orvus and Vinsol resin, produced a concrete which was highly resistant to scale. This fact is clearly shown by the data presented in Table II. Figure 3 contains illustrations of the relative condition of the different pavement surfaces after a definite number of freezing and thawing cycles.

Freezing and Thawing of Field Specimens:

During construction of the durability project representative samples of concrete were molded into 3"x6"x15" beams for further examination in conjunction with the scaling studies. The beams were subsequently subjected to accelerated freezing and thawing tests in water to determine their relative resistance to disintegration by freezing and thawing action. The progressive deterioration of each specimen was measured by change in value of Young's modulus found by the sonic or dynamic method. The information sought was concerned primarily with the effect of the air entraining materials on the durability characteristics of the concrete, as compared with standard construction.

The freezing and thawing cycle consisted essentially of a 24 hour period in which the specimens were frozen in water over night and thawed the next day. A sonic reading was taken at the end of each five or ten cycle period to observe and record the progress of disintegration.

TABLE II
COMPARATIVE RESULTS FROM SCALING STUDIES

Year	Material	Cement	1940-1941		1941-1942	
			Cycle	% Scale	Cycle	% 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
	Standard	1	53	61	41	100
	Standard	1	15	100	9	100
	Standard	2	21	100	32	100
	Standard	2	27	56	7	100

* 1942 studies continuation of studies on 1941 panels.

The results from the freezing and thawing tests on the field specimens as presented in Table III indicate quite definitely that the air entraining materials Orvus and Vinsol resin imparted to their respective concretes the ability to resist disintegration by freezing and thawing action to a greater degree than that possessed by standard concrete mixtures.

Freezing and Thawing of Core Specimens:

A comparative durability study of core samples representing the various concrete mixtures embodied in the durability project was made in conjunction with the accelerated scaling studies and the laboratory freezing and thawing tests on molded field specimens. In conducting the core study three objectives were in mind: first, to gather additional data of value in evaluating the factors under consideration in the durability project; second, to observe the relative durability between the top and bottom of the pavement slab; and third, to determine the comparative merits of freezing and thawing concrete in a calcium chloride solution as compared to freezing and thawing in tap water.

The cores were removed from the pavement slab 4 months after completing pouring operations on the durability project, incidental to the Department's routine core check procedure for ascertaining the thickness of the pavement slab. Because of the large number of test areas involved in the study only one core from each test section was selected to represent the concrete in freezing and thawing. Companion cores from the same test areas were used to check pavement thickness and to determine the compressive strength of the concrete. At the time of conducting the tests on the core specimens the concrete had attained an age of 21 months X

Each core used in the durability study was cut transversely into three

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The results in Table IV are further proof indicative of the superiority of concrete with entrained air to resist deterioration by freezing and thawing action as compared with concrete without the entrained air.

Another significant fact indicated by the data is that with but few exceptions, the concrete segments representing the top of the pavement were less durable than those representative of the bottom of the pavement. This is true for either method of freezing and thawing. However, the variation in durability of the top and bottom segments from the mixtures containing Orvus or Vinsol resin was considerably less than in the case of standard concrete.

In general, the data also indicate that the relative durability of the various concrete mixtures was not affected by the method of test. Only the rate of deterioration was changed.

Limestone Aggregate Concrete with Air Entraining Material

On the basis of results obtained from the durability studies associated with the Michigan Test Road it was decided to experiment further with the air-entraining materials by using them in concrete made entirely from limestone aggregates. Consequently, Project M 78-28, C2 located on M-94 in the city of Manistique, Schoolcraft county was chosen for conducting the experiment with limestone aggregates.

The purpose of this work was an attempt at improving the objectionable characteristics of stone sand in concrete, such as bleeding, poor workability, difficult finishing and excessive scaling by the addition of an air-entraining material with and without added fines.

The project was constructed with limestone aggregates obtained from the Inland Lime and Stone Company quarries located at Manistique, Michigan. Orvus, air-entraining material, was added in specified amounts approximate-

TABLE III
COMPARISON OF RESULTS FROM FREEZING AND THAWING STUDY

Material	Brand Cement	Spec. No.	CYCLES OF FREEZING AND THAWING			
			Age 5 Months		Age 1 Year	
			50% Red. in Mod.	100% Red. in Mod.	50% Red. in Mod.	100% Red. in Mod.
Orvus	1	3	43	80	40	90
Orvus	2	4	30	62	30	100
Vinsol Resin	1	2	45	80	--	---
Vinsol Resin	2	4	47	75	25	80
Standard	1	2	30	60	20	85
Standard	2	4	32	55	15	75

sections approximately 2 inches thick representing the top, middle and bottom portion of the pavement. The top and bottom sections were further divided into two equal segments. One segment from the top and bottom of each core was reserved for freezing and thawing in a 10 percent solution of calcium chloride. The remaining segments from the same cores were frozen and thawed in tap water for comparison with the calcium chloride treatment. The middle section of each core was retained for absorption and permeability tests.

Freezing Thawing Tests:

In conducting the freezing and thawing tests on the core segments, the same freezing and thawing cycle and equipment, as employed for the sonic beam specimens and previously described, were used. The specimens frozen and thawed in the 10 percent calcium chloride solution were kept in the solution during the entire freezing and thawing cycle. The calcium chloride solution was checked for concentration after each five cycles and thoroughly agitated at the beginning of each freezing period.

At the end of each five or ten cycles of freezing and thawing, the specimens were removed from the rubber containers, wiped off and visually examined. The specimens were examined in particular for indications of scale development on their surfaces and failure of bond between mortar and aggregate. The visual inspection was supplemented by noting the sound or ring given forth when the specimen was struck lightly with a hammer. The test was continued to the point where the specimen had totally disintegrated as evidence by complete crumbling of mortar or when the concrete could be easily broken apart by light tapping with a hammer. X

The cycles of freezing and thawing necessary to obtain complete disintegration for each concrete segment have been summarized in Table IV.

TABLE IV
COMPARATIVE RESULTS FROM CORE STUDY

Material	Brand of Cement	CYCLES FOR DISINTEGRATION					
		10% Calcium Chloride			Water		
		Top	Bottom	% Var.	Top	Bottom	% Var.
Orvus	1	140	206	- 52	205	205	0
Orvus	2	55	130	- 58	110	200	- 45
Vinsol Resin	1	145	186	- 22	175	170	+ 3
Vinsol Resin	1	185	165	+ 13	200	200	0
Vinsol Resin	2	130	165	- 21	205	200	+ 3
Vinsol Resin	2	130	145	- 10	215	200	+ 8
Standard	1	45	65	- 31	120	135	- 11
Standard	1	35	78	- 55	120	195	- 38
Standard	2	50	35	+ 43	80	110	- 27
Standard	2	45	70	- 36	70	135	- 48

powder
 ly .05 per barrel of cement throughout the entire project. In the north half of the pavement only, silica dust was added in addition to "Orvus" at the rate of 11.81 pounds per sack of cement.

It was observed that Orvus alone reduced considerably the bleeding so typical of stone sand projects and slightly improved the workability of the concrete over that of untreated stone sand projects. With the use of fines (Silica Dust) in addition to the Orvus, there seemed to be a complete lack of bleeding and the workability of the mixture was materially improved.

Beam tests ~~on both areas~~ *all* indicate that the concrete in ~~both~~ cases was up to specification requirements both for 7 days and 28 day periods. *X*

The pictures in Figure illustrate the character of the concrete containing Silica Dust and Orvus.

Accelerated Scaling Studies

The test panels for scaling study were 3 feet by 12 feet so constructed to hold a layer of water 1/4 inch deep over the surface of the concrete. The test procedure consisting *ed* of freezing of water at night and thawing during the day with an application of 5 lbs. of calcium chloride per test area. The test was conducted in the same manner as described under Michigan Test Road Studies.

Results of Tests

At the completion of sixty-six cycles of freezing and thawing conducted during the winter of 1941-1942, there was no indication of scaling either in the section containing Orvus or the section containing both Orvus and Silica Dust. Recent visual observations reveal that no surface sealing has taken place during the life of the project.

PAVEMENT CONSTRUCTION WITH AIR ENTRAINING MATERIALS

On the basis of the encouraging results obtained from the durability studies associated with the test road and other projects, the Department authorized in 1941 the construction of 6 concrete pavement projects containing Orvus as the air entraining material. At that time Vinsol resin portland cement was not readily available for pavement construction. The 6 projects totaled approximately 18.5 in length.

From 1941 until the present time, there have been constructed approximately 75 miles of concrete pavements containing Orvus. During the summer of 1943 specifications for Vinsol resin portland cement were officially recognized by the American Society of Testing Materials and by the Federal Government. Consequently the various cement manufacturers prepared themselves to furnish Vinsol resin cement for highway construction upon request. There are ^wnoe under construction approximately 20 miles of concrete pavements. These pavements are being constructed with Vinsol resin cement.

With the advent of Vinsol resin cement, the practice of adding air entraining materials at the mixer has entirely ceased in Michigan. Some factors which have led to ^{The discontinuance} ~~its abandonment~~ of Orvus air entraining material ^{are} ~~is~~ as follows:

1. The Orvus material plus labor cost to handle it is an item of expense to the contractor, whereas Vinsol resin portland cement is furnished to the contractor at the same cost as standard portland cement.
2. On account of the personnel influence in the method of handling Orvus there was encountered some difficulty in obtaining uniform mixtures.

3. Recently it was noted that the Orvus material appeared to vary in quality from time to time which influenced to a certain extent the yield and air content of the mixture.
4. In cold weather hot water is necessary to dissolve the Orvus and keep it in a fluid state.

On the project, Orvus was dissolved in water to produce a solution of known concentration so that a one quart measure of solution per batch of materials would contain the proper amount of Orvus to produce the required drop in weight. The Orvus solution was added at the skip but in some cases permission was granted to add it at the batching plant.

Concrete Mix Design with Air Entraining Materials

In designing the concrete mixture to contain an air entraining material the following procedure is generally followed. The proportions for a standard portland cement mixture are determined under the Department's regular procedure using the mortar void method and employing a consistency of 1 1/2 to 2 1/2" slump. The relative water content is then reduced to maintain the same slump when a certain quantity of air entraining material is used. In the case of Orvus, .02 to .10 pounds per barrel of cement has been found to work satisfactorily for Michigan's aggregates, while for Vinsol resin cement we find that 0.15 \pm 20% pounds per barrel of cement is giving desired results. The drop in weight per cubic foot of concrete is held between 3 and 6 pounds. The mix design is based on a 4 pound drop per cubic foot.

In the field, the proper air content in the mixture is determined by checking the unit weight. Any discrepancy between actual weight and design weight per cubic foot is correct by adjusting the amount of Orvus

added, or in some cases the Orvus content has remained fixed and the quantity of sand changed. In the case of Vinsol resin cement the only adjustment possible will be in the quantity of sand per batch.

Certain construction procedures are closely observed in order to obtain maximum benefit from the use of air entraining materials. In the first place it is important that the water content be controlled to very narrow limits. The water content of the mixture greatly influences the amount of entrained air which can be incorporated into the concrete. Also the mixing time should not exceed the normal time of approximately 1 minute. Prolonged mixing due to poor coordination of operation conditions are avoided as much as possible to prevent ^{depression} air entrainment. X

Since the use of air entraining admixtures materially shortens the time interval between placing and finishing, the concrete mixer now becomes the controlling factor in production instead of the finisher, as in the case of plain concrete ^{tires} ~~mixers~~. X

SUMMARY

The material presented in this report concerning air entrained concrete in general and in particular the experiences of the Michigan State Highway Department in the use of air entraining materials as associated with the Michigan Test Road and other pavement projects, indicate the superior qualities of concrete containing a certain amount of entrained air over that of standard portland cement concrete. Concrete containing entrained air within definite limits possesses remarkable resistance to surface scaling, as well as unusual resistance to disintegration due to freezing and thawing action.

Concrete with entrained air also possesses during the plastic state, better workability than normal concrete and practically no segregation or bleeding are experienced. However, its finishing characteristics are somewhat influenced by extreme fluctuations in air temperature and relative humidity. Also, there is a tendency for the concrete to become sticky and thus cause trouble during straight edging and floating operations. These difficulties may be overcome to a certain extent by proper manipulation of material quantities and finishing operations.

At the present time it is an inherent property of concrete with entrained air to have lower ^{comp} compression and flexural strengths than normal concrete. This reduction in strength, under properly controlled conditions, is not considered a serious factor in highway construction because in general concrete strengths usually exceed design requirements. It is believed that this condition will be minimized in the future by the proper adjustment of present concrete design methods to include air^{en} entraining materials. X

An air entraining material ground into the portland cement at the mill is preferred over adding air entraining materials at the mixer for several reasons, the most important of which is that it eliminates the personal influence at the mixer resulting in a saving in operation costs and providing some assurance that the mixture may be more uniform in quality.

Certain construction procedures must be closely observed in order to obtain maximum benefit from air entraining materials especially with respect to water content and time of mixing.

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

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