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Theory of Air Entrainment

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INTRODUCTION

The purpose of this thesis was to accumulate all the important information of the past related to the entrainment of air in concrete. As the study of air entrainment is a relatively new subject, most of the work done on it is scattered in the various Engineering publications issued at different times and thus uncoordinated. The author has tried to collect this scattered information and to give a complete picture of air entrainment so as to be of use to the Engineer and layman.

The improvements obtained through the use of air entraining concrete over that of plain concrete are durability, workability, density, resistance to scaling, and lack of segregation of the concrete ingredients, indicate the important part they are going to play in the science of concrete in the future. The detrimental properties of the air entraining agents results in the lowering of strength, as will be discussed later. This can be eliminated, to a large extent, by the introduction of air at its optimum limit and by the reduction of water cement ratio.

I THEORY OF AIR ENTRAINMENT

(a) and its effect on properties of concrete
(b) optimum air content

THEORY OF AIR ENTRAINMENT

Air entrainment is the process of purposeful introcudtion of a definite quantity of air into the concrete mixture in excess of that normally found in standard concrete. This additional air unlike the air in plain concrete, must however exist in the form of minute, disconnected bubbles uniformly distributed throughout the concrete mass.

Concrete mixtures posses naturally a high coefficient of friction which is lessened rather inefficiently by cement water paste. Neither angular grains of cement nor the water have a lubricating value. The quantity of water is limited due to the adverse effect of excess water on strength, cohesion and durability. The quantity of cement used is limited by factor of economy, heat generation and columetric stability. Cement is generally used in excess to increase plasticity which is detrimental to concrete and a poor source

Spheroids

Spheroids are added aggregates. The development of foam in concrete mixtures provides a lubricant of high value. The effective spheroids of air range in size of No. 16 to No. 20 sieve size. They constitute an added aggregate in the mixture possessing complete flexibility of shape.

The introduction of spheroids reduces the internal friction of the concrete mixture and it allows the ingredients to move and arrange easily with respect to each other. The foaming action of an admixture causing the spheroids has thus a great lubricant value and avoids the need of using excess cement to accomplish this purpose. Thus cement is allowed to perform its main mission of coating and cementing the rigid aggregate particles. The need for using water as a lubricant is also eliminated.

<u>Air Entrainment Supports Density Theory</u>

The reduction of water (of convenience evaporable and migratory) gives us greater concrete density. Purposeful air entrainment achieves this best so it conforms to the above theory.

Introduction of air (an extra fine aggregate of zero coefficient of friction) results in lessened need for the rigid fine aggregates in about the same volumetric proportion. The use of air entraining agents should thus be accompanied by a mandatory corresponding reduction in the quantity of sand to avoid "over sanded" mixture.

The combined effect of the reduction in water (0.5-1.0 gal./bag of cement) and of rigid fine aggregate results in a mixture more resistant to the future migration of water. These spheroids also serve as pressure relief (due to hydrostatic pressure or crystal growth).

The effect of the air entraining admixture on concrete according to Wuerfel is a function of the amount and condition of the air entrained i.e., number, size and degree of distribution of the bubbles of air in the mortar component of the mixture rather than on total volume.

The chemical effect of these admixtures appears to be limited entirely to the possible presence of types of other than sudsing compounds, such as accelerators, deflocculetors, or gas-generating agents. Taking only the sudsing agent, the effect of entrained air is cumulative, as indicated below:

a. The entrained air acts as a very plastic and stable non-reactive fine aggregate of high lubricating value.

b. Its presence permits a marked reduction in water cement ratio necessary to produce the desired placeability of the mixture and

c. a reduction in the sand total aggregate ratio normally required by approx. 1.3 times the amount of air entrained: thereby reducing the total surface area of rigid aggregate to be coated and lubricated by the cement-water paste.

d. Reduction in W/C° effects a basic increase in the strength and durability of the cementing medium, and the reduction in the total water present in the mixture reduces the amount of excess water available for formation of channels through the matrix of the concrete; thereby reducing permeability and bleeding.

e. Reduction in bleeding is increased beyond that affected simply by reduced W/C by immobilization of additional water through adsorption on the air bubbles. Reduction in bleeding results in diminished separation

°Water-cement ratio

of the matrix from the under side of coarse aggregate particles and in diminished floatation upward of laitance.

f. Finally the numerous well dispersed air voids provide reservoirs for the relief of pressure created in concrete caused by temperature change and by the expansion accompanying the transition of water to ice. Mis contribution to durability is reinforced by the reduced W/C and lack of channelization of the matrix due to bleeding.

The entrained air is more closely related to the fine aggregate than to any other component therefore the optimum percentage of air entrained should be a function of the quantity of fine aggregates in the mixture rather than a fixed percentage of the total mixture.

<u>Behaviour of Entrained Air</u>.

The presence of the numerous well dispersed air bubbles tends to immobilize the missing water through absorption of the air bubbles and by interrupting the continuity of the water channels or capilleries, which have a tendency to form through displacement or readjustment of the ingredients in the fresh concrete during placement. This fact <u>reduces the bleeding or water gain</u>.

As the water cement ratio is reduced the durability is increased and the closing of the water channels results in greater imperviousness. These air voids relieve the pressures caused by thermal volume changes and expansion of water turning to ice.

Optimum Air Content

The optimum air content is considered to be 3-6 percent by volume computed on the basis of the theoretical weight of air free concrete of the same proportion. This is air content at which it has been shown, that with the gain in the scale resistance and durability by the air entrained concrete,there would be no serious loss in flexural or compressive strength.

Unit Weight of Concrete

The increase in the volume of voids ratio from that 1 to 1.5 0/0 (normally) to 3 to 6 percent results in a decrease of 3 to 6 pounds per cubic foot in unit weight of concrete.

II METHODS USED FOR AIR ENTRAINMENT IN CONCRETE

a. air entraining admixture
b. air entraining Portland cement
c. compound air entraining admixture
d. natural cements with air entraining materials

METHODS OF AIR ENTRAINMENT IN CONCRETE

Air is entrained in concrete by adding materials to the missing water which reduces its surface tension, causing it to foam easily and consequently entraining air under the mechanical agitation of the mixer.

There are four methods of entraining air in concrete which are discussed in detail as follows:

1. Air entraining admixture
2. Air entraining P. C.
3. Compound air entraining admixture
4. Natural cements with air entraining material

The above mentioned mechanisms whereby air can be entrained in concrete are not the only one, and some people contend as to their being the most satisfactory. Aluminum and hydrogen peroxide have been used to incorporate air or rather hydrogen and oxygen, respectively, in concrete mixes. These function by generating the gases instead of reaction with constituents of the cement. They bear no relation to surface tension reducing compounds.

There is still another method of introducing air above the normal amount, into concrete and that is by use of cement dispersing agent. These are surface active chemical compounds which are preferentially adsorbed by cement, endowing the cement particles with electromatic charges which make them mutually repellent. These compounds do not lower the surface tension of water to a marked degree and do not form stable foams with water alone, although what they may do in a cement suspension is something different. They are not wetting or foaming agents and would not be applicable to those uses of wetting or foaming agent which depend on surface tension reduction. The mechanism whereby they entrain air is evidently not the same as that of foaming agents and is yet to be disclosed. It is suggested that it is related to increased effective surface area of the cement and the finer effective size of the cement particles in the dispersed state.

In addition to the foregoing materials the ones listed below have been used in laboratory and in fields for the purpose of air entraining.

1. Animal or vegetable fats and oils such as tallow and olive oil and their fatty acids such as stearic and oleic acids.

2. A commercial product known as Legro which consists largely of oleic and resin acids.

3. Various welling agents such as the alkali salts of sulfated and sulfonated organic compounds.

4. Water soluble soaps of resin acids and animal and vegetable fatty acids.

5. Miscl. materials such as the sodium salts of petroleum sulfonic acids, etc.

Air Entraining in Portland Cement

There are two types of Standard Portland cement now available, to which a certain amount of air entraining materials have been added at the mill. It is designated types IA and IIA and is covered by American Society for listing materials spec. Designation C175-46T.

The amount of air that the cement will entrain is based on the amount of entraining material added at the factory and the conditions of the mortar to achieve this volume are specified. The air content of the <u>mortar</u> which is tested and prepared in accordance with A. S. T. M. method C185-47T has to be 18 percent by volume with ± 3 percent tolerance.

Although the above mortar test is developed to give an approx. ratio of 3:1 between the amount of air in the mortar and in the concrete, but such relationship is very difficult to be obtained.

<u>Compound Air Entraining Admixtures</u>

These compound air entraining agents are those which besides their air entraining properties, contain various types of accelerators and deflo-culators. The addition of these materials serves to increase the strength and bonding properties. These types of admixture is added at the mixer.

<u>Natural Cements with Air Entraining Materials</u>

Standard Portland Cement is sometimes mixed in the ratio 5:1 to air entrained natural cements and it seems to produce a satisfactory air-entrained concrete. The natural air entrained in natural cements must conform to the A. S. T. M. spec. C10-37 and also meet the mortar test for air content stated above for air entraining Portland cement.

a. Air Entraining Admixtures. Two Types.

Air entraining agents which have been successful are of soapy nature. Their soapy action which is their natural quality has nothing to do with any subsequent action with the cement. Neutralized Vinsol resin (NVX) and Darex are examples of this type.

The other types of admixtures used as air entraining agents are those which develop their foaming action, only due to reaction with the hydroxides of the alkali metals present in the cement. In this case the amount of air entrainer produced is not proportional to the amounts of these substances that are added, but also the amount and availability of the natural alkali oxides that are present in the cement. Rosins, flake Vinsol resin, and the various animal fats can be stated as examples of this type. Owing to lack of consistency in the results obtained from these types where the amount of air entrained is unduly affected by the time of mixing, the use of these products is not recommended.

There are many other substances which have the properties of air entraining but unless the exact nature of their effect on the quality of concrete has been proved through research and experience their use is not encouraged.

Flake Vinsol resin obtained by selective extraction from pine wood. It is composed chiefly of a mixture of various resin acids which combine with alkali to form soaps.

Neutralized Vinsol resin (Sodium resinate) is made by treating the resin with commercial sodium hydroxide (caustic soda).

Darex (AEA) is a triethanolamine salt of a sulphonated hydrocarbon. (Further discussion follows at the end of this paper and is under the heading of "Supplementary Notes").

III COMPARISON BETWEEN THE USE OF AIR ENTRAINING CEMENTS AND USE OF ADMIXTURES.

AIR ENTRAINING CEMENTS VERSUS ADMIXTURES

There is no great comparative gain in the two methods of using admixtures, i. e., that of mixing it with the cement or mixing it at the mixer with the batch. It is left to the Engineer whichever method of control he wishes to chose. The results would be satisfactory if proper control has been exercised.

The amount of air entraining material serves as a control when mixed at the mixer if the mix has been established.

In case of air entraining cements, the amount of air entraining material is fixed but if required, more of it can be added in the mixer in case of deficiency, and so can the cement ratio be increased.

This additional use of admixtures to meet a deficiency is done either mechanically by means of an automatic dispensing device or manually handled. A solution of admixture with water is kept ready and must be enough to last for one day's pour. This solution must be protected against freezing in winter and the container kept clean at all times.

From the point of view of work in the field, it would appear that a more uniform quality of concrete is likely to be produced by using air entraining Portland cement, than by adding the very small quantities of air entraining agents during mixing.

IV FACTORS AFFECTING AIR CONTENT

a. Type and grading of aggregate
b. Effect of sand percentage
c. Effect of coarse aggregate
d. Effect of amount and brand of cement
e. Effect of amount of agent
f. Effect of ratio of sodium hydroxide to Vinsol resin
g. Effect of consistency
h. Effect of mixing time
i. Effect of temperature
j. Effect of vibration
k. Effect of depth of concrete

AIR CONTENT AFFECTING FACTORS

The amount of air entrained in concrete has to be kept at the optimum limit in order to get the best results from air entrainment, therefore the proper design of the mix to achieve this desired air is of ultimate importance. All factors affecting the air content have to be carefully considered, especially the effect of W/C ratio which will be very marked in lean mixes than in rich mixes.

The amount, type and grading of the aggregates, type and quantity of cement, mixing time, method of mixing, temperature, amount and type of air entraining admixture, all have a great effect on the quantity of air entrained in the mix.

Type and Grading of Aggregate

Consideration must be given to the nature of the aggregates in determining the amount of air entrained. It has been found that concrete made with crushed stone or slag will contain about 1 percent more air than comparable concrete made with rounded gravel. This can be accounted by the fact that more sand is needed when crushed stone is used (Fig. 9) (Cordon).

The data used by Walker and Bloem for concrete using two different Vinsol resin solutions are shown in Fig. 5.

Only a few tests have been made on coarse aggregate, but the limited data available indicate that the coarse aggregate has little effect, except insofar as it affects the amount of sand required. (Bloem and Walker).

Effect of Percentage of Sand on Air Content of Concrete.

(Vinsol resin added at the mixer in solution with NaOH, 43 parts water by wt. used for exp.)

Experiments run by M. G. Gonnerman show that a reduction in the percentage of sand in a mix caused the air content to decrease. Reducing the sand percentage from 40 to 22 percent decreased the air content as much as 1½ percentage points, the amount of reduction depending upon the presence or absence of Vinsol resin in the mix. The rate of decrease of air content with reduction in percentage of sand was slightly higher when Vinsol resin was used in the mix. The results of the experiments also show that a reduction in sand percentage can largely offset the reduction in flexurel and compressive strength that occurs when the same percentage of sand is used with the air entraining addition as with the concrete without addition. It is also observed that by reducing the percentage of sand when the air entraining addition is used, the strength can be maintained at approximately the same level as those for the concrete without the admixture.

The Effect of Coarse Aggregate on Air Content.

As the size of the coarse aggregate used in concrete increases the optimum quantity of total air in the mixture is reduced. From data available (by Wuerpel) the air content of the mortar and the overall benefit to the concrete can be maintained about equal, when the total air content is as shown below for concrete containing various sizes of coarse aggregate:

C. A. Max. size in inches	Total Air %
3/4	5.5
$1\frac{1}{2}$	4.5
3	3.5
6	2.5

Amount and Type of Cement

The quantity of agent required to entrain a given amount of air is influenced by the type of cement, also a smaller amount of agent is required for lean mixes than for rich mixes. (Cordon Fig. 10).

Effect of Amount of Vinsol Resin on Air Content of Concrete Mixes with Constant Cement Content.

It can be seen from the results of tests run by Gonnerman that the amount of air entrained in a concrete mix may be readily controlled by changing the percentage of Vinsol resin added. The ability to control the amount of entrained air by the percentage of Vinsol resin added in the form of soap solution may at times be of considerable advantage since the air content for any given set of conditions can be maintained at the desired amount by adjusting the quantity of solution added to the batch. It has been observed that .005 to .01 percent of Vinsol resin is required when added in solution during mixing to markedly increase the resistance of concrete to surface scaling and to freezing and thawing.

Effect of Ratio of Sodium Hydroxide to Vinsol Resin in Air Content.

It has been found that Vinsol resin is not very effective in entraining air when added to the batch in powdered form. Therefore, it generally is added in NaOH-water solution and the discussion follows below.

Results of studies made by Walker & Bloem indicate the relationship of Sodium Hydroxide to Vinsol resin and the effect of certain variation in their proportions on the air content and compressive strength of concrete. It is shown that air content is increased as the wt. of the Sodium Hydroxide approaches the wt. of the Vinsol Resin. Beyond that the material becomes less active, due to a salting out action caused by the excessive amount of Sodium Hydroxide (Fig.).

Tests were made with solutions with the ratio of the sodium hydroxide to the resin varied from 1.1 the usual recommendation, to 5.0. The amount of Vinsol resin was kept at 0.009 percent of the cement. The results of the data are shown in Fig. 8. It appears, for most of these tests, the activity of the solution increased up to the point where the weight of the sodium hydroxide about equaled that of the Vinsol resin used. Beyond this point the solution was less active, probably due to a "salting out action" caused by the excessive amount of the sodium hydroxide.

Consistency of the Mix

Experience shows that the wet mixes entrain more air than dry, stiff mixes. Therefore it is important to keep this aspect in view at all times and keep within reasonable limits.

Effect of Mixing Time on Air Content

There is no definite relation set up so between the time of mixing and air content. It has however been shown with the newer air entraining admixtures that the amount of air content rises slightly during the first few minutes of mixing time (3-12 min.) and then decreases with additional mixing. The total amount of air entrained is also function of the type of cement used.

Tests on the effect of mixing time on concrete carried out by Walker & Bloem show that no differences in results were found when three air entraining agents, i. e. flake Vinsol resin, sodium resinate (N.V.X.) and Darex were used. The following is the table of results obtained:

Mixing time	Concrete without admixture		Concrete with admixture		
	Compressive Strength	Slump	Compressive Strength	Slump	Air Content
6	98	97	94	93	94
12	100	100	100	100	100
30	98	74	96	74	86
90	98	35	101	35	58

Although the data are too few to draw conclusion still it can be seen from the results of the slump tests, as well as measurement of air content, that for this mixer, 12 minutes were the adequate time of mixing. After this, both slump and air entrained were decreased by additional mixing.

Effect of Temperature of the Concrete on Air Content.

It has been shown by experiments that the amount of air entrained decreases as the temperature of the concrete rises. Figs. 6 and 7 show results of tests made by Messrs. Stan Walker and Delmar Bloem on concrete using Vinsol resin, sodium resinate and Darex as admixtures. By controlling the temperature of the ingredients, concrete was mixed which had temperatures after mixing, ranging from 46 to 106°F. It can be seen from Fig. 6 that in each admixture the amount of air entrained decreased as the temperature of the concrete increased. Fig. 7 shows the amount of air as a percentage of the amount at 70°F. It is interesting to note that inspite of using different admixtures and the different amounts of air entrained by the quantities of them used, all points fell on the same curve. The amount of air entrained at 50°F. was 150 percent and at 100°F., 77 percent of that to 70°F.

Effect of Vibration on Air Content.

Vibration causes a slight reduction in air content. This is believed due to the compressive action of the solid particles on the voids which are pushed upward. Studies by Wuerpel indicate that the apparent reduction in air content by vibration is not sufficient to be reflected in the durability properties of the concrete.

The phenomenon of the reduction of entrained air due to vibration is explained by C. E. Wuerpel who relates it to the nature of the voids formed in plain concrete and in purposedly entrained air. The air entrained in plain concrete is present usually in large voids of sufficient volume to develop enough buoyancy, causing a rapid upward migration under the influence of vibration. There has been little evidence of the buoyant force of the voids formed by the sudsing agents which are very minute and widely spread, on the other large upward movement of air voids is noticeable to naked eye in plain concrete under the influence of vibrations. The apparent reduction in air content in concrete with admixture may be attributed to the loss of large bubbles of incidentally entrapped air typical of plain concrete, which are also present in entrained concrete. This reduction in apparent air content may be due partially to shrinkage of the concrete, evaporation of moisture, and by partial filling of some of the air voids.

In spite of the fact that there is reduction in air content due to vibration, the extent of the reduction is not of an alarming nature as to affect beneficial properties of concrete.

Effect of Depth of Concrete on Air Content

Experiments by Walker & Bloem indicate that in high seċtions of concrete containing entrained air, there is apparent movement of the air from the bottom to the top section because the air is partially compressed due to superimposed concrete.

Columns of 6 inches in diameter and 4 ft. in height were molded for the experiments. The concrete was placed in 12 in. "lifts" each of which was rodded 25 to 30 times as required in molding 6x12" cylinders . After the concrete had hardened, the column was broken into four pieces and the air content of these computed. There was a decrease in the indicated amount of air with distance from the top of the column. It appears that these differences were due to the compression of the air due to the weight of the superimposed concrete. This contradicts the statement made by some writers that there is no movement of air from the bottom to the top section for the method if placement used.

V. EFFECTS OF ENTRAINED AIR ON PROPERTIES OF CONCRETE

a. Strength, modulus of elasticity
b. Durability--reaction to freeze and thaw
c. Scale resistance
d. Bleeding (water gain)
e. Bonding properties between steel and concrete
f. Thermel properties
g. Workability
h. Uniformity of concrete
i. Massive structures
j. Use of colour pigments
k. Application of air entrained concrete

EFFECT OF ENTRAINED AIR ON THE STRENGTH AND DURABILITY OF HARDENED CONCRETE

It has been found that entrained air in the normal amounts of 3 to 6 percent exercises a great effect on the strength and durability of concrete.

It has been also experienced that the compressive strengths have been increased up to 6% for lean mixes containing less than 5 a/sacks per cubic yard, while ordinarily each percentage increase in the amount of air in plain concrete reduces the compressive strength by 3 to 4 percent and flexural strength 2 to 3 percent. The above effect on the mixes of the entrained air has not been definitely understood.

Effect on Strength

It is shown by various experiments that the flexural strength of concrete is reduced from 2 percent to 3 percent and the compressive strength from 3 to 4 percent for each 1 percent increase in the amount of air over that which exists in plain concrete. These comparisons are based on the fact that the amount of concrete used is the same and that the percentage of sand and amount of water have been reduced to the minimum to get satisfactory workability. This shows a reduction of 12 percent in flexural strength and 18 percent in compressive strength for concrete containing 6 percent of total air as compared with plain concrete containing 1 percent of air. Although this reduction in strength has to be given consideration in design, yet it has been pointed out by the Hy. Research Board, that in Bridge design, with the high factor of safety adopted, the strength developed is far higher than the minimum requirement, and the comparative gain in durability and workability offset the 18° percent loss in crushing strength.

The thickness of the slab may be increased if it does not come up to the established value of mod. of rupture of 550 lbs. per sq. inch at 14 days as the minimum requirement for flexural strength.

Decrease in Strength with the Entrainment of Air. (Cordon)

The strength of the concrete decreases uniformly with increases in air content of the fresh concrete as shown by Fig. 6. The decrease amounted to 125 psi. about 5% average for each 5 of air entrained at const. water cement ratio by weight. Also at W/C held constant as shown in Fig. 6a, the same reduction in strength for each percent of air entrained for the higher constant W/C .65 as for the lower constant W/C of .45. When the cement content is held constant, and the water cement ratio is reduced through reduction in water content as a result of the entrained air, the change in strength for each percent of air is not constant and ranges from a slight increase for mixes of low cement content to about 200 psi. reduction for each percent of air for mixes of high cement content. It is also observed that there is little advantage keeping the cement content constant when using more than 6 sacks per yard, since the reduction in strength as the air increased is about the same as that for content W/C.

Fig. 1 shows results of tests made by Messrs. Walker and Bloem of 7 and 28 day compressive strength S of concrete containing 4.5, 5.5, and 6.5 sacks of cement per cu. yard. Vinsol resin was added in amounts of 0, 0.005, 0.0.0, 0.015, and 0.020 percent of the wt. of cement, resulting in air contents up to about 9 percent. It will be seen that for the 5.5 and 6.5 sack concrete, strength was reduced as air was entrained. For the lean mixes (4.5 sack) the strength was slightly increased for air contents up to about 6 percent. This beneficial effect on the lean mixes, it seems reasonable to suppose, was due to the improvement in workability--in spite of the fact, that according to usual standards, the air free mix was workable.

For 5 percent added air, the percent change in strength is as shown in the following table.

Cement sacks per cu. yd.	7 days	28 days
4.5	9	4
5.5	-12	-16
6.5	-17	-20

There is also a close relationship between the entrained air and compressive strength reflect not only the effects of the air but also of the water used which has to be reduced in order to achieve same consistency. The authors and other writers have suggested that the air affects the strength exactly as so much water. This gives a good basis for design purposes, although not being true.

Fig. 2 shows 28 days compressive strengths plotted in relationship to the gallons of water plus air per sack of cement. Curves derived by interpolation from the original data, are shown for 0, 2, 4, 6, 8 percent of air. The slopes of these curves decrease as the percentage of air increases.

Fig. 3 shows conventional water cement ratio strengths relationship for the same data as used in Fig. 2. It may be seen that concrete containing 4 percent air and having a specified strength can be obtained by reducing the water cement ratio about 1 to 1½ gallons per sack below that required to produce the same strength in normal cement concrete.

(Corden)

a. When W/C is held constant, the compressive strength of concrete would be reduced approximately 200 psi. for each percent of air entrained in the fresh concrete by Vinsol resin. (This value does not apply where accelerators are used in combination with the air entraining agent.) Fig. 6.

b. Where the cement content is kept constant the change in strength ranges from practically no change for concrete of low cement content to a reduction of around 200 psi. for each percent of air entrained for concrete of high cement content. Fig. 6a.

c. The modulus of elasticity of an average concrete having the same water cement ratio and the same aggregate grading, will be reduced approximately 105,000 psi. for each percent of air entrained in the fresh concrete. Fig. 7.

d. The ratio is not significantly affected by the entrainment of air.

Effect on Modulus of Elasticity

There is a decrease in the modulus of elasticity when air entraining concrete is used. Fig. 7 shows the difference in the decrease of mod. of elasticity when using different aggregates. The slopes of the regression lines correspond with the average of all tests, and at the same water cement ratio a loss of approximately 105,000 psi. static modulus of elasticity for each percent of air entrained can be expected for average concrete mixes.

According to Gonnerman there is a decrease in the modulus of elasticity of about 3 percent for each percentage point increase in air content of the fresh concrete.

Effect of Air Entrained Cement on the Resistance to Freezing and Thawing Action.

The air entrained cement posses greater resistance to freezing and thawing action.

Fig. 9b shows the effect of Vinsol resin on resistance to freezing and of limestone sand concrete as the result of experiment run by A. T. Goldbeck on limestone sand.

Fig. 4a shows results of tests by H. J. Gonnerman with 13 air entraining Portland cements, eight of the cements were ground with .05 percent of beef tallow and five with .05 percent Vinsol resin. Included in the tests were normal Portland cements from the same plants that furnished the air entraining products. It is clear from the curves of durability tests that the cements ground with tallow and Vinsol resin gaveequally good results. It is also clear that when the air content was increased only a relatively small amount over that of the concretes made with the normal Portland cements, a very great improvement in resistance to freezing and thawing was obtained. This was indicated by the low expansion, small reduction in modulus of elasticity and low loss in weight for air contents slightly above those obtained with the normal Portland cements which were generally less than about 1 percent. Concretes having air contents of about 3 percent (An increase of about 2 percent over that of normal Portland cement concrete) showed about as good resistance as those with higher air contents. Air contents in excess of about 5% (above optimum limit) should be avoided, because they are accompanied by a considerable falling off in strength, without any compensating gain in resistance to freezing and thawing.

Effect of Entrained Air on Scale Resistance

It has been shown by so many experiments in the laboritories and observation in the field that entrained air in concrete increases its resistance to scaling due to chloride salts used for ice control and by frost action.

Following are some of the results of experiments on accelated scaling studies conducted.

Photographs taken by Gonnerman showing the top surfaces of typical slabs containing normal Portland cement and air entrained Portland cements from experimental projects after they had been subjected to as many as 375 cycles of the surface scaling test speak very high of the values of air entrainment. The specimens containing the air entraining Portland cements showed only slightly, if any scaling after 300 to 375 cycles of this severe test, whereas companion specimens without the air entraining addition showed serious scaling after 40 to 75 cycles. These results are typical of many others obtained during the past 10 years.

Method of Evaluating Durability.

The progressive drop in dynamic modulus "E" is measured after subjecting the specimen to freezing and thawing action, and is in terms of the number of freezing and thawing cycles. A sonic apparatus is used for this purpose.

A radio frequency oscillator furnishes power to a driving machanism which in turn vibrates the speciman. A radio loud speaker adapted to this purpose and there is also a pick up which receives the vibrations that are transmitted from the specimen, and pass them to a vacuum tube volt meter. The voltmeter indicates the natural resonance of the concrete by maximum deflection of the dial hand. The frequency at which the dial is vibrating is shown on another dial. Knowing the frequency and constants of a certain specimen, the dynamic modulus can be calculated by using the following formula:

$$E = KdN^2$$

E= modulus of elasticity. #/sq. K= constant depending on dimension of specimen, mode of vibration and condition of restraint.

d= specific gravity
N_2= fundamental frequency cycles/sec.

Effect of Cement Content and Air Entraining Material on Durability. (Wuerpel results).

Influence of Water Content on Durability. Figure .

Effect on Volume Changes.

Studies made by Wuerpel show that a change was brought about in the normal shrinkage and expansion characteristics of concrete by the use of air entraining agents.

Bulking Effect

Bulking effect of the entrained air causes an increased volume of concrete, so quantity of materials that produce one cubic yard of concrete when normal cement is used will yield more than that with air entraining cement. It is necessary to compensate for this increase in yield by adjusting the mix slightly so as to maintain the desired cement content. Because the entrained air greatly improves workability characteristics and increases slump, the adjustment of the mix should be accomplished primarily by reducing the sand and water content.

Effect of Air Content on Durability

Freezing and thawing action results in the loss in weight, expansion of concrete and drop in modulus E. The influence of air on these three factors is shown in Fig. by Gonnerman.

<u>Miscel. Factors</u>

It has been found that abnormal air contents improve the durability of concrete containing either mediocre or good limestone but there is no appreciable improvement in durability when the concrete contains check aggregates.

<u>Effect on Bleeding (Water Gain)</u>

By using air entrained cement we can reduce the amount of water gain, generally called "bleeding".

<u>Bonding Properties Between Concrete and Steel</u>

It has been shown by the work of Wuerpel and P. C. A. that the strength of bond between concrete and steel is not materially affected by the use of air entraining materials provided the mix is properly designed and controlled, and the air content kept within 3 to 6 percent. The data also indicate air entraining admixtures when used in concrete having a cement content of 6-0 bags per cu. yd. enables the concrete to achieve at least parity with plain concrete.

Wuerpel also mentions that the introduction of air entraining agents of optimum quantity in reinforced concrete reduces the bond of concrete to steel by not greater than 10 percent, <u>but the uniformity of the bond increased</u>. This advantage of greater uniformity offsets completely the slight reduction in bond strength and on the whole the reinforced concrete is benefited.

Thermal Properties

Experiments run by Wuerpel indicate that the presence of the distributed air voids in air entraining concrete do not materially reduce the rate of heat diffusion when the amount of entrained air is within the optimum limit. Average thermal diffusivity values in sq. feet per hour of concrete without air entraining admixture was 0.035 and when the admixture was used became 0.034.

Effect on Workability. (Cordon)

The workability of the air entrained concrete is improved as the amount of air entrained increases. Due to the increase of slump thereby permitting a reduction in wa er content as shown in Fig. 3 (Cordon). The workability was found to be better than that of the concrete of lower air content as measured by "Power's remolding appartus" where slump is held constant through reduction in cement and water. Fig. 5 shows that the workability of a mix made with natural aggregates and containing 3% air with a 1½" slump is about equal to that of a mix containing 1% air with a 3" slump, even though the cement content has been reduced.

Effect on Uniformity of Concrete

Homogenueity is greatly increased by use of air entraining agents in concrete.

Studies made by Kennedy bear out the fact that homogenueity is closely related to bleeding. The less bleeding the more uniform the concrete from top to bottom. As air entrainment reduces bleeding, it is reasonable to believe that homogenueity will be increased.

Air Entraining Concrete for Massive Structures. (Wuerpel).

Using air entraining concrete in large concrete structures employing lean mixtures and large size aggregates (above 2" max. size) Wuerpel has brought out interesting information from lab. studies. The total amount of air entrained can be less than that in pavements due to reduction of mortar content due to the presence of large size aggregates. It was also shown that the total air content of 2.7 percent in a lean concrete mix containing 6 inch aggregate is comparable so far as the mortar constituent is concerned to a total air content of 4.0 percent in a pavement concrete containing 1½ inch aggregates. The procedure of finding the unit weight of mass concrete by wet screening should not be followed as it will give wrong results, because a considerable amount of entrained air would be lost. A 2 cubic foot measure is recommended to find the unit weight.

Air entrained concrete can be pumped with excellent results and as good as standard concrete. There would be a normal slump loss 1 to 2 inches per 1,000 ft. of pipe. The average slump at the mixer is 4 inches using 5-6 bag mixes. The passing through the pipe of concrete improves its workability by compaction and release of the plastic concrete as it passes through the pipe. Air content is not affected by pumping.

VI. DESIGN OF AIR ENTRAINING CONCRETE

a. Amount of mixing water
b. Amount of sand
c. Effect on yield
d. Quality of ingredients
e. Moisture condition of the aggregate
f. Addition of $CaCl_2$

DESIGN OF AIR ENTRAINING CONCRETE

Effect on Mixing Water Required

Changes in design of concrete have to be adopted when air entraining agents are used inorder to arrive at comparable strength values to those of ordinary concrete. The factor that is given most consideration is the water reduction of water and sand content.

Due to the introduction of air entraining agents, the slump of a concrete mixture can be kept at a desired value, in spite of reducing the amount of water that was first used to get that value. The reduction in water cement ratio in turn causes an increase in strength, impermeability and durability of the mortar and reduces the bleeding. The water content of an average concrete mix may be reduced apporx. 6 pounds per cu. yd. with rounded aggregate according to Cordan, and 8 pounds per cu. yd. with angular aggregate for each percent of air entrained. The ordinary practice is to reduce the water content from ½ to 1 gallon per sack of cement when air entraining concrete is used. Fig. 2 (Cordon).

According to Walker and Bloem, the requirements of mixing water are reduced as air is entrained. Fig. 4 shows the amount which the mixing water may be reduced for different cement contents, with the reduction expressed as a percentage of the volume of air entrained in a unit volume of concrete.

The diagram shows that the reduction in mixing water ranged, for the 4.5 sack concrete, from 74 percent of the air; for the 2 percent of air to 48 percent for 8 percent of air; for the 5.5 sack concrete, the range was from 52 percent to 32 percent; and for the 6.5 sack concrete from 35 to 23 percent. This indicates that as more air was entrained it became progressively less efficient in reducing mixing water; also, the air was progressively less efficient as the cement content was increased.

Effect of Sand Content on Air Entrainment.

The sand content can be generally reduced by approx. 1% of weight of total aggregate for each percent increase in entrained air up to at least 8% without any appreciable change in slump or workability. Fig. 4.

Each percent reduction in sand permits a 2-5 lb. per cubic yard reduction in water in addition to that mentioned before.

Effect of Air Content on Yield.

The increase in yield due to the using of entrained air can be checked by reducing the sand content of the batch by 3 to 4 percent of the combined weight of the fine and coarse aggregate, or 1 to 1.3 times the amount of air entrained. The coarse aggregate should be reduced if there is a tendency for the concrete mixture to become harsh.

Quality of the Ingredients.

The type of aggregate used must be properly controlled as to quality. Air entrainment will not improve the qualities of concrete in which poor aggregate have been mixed. The aggregate must be of medium or good quality before any of the benefits that are connected to the use of air entrainment can be realized.

Moisture Condition of the Aggregate and Concrete.

It has been found that aggregate whose pores were saturated with moisture after being used in the concrete caused a decrease in the resistance of the specimen to freeze and thaw test, as compared to using aggregates which were in a relative dry condition before mixing. Therefore, it is important that the water should be kept at the minimum in order to obtain a relative impervious concrete.

Air Entrainment with Calcium Chloride.

It has been found by laboratory tests that the addition of Calcium Chloride in amounts up to 2 percent, added at the batch either in solution or dry form, increases early strengths without decreasing the effectiveness of the air entraining material. Fig. 19.

VII. METHODS OF MEASURING AIR CONTENT IN PLASTIC AND HARDENED CONCRETE.

a. Determination of air in plastic.
b. Determination of hardened concrete.

METHODS OF MEASURING AIR CONTENT IN PLASTIC AND HARDENED CONCRETE

Gravimetric Method.

This is also called the unit weight method, and is performed by comparing the wt. per cubic foot of the plastic mixture (air entrained) with the theoretical air free unit weight in accordance with A. S. T. M. Method C138-44. We have a precise knowledge of the specific gravities, moisture content of the ingredients used, and also the weight per unit volume in order to arrive at accurate results.

$$\text{Percent of air} = \frac{\text{Theoretical unit wt.} - \text{measured unit wt.}}{\text{Theoretical unit wt.}} \times 100$$

A. S. T. M. Des. (C138-44) assumes that the difference between the unit weight computed from the absolute volume of the cement plus water plus aggregate and the unit weight determined with the freshly mixed concrete is due to the amount of entrained air in the mix.

Volumetric Method.

It is a method by which we can measure the amount of air entrained directly and is described in A. S. T. M. Method C173. The weight of the concrete per unit of volume has to be determined and the displacement, in water of a weighed sample of the concrete after elimination of the entrained air from the sample while immersed in water. This method is open to errors in measurement and is also tedious of execution. Errors may result from failure to remove all the entrained air. In spite of these errors, it is still considered to be a basically sound method.

Pressure Method.

The air content in concrete can also be measured by the reduction in volume when an external known pressure is applied to it. The amount of air can thus be easily determined since this is the only compressible ingredient in the concrete.

There is a special magnesium alloy apparatus developed to determine the air content of this method.

The concrete to be tested is placed in 3 layers in the lower part in the same manner as is required for the standard yield test (A. S. T. M. Des. C138-44). The two sections are joined and water introduced until the level is above the zero mark in the glass gage, then adjusted by bleeding to exactly the zero mark. An air pressure of 15 lbs. is applied by means of a cycle pump. The water level is read when the pressure becomes steady. This will be the uncorrected value. Blank determinations on both sand and coarse aggregate should be run correct for perosity of aggregate grains. The sum of these two values must be subtracted from the first reading to obtain correct gage glass reading. The % of air in concrete $= \frac{\text{Vol. of air}}{\text{Vol. of concrete}} \times 100.$

Camera Lucida Method for Determining Air Content of Hardened Concrete.

This method involves the use of camera Lucida in conjunction with a suitable microscope.

A camera Lucida is a mirror (or prismatic) attachment that permits the simultaneous viewing of both the speciman under the micro-scope and an enlarged area on which the actual microscopic observation may be accurately traced. In this manner an enlarged tracing is obtained of the air voids and aggregate particles in the suitable prepared surface of the concrete specimen. This method shows the air voids the hardened concrete and also their size, shape and distribution. There it can be used as a check on the previous methods.

Method of Determining Entrained Air in Fresh Concrete.

This method is used by State Highway Commission of Indiana both in the laboratory and in the field and is quite simple and accurate. It is based on the equation

Percentage of air $= \frac{(T-A)100}{T}$ in which $T =$ unit weight of the air free concrete, and $A =$ unit weight of the concrete containing air. The above equation is applicable regardless of the method of employed for determining air content. The determination of A is made by the same procedure as that employed in the yield test (cement content) using a 0.5 cu. ft. cast aluminum yield bucket. T is determined by measuring the volume, by displacement in water, of a sample of fresh concrete of known weight. The apparatus used consists of the yield bucket and a nook gage which converts the device into a pycometer the volume of which is calibrated with water of known temperature (0.452 cu. ft. in Table 1). The necessary data and computations for the complete air determination tests consists of four weighings, five subtractions, three divisions, and one multiplication, all very simple to do. Example is given in Column 1 of Table 1.

After A is determined the operator removes concrete from the yield bucket until approximately 30 lbs. remain (line E, Table 1). After weighing (line D) sufficient water is added to inundate the sample completely. The hook gage is set in position and water added until the "Dimple" in the water surface breaks. The hook gage is then removed and the gross weight obtained. From this line D is subtracted to obtain line E, the weight of the water to fill the pycnometer to the hook gage point. The weight of the water is converted into cubic feet, recorded in line G, and subtracted from the calibrated volume of the pycnometer (line V) to obtain line H, the absolute volume of the condrete sample in cubic feet. T is then obtained by dividing the weight of the sample (line E) by its absolute volume (line H) obtaining as shown in the example 154.64 lbs. per cu. ft. The formula $\frac{(T-A)100}{T}$ is then used to compute percentage of air which is recorded in line P.

Table 1-- FORM USED BY INSPECTOR IN THE FIELD, STATE HWY. COMMISSION OF INDIANA.

AIR CONTENT REPORT

Contract No._______ Project No.________ Section____194___

Test Number	1	2	3	'
Wt. of container and ½ cu. ft. concrete	85,000			
Wt. of container, empty, clean and dry	10,000			
Wt. ½ cu. ft. concrete	75,000			
Wt. of 1 cu. ft. concrete	150,000			A
Wt. of container and concrete sample	40,000			D
Wt. of container, empty, clean and dry	10,000			
Wt. of concrete sample	30,000			E
Wt. of container concrete sample and water to gage point	56.10			
Wt. of container and concrete sample	40.00			D
Wt. of water to fill container to gauge point	16.10			F
Vol. of water in cu. ft. $\frac{F}{62.30}$	0.258			G
Calibrated vol. of container at the hook gage point	0.452			V
Less Vol. of water--cu. ft.	0.258			G
Absolute vol. of concrete sample in cu. ft.	0.194			H
Wt. of solid concrete on air free basis $\frac{t}{H}$ lb. per cu. ft.	154.64			T
Air content= $\frac{T-A}{T}$ x 100	3.00			P

Modified Mortar Voids Method

Modified mortar voids method is quite suitable for design of concrete with air entrained in it. The relative water content, an empirical factor used in the design, is reduced from 1.215 to 1.15 to allow for the decrease in water required for this type of mix. The yield and void content are adjusted by reducing the sand content so that the cement factor is kept at 5.5 sacks per cu. yd. of concrete and the total void content kept within specified limits. These adjustments are made at the laboratory and used in the proportional chart prepared for the specific materials to be used on a given project. The theoretic wt. of the air free concrete is also given on the chart to facilitate computations of air content in the field.

It is possible to adjust the amount of air entrained to that required in both cases, when air entraining cement is used or when the admisture is added at the mixer. In case the air content can be raised by adding more of the air entraining materials directly to the batch when air entraining cement is used.

VIII. PROPORTIONING METHODS

PROPORTIONING METHODS

1. Need for Proper Control. The proportioning methods must be carefully taken into consideration in order to get a uniform batch of concrete and so must be the handling and weighing equipment. This will avoid variation in moisture content and grading of the aggregates.

2. Improper placement, spreading and handling in forms may result in segregation, water gain, lamination, and non-uniformity. Careful attention must also be given to finishing and curing methods.

3. Proper consideration should be given to the location of the concrete structure with respect to water, drainage facilities and general working conditions in order to get a durable structure. Complicated forming and placement of reinforcement steel should not be designed, because in case of poor workmanship, it might result in inferior finished product.

IX. MIXING OPERATIONS

Use of Automatic dispensing devices for the admixture

Mix adjustment

Constructional practice

Manufacture of Air Entraining Concrete.

There are three types of manufacturing concrete, site mixed, central mixed and transit mixed concrete.

Site mix can be practised through a mobile concrete paving mixer and stationary mixing plants at the site of structures where the concrete is transported directly to the forms by manually operated buggies or by pumping methods.

Central mixed concrete is that which is manufactured at a stationary plant and transported over a considerable distance by means of agitating or non-agitating truck equipment.

Transit mixed is referred to concrete which is completely mixed in transit by specially designed truck mixers.

a. The site mix offers a very good control and inspection of concrete manufacture. One minute is considered a good mixing time to obtain optimum air content, while more time has to be given to smaller stationary mixers.

b. The air entrained concrete can be mixed at a central mixing plant and transported for a period of 90 minutes without any effect on either the air content or the slump. Dump trucks and truck agitators have been successfully used to transport the mixed concrete to the point of delivery. The mixed concrete can also be transported in truck mixers, operating at agitator speed. The good spped for truck agitation is 2 rpm.

c. Transit mix procedure is not recommended for air entraining concrete as no definite control can be exercised. The following are the main objections to it:

1. Due to change in consistency with distance, time of haul and time of discharge the amount of water used has to be in excess of that in the given design to compensate for drop in consistency.

2. The air content will also vary.

3. Two trucks would be required for handling concrete and both won't give uniform results.

4. Complications arise due to delay in traffic.

5. Greater difficulty in smooth running.

Automatic Dispensing Equipment for Air Entraining Materials

Most cement mills use automatic dispensing equipment in the manufacture of air entrained cements nowadays.

A metering device is necessary when air entraining materials are added at the mixer in order to get accurate results. Such dispensing equipment can be bought in the market.

Adjusting the Mix to Meet the Desired Air Content.

If a trial batch shows that the air content is not within a permitted range, say 3-6%, it may be possible to adjust it by changing the sand content, taking at the same time into consideration avoiding an over sanded or under sanded mixture. If the difference is not too great it can be removed by drying or adding a little water. The air content may also be increased by increasing the mixing time, which is very effective when the cement has been ground with powdered or flake Vinsol resin. Blending in plain Portland cement may correct excessive air due to long continued mixing.

Constructional Practice

Air entrained concrete is more sticky due to its greater plasticity and cohesiveness as compared to plain concrete, with the result that it sticks to the screed of road finishing machines and thus tears the surface. This is more true in case of richer mixes. This can be corrected by increasing the number of transversal oscillations of the screed per foot of forward motion. Steel tools have been used for final finishing in some cases. There is little or no bleeding (water gain) between the initial screeding and final hand finishing, it is necessary to keep all finishing operations well up behind the mixer, particularly in hot dry or windy weather.

X SUPPLEMENTARY NOTES

a. Darex AEA
b. Stewart Field Demonstrates Value of Air Entrainment (Extract)

EXTRACT FROM AN ARTICLE BY MESSRS. H. M. KENNEDY AND BRIGHT

Darex AEA.

This is an air entraining agent manufactured, developed and produced by Dewy and Almy Chemical Co. and is now being used in the manufacture of air entraining cement and as an addition at the mixer on field construction jobs, at ready mixed concrete plants and in concrete product plants. This material was originally intended as a companion product to TDA; that is as an air entraining agent and grinding aid for Portland cement.

Principle of gauge water addition is most favorable and easy method of controlling the air content. Measurement of the entrained air is by making unit wt. determination on the green concrete and so the amount of entrained air can be adjusted as to the required need.

Air content affects richness of mix, water content or slump, graduation and percent of sand.

Dares AEA is delivered in a neutral solution ready to use.

Batching methods have been developed to dispense accurately any predetermined quantity of this solution. Quantity rigid in each batch is small, in most concrete it amounts to from one to one and one half fuild ounces per sack of cement.

With 5% air entrainment using Darex AEA either as an interground ingredient of the cement or as a gauge water addition, there is not the loss in strength generally associated with air entraining concrete.

Table 1 gives results of field tests made on ready mixed concrete. This shows the reduction in water content with the use of Darex AEA with no change in slump. The reduction in water together with the Darex AEA acts to increase the strength of the cement paste so as to offset the strength loss which naturally results from the inclusion of air in the concrete. The table also shows the gain in strength which may be expected for mixes leaner than five sacks of cement per cubic yard and that for the richer mixes, the strength loss is relatively small.

EFFECT OF DAREX AEA ON CONCRETE COMPRESSIVE STRENGTHS
(Typical Data)

Addition	Sacks cement cu. yd.	W/C by wt.	Slump inches	Weight cu. ft.	Compressive strength 7 days	28 days
None	3.90	.753	1.25	150.0	1500	3130
Darex AEA	4.05	.610	2.00	144.6	2766	3930
None	4.40	.710	3.50	152.1	1580	2400
Darex AEA	4.60	.636	3.00	146.6	2480	3540
None	4.93	.602	2.00	150.0	2640	4495
Darex AEA	5.06	.522	2.13	145.0	3130	4450
None	5.53	.575	3.00	152.1	3075	4850
Darex AEA	5.53	.510	3.00	146.0	3100	4930
None	5.79	.550	2.00	153.0	3120	4600
Darex AEA	5.87	.483	2.00	174.0	3365	4670
None	6.00	.530	3.75	147.5	2940	4730
Darex AEA	6.00	.490	3.25	143.6	3225	4875
None	6.60	.496	5.00	152.9	3600	5300
Darex AEA	6.50	.467	4.50	147.7	3650	5270

Production of concrete pipe by the tamp method it is desirable to have a small amount of plasticity in order to get better compaction and also improve its appearance and lower absorption. The improvement in compaction diminishes the danger of collapse of the green pipe during the stripping operation. Too great plasticity is also undesirable as the mix becomes mushy and tamping sticks are broken, thus hindering production. The amount of air entraining agent required is about one half the amount used normally and it is desirable to change the quantity accordingly to changes in aggregate grading. In the Packerhead process, the amount of air entraining material used is approximately twice as much as would be used normally. The use of Darex AEA could give sharper corners and edges on the pipe. It also reduces the sucking action which is of great help in stripping operations. The pasticising action of the air entrainment agent enables the concrete to flow more readily around the reinforcing wire so that dislocation of the wire is minimized.

The use of Darex AEA in building block results in improved surface texture reduced absorption, increased strength and elimination of green breakage and culls, that ordinarily are the result of adverse changes in aggregate graduation. Larger quantities of the entraining agents are used than ordinary, and the optimum quantity determined by actual performance.

The advantages of using Darex AEA in the manufacture of case stone are:

1. Greater plasticity resulting in better filling of the mold.

2. Reduction in bleeding and segregation.

3. Greater durability of the finished product.

STEWART FIELD DEMONSTRATES VALUE OF AIR ENTRAINMENT.
(An Extract)

Stewart field is the U. S. Military Academy's airfield at Westpoint has shown the benefits of air entraining concrete as used by Corps of Engineers for all the complete job. Eighty-two percent of all paving which equals 1.29 million square yards of concrete and three auxiliary airports contain over 500 thousand sq. yards of paving of which 62 percent is concrete. Air entraining agents were used in all these four aerodromes except for a small portion of Stewart Field.

A typical cubic yard mix consisted of 6-1 sacks of air entraining cement; 1142.9 lbs. of sand; and equal amounts of two sizes of gravel ($1\frac{1}{2}$ inch and 3/4 in.) or 1003.5 lb. With 5 gallons of water per sack of cement, this mixture yielded an airless volume of 25.98 cu. ft. The theoretical wt. of the concrete at this yield was computed to be 153 lbs. per cubic foot. The actual measured wt. per cubic foot was 146.9 lb. making actual yield 27 cu. ft. With these aggregates, the amount of air was found to be 4 per cent by weight.

The aggregates used, local sand and gravel, Long Island sand and crushed stone; and manufactured dolmitic sand and local gravel. Air entraining cement used met the Federal

Specification that the cement be treated with Vinsol resin, in an amount not less than 0.025 percent and not more than 0.045 percent by wt. of cement.

Average Compressive Strengths			°
1944 works	7 days	3182 psi	559 psi
1944 works	28 days	4611 psi	700 psi
1944 works	90 days	4769 psi	741 psi

° Average flexurel strengths.

Three 6x12" cylinders and three 6x6x28" beams were made for each day's run.

Adv. fair entrainment:

1. Better workability with stone, sand used.
2. Practically no bleeding
3. Only normal finishing operations were required.

Design Details

Pavement design for a 8-6-6-8 cross section for each 25 ft. strip the thickened edge being attained in a distance of 3 feet from the longitudinal tongue and groove construction joints. At longitudinal expansion joints and at outside runway edges, the edge thickness was attained in a one lane thickness or 12½ ft.

Transverse expansion joints are spaced every 100 ft., with intermediate expansion joints of the dummy type sapced on 20 ft. centers being cut one quarter of the pavement depth except on 1944 work where they were cut to a depth of one third of the slab thickness. All expansion joints have 3/4 inch non-extending filler. Transverse expansion joints have as load transfer units 1 inch palin round bars, 24 inch long spaced 12 inches on centers. Half inch deformed tie bars 30 inches long set 30 inches apart were used in the joints longitudinal dummy joints adjacent to longitudinal expansion jts. and the outside edges of the runways.

Premolded bituminous fiber ribbon 1/8 inch x $1\frac{1}{2}$ inch, was used in longitudinal dummy joints in 1943 construction. This practice was dropped due to light spelling along this type of joints. Spelling occurred when the top of the ribbon was below the surface of the concrete and not when it was above or levelled with it.

Reinforcement

No reinforcement was used in any slab except for small apron areas amounting to less than 1%.

Subsoil

Gravel blanket with a minimum depth of 12 inches was laid and compacted due to poor supporting quality of the subsoil. Bearing tests on this prepared subgrade using a 30 inch diameter plate showed an average bearing strength of 35 psi. at a 0.1 inch deflection.

Construction Equipment

Batches averaged 36 cu. ft. and transported from central plant to pavers in two and three batch capacity trucks. Mixing water was supplied by tank trucks. The batching plant was equipped with a 385 bbl. bulk cement bin and weighing hopper (screw conveyor and bucket elevator) and a 150 ton three compartment agg. bin with weighing hopper.

Production

For 34E average daily production was 600 cu. yd., max. 846 cu. yd. This equivalent of 1200 lineal ft. and 1700 lineal feet resp. of 25 ft. wide slab. Concrete was vibrated along the sideforms and the joints.

Use of Color Pigments on Air Entrainment.

Color pigments made from iron oxides can be used successfully with air-entraining without any loss in strength, durability or scale characteristics of the concrete. Experiments run by the National Crushed Stone Association show that air entrainment in concrete containing limestone aggregates both coarse and fine, materially improve durability and resistance to scaling. Fig. 20. It also improves excessive bleeding, poor workability and difficult finishing.

Application of Air Entrained Concrete.

Air entrained concrete has been used to great advantage in general concrete work such as foundations, walls, paving, sidewalks, slipform work, granite, and in concrete pipe and block.

Main experience in the use of air entrained concrete has been in the field of pavements, however excellent resistance to alternate freezing and thawing indicates that it should prove advantageous in the construction of bridges.

TEST PROCEDURE FOLLOWED BY CORDON

The following describes the test procedure adopted by Cordon for all the results shown in Fig.   . In the 102 concrete mixes a range of slumps, water cement ratios, air percentages, brands of cements and types of aggregates were included. The percent of entrained air used was found by absolute volume method and was an independent variable throughout the entire investigation, and the amount of air in each set of 6 mixes was varied by increments of 1 percent from approx. 0 to 6 percent. Agent was added to all mixes to obtain a pre-established percentage of air regardless of the amount of agent required. A standard solution of Vinsol Resin was made before the mixing program started, and this supply was used throughout, with the exception of 12 mixes in which another commercail air entraining agent was used.

Mixing Procedure

All the mixing was done in a $1\frac{1}{2}$ cu. ft. tilting laboratory mixer with a mixing period of 5 minutes. The following was the charging sequence:

1. One half of the mixing water and agent,
2. sand, gravel and cement combined,
3, remaining half of mixing water and agent.

The air entraining agent was combined with the mixing water before introduction into the mixer. After the mixing period, the mixer was discharged into a large pan and reworked with a shovel. The following tests were made on each batch of fresh concrete:

Slump test -- ASTM Des. (C143-39)

Unit weight -- ASTM Des. (138-44)

"Powers Remolding Test for Workability"

Three 6x12 inch cylinders from each batch were tested for compressive strength, ASTM Des. (C192-44T), and elastic properties.

Modification and Adjustment of Standard Computations

Table 5 of the ACI Standard Recommended practice for the design of concrete mixes can be slightly modified for air entrained concrete by including the following information:

a. Reduce the sand percentage by one for each percent of air entrained.

b. For air entrained concrete, reduce the water content 8.5 lb. for well rounded natural aggregate and 10.5 lb. for angular aggregate for each percent of air entrained.

c. For the same W/C ratio reduce strengths shown in table by 200 psi. for each percent of air entrained in concrete.

Computation of Trial Mixes.

We can very easily modify the trial mix computations as outlines in the recommended practice and allow for entrained air by simply treating the air as another ingredient of the concrete mix which replaces an equal volume of aggregate. The sample computations shown on pages 657 and 658 of the above mentioned standards can be modified as follows:

(Assuming 3% air)

Cement content = $\frac{\text{net water content}}{\text{water cement ratio}} = \frac{305}{0.53} = 575$ lb. per cu. yd. $= \frac{575}{94} = 6.12$ sacks per cu. yd.

Absolute volume water + cement = $\frac{\text{Water content}}{62.4}$ + $\frac{\text{cement content}}{\text{spec. gravity} \times 62.4} = \frac{305}{62.4} + \frac{575}{3.15 \times 62.4} = 7.81$ cu. ft. per cu. yd. concrete

Absolute vol. air = percent air x cu. ft. per cu. yd. of concrete

Absolute vol. of total aggregate = 27 - abs. vol. (water + cement) - abs. volume of air = 27 - 7.81 - 0.81 = 18.38 cu. ft. per cu. yd. of concrete.

Absolute volume of sand = percent sand x absolute vol. total aggregate = 0.42 x 18.38 = 7.72 cu. ft. per cu. yd. of concrete.

Absolute volume of coarse aggregate = abs. vol. total aggregate - absolute volume sand = 18.38 - 7.72 = 10.66 cu. ft. per cu. yd. of concrete

Sand content = absolute volume x sp. gravity x 62.4 = 7.72 x 2.65 x 62.4 = 1,277 lb. per cu. yd. of concrete

Coarse aggregate content = 10.66 x 2.55 x 62.4 = 1,696 lb. per cu. yd. of concrete

Trial mix proportions = $\frac{575}{575} : \frac{1,277}{575} : \frac{1,696}{575} = 1: 2.22: 2.95$ say 1: 2.2: 3.0

Computation of Air Content

For mortar containing soap forming materials ASTM Des. (C173042T) "Test for air content of concrete" is not recommended. The best method is ASTM Des. (C138-44) which assumes that the difference between the unit wt. computed from the absolute volume of the cement plus water plus aggregate and the unit weight determined with the freshly mixed concrete is due to the amount of entrained air in the mix.

The percentage of air $\dfrac{(\text{Theoretical unit wt.} - \text{measured unit wt.} \times 100}{\text{theoretical unit wt.}}$

Using weights computed in the foregoing trial mix computation, the percent air can easily be determined as follows: (Measured unit wt. 142.7 lb/cu. ft.)

Theoretical unit weight $\dfrac{\text{weight cement} + \text{weight water} + \text{wt. agg.}}{\text{solid volume of cement} + \text{water} + \text{cement}}$

$$\frac{575 + 303 + 2973}{27 - 0.81} = \frac{3853}{2619} = \frac{147.1 \text{ lb.}}{\text{cu. ft.}}$$

and % air $\dfrac{147.1 - 142.7}{147.1} \times 100 = 3.0$ per cent

<u>Designation 24 of the U. S. Bureau of Reclamation</u> concrete manual outlines a general method for the computation of per cent voids based on the actual mix parts of any combination of cements, water and aggregate. Sollowing is simplified form of the method described:

Percent air $= 100 - \dfrac{\left(\frac{1}{G_c} - W/C - \frac{PA}{GA}\right) 100W}{62.4\ P_t}$ where

P_t = Total parts (cement, aggregate, water) in mix (by weight).

PA = Parts of aggregate (by weight).

G_c = Specific gravity of cement

GA = Specific gravity of aggregate

W = Measured unit wt. of fresh concrete

W/C = Water cement ratio lb. per cu. ft. by weight.

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Pocket Ser. 11 Supplement

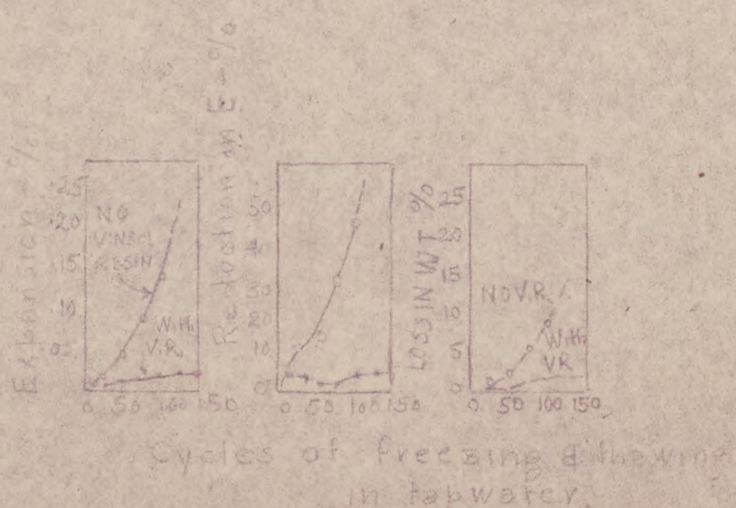
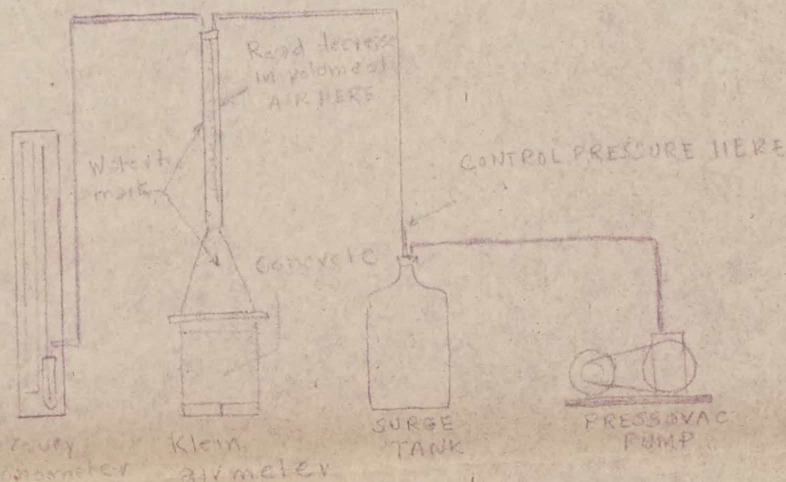


Fig 9. Results of freezing and thawing tests of 3x3x11 1/4-in. concrete prisms containing .01 percent Vinsol resin by wt of cement, added in a NaOH-water solution at mixer.



Schematic Layout of Klein air meter

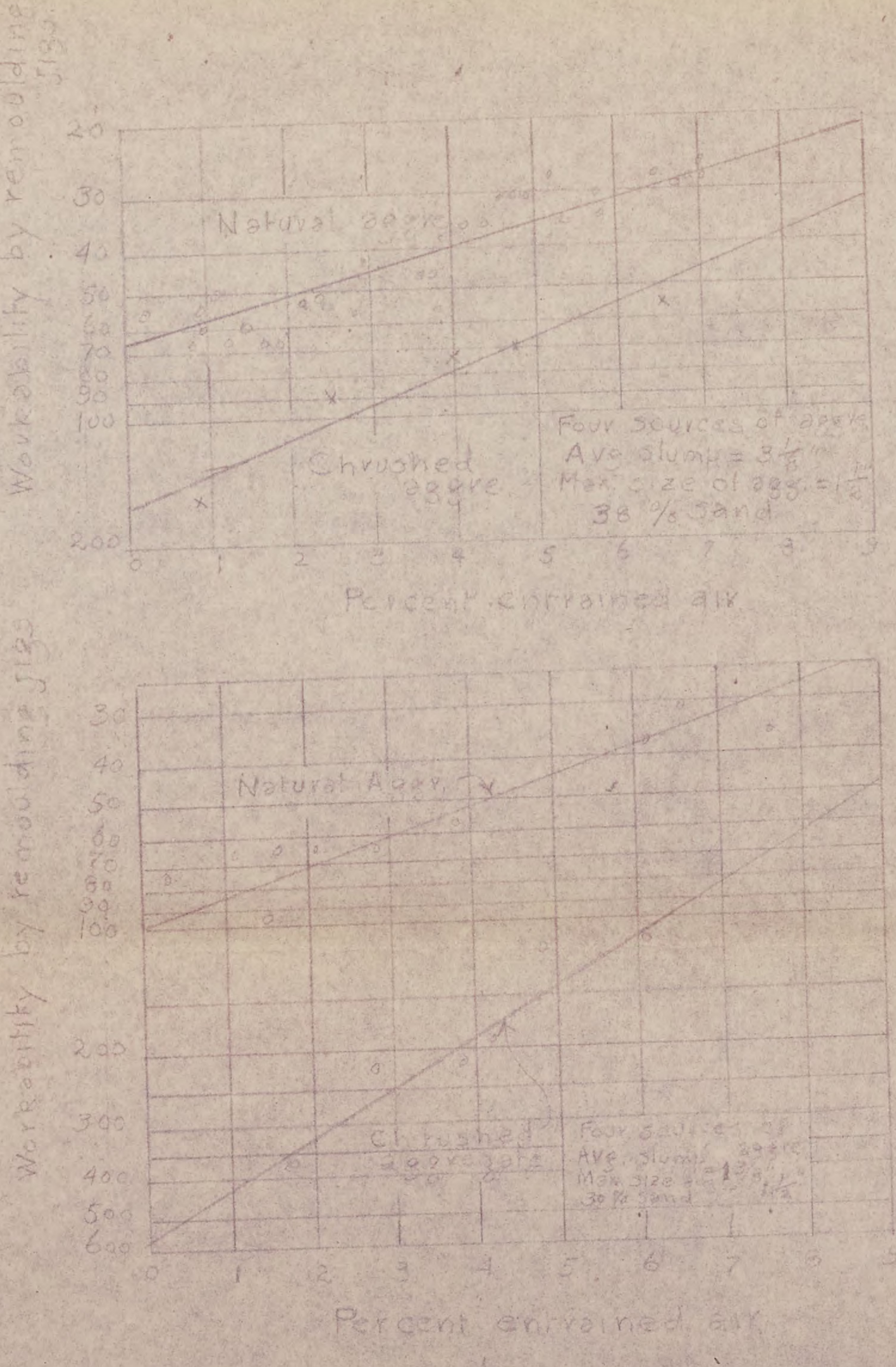


Fig 5 — At the same slump the workability of concrete is increased as the percentage of air is increased

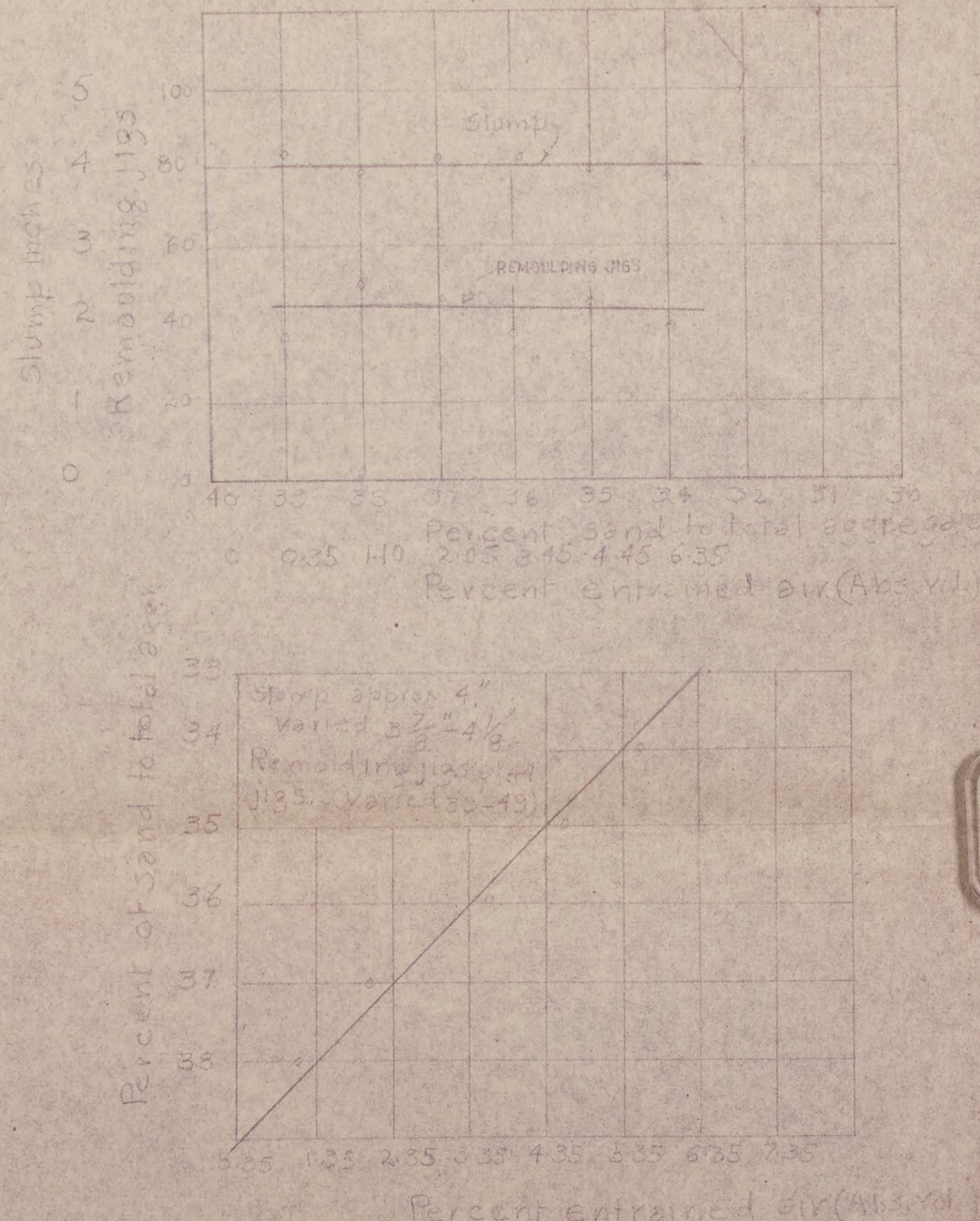
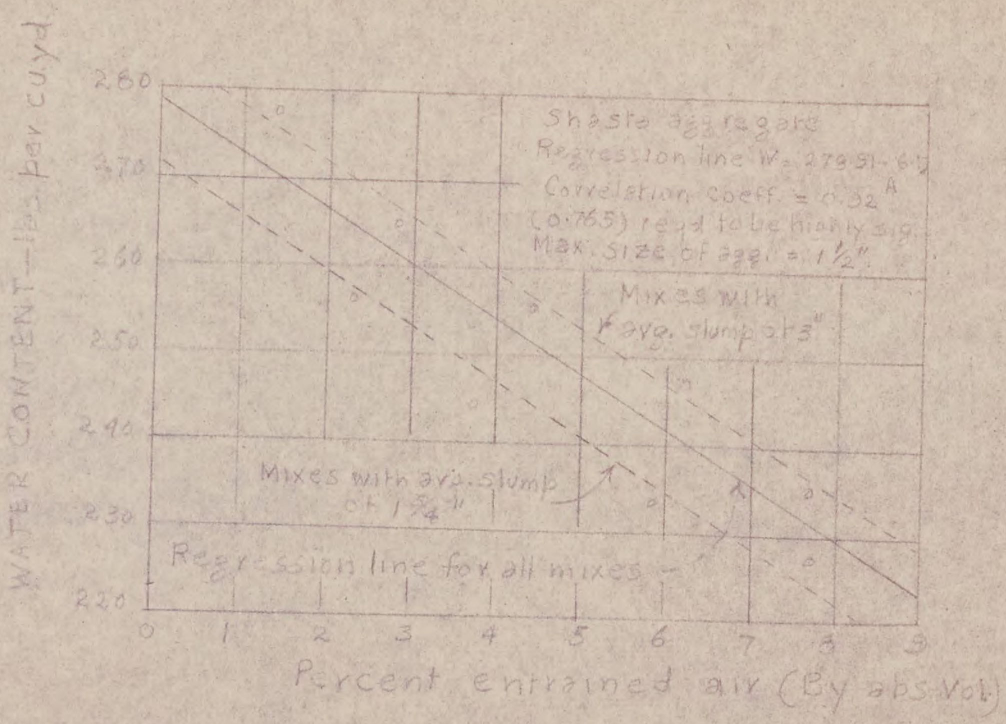


Fig 4 — The workabilty & slump remain about the same if the percentage of sand is reduced by one for each percent increase in air content.



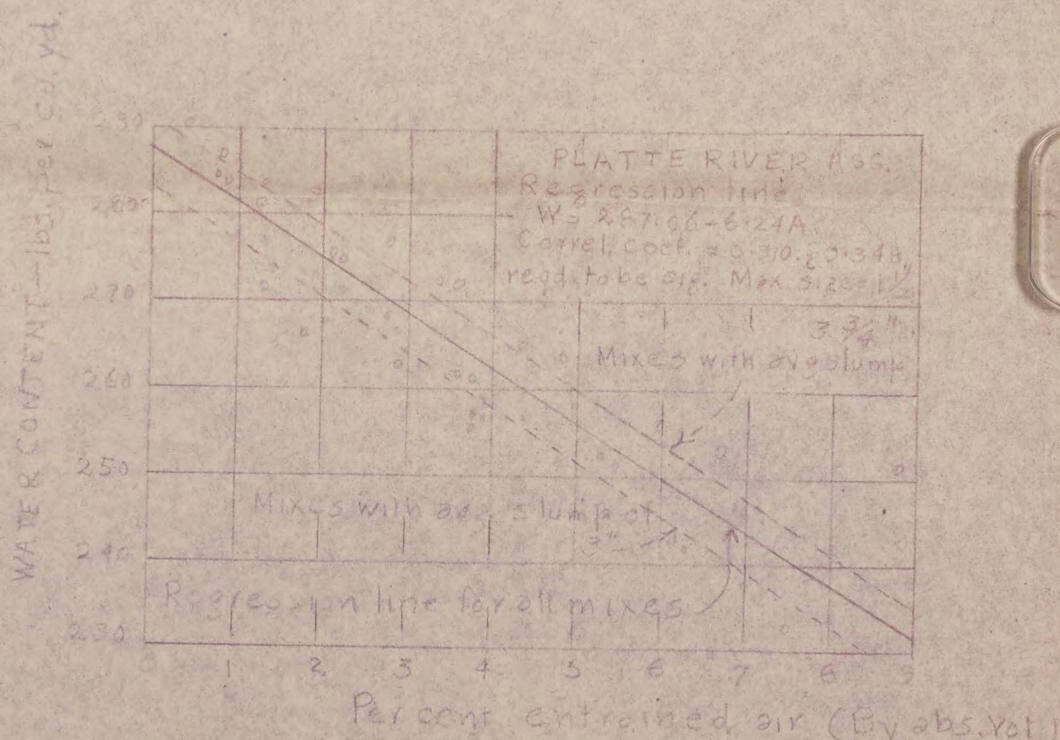


Fig. 2a – The decrease in water content due to air entrainment is approximately the same for different slump.

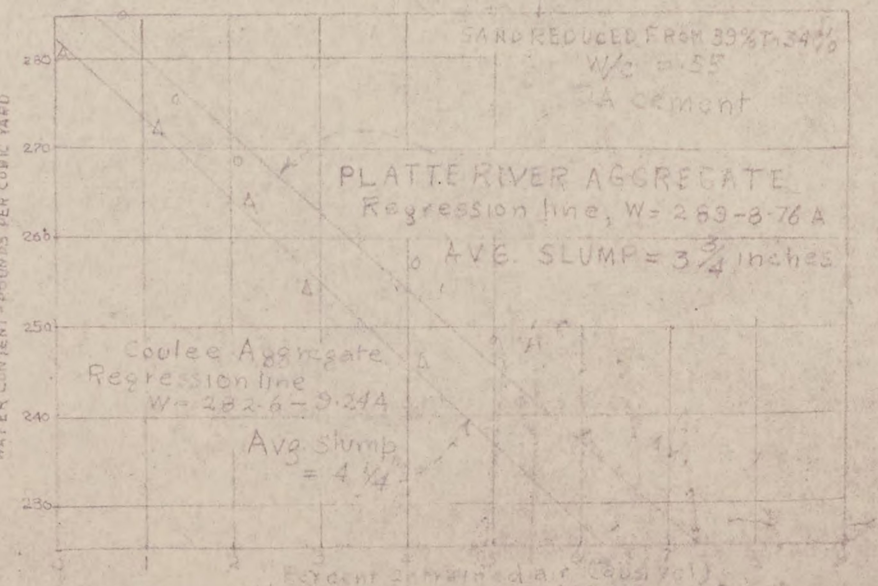


Fig 26 - If the percentage of sand is reduced by one for each percent increase in air content a reduction of ... lb of water per cu. yd. is realized for each percent of air entrainment.

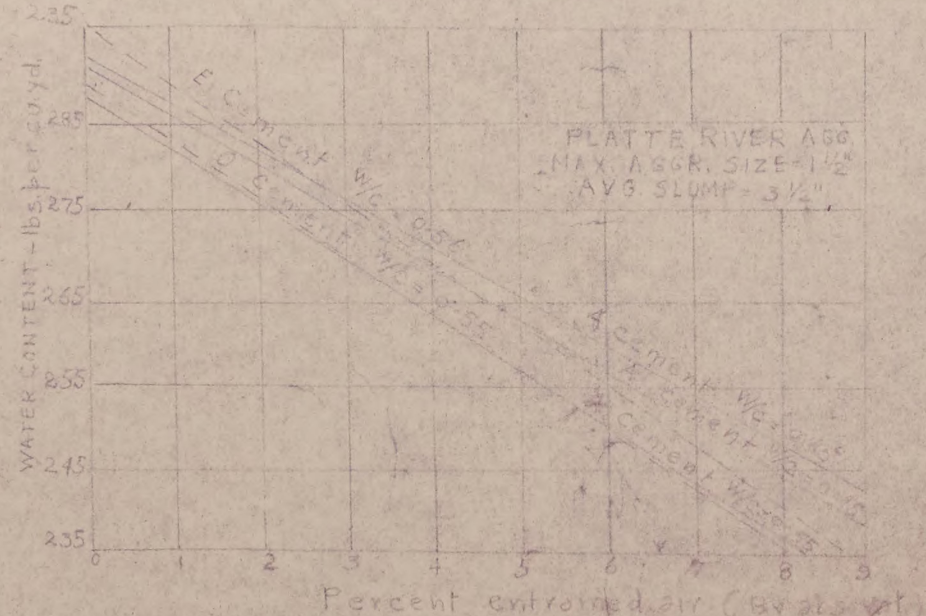


Fig 5. — The reduction in water content for each increase in air entrained is about the same regardless of the water cement ratio or the brand of cement.

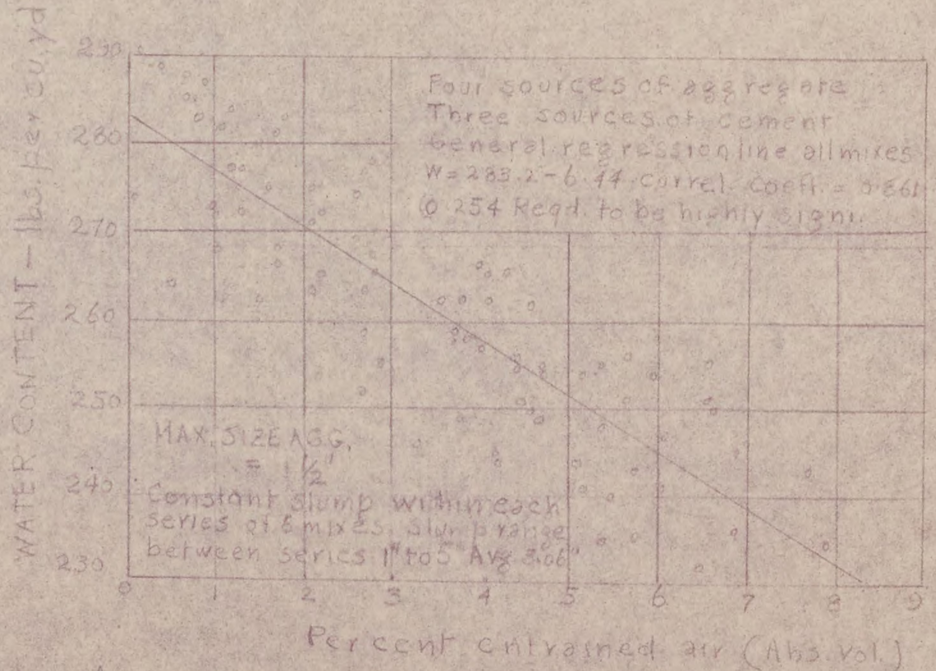


Fig. 1 — An average reduction of 6.4 lbs. of water per cu. yd. of concrete results from each one percent increase in air content

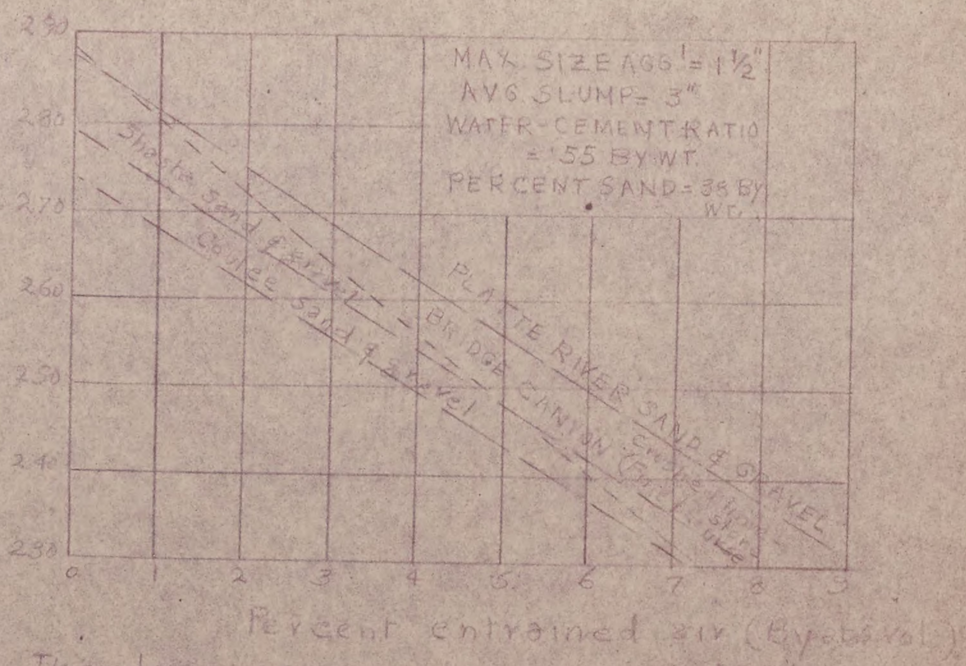


Fig 2 — The decrease in water content due to air entrainment is approximately the same for different natural aggregates, but is greater for crushed aggregate

Fig. 7 – Modulus of elasticity is decreased 105,000 psi for each %age increase in air content.

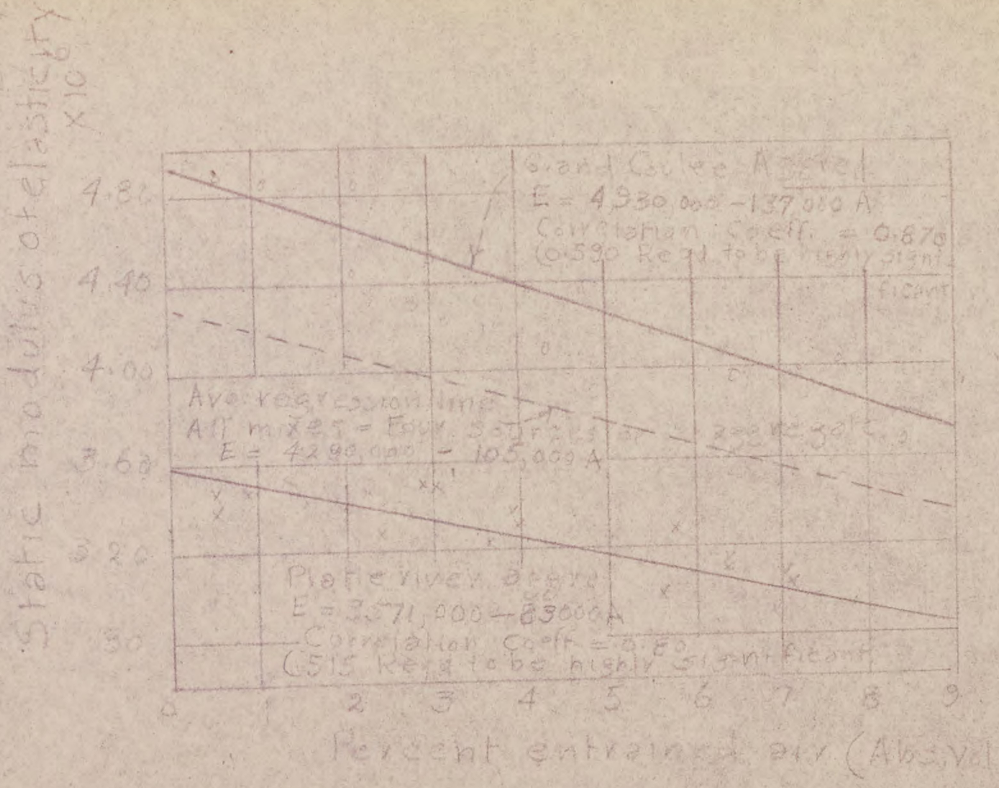
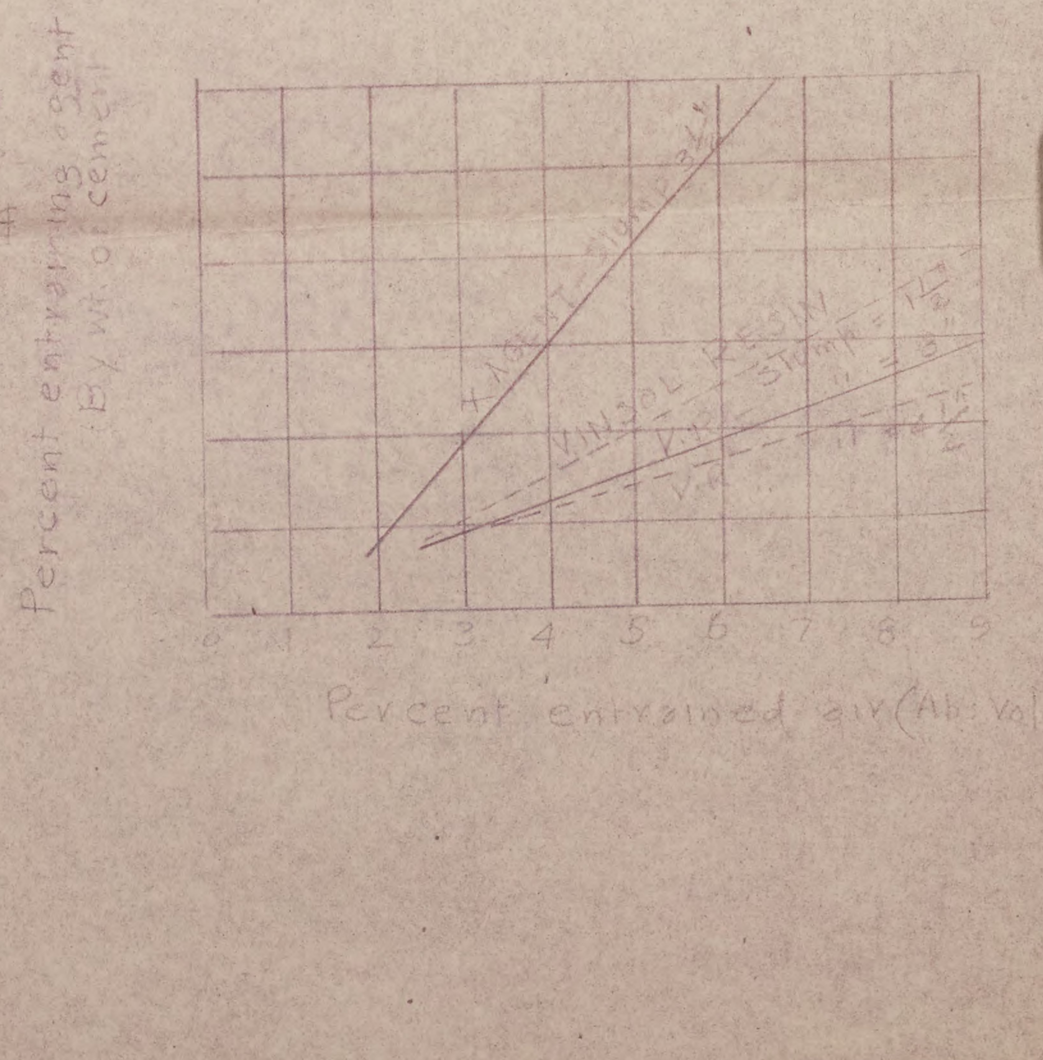


Fig. 8 – The amount of air entrained in a given mix, is influenced by the slump & the kind of agent used.



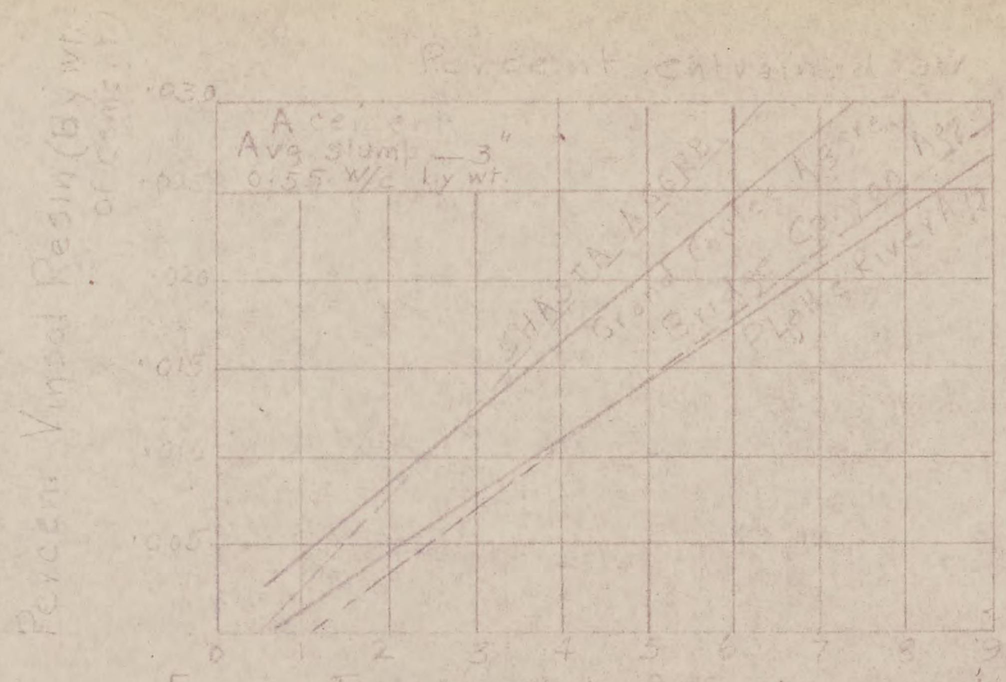


Fig 9 – The amount of air entrained in a given mix is influenced by the aggregate used

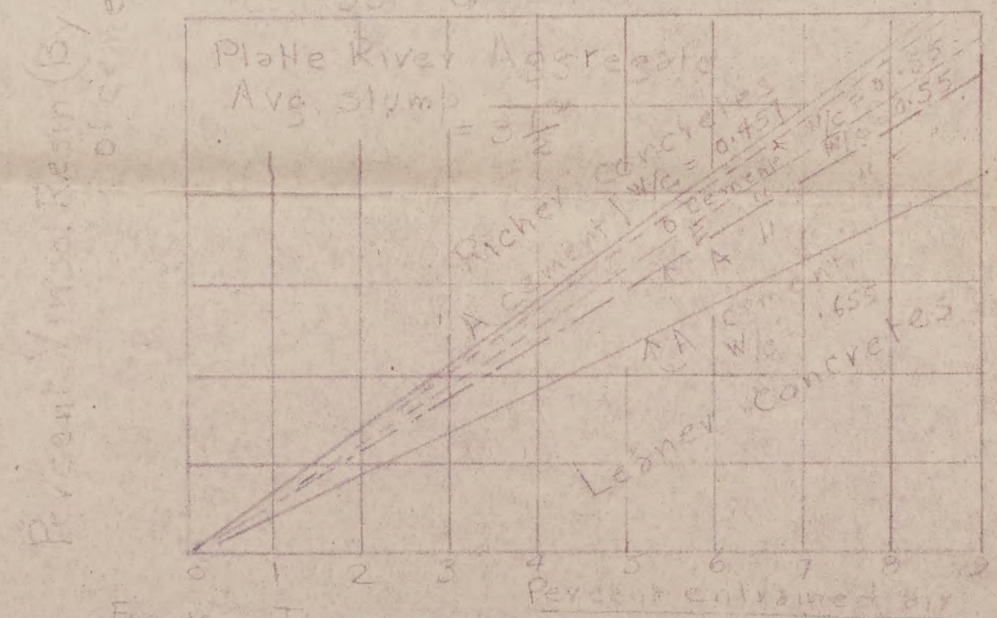


Fig 10 – The increase of entrained air in a given mix is affected by the brand of cement & the W/c ratio.

(By W. A. Cordon

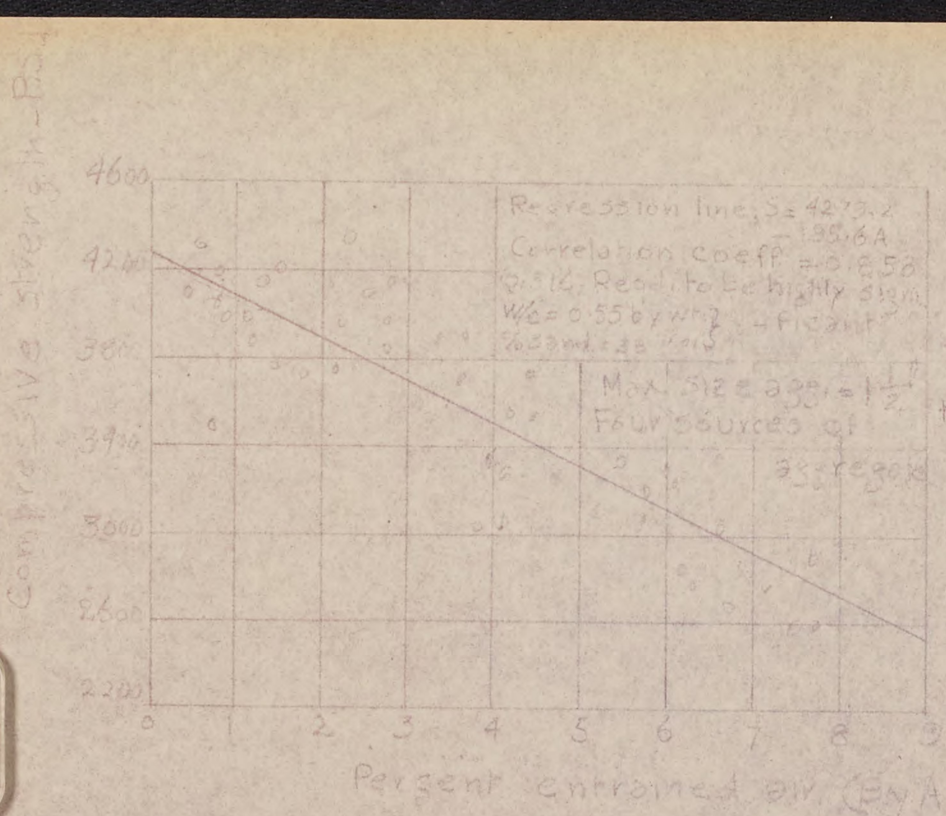


Fig. 6 – Concrete having the same water cement ratio & the same aggregate grading is reduced in strength approx 195 psi for each % increase in air content.

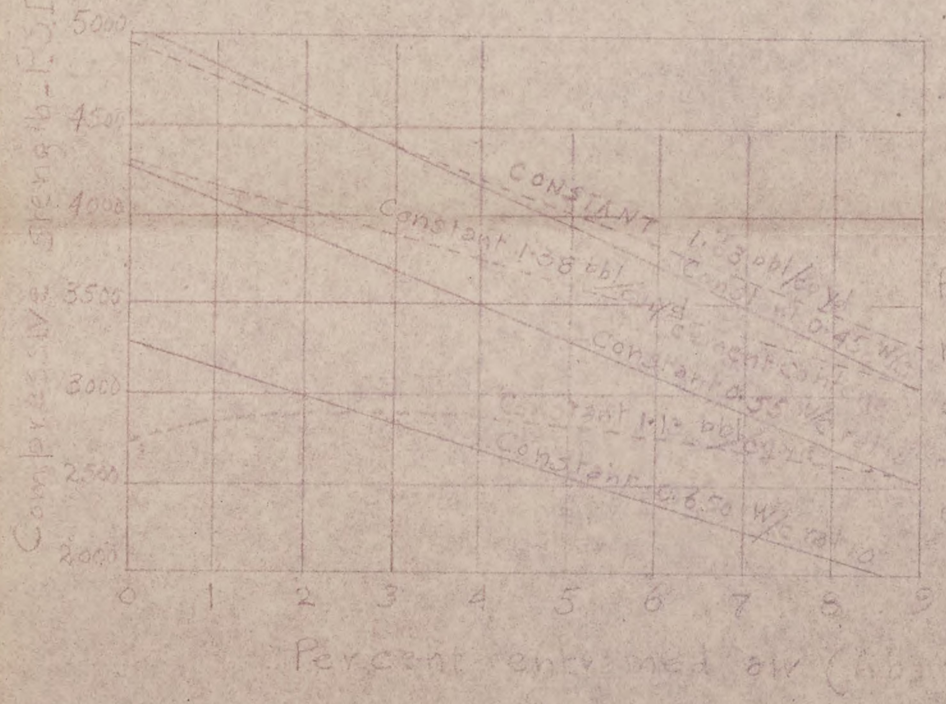


Fig. 6A – The decrease in strength as the air content increases is about the same for different water cement ratios but for constant cement contents is influenced by the amount of cement in the mix.

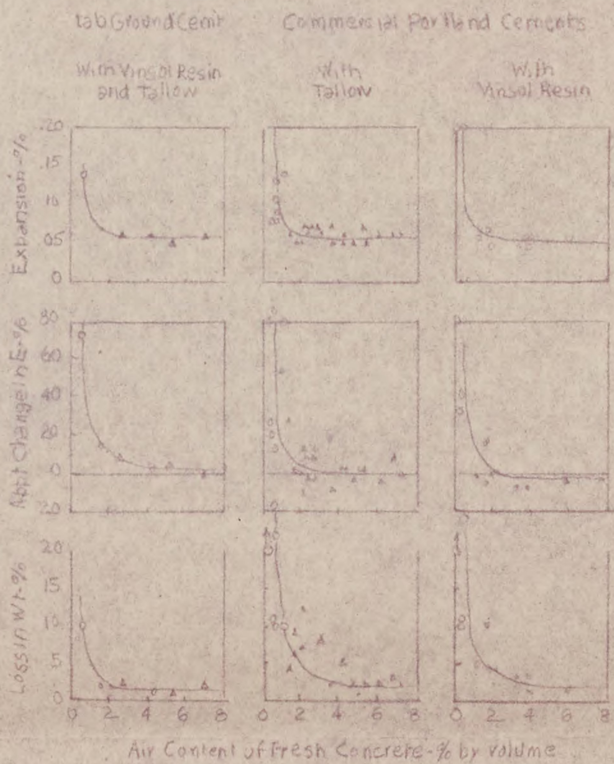


Fig. 1 — Results of freezing and thawing tests of 3x3x11 1/4-in. concrete prisms containing cements ground without and with tallow or Vinsol resin.

225 cycles

○ Concrete made with cements without addition

△ Concrete made with cements ground with tallow used alone and blended with cement without tallow.

● Concrete with cements ground with Vinsol resin used alone & blended with cement without Vinsol resin.