THE EFFECT OF AIR ENTRAINMENT UPON COMPRESSIVE STRENGTH OF CONCRETE

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The Effect of Air Entrainment Upon Compressive Strength of Concrete

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Preface

The process of purposefully introducing air into concrete came primarily as a remedy for surface scaling of concrete pavements due to freezing and thawing and to application of chlorides. Exhaustive tests have proved that it has accomplished its purpose quite admirably. And the benefits of this fifth ingredient, air, do not stop with merely improved durability for highway pavements. Entrained air also improves workability of the fresh concrete, reduces segregation, and hence reduces bleeding or water gain. But all this benevolence has not been gotten free. It must be paid for and the price is a reduction of the compressive, tensile, flexural, and bond strengths of the hardened concrete. Small additions of air over and above optimum quantities cause serious reductions in strength and the absolute control of quantities of entrained air is still in a development stage. In pavement work discrepancies of this nature have not proved prohibitive. But flexural strength is not affected as severely as is the compressive strength. The question would then arise as to whether air entraining agents may be used as freely in structural work as they are being used in highway work without stringent and exacting controls over quantities of air entrained. It is the understanding of the author that over the past two or three years the use of air entraining concrete has come to be known as a cure all for all types of concrete ills. This, of course, is not true. With this in mind I have explored a small phase of the disadvantages of air in concrete. I shall present the material in two parts. The first part presents a result of library research of the broad subject; the second part reports the findings of laboratory work concerning reduction of strengths caused by entrained air.

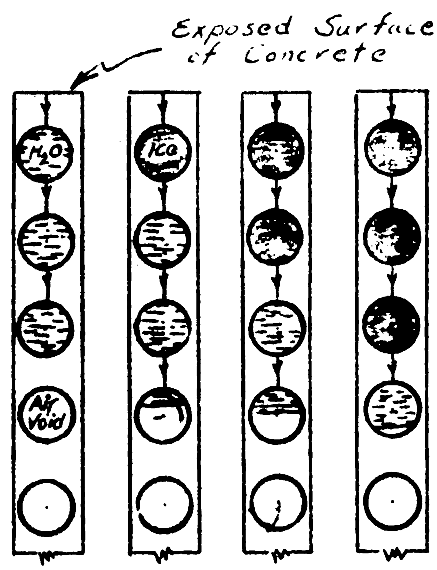
Background

Although the benefits caused by abnormal quantities of air voids in concrete have been recognized off and on for a number of years it has been only during the last decade that air entrainment has proved its real worth. In the late 1920's a Professor C. A. Scholer, of Kansas State College, noted that cement containing a metallic stearate produced concrete having greatly improved resistance to cycles of freezing and thawing. He also observed that this concrete of superior durability possessed a subnormal unit weight. During the early 1930's tests were performed in which air was deliberately entrained in concrete. In every case resistance to freezing and thawing was found to be improved -- apparently in direct proportion to the reduction of unit weight. Although this new improved durability was much to be desired it seemed inseparable from the horrible prospect of lower unit weight. For up until, and during, this time the best concrete was the most dense concrete. Because of this deep rooted density concept the idea of intentionally lowering unit weight was out of the question. In the years following, however, the surface disintegration of concrete pavements apparently became so serious that the then dormant lower unit weight theory was again revived. However, even at this time (1935-38) it was not generally accepted that

The entrained air was the cause for improved durability. Many attributed it to some unkown action of the admixture. Between 1938 and 1940 several test roads were built as a part of a growing country-wide research program. Since 1940 a great deal of conclusive investigation has been carried on. Air entrainment in concrete is now hailed by some as the greatest discovery since the water-cement ratio law. Much has been learned about the subject -- much is yet wanting to be known.

Any question as to whether improved durability found in the less dense concrete is due to air or merely to the agent has been answered. Tests run by H.L.Kennedy made a comparison between three concrete mixes. One mix was a plain concrete containing the normal amount of approximately one percent air. The other two were mixes employing an air entraining agent which caused an above-normal percentage of air. From one of the latter mixes the entire air content was removed by vacuum -- even most of the normal one percent. Durability tests of the specimens showed: the mix with additional air was greatly improved; the mix with an identical amount of agent but with the air removed showed little or no improvement. In fact, the mix from which more than the added air was removed showed decreased durability. The effect of entrained air seems to be independent of the means used to gain the added air.

How does air produce an improved concrete? What is its function? The theories answering these questions seem to be in close agreement and quite widely accepted. The millions of evenly dispersed minute air bubbles immobilize the mixing water. This causes reduced capillary and water channel structure which in turn increases durability by minimizing migration of water into and out of the hardened concrete. Ruinous percolating chlorides which are applied to pavements for ice removal are hindered. H.L.Kennedy advances the pictorial explanation shown in fig.1 of how the tiny air pockets reduce surface disruption due to freezing. The presence of available air voids relieves the inward pressure as freezing progresses. This pressure tends to lower the freezing point of the water. If sufficient voids are provided for the water to creep inward as freezing progresses, disintegration of the structure is prevented. In addition to enhancing concrete durability, entrained air also improves workability and placeability of fresh concrete. Honeycombing and segregation are thereby partially eliminated. The multitudes



Concrete Air Void Diagram

Fig. 1

of tiny bubbles act almost as ball bearings -- they lubricate the mix. The majority of these air spheroids have a sieve size ranging from the 30 to the 100 sieve. It is obvious that each bubble is comparable to a grain of fine aggregate. Such is exactly the case. The bubbles constitute an additional aggregate in the mix possessing complete flexability of shape. Because the air imparts these qualities to the fresh concrete a reduction in both sand and water is possible. In fact, it is advisable to make this reduction when incorporating air in a normal mix in order to maintain the cement factor per cubic yard. A reduction in water also regains a part of the lost strength.

Let us look briefly to the agents which are used to entrain air in concrete. Virtually all of them depend upon a foaming action for the entrainment of air. Vinsol Resin, Darex, Ayr-trap, and Orvus are a few of the many commercial agents being offered today. To date, Vinsol Resin and Darex are the only ones which have been accepted and incorporated in A.S.T.M. specifications. Among those used in early studies were natural wood resins, animal and vegatable fats, various wetting agents, water soluble soaps of resin acids, etc. It seems safe to say that Vinsol Resin is the most popular agent in use at the present time.

With the admittance now that the process of purposeful entrainment of air in concrete has been far from completely harnessed, let us examine the variable factors. Why is it that so much difficulty is encountered in successfully predicting air content obtained in field work? Certainly it is in the field that close control is most to be desired. Stanton Walker and D.L. Bloom have compiled a list of these variables which seems to incorporate and agree quite well with other available writings on the subject. The following was presented in an article in the ACI Journal, Vol17, No 6, June,1946:

"It is generally conceded that the following factors are responsible for major variations in air content when the percentage of air entraining agent is held constant.

1.) Richness of mix -- lean mixes entrain more air than rich mixes. Percentage of air has been found in some cases to vary from ½ to 8% when using an air entraining cement containing a given percentage of air entraining agent, cement content varying from four to seven sacks per cubic yard.

2.) Percentage of sand -- combined aggregates containing high percentages of sand will entrain more air than the same total aggregates containing lower percentages of sand. In one case on record, increasing the sand percentage from 38 to 42% by weight of total aggregate increased the entrained air from 4.0 to 5.5%.

3.) Sand gradation -- a deficiency in -30 to +100 mesh sand, or conversely an excess of +30 or -100 mesh sand will reduce the percentage of entrained air by as much as 3%.

4.) Consistency -- high slump concretes (up to 6in.) will entrain more air than low slump concretes, all other conditions being the same. Increasing the slump from 2" to 4" will increase the entrained air approximately 1½%. The same slump increase in high slump concrete, say six-inch, will not affect the percentage of entrained air as much.

5.) Temperature -- temperature of the concrete as controlled by atmospheric temperature and temperature of the mixing water, aggregates, etc., has a slighteffect on percentage of air entrained. The higher the temperature, the lower the percentage of air. A range of approximately 2% may be expected between temperatures of 40°F. and 90°F.

6.) Length of mixing and type of mixer -- large or small variations in air content may result from these variables, depending upon the type of mixer and type of air entraining agent used.

7.) Age of cement -- where air entrainment is accomplished by the use of air entraining cement, age of the cement has been found to have a small effect on the amount of air entrained in the concrete, depending upon the type of air entraining agent used.

There is at least one more variable which perhaps should be added to this list. Charles E. Wuerrel notes in the June, 1945 issue of the Crushed Stone Journal that crushed stone has been observed to entrain more air, using identical mixes, than does gravel. He illustrates a case in which the gravel concrete entrained 4.4% air contrasted to a 5.4% entrainment with the stone.

Special note should be given to items 2 and 3, concerning the amount and gradation of sand in the mix. The sand phase of the air entraining mix commands a high priority in all recent discussion. Kennedy states that the amount of air entrained in concrete by a fixed percentage of air entraining agent is a function of, among other things, the percentage of sand by volume of the concrete. In a separate bulletin he contends that for a given percentage of air entraining agent, and constant mixing conditions, the quantity of air entrained by the aggregate is a function of the particle size, the optimum range being between the

No. 30 and No. 100 sieve sizes. Tests seem to indicate that either excessively course or excessively fine sands, as opposed to well graded sands, will decrease the effectiveness of the air entraining agent. Proper control of the sand phase is an important part of the design of an air entraining mix.

Another of the more interesting variables is the richness of the mix. Tests have shown that a neat cement paste incorporating an air entraining agent generates but a small percentage of air even with very thorough mixing. The resultant paste, instead of being more plastic, is actually less plastic. The paste assumes a stiffer consistency. It would seem from this that the cement in the mix hinders, rather than aids, air entrainment. This theory is proven in the actual concrete mixture. The richer mixes, those with a higher cement factor, consistently entrain less percentages of air than do the leaner mixes. These facts can only reflect back as proof of the previous paragraph in which it was said that the entrained air is a function of the aggregate. This conclusion is axiomatic since everything else has been eliminated.

Length of mixing time is a much discussed variable affecting an air entraining concrete. This problem would, in all probability, have been of little concern had it not been for the ever growing transit-mix industry. Until recently the condition of extended mixing causing excessive amounts of entrained air was particularly bothersome in the case of Vinsol Resin. Previously, Vinsol Resin was interground with the clinker or added at the mixer in its plain condition. To effect air entrainment, the plain Vinsol Resin had to react with alkalies, formed when the cement and water combined, in order to become available as a foaming agent. In other words, the Vinsol Resin became sodium resinate at the time of mixing. Obviously, the completeness of this chemical reaction was a function of the mixing time. This condition has now been eliminated by and large now by neutralizing the Vinsol Resin (making into a soap - the sodium resinate) before it is added either at the cement factory or at the mixer. However, even neutralized Vinsol Resin, called NVX, still shows some inconsistencies due to mixing time when it has been interground with the clinker. The variation seems to be dependent upon the individual cement. When NVX is added at the mixer the above mentioned inconsistency is greatly reduced. The effect of extended mixing time with Darex seems to closely approximate conditions found with NVX.

With this background of the subject in mind let us turn to a laboratory consideration of the possible results which may come from any of the several discussed variables affecting air content in concrete.

Laboratory Work

The primary purpose of this paper is to show how air entrainment in concrete affects the strength of the concrete. You have seen the relative unpredicableness of air entrainment; let us now examine the effect that these variations might have upon the resulting concrete. The task was undertaken with vengeance, with no apologies to any quarter. In the normal design of an air entraining concrete mix care is taken to partially compensate for a reduction in strength caused by the additional air. A standard state highway mix, for example, is redesigned. The percentage of aggregate, usually only the sand, is reduced to counteract the bulking effect of the air and thereby maintain the original cement factor. The increased workability due to the lubricating action of the air permits a reduction of the water-cement ratio. This,too, regains part of the lost strength. These factors are all considered by the trained concrete technician or concrete engineer. But certainly everyone who is using air entraining cements and air entraining agents today is not aware of all these facts. A bag of air entraining cement is just as common now as was a bag of plain cement ten years ago. Because of its improved qualities pertaining to workability, segregation, and water gain, air entrain- concrete has come to be used in every type of work.

For this reason it is interesting to see just what the results are when a plain concrete mix is turned into an air entraining concrete merely by the addition of an air entraining agent. This is what has been done in the laboratory. A 4500 psi. plain concrete mix was designed to which was added various percentages of neutralized Vinsol Resin (NVX).

The aggregate analysis is given in tables 1, 2, and 3. The course aggregate was a very smooth, well rounded gravel. The mix used was 1:2.4:3.5 by weight with a water cement ratio of 5½ gal/sack. Type I Huron portland cement was used. The NVX which was in the powdered form was made into solution so that 100cc of solution contained one gram of NVX. It should be recognized that this is not a true one percent Vinsol Resin solution since the NVX has a Vinsol content of approximately 88%. The remainder is made up of the 6% caustic neutralizer plus moisture and non-volatile oils. The first batch was the control batch which contained no added air entraining agent. Six 6"x12" test cylinders were made from each batch -- three to be broken at 7 days and three to be broken at 28 days. After setting 24 hours at room conditions the cylinders were placed to cure in a standard moist closet maintained by the Michigan State Highway Department.

A mixing time of 6 minutes was used. It was learned from the Highway Department that at least six minutes was

Aggregate Analysis

	Fine	Course
Percent Free Moisture	2.3% *	1.32% *
Bulk Specific Gravity	2.67	2.69
Unit Weight per cu. ft.	112.5 lb.	109.5 lb.

*values varied

Sieve Analysis

Fine

Sieve	Percent Retained	Percent Passing
# 4	0.62	99.38
# 8	10.81	89.19
#16	29.94	70.06
#30	50.91	49.09
#50	80.67	19.33
#100	97.31	2.69

Course

Sieve	Percent Retained	Percent Passing
1½"	0	100
1"	10.13	89.87
3/4"	25.60	74.40
1/2"	51.00	49.00
3/8"	76.75	24.25
No.4	100	0

required for thorough mixing in this particular machine. An undue amount of difficulty was experienced with the mixer. The machine originally had been of the double open end, horizontal type powered by a gas engine. It has now been converted to a single open end tilting type with electric motor. The opening, however, is so small that a funnel has been devised with which to charge it. In using one half of the normal six cylinder batch as a buttering batch, the machine so robbed the mix of mortar that the discharge consisted almost solely of course aggregate. The barrel of the machine is so intricate and clogged with hardened concrete that emptying is very difficult. This condition has come about because the machine discharges so incompletely and sluggishly. If there is to be one definite conclusion drawn from this work, that conclusion is the definite need for a remedy of the situation.

Aside from the mixer the only other difficulty encountered was with the varying surface moisture of the aggregate which was gotten from outside stockpiles. It was interesting to note that a small increase in the surface moisture, which increased the W/C ratio and produced a wetter mix, caused a marked reduction in the resulting air content. This fact seems to be diametrically opposed to the general rule (see item 4, page 5). Because of this, strict control had to be maintained over the aggregate from day to day.

The air content of the fresh concrete was calculated by means of the theoretical weight method. Following is a sample computation:

$$\text{Percent Air} = \frac{\text{Theoretical Wt.(air free)} - \text{Wt. Concrete}}{\text{Theoretical Wt.(air free)}}$$

The theoretical air free unit weight of the concrete is found by dividing the total weight of the component ingredients in the batch by the total absolute volume of the component ingredients in the batch, ie,

total weight of components =

cement	29.25	lbs
FA	70.25	
CA	102.50	
water	14.00	
	216.00	lbs

total absolute volume components =

$$\text{cement} \quad \frac{29.25}{3.15 \times 62.4} = .1488 \text{ cu ft}$$

$$\text{FA} \quad \frac{70.25}{2.67 \times 62.4} = .4220$$

$$\text{CA} \quad \frac{102.5}{2.69 \times 62.4} = .6120$$

$$\text{water} \quad \frac{14.0}{1 \times 62.4} = .2242$$

$$1.4070 \text{ cu ft}$$

So, theoretical air free unit weight $= \frac{216}{1.407} = 153.5$ lbs/cu ft

Therefore, percentage of air in concrete $= \frac{153.3 - \text{Weighed Unit Weight}}{153.3} \times 100$

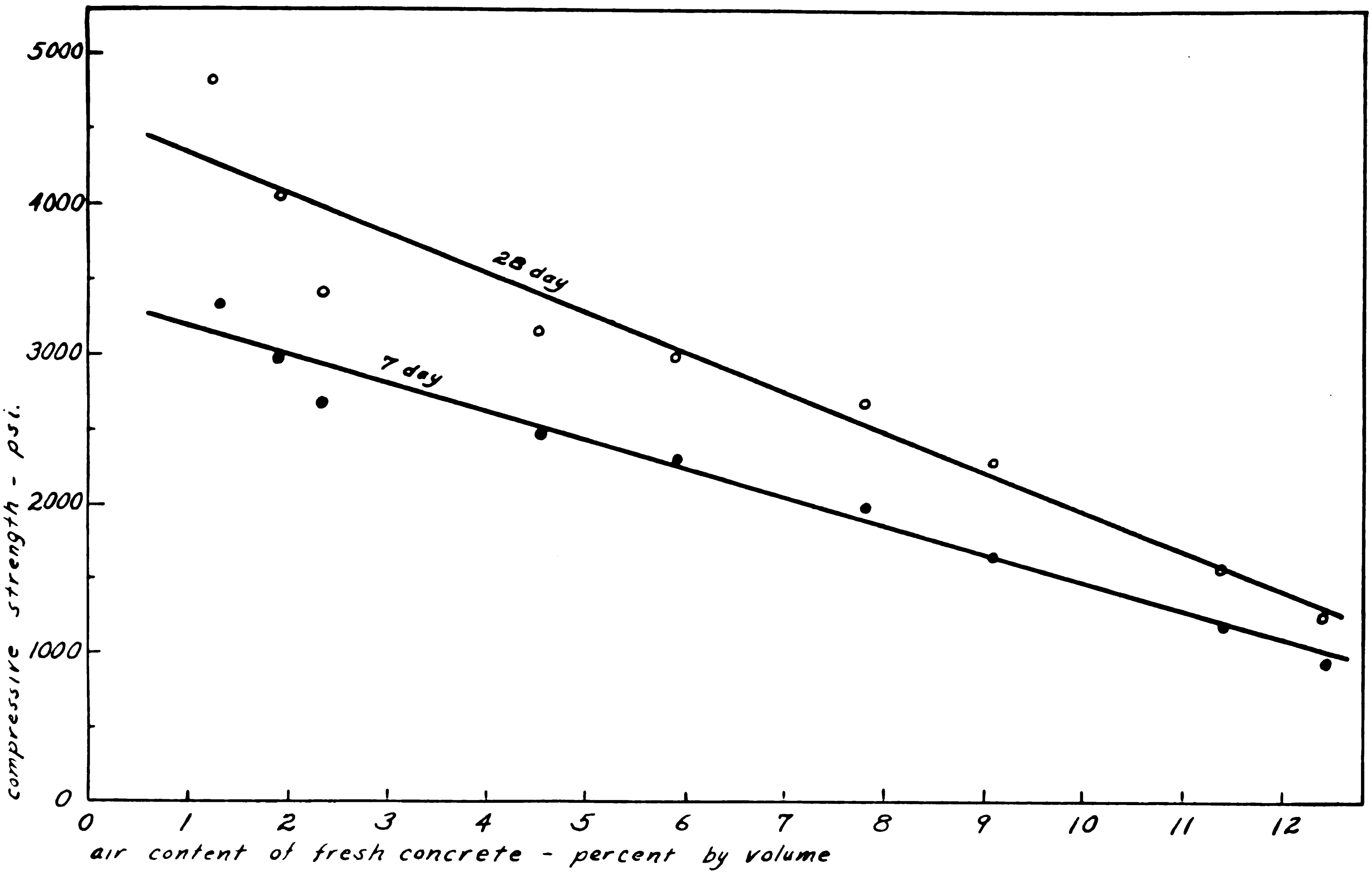
Batch	% NVX by wt of cement	% AIR by vol	lb/cu ft Unit Weight	Slump in.	Compr Strength* psi 7 day	Compr Strength* psi 28 days
AT-2	none	1.3	151.5	1"	3391	4798
AT-3	.0025	1.9	150.5	2"	2992	4090
AT-4	.0050	2.3	150.0	4"	2686	3418
AT-5-R	.0075	4.6	146.5	4"	2486	3205
AT-6	.0100	5.9	144.5	4½"	2289	2988
AT-8	.0150	7.8	141.5	6½"	1993	2663
AT-9-R	.0200	9.1	139.5	7"	1718	2325
AT-10	.0300	11.4	136.0	7"	1168	1650
AT-11-R	.0500	12.4	134.5	8"	950	1351

*average of 3 cylinders

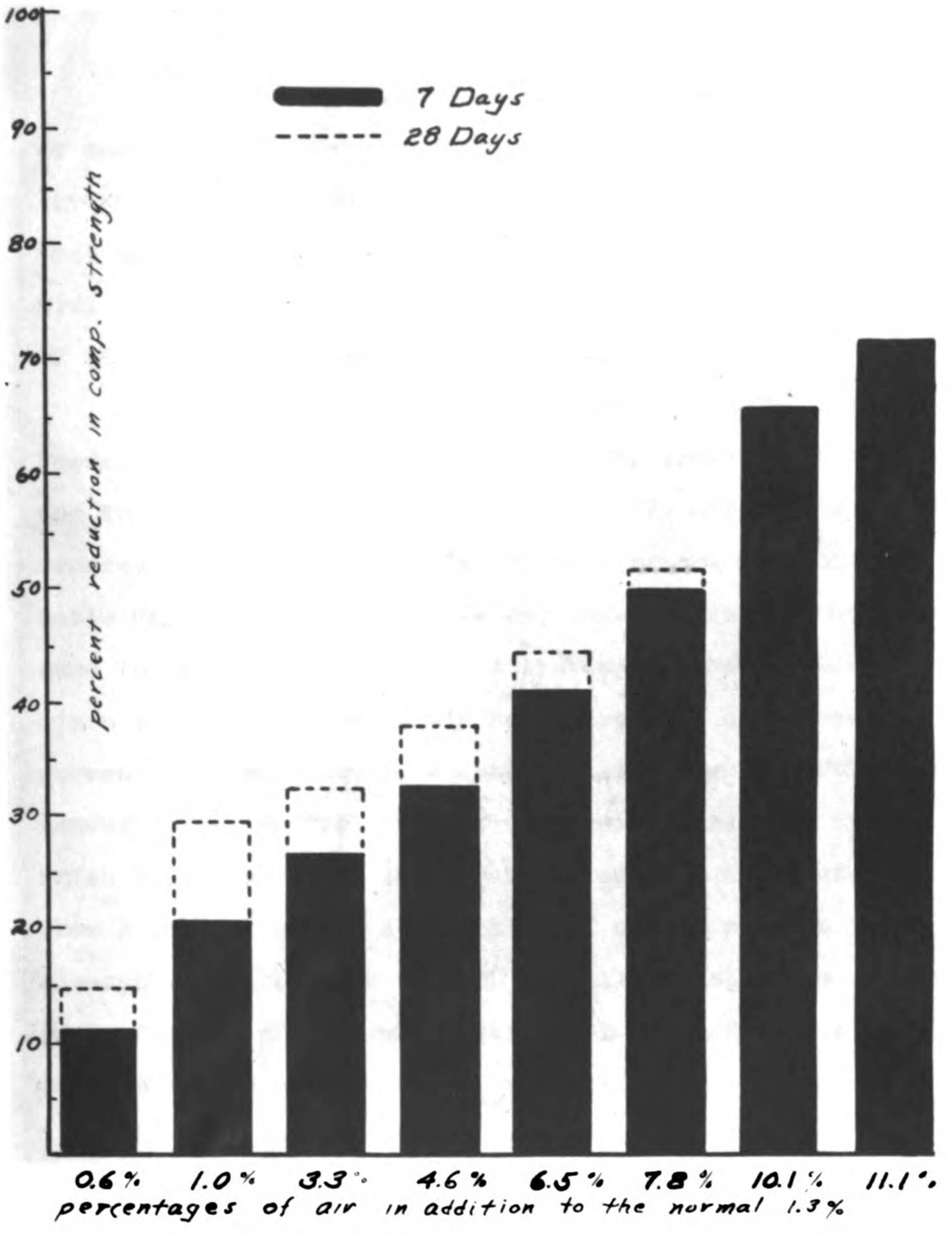
1:2.4:3.5 mix by wt.
5½ gal/sack W/C ratio

Table 4

Table 4 gives a complete tabulation of the percentage of NVX used in each batch, the percentage by volume of air entrained, the slumps, unit weights, and resulting strengths at 7 and 28 days. The curves in Fig. 2 show the strength relations at 7 and at 28 days as the air content is increased. Figure 3 presents a graphical picture of the marked reductions in compressive strength due to the entrained air.



AIR - STRENGTH RELATIONS
Fig. 2



PERCENT REDUCTIONS IN STRENGTH

Fig. 3

Conclusion

Figure 3 is conclusive in itself. Strength reductions of such a high order are unallowable even in pavements, to say nothing of structural work. It should be borne in mind that the mix used in these tests was a comparatively rich mix. A leaner mix would have entrained greater quantities of air and reduced the strength more.

Mr. E. Mayfield, Sales Supervisor for the Hercules Powder Company, makers of Vinsol Resin, wrote the following in his letter of April 27, 1948: "To offset the increased bulk and to maintain the same cement content per cubic yard of concrete, it is customary to reduce the fine sand in the mix. It is our understanding that concrete mixes so designed frequently have strengths only about 5 percent less than would be obtained with normal portland cement." Mr. Mayfield speaks of an air entraining cement which is manufactured to entrain an optimum air content of from 3 to 5 percent. A reduction of only 5 percent in strength is negligible -- such a small reduction is absorbed by factors of safety. Under ideal conditions the reduction may be held down to 5 percent. In fact, in very lean mixes it has been shown that the allowable slash in water content due to the added air has actually caused a higher strength. But we have seen how the air content may inadvertently vary several percentage points, and we have seen how great an effect an addition of one or two percent of air can have upon the compressive strength. Of course, if the variance acts to lessen the amount of entrained air, the consequence is not as important.

Until the science of air entrainment in concrete becomes more exacting, probably the best solution to the problem is the discreet use of air in any work where strength, not durability, is the more important factor. The various interested parties who are conducting tests on the subject are now strongly promoting a step that will bring air entrainment closer to more exacting control. That step is the use of air entraining agents added at the mixer in favor of the use of air entraining cements which have had the agent interground with the clinker. Control of the air has been proved to be more accurate by this method.

Perhaps one of the biggest hazards in the use of air in concrete is the temptation that it offers for economy. An excellent appearing concrete can be made with a very low cement content if sufficient added air is entrained with the mix. But strengths would be so low that despite the relief of stresses provided by the added air, the concrete would not be serviceable. Strength is still a requirement of portland cement concrete, and air is not a substitute for portland cement.

Photomicrographs

On the following pages is presented a series of photomicrographs showing the structure of the hardened concrete specimens made in this test. It is interesting to note the step by step increase in porosity. The first six micrographs are enlarged 8 times. The last two, which compare the normal concrete with the same mix with 12.4% air, are enlarged 14 times.

Photomicrographs Showing

Structure of Hardened Concrete

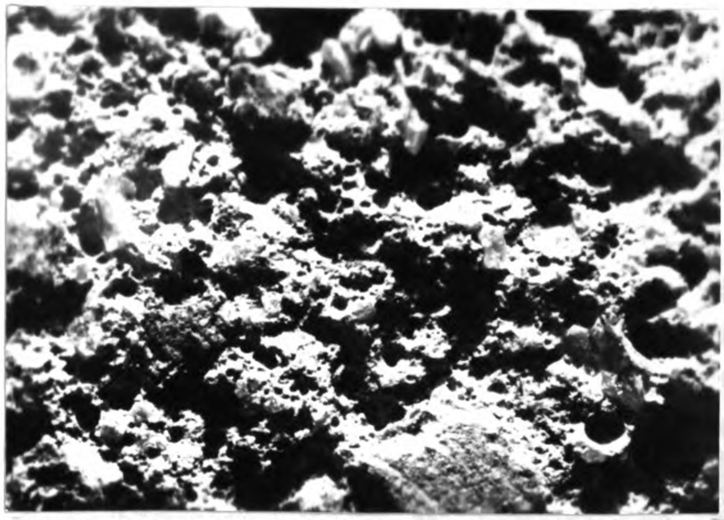
Specimen AT-2
No NVX added
1.3% air
ground surface
magnified 8x

AT-4
.005% NVX
2.3% air
ground surface
8x

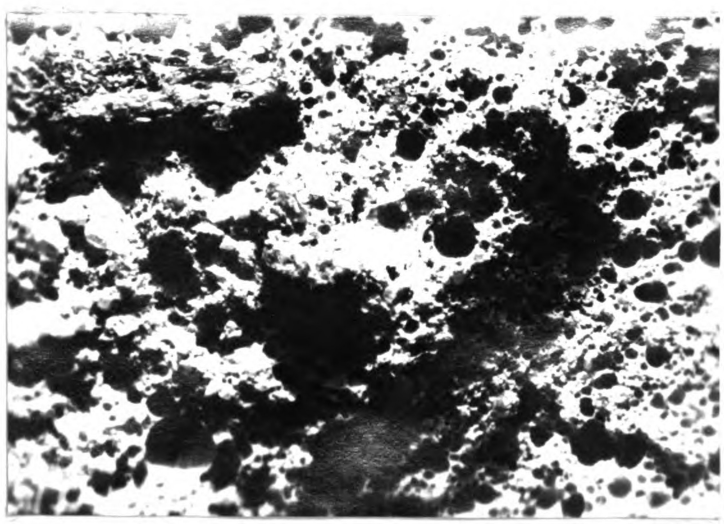
AT-6
.01% NVX
5.9% air
ground surface
8x

AT-8
.015% NVX
7.8% air
ground surface
8x

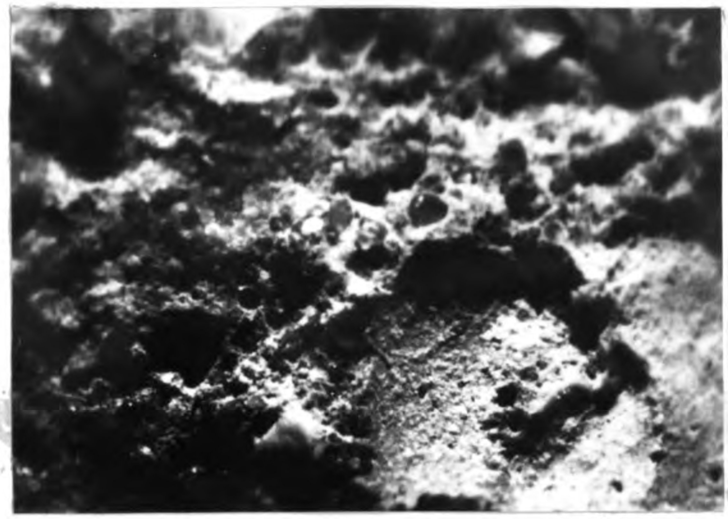
AT-10
.03% NVX
11.4% air
broken surface
8x



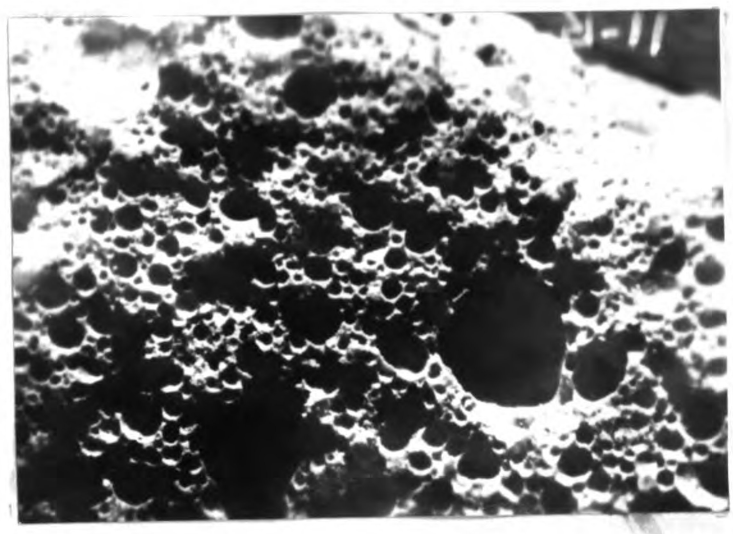
AT-11-R
.05% NVX
12.4% air
broken surface
8x



AT-2
No NVX added
1.3% air
broken surface
14x



AT-11-R
.05% NVX
12.4% air
broken surface
14x



A striking comparison between a normal concrete and a concrete which contains 12.4% entrained air. Note the extreme spongy texture of the lower micrograph.

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