DEVELOPMENT OF CEMENT-SLURRY MIXTURES FOR USE IN CORRECTING PUMPING PAVEMENTS

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SYNOPSIS

This paper presents the results to date of an investigation undertaken by the Joint Highway Research Project of Purdue University to develop better materials for use in correcting pumping concrete pavements. Cement-slurry mixtures have been developed which have desirable workability characteristics and which are made with portland cement as the major ingredient and with calcium aluminate cement as the minor active ingredient. These mixtures have an initial almost water-thin consistency which is maintained for a controlled length of time, at the expiration of which a fast-thickening action takes place. After thickening has occurred, the slurry mixtures set rapidly so that very little bleeding takes place and consequently their original volume is maintained.

The qualitative and quantitative effects of variables affecting the workability, strength, and durability characteristics of these mixtures have been systematically investigated until it is a relatively easy matter to formulate mixtures from a variety of standard portland cements which will function satisfactorily under a variety of field conditions. Field trials with a simulated pavement slab have established that mixtures which will completely fill a void existing under a concrete pavement slab should have a consistency of not more than 25 sec. on the basis of test with the Stormer Viscosimeter using a forked rotor. Thickening should take place in 10 to 20 min. depending upon equipment used. Investigation has shown that many factors affect initial consistency, thickening time, and setting time of calcium aluminate-portland cement mixtures. These include age and brand of portland cement, water-cement ratio, air temperature and temperature of all ingredients, and calcium aluminate-portland cement ratio. However, even with this large number of variables, it has been demonstrated that the practical problem of proportioning ingredients in the field to produce mixtures with satisfactory characteristics is easily accomplished if two principles are followed:

(a) Initial consistency and the time-consistency relationship up to the time thickening begins should be controlled by using sufficient water.

(b) Thickening and setting time should be controlled by varying the calcium aluminate-portland cement ratio.

The corrective procedure for pumping action of concrete pavements requires that the void under the pavement caused by pumping be filled in order to restore the foundation support of the pavement slab. Further, the void-filling material should be superior to the soil which it replaces in that it should itself resist the pumping action.

The Joint Highway Research Project of Purdue University has long been intensely interested in this problem and has used both mud-jack mixtures and asphalt cements in field experiments. About two years ago it was decided to initiate laboratory work leading to the development of void-filling materials with more desirable characteristics. It was considered that the ideal material would be one which could be easily pumped through a hole in the concrete pavement with available equipment, thin enough in consistency to completely fill the void, and which would harden or set quickly after placement without appreciable loss in volume. In addition, the material should be durable and, if at all possible, impervious to water.

Several materials were considered and at least briefly investigated. These included sodium silicate with calcium chloride, bentonite, bentonite and lime with kerosene or tall oil (sulphite liquor), and fine soil with various chemicals. The use of liquid asphalts was considered. Some of these materials seemed to show promise as mud-jack mixtures where rather heavy consistency is used, but they did not satisfy the requirement of thin consistency with quick setting. Both thermo-plastic and thermo-setting resins were considered. Certain of the thermo-plastic resins showed promise because they have rather sharp melting points, and those thermo-setting materials which can be set with a liquid catalyst are quite definitely well adapted to the problem. However, both of these classes of materials must be ruled out at the present time because of economical considerations. In addition to all of these materials, neat cement was also considered and proved to be the most promising of the materials investigated.

GENERAL CHARACTERISTICS OF CALCIUM ALUMINATE AND PORTLAND CEMENTS

There are several different cements on the market each with distinct setting and hardening characteristics. The term "quick-setting" is commonly applied to some of these materials whereas they are in reality "slow-setting" but "quick-hardening". The term "setting-time" usually refers to the length of time after mixing that the cement requires to stiffen to a point where it can no longer be worked without disruption. After setting, cements harden or develop strength at various rates depending upon their composition. Standard portland cement is essentially a calcium silicate cement which sets in about three hours under normal conditions and then hardens slowly, gaining strength up to 28 days and beyond. Calcium aluminate cement contains compounds of calcium and aluminum as the principal constituents. It is slower setting than portland cement, requiring about five hours at 70 F. However, it hardens very rapidly and at 24 hr. has reached practically full strength.

When calcium aluminate and portland cements are mixed, it is possible to obtain a flash set or controlled fast setting depending upon the proportions used. The strength of the combination, as well as of the individual cements, follows in general the well-known law of water-cement ratio. Also, since the setting and hardening of all cements results from chemical action, the hardening of the individual cements as well as combinations of them is accelerated by heat and retarded by cold. Mixtures of calcium aluminate and portland cements have been used in oil-well work where quick-setting and fast-hardening cements are sometimes desirable. Since these mixtures apparently possessed characteristics applicable to the problem of filling voids beneath concrete pavements, it was decided to investigate the development of such mixtures for this purpose.

In developing these cement-slurry mixtures, it has been necessary to measure consistency of the mixtures and to introduce a new concept on the time-consistency curve in addition to the concepts of setting and hardening. This concept has been called "thickening time".

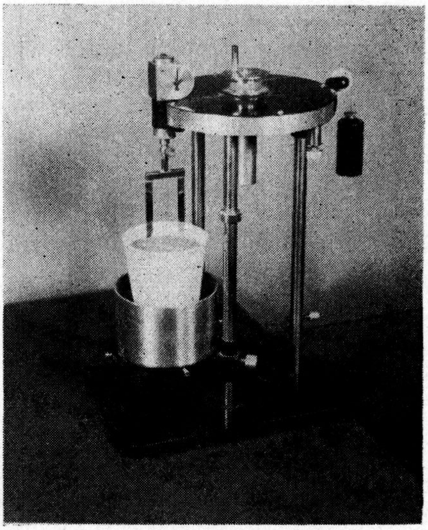

Figure 1. Paint Model Stormer Viscosimeter with Forked Rotor

The Paint Model Stormer Viscosimeter with the forked rotor has proven to be very useful in measuring the consistency of cement slurries and in arbitrarily defining thickening time. This instrument is pictured in Figure 1. In making a consistency measurement, the forked rotor is immersed to a standardized depth in the cement slurry and then rotated by releasing the clutch and allowing a falling weight to apply a constant force. The time required for 100 revolutions of the forked rotor is measured in seconds and recorded as the consistency of the material under test. Thickening time is arbitrarily defined as the time after mixing that the constant force will no longer turn the rotor. At this time the mixture can still be mixed or stirred since it has the consistency of a very heavy cream.

In the laboratory, consistency measurements have been made each minute starting with the end of the second minute after the addition of water. Thus, the mixtures are stirred to some extent during thickening when this means of measurement is used. Thickening times given in this report were obtained under this condition. Thickening and setting are somewhat more rapid if they are allowed to occur without agitation.

EXPERIMENTS TO ESTABLISH LIMITS OF CONSISTENCY AND THICKENING TIME

From general considerations, and the fact that the mixtures were to be used in conjunction with lifting of the pavement slabs by means of a hydraulic jack, it was thought that the mixtures should be thin enough in consistency to fill completely the voids and should set fast enough that the jack and lifting rig could be freed for further use in the shortest possible time. Also, it was considered that that mixture should not change greatly from its initial consistency for a period of 10 min. or so in order that the pump used to force it under the slab would not become clogged. In addition, it was realized early in the experimentation that a thickening time of 10 to 20 min. was desirable even if the mixture was used without the pavement jack, because rapid setting is necessary to prevent excessive bleeding of the mixture with resulting loss of volume and only partial filling of the void.

The development of these mixtures was started in the laboratory during the winter months, and although desired setting time and consistency were not accurately known, it was established that consistency could be varied over a wide range by varying the water-cement ratio and that rate of set could be controlled by controlling the calcium aluminate-portland cement ratio. Preliminary tests showed that the mixtures were capable of developing considerable strength even though rather high water-cement ratios were used to obtain almost a water-thin consistency. Also, during the preliminary testing, it was found that measurements with the Stormer Viscosimeter using the forked rotor were convenient and satisfactory for specifying consistency in the range probably desirable.

When the weather became suitable, and after it had been decided to use a Koehring No. 10 Mud-Jack for the work, some experimental work was done in the field to establish the range of consistency and setting time which would be desirable. A simulated pavement slab was made of wood and weighted with concrete blocks. This was placed on top of the ground in such a position that a wedge-shaped void existed under it varying from about 1-in. to zero thickness in a distance of 8 ft. Batches of quick-setting cement slurries were made and pumped through a hole in this simulated pavement slab by means of the Koehring machine. While mixtures had been made in the laboratory by mixing the dry cements before adding water, it was found that in the field mixing was done more easily by making separate slurries of the cements and then combining the slurries just before use.

After allowing sufficient time for hardening, the concrete blocks were removed and the wood lifted for inspection of the slurry mixtures. From these experiments it was determined that the cement-slurry mixtures should preferably have a consistency and thickening time, on the basis of the Stormer Viscosimeter tests, of not more than 25 sec. and between 10 and 20 min., respectively. It was also determined that the mud-jack was capable of pumping mixtures considerably more viscous, and that the arbitrarily defined thickening time on the basis of the Stormer Viscosimeter tests was conservative enough that there was little danger of the mixture setting-up in the machine if reasonable care was used. At consistencies of less than 25 sec. the mixture flowed readily and filled the void under the simulated pavement slab completely, flowing out to a very thin feather edge. If the mixture was heavier in consistency than the value of 25 sec., it was not sufficiently fluid to completely fill the void. With reference to thickening time, mixtures which thickened in 10 to 20 min. (Stormer Viscosimeter test), and set in 10 to 20 min. more, did not bleed under the slab and therefore did not lose volume. If the thickening and setting times were increased to much greater values, bleeding of water to the surface of the mixture occurred and voids on the top surface remained when the water was regained by the cement.

CONSISTENCY OF CALCIUM ALUMINATE-PORTLAND CEMENT SLURRIES

Figure 2 shows the effect of percentage water on the initial consistency of slurries made with a constant calcium aluminate—portland cement ratio. It will be noted that the change in consistency with change in water content is not great until a point somewhat below 60 percent water is reached. Also, it will be noted that, with this particular mixture, a water content as low as 50 percent by weight of cement could be used and still satisfy the requirements for initial consistency as determined by the field trials. However, variations in water-cement ratio also have an effect on thickening and setting time, lower water-cement ratios resulting in faster thickening and setting.

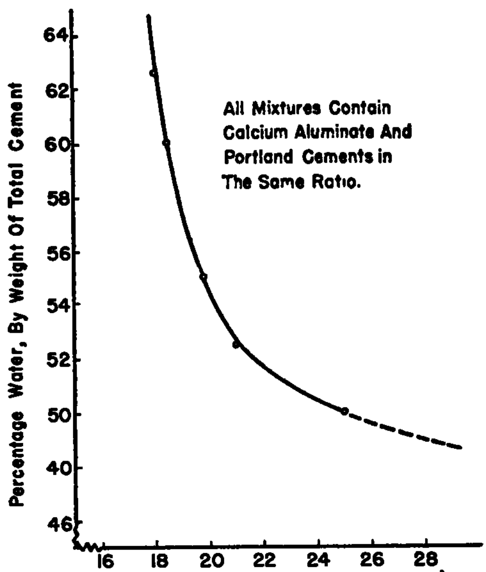

Figure 2. Relation Between Percentage Water and Initial Consistency

Since it seemed desirable to work in the laboratory at a water content that would not be too critical, it was decided to standardize the tests at a water content of 60 percent by weight of the total cement. This choice proved to be a fortunate one because it has since been learned that temperature is an important variable, as will be discussed.

THICKENING TIME OF CALCIUM ALUMINATE-PORTLAND CEMENT SLURRIES

Having established the necessary water-cement ratio to produce the desired consistency, the next step in the laboratory development of the cement-slurry mixtures was to establish the calcium aluminate-portland cement ratio which would produce the desired thickening and setting time. As pointed out when discussing the general characteristics of portland and calcium aluminate cements, it is possible to produce a flash set or controlled setting within limits by varying the proportions of the two cements. Mixtures with the most desirable setting characteristics are made with portland cement as the major ingredient. This is fortunate because the cost of portland cement is roughly one-third to one-fourth that of calcium aluminate cement.

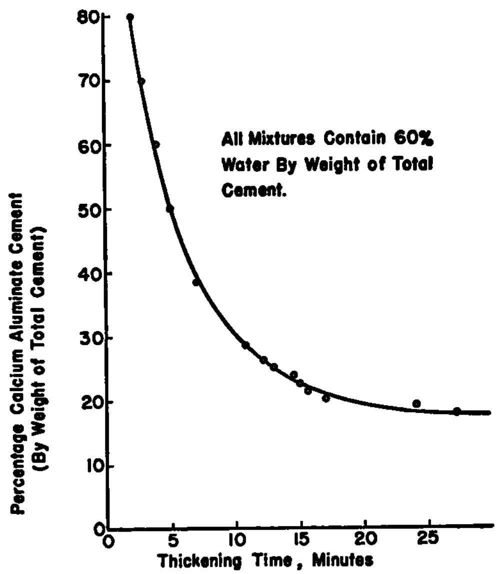

Figure 3. Relation Between Percentage Calcium Aluminate Cement and Thickening Time

Figure 3 shows the relation between thickening time (Stormer Viscosimeter test) and percentage of calcium aluminate cement by weight of total cement for mixtures made with one portland cement and containing 60 percent water. It will be noted that for the particular cements used and at a water content of 60 percent by weight of total cement, thickening times of from 10 to 20 min. may be obtained with a variation of 19.5 to 30.5 percent calcium aluminate cement. The curve covers the range from 0 to 80 percent calcium aluminate cement. Although this curve shows that rapid-thickening mixtures may be obtained in the range of about 18 to 80 percent calcium aluminate cement, it does not necessarily follow that all of these mixtures will be fast-setting or will have desirable time-consistency characteristics.

Figure 4 has been prepared to show the relationship between time and consistency for cement slurries with almost ideal characteristics. Notice that for each of the mixtures, varying in thickening time from 6 to 20 min., consistency is practically constant with time up to the point where thickening begins. All of the mixtures shown also have good setting characteristics in that they set with practically no bleeding. These mixtures are typical of those which have been produced in the laboratory with proper proportioning of materials. This factor of constant consistency with time up to the time thickening

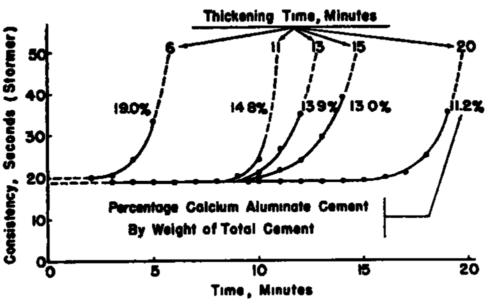

Figure 4. Time-Consistency Curves for Calcium Aluminate-Portland Cement Mixtures with 60% Water by Weight of Total Cement.

begins is a most important characteristic for successful cement-slurry mixtures. Also, the position and shape of the time-consistency curve for a trial mixture provide the basis for deciding what changes in proportions are necessary to produce a mixture from the particular ingredients that will have the most desirable characteristics.

EFFECT OF CEMENT, TEMPERATURE, AND WATER VARIABLES ON THE CHARACTERISTICS OF CEMENT-SLURRY MIXTURES

In order not to confuse the reader by discussing other factors to be considered in the proportioning of cement-slurry mixtures before he was familiar with the general considerations, the effect of certain cement, temperatures, and water variables has purposely been ignored up to this point. It has been found from experience that age and brand of portland cement, air temperature and temperature of the ingredients, and water-cement ratio all effect initial consistency, time-consistency relationships, thickening time, and setting time. In view of the large number of variables, and especially when their interrelationships are considered, it might well be considered that such mixtures would not be practical. However, several hundred tests have been performed in the laboratory, and while the individual effect of each variable has been difficult to determine, the practical proportioning of cement-slurry mixtures for use in filling voids under a concrete pavement has been resolved to a rather simple procedure.

Effect of Age and Brand of Cement

One of the first factors to be considered is the brand or particular batch of portland cement. Figure 5 shows the relation between percentage calcium aluminate cement and thickening time over the practical range for two brands of portland cement in mixtures containing 60 percent water at constant temperature. With portland cement "A", a change in thickening time from 20 to 10 min. is accomplished by increasing the percentage calcium aluminate cement from 11.5 to 15.5, a range of 4 percent. With brand "B", the same change in thickening time is accomplished by increasing the percentage of calcium aluminate cement from 19.5 to 30.5, a range of 11 percent. While mixtures made with brand "A" are more economical than those made with brand "B", portland cement "B" has the advantage of being less critical with regard to proportioning. These two cements represent extremes of those that have been tested, all other brands or particular batches being intermediate between these two.

It has been possible to design satisfactory mixtures from all of the brands and batches of portland cement that have been tested provided that cements were not too old. In general, the fresher the portland cement, the more reactive it is and the less the amount of calcium aluminate cement necessary to produce satisfactory mixtures. On the other hand, if the portland cement is too old it is not possible to make satisfactory cement slurries from it. Benefit has been derived when using old portland cements from the use of a mechanical mixer to disperse the cement in water, but when the cement is too old even this procedure does not prevent bleeding before setting occurs even though desirable consistency and thickening times are obtained.

In contrast to the portland cements, the calcium aluminate cement seems to have constant characteristics regardless of age, up to many months at least. All of the calcium aluminate cement used in this investigation has been of one brand, the only cement of this type produced in this country so far as is known. It is marketed under the trade name "Lumnite" and is produced by the Atlas Lumnite Cement Company.

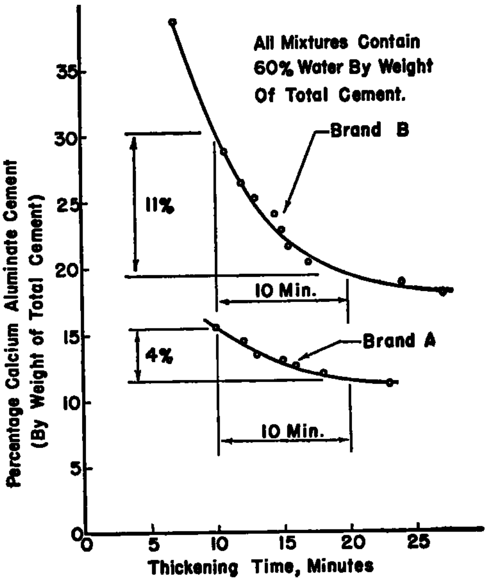

Figure 5. Effect of Brand of Portland on Thickening Time of Calcium Aluminate-Portland Mixtures

cements in the same ratio, with the mixing water temperature varied from 50 F to 80 F.

These curves do not show directly the effect on thickening and setting time of the variables under consideration. However, these effects may be interpolated in a qualitative sense if it is remembered that thickening and setting times are affected in the same general way as is initial consistency. It should be pointed out that the data must be interpreted in a qualitative sense only, especially when the effect of temperature is under consideration,

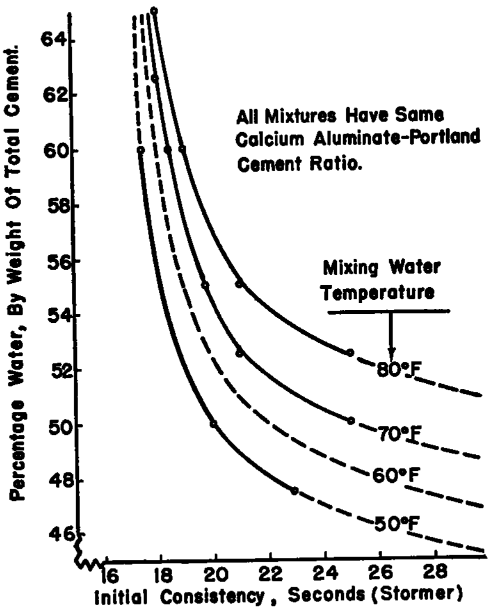

Figure 6. Effect of Percentage and Temperature of Mixing Water on Initial Consistency

Effect of Temperature, Water-Cement Ratio, and Calcium Aluminate-Portland Ratio

Of all of the variables considered in this investigation, the interrelationship between temperature, water-cement ratio, and calcium aluminate-portland cement ratio has been most difficult to determine systematically in terms that could be clearly presented. From several dozen curves plotted to show the effect of these variables, Figure 6 has been prepared in the hope that it will enable the reader to visualize the qualitative effects of the variables under consideration. In this figure, the percentage water is plotted against initial consistency for mixtures made with the same

because the tests were conducted in the laboratory at room temperature and only the temperature of the mixing water was varied. However, the curves do show the general effect of temperature changes even though different quantitative results would be expected in the field if all of the ingredients and the air were at the same temperature.

It is apparent from Figure 6 that lower water-cement ratios and higher temperatures produce higher initial consistencies. Also, it is apparent that the effect of changes in temperature on initial consistency is less marked the higher the water content, and becomes of no practical significance if a high enough water content is used. Likewise, the lower the temperature the less effective is a change in water content in altering initial consistency.

These same general statements also apply to thickening time and setting time, but the real meaning of the curves in regard to thickening time and setting time is best understood if it is considered that thickening and setting result from a chemical reaction between certain ingredients in the two cements, and that this reaction proceeds at a faster rate the higher the temperature until the fast-reacting ingredients are spent. The reaction rate is probably also somewhat dependent on the amount of water present.

Thus, if too little water is present, or the ingredients are at too high a temperature initially, the reaction will proceed so fast that initial consistency is affected materially. Consistency will increase rather rapidly with time beginning with the first minutes after mixing, and even though the mixture thickens, the fast-reacting ingredients may be so depleted by this time that setting will not occur fast enough to prevent bleeding.

On the other hand, if adequate water is present and the temperature is low, heat generated in the first minutes of the reaction (slow because the temperature is low) is absorbed in raising the temperature of the whole batch until finally, if enough reacting ingredients are present, the temperature is raised to the point where reaction is rapid and the mixture thickens and sets in desirable fashion. During the time that the temperature of the whole batch is being raised, the consistency remains at a constant value. When the ingredients are being mixed at too high a temperature, additional water must be added, which in itself probably slows the reaction and which provides more material to absorb the heat generated by the reaction in its first stages, thereby maintaining the initial fluid consistency for the desired time. It is probably true that if the ingredients become too hot, successful mixtures cannot be prepared from them because so much water would be required that strength would be seriously impaired. However, work has been done in the field with these mixtures when the temperature was above 80 F. and the results were entirely satisfactory. It is important when working with cement-slurry mixtures in the summer months that the cements be protected from the direct rays of the sun. It is also true that mixtures with desirable characteristics are made and controlled more easily when the weather is not too warm. This is fortunate because it has also been found that faulting of the pavement slabs is best corrected in cool weather when the joints are open.

The results of these tests have shown that cement-slurry mixtures with desirable characteristics are easily proportioned if two general principles are followed. First, initial consistency is primarily dependent upon the water-cement ratio; second, thickening and setting times are dependent primarily upon the proportions of calcium aluminate and portland cements. In proportioning mixtures for use, the first principle is to use sufficient water. The water content should be high enough not only to give a satisfactory low consistency under particular conditions, but should also be sufficient to maintain this low consistency over the temperature range to be expected during the working day. Sufficient water should also be used that inaccuracies of proportioning in the field will not materially affect results. From the data which have been obtained, 60 percent water by weight of total cement appears to be a good average value for field use under average conditions. If the proper water content is used, it is only necessary to increase the proportion of calcium aluminate cement until the desired thickening time and setting time is reached. If these principles are followed, mixtures may be proportioned in the field without benefit of laboratory tests. It is only necessary to have on hand a supply of small containers (paper cups serve very well) and to check batches for setting characteristics periodically by sampling them and observing changes in appearance with time.

STRENGTH AND DURABILITY OF CALCIUM ALUMINATE-PORTLAND CEMENT MIXTURES

Standard 2-in. cubes were made in duplicate from a standard laboratory mixture composed of 13.2 percent calcium aluminate cement and 60 percent water by weight of total cement. They were cured in the moist room, the molds being removed after one day. Duplicate cubes were tested on a Southwark-Emory testing machine after 3, 7, 14 and 28 days in the moist room. The average results are shown in Figure 7. It can be seen that the specimens gained strength rapidly up to approximately seven days and then gained strength very slowly, reaching a value of 3,300 lb. per sq. in. at 28 days.

After curing for 28 days, specimens of this mixture were immersed in water to about one-half their depth and frozen for 24 hr. They were then thawed in water for 24 hr., this procedure constituting one cycle. After eight such cycles of freezing and thawing, the cubes developed cracks. Further cycles of freezing and thawing produced more and more cracks, the cubes ultimately being reduced to small fragments. Even at this stage, however, there was no scaling or softening of the surface, each individual fragment remaining hard and firm.

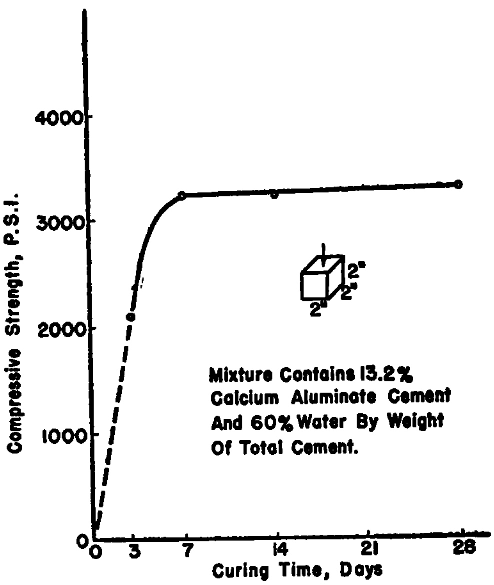

Figure 7. Relation Between Compressive Strength and Curing Time for a Satisfactory Cement Slurry

EFFECT OF ADDING ASPHALT EMULSION

With the hope that improved durability, without serious loss in strength (because of reduction in water-cement ratio), could be obtained by the addition of asphalt emulsion, two cement-mixing asphaltic emulsions have been incorporated in cement-slurry mixtures. These emulsions have been designated No. 1 and No. 2. They were each used in two different quantities in the standard laboratory mixture (13.2 percent calcium aluminate cement and 60 percent water based on total weight of cement). It was found that essentially the same consistency and setting time (Stormer Viscosimeter test) could be maintained with 6.7 percent less water (based on the quantity used in the standard mixture) by adding the equivalent of 0.4 gal. of emulsion No. 1 per bag of portland cement; also, with 13.3 percent less water by adding the equivalent of 0.8 gal. of emulsion No. 1 per bag of portland cement. Emulsion No. 2 was only half as effective in reducing the water required. The compressive strength of these mixtures was measured at various ages and the mixtures containing emulsion No. 1 were subjected to freezing and thawing after curing for 28 days. Methods of test were the same as for mixtures without the emulsion admixture.

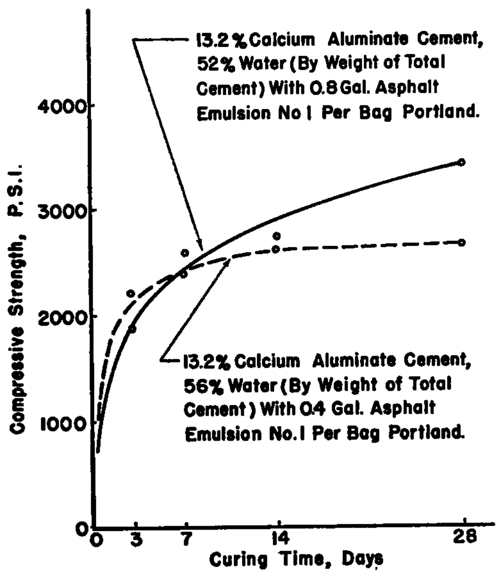

Figure 8. Relation Between Compressive Strength and Curing Time for Slurries with Asphalt Emulsion No. 1

The results of the compressive strength tests are shown in Figures 8 and 9. In general, the effect of the emulsions was to reduce strength (compare with Fig. 7), although the reduction was not as great for mixes containing emulsion No. 1 as for those containing emulsion No. 2. Although the results for emulsion No. 1 are not entirely consistent, it appears that with the larger amount of emulsion, strength has not been reduced at 28 days even though the gain in strength is slower than for the mixture without emulsion. The mixtures containing asphalt emulsion No. 1 were not any more resistant to freezing and thawing than those without this admixture. It is possible that larger amounts of asphalt emulsion would be more

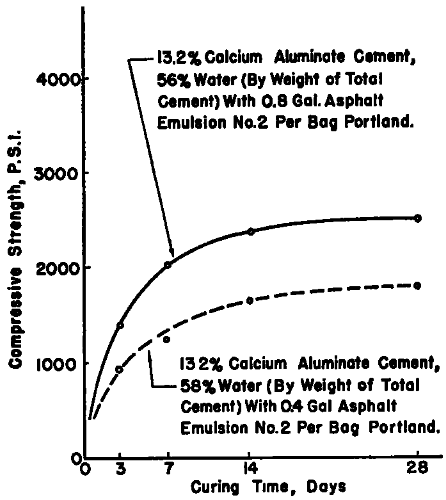

Figure 9. Relation Between Compressive Strength and Curing Time for Slurries with Asphalt Emulsion No. 2

effective, but it first must be established that desirable thickening and setting characteristics can be maintained when larger amounts are used.

EFFECT OF ADDING INERT MATERIAL

It was thought that perhaps less costly and even more satisfactory cement-slurry mixtures could be formulated with the addition of some inert material. It was found that the inert material should be of the same order of fineness as the cement itself if settling and bleeding with loss in volume is to be prevented. Fly ash was tried, but it was found that the percentage of calcium aluminate cement had to be materially increased to retain desirable setting characteristics. Fly ash, like other puzzolanic materials, does have the effect of flattening the time-consistency curve up to the time of thickening and in some mixtures might prove beneficial for this reason. It is possible that fly ash might improve durability also, but tests to determine this effect have not been undertaken. A fine limestone dust appeared to offer considerable promise and tests were performed using an agricultural limestone manufactured for feeding purposes.

Mixtures were made using portland cement, calcium aluminate cement, and limestone dust by adding limestone dust in increasing amount to the standard laboratory calcium aluminate-portland mixture. In these mixtures the calcium aluminate-portland cement ratio was maintained at 13.2 percent calcium aluminate cement on basis of total cement, and the water-solids ratio was maintained at 60 percent water based on total solids. Limestone dust was added in amounts equal to 10, 20, 30, and 45 percent by weight of total solids. The consistency, setting time, strength, and resistance to freezing and thawing of these mixtures was measured by the same methods used previously. Measurements of consistency with the Stormer Viscosimeter showed that these mixtures with limestone dust, with the same water-solids ratio as for mixtures without it, had an initial consistency value very nearly equal to that of the mixture without limestone dust. Also, although no time-consistency curves are shown for these mixtures, the time-consistency relationship was obtained for each and it can be stated that the limestone dust was beneficial in this respect. In general, the limestone dust has the effect of causing the mixture to maintain its initial fluid condition for a greater portion of the thickening time. Duplicate specimens were made for the strength and freezing and thawing tests.

Figure 10 shows the relationship between thickening time and percentage of limestone dust for mixtures in which the water-solids ratio and calcium aluminate-portland ratio were held constant. It can be seen that the limestone dust had the effect of gradually increasing thickening time with increases in quantity so that at 30 percent limestone dust the thickening time had been increased from 15 to 21 min. This thickening time of 21 min. has been shown to be slightly too slow for good performance. When the limestone dust was increased to 45 percent, the mixture failed to thicken within one-half hour and no thickening-time value was obtained. Although no measurements have been made, it was also noticed that the limestone dust had the effect of increasing the time of hardening of the mixtures after thickening and setting had taken place.

Compressive strength-curing time curves for the mixtures containing 10, 20, and 30 percent limestone dust by weight (based on total solids) are shown in Figure 11. If these curves are compared with the compressive-strength curve for the same mixture without limestone dust, Figure 7, it can be seen that the limestone dust apparently has the effect of causing the mixtures to gain strength more slowly, and to decrease strength if as little as 10 percent or as much as 30 percent is used. However, the mixture containing 20 percent limestone dust had the same compressive strength at 28 days as the corresponding mixture without limestone dust even though at all earlier ages its compressive strength was appreciably lower.

The freezing and thawing tests on these mixtures containing limestone dust showed them to be superior in durability to those without limestone dust. Whereas the mixtures without limestone dust developed cracks in eight cycles of freezing and thawing, the mixtures made with 10 and 20 percent limestone dust were frozen and thawed 18 and 15 times, respectively, before any cracks appeared. There was some slight scaling of the surface of the cubes. The mixture containing 30 percent limestone dust, while not developing cracks in 25 cycles, had scaled very badly at this time.

Asphalt emulsions No. 1 and No. 2 were used in cement-slurry mixtures containing limestone dust in the same way, and in the same amounts, in which they were used in mixtures without limestone dust. Both of the emulsions had the effect of materially increasing resistance to freezing and thawing, being about equal in this respect. The larger amount of emulsion was more effective in each case. With 10 and 20 percent limestone dust and either emulsion No. 1 or emulsion No. 2, good resistance to freezing and thawing was obtained. Mixtures containing 30 percent limestone dust were inferior in resistance to freezing and thawing even when the asphalt emulsions were incorporated. Strength tests made on these mixtures containing limestone dust and asphalt emulsion before and after

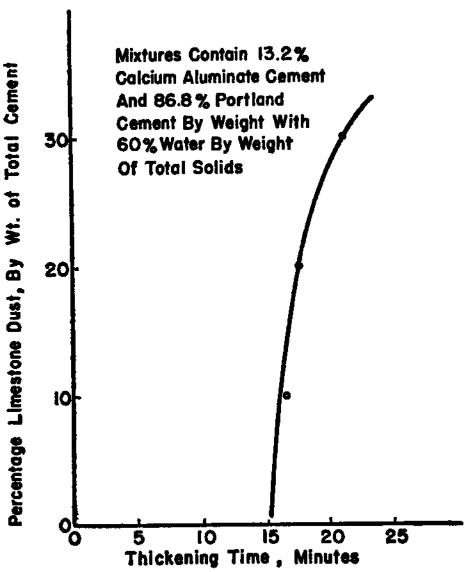

Figure 10. Relation Between Percentage Limestone Dust and Thickening Time

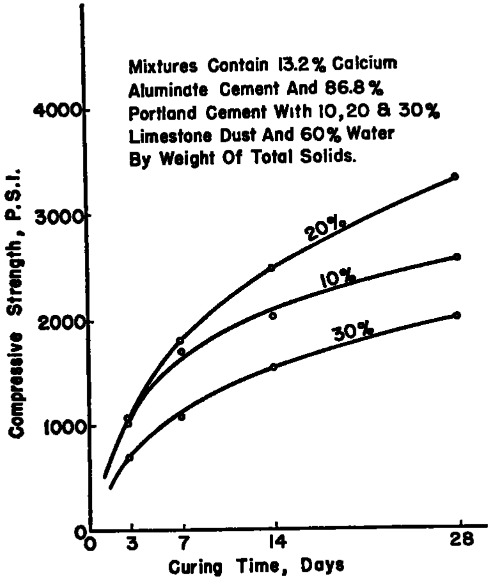

Figure 11. Relation Between Compressive Strength and Curing Time for Mixtures with Limestone Dust

25 cycles of freezing and thawing, showed that all of the mixtures deteriorated very little in compressive strength. Failure was confined to slight scaling of the surface on some specimens containing 10 and 20 percent limestone dust, and to rather severe surface scaling on the mixtures containing 30 percent limestone dust.

EFFECT OF SUBSTITUTING NATURAL FOR PORTLAND CEMENT

Because portland cement was not available in some instances, tests were undertaken in the laboratory to determine the effect of substituting natural cement for portland cement in the cement-slurry mixtures. It was first determined that the proportions used in the standard laboratory mixture (13.2 percent calcium aluminate cement, 86.8 percent portland cement, and 60 percent water by weight of total cement) were not satisfactory when natural cement was used, and in order to maintain satisfactory consistency and thickening time it was necessary to use the proportions, 10 percent calcium aluminate cement, 90 percent natural cement, and 75 percent water by weight of total cement.

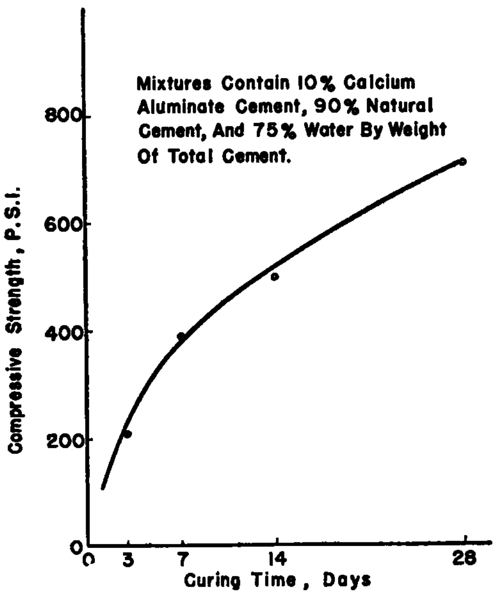

Figure 12. Relation Between Compressive Strength and Curing Time for Natural Cement Mixtures

This change was necessitated in part, no doubt, because of the fact that the specific gravity of natural cement is appreciably less than that of portland. It was determined, however, that this fact explains only part of the necessary change.

Standard 2-in. cubes were made from this mixture and subjected to the compression and freezing and thawing tests used for evaluating the previous mixtures. Figure 12 shows the relationship between compressive strength and curing time for these mixtures made with natural cement. Comparing this curve with that for similar mixtures made with portland cement (Fig. 7) it can be seen that the cubes made from natural cement were not only very much weaker at all ages up to 28 days, but also that these mixtures develop strength more slowly. After curing for three days, the natural cement mixture had a compressive strength only one-tenth as great as the portland-cement mixture of the same age. At 28 days the proportion is more favorable, but the natural-cement mixture even then had a compressive strength less than one-fourth as great as that of the portland-cement mixture at the same age.

In the freezing and thawing tests, the natural cement mixtures showed signs of disintegration after four cycles of freezing and thawing as compared with eight cycles for the mixtures made with portland cement. Also, while the portland-cement cubes cracked without scaling or softening, the cubes made of natural cement failed by scaling and disintegrating inward from all faces, and after some eight cycles had been reduced to only about one-half their original size.

No tests have been performed using inert material or additives in mixtures made with natural cement. It is quite possible that both the strength and durability of these mixtures may be improved by this means and such tests should be performed if there is reason for using natural cement in the field.

EFFECT OF USING CALCIUM CHLORIDE

In the interest of economy, attempts were made to substitute inorganic salts for all or part of the calcium aluminate cement in the cement-slurry mixtures. Several inorganic salts were considered and the possibility of using calcium chloride was rather extensively investigated. In these experiments, calcium chloride was added to the mixing water.

It was found that, with a water-cement ratio of 0.6 by weight and at room temperature, it was necessary to use a concentration of calcium chloride of about 20 percent by weight of water in order to produce fast thickening and setting of the portland cement being used. However, the initial consistency of this mixture was much too high and it showed an entirely unsatisfactory time-consistency relationship. When enough water was added to reduce the initial consistency to a satisfactory value, the mixture either did not thicken in a reasonable time or did not set rapidly enough after thickening to prevent bleeding. In any case where the thickening time was satisfactory, the time-consistency relationship was unsatisfactory. It has been concluded from these experiments that calcium chloride and portland cement alone will not produce a satisfactory cement-slurry mixture for use in correcting pumping pavements.

Similarly, attempts to substitute calcium chloride for part of the calcium aluminate cement have not proved successful for the same reasons described above. It is possible that at temperatures near the freezing point of water some economy could be effected by the use of calcium chloride in small amount. However, as much or more saving probably could be effected at these temperatures with more ease and safety simply by reducing the quantity of mixing water from that used in a mixture designed for normal temperatures.

CONCLUSION

While the possibility remains that considerable improvement in cement-slurry mixtures for use in correcting the pumping action of concrete pavements will be forthcoming from experiments that are still in progress, nevertheless the development work has progressed to the point where satisfactory mixtures with good workability, strength, and durability characteristics can be proportioned from calcium aluminate and portland cements. Further, the qualitative and quantitative effects of variables affecting the characteristics of these mixtures have been systematically investigated until it is possible to formulate mixtures from a variety of standard portland cements which will function satisfactorily under a variety of field conditions. From the results of this development work, the following general conclusions seem justified:

1. Cement-slurry mixtures with satisfactory characteristics for use in filling voids under concrete pavements can be made with portland cement as the major ingredient and calcium aluminate cement as the minor ingredient.
2. Cement-slurry mixtures can and should be proportioned so that they will have an initial consistency (Stormer Viscosimeter test) of about 20 sec. or less, a practically constant consistency of this initial value up until the time thickening begins, a thickening time of 10 to 20 min. depending upon equipment to be used, and a setting time after thickening fast enough that bleeding sufficient to cause appreciable change in volume will not occur.
3. Many factors affect the initial consistency, thickening time, and setting time of calcium aluminate-portland cement slurries. These include age and brand of portland cement, water-cement ratio, air temperature and temperature of all ingredients including water, and proportion of calcium aluminate to portland cement. The potency of the calcium aluminate cements used has not varied appreciably from batch to batch or with age up to several months. In spite of the many variables which affect results, the practical problem of proportioning cement-slurry mixtures which will have satisfactory characteristics is relatively simple if two principles are followed:
   - (a) Initial consistency and the time-consistency relationship up to the time thickening begins should be controlled by using sufficient water.
   - (b) Thickening and setting time should be controlled by varying the calcium aluminate-portland cement ratio.

   Within reasonable limits, and with due regard for economy and satisfactory strength, there is very little danger of using too much water. From the standpoint of good workability, it is much better to use more water than necessary rather than not to use enough. The higher the water-cement ratio, the less do temperature changes effect the workability of cement-slurry mixtures.
4. Well designed calcium aluminate-portland cement slurries without the addition of

inert ingredients or admixtures develop a compressive strength of over 3,000 lb. per sq. in. in 7 days and are resistant to freezing and thawing in that they do not soften even though they may crack.

5. Asphalt emulsion of the types and in the quantities used reduces the strength of calcium aluminate-portland cement slurries, particularly at ages less than 28 days, without materially increasing resistance to freezing and thawing.
6. At a constant calcium aluminate-portland cement ratio, limestone dust may be added to calcium aluminate-portland cement slurries in amounts of at least 20 percent, but not exceeding 30 percent, by weight of the total cement without adversely affecting workability. Addition of this inert material reduces compressive strength, particularly at ages of less than 28 days, but improves the resistance of the material to cracking when undergoing freezing and thawing.
7. Cement-slurry mixtures with satisfactory compressive strengths and the best resistance to freezing and thawing were made with the addition of both limestone dust and asphalt emulsion to the calcium aluminate-portland cement mixture.
8. Within the limit of experiments conducted in this investigation, mixtures made with natural cement and calcium aluminate cement, while having satisfactory workability, are much infe'ior to calcium aluminate-portland cement mixtures with regard to compressive strength and resistance to freezing and thawing.
9. With the possible exception of work done at temperatures near or below the freezing point of water, calcium chloride is not beneficial to the workability of calcium aluminate-portland cement slurry mixtures.
10. While small laboratory batches are best made by mixing the two cements and then adding water, field mixing is best accomplished by making a slurry of the calcium aluminate and portland cements separately and then combining them just before use.

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