FUNCTIONS OF STEEL REINFORCEMENT IN CONCRETE PAVEMENTS AND PAVEMENT BASES[1]

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SYNOPSIS

Investigation of steel reinforcement carried on by the Highway Research Board, 1924-1925, disclosed benefits furnished by reinforcement in concrete pavements not readily explainable by existing knowledge on reinforced concrete Subsequent study has indicated more and more that some of the benefits furnished by reinforcement are due to the influence it exerts upon the internal stresses and other factors which affect the strength and durability of concrete In this report, therefore, the more or less intricate phenomena occurring, both during and subsequent to the hardening period of concrete, are briefly analyzed in an effort to explain these benefits When first deposited on the subgrade in the plastic state, the concrete may shrink due to loss of moisture and solution of cement constituents After hardening it may swell due to moisture absorption, may shrink due to moisture loss, may expand due to rise in temperature, may contract due to drop in temperature, may warp due to temperatures or moisture contents in the tops of the slabs differing from those in the bottoms of the slabs, may distort due to nonuniform subgrade support, may deflect due to traffic loads, and finally, may be subjected to the disintegrating influence of frost or other detrimental physical or chemical action This report attempts to explain the functions of steel reinforcement with respect to the stresses caused by these phenomena

FOREWORD

The great magnitude of the compressions produced by the surface tension of water plays a very important part in the discussion to follow Therefore attention is called to them at this time

The high stability furnished by coatings of thin water films on grains of beach sand is well known The effect produced by the thin water films coating the surfaces of colloidal particles is still more spectacular.

[1] This report is supplementary to "Economic Value of Reinforcement in Concrete Roads," Fifth Annual Proceedings, Part II, Highway Research Board (1), "Steel Reinforcement in Concrete Pavements," Eighth Annual Proceedings, Highway Research Board (2), "The Phenomenon of Shrinkage and Its Influence upon the Integrity and Durability of Concrete Pavements," Tenth Annual Proceedings, Highway Research Board (3)

The numbers in parenthesis refer to the bibliography at the end of the report

Thus in the shrinkage of soil the force produced by surface tension (4) to consolidate the soil particles may equal that produced by an external compression of several thousands of pounds per square inch

Likewise, the surface tension of the " solidified water " (5) which causes dried soil to exist in the form of cakes instead of dust, may be equivalent to a very high compression This is demonstrated by the work of the soil scientist, Keen, which was called to the attention of the Committee on Materials by F V Reagel In his book on the physical properties of the soil (6), Keen shows that when briquets made of clean sand with five per cent of portland cement admixture had a crushing strength of 3 kg, similar briquets of sand with an equal amount of Susquehanna clay colloids held together by surface tension had a crushing strength of 55 kg or 18 times as much, and furthermore, that when 10 per cent of portland cement in the sand furnished a strength of 19 kg, 10 per cent of clay compressed with solidified water furnished a crushing strength of 96 kg

INTRODUCTION

Some of the early concrete pavements constructed to meet the demands of increasing motor vehicle traffic before a knowledge of future load requirements was available were, in the light of present day knowledge, obviously too thin Nevertheless, the exceptionally high salvage value of many of the worst of these pavements, which subsequently became bases for new wearing courses, discloses that even they furnished a very satisfactory return on the capital investment Generally, replacements in appreciable amount of even the early pavements were due more to changes of grade or location than to structural failures Thus the suitability of concrete for road building purposes has been well demonstrated

The type of cracking which occurs in the thicker present day road slabs does not necessarily indicate either a structural inability to support wheel loads or that the concrete is deficient in other properties required for good pavements Furthermore, whether the condition of the pavement becomes undesirable or not depends, not on the extent to which this type of cracking occurs, but on the degree to which it is controlled

Thus, for instance, a concrete street pavement, with comparatively few irregular cracks, may be considered in an undesirable condition, at least visually, when at the same time an adjoining sidewalk, with many times as much cracking, but controlled, is considered a perfectly satisfactory structure Therefore, not the elimination of cracking, but its control, is the essential requirement in pavement design In this connection it has been found that

(a) Steel reinforcement is effective for reducing both transverse and longitudinal cracking (1)

(b) Under certain conditions steel reinforcement may also be used economically to prevent corner breaks in concrete pavement (2)

(c) Steel reinforcement at cracks tends to hold together fractured slabs (1).

How steel reinforcement serves to hold fractured slabs together is readily understood How it serves to reduce the amount of cracking, however, is not so readily apparent, especially when one considers that rigid concrete stretched to the breaking point brings into play less than 10 per cent of the strength of the steel And this means that in a slab six inches thick, with a tensile strength of 200 pounds per square inch when stretched to the breaking point, the incorporation of 48 pounds of steel per 100 square feet (24 pounds each way) would only increase the tensile resistance about two pounds per square inch

This increase of two pounds per square inch does not explain the Highway Research Board conclusions that (a) "Mesh reinforcement, 25 to 56 pounds and bar mat 64 pounds per 100 square feet reduced cracks 35 to 70 per cent or more than one inch of additional thickness in pavements of like thickness "(1)

Neither does this increase of two pounds per square inch, nor for that matter, any existing theory of reinforced concrete, explain how in certain tests (2), 0 2 of one per cent of fabric reinforcement increased the resistance of both four- and six-inch slabs on wet subgrades (to impacts) by as much as 50 per cent

These phenomena could be readily explained, however, if reinforced concrete were assumed to have characteristics as follows:

1 That throughout its life it is acted upon by two distinct sets of forces, those productive of volume change and those opposed to volume change

2 That the volume change of concrete due to these forces is the principal cause of much of the cracking which occurs in the present day pavements

3 That the strength of a given concrete, instead of being constant at any particular age, varies, depending upon the relative extent to which these two sets of forces are acting

The following results furnished by research are of special importance with respect to the foregoing assumptions

1 Core strengths may vary appreciably in different locations in the same concrete pavement slabs.

2 More cracking may occur with one type of aggregate than with another, and furthermore, the concrete in which the greater number of cracks occur may be the stronger

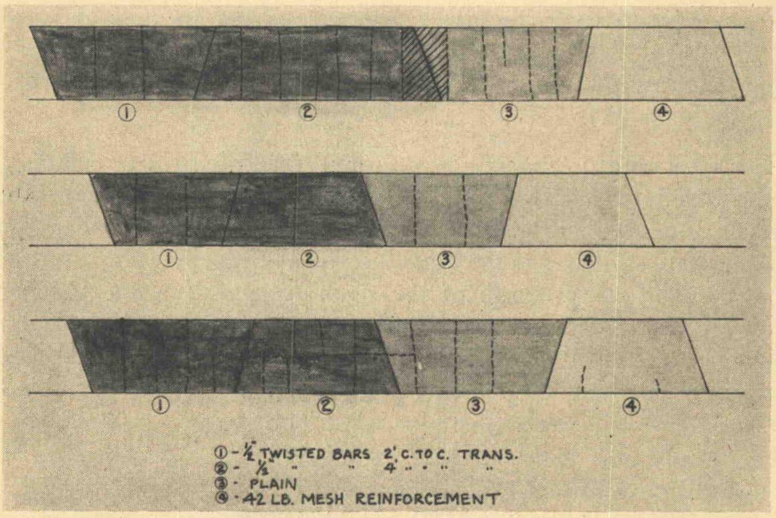


Figure 1. Cracking on the Sycamore—De Kalb Experimental Road. Built by A. N. Johnson in 1912. Surveyed in 1925. Well Distributed Reinforcement Practically Prevented the Occurrence of Transverse Cracks in Slabs 50 Feet Long

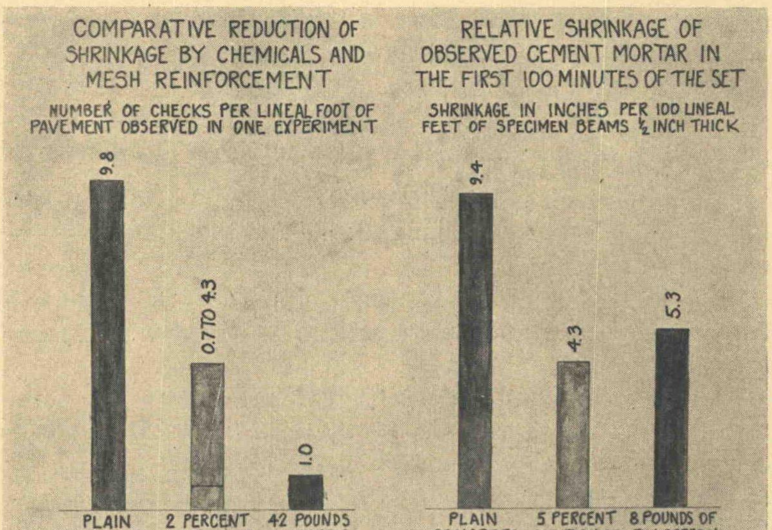


Figure 2. Showing How Calcium Chloride and Steel Reinforcement Reduced the Shrinkage of Mortar in the Laboratory and the Number of Shrinkage Cracks in Experimental Sections in the Field. From the Exhibit of the Bureau of Public Roads at the Road Show in 1931

3. Mortar cracks occurring during the hardening of hand-finished plain concrete may be very appreciably reduced by an admixture of calcium chloride, by the incorporation of single layer fabric reinforce-

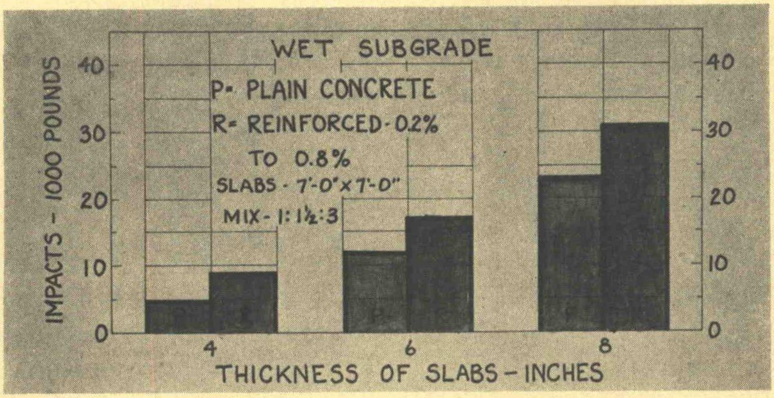


Figure 3. Resistance of Test Slabs to Impact. Showing How Wire Mesh Increased the Resistance of Slabs Laid on Wet Subgrades to Impacts in the Arlington Tests (2)

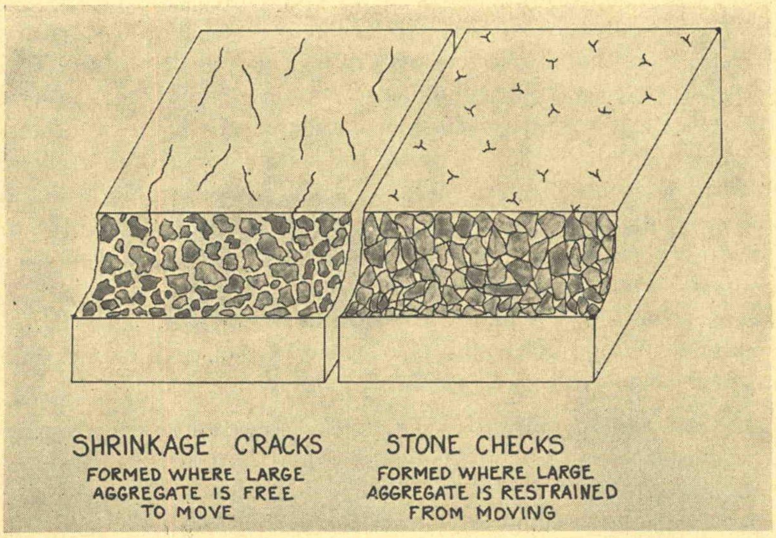


Figure 4. Illustrating the Change from Shrinkage Cracks to Stone Checks with Increased Consolidation of the Large Aggregate Particles as Suggested by Observations of Experimental Road Sections

ment and still more by the incorporation of double layer fabric. See Figures 1, 2, 3.

4. Shrinkage may be manifested as either mortar cracks or small check cracks between the stone fragments, depending upon the extent to which the large aggregate particles are consolidated. See Figure 4.

Accordingly, it seems evident that steel reinforcement proves beneficial in pavements and pavement bases because of the influence it exerts upon certain characteristics of concrete not generally considered in the structural design of concrete slabs

In order to explain these benefits, therefore, it is necessary to analyze briefly the more or less intricate physical phenomena which control the internal stresses and other factors affecting the strength and the durability of concrete

DISCUSSION

Decay of wood, rusting of iron and weathering of hard rock (7), bear witness that all known materials struggle continually for existence with nature's destructive agencies Materials comprising structures are required to resist the additional forces produced by artificial loading Therefore, in the design of structures, all of the destructive agencies, both natural and artificial, must be considered

When first deposited on the subgrade in a plastic state, the concrete comprising both pavements and pavement bases may shrink [2] due to loss of moisture, and may lose volume due to solution of cement constituents (3) After hardening, it may swell due to moisture absorption, may shrink due to moisture loss, may expand due to rise in temperature, may contract due to drop in temperature, may warp due to the temperature or moisture content in the top of the slabs differing from that in the bottom of the slabs, may distort due to non-uniform subgrade support, and may deflect due to traffic loads Also, under certain conditions, the concrete may be subjected to the disintegrating influence of frost moisture, or other detrimental physical or chemical action

How steel reinforcement increases the life of road slabs, therefore, must be explained by its ability to assist the concrete to withstand at least some of the destructive effects produced by:

1 Stresses due to shrinkage of the concrete during the initial hardening period (concrete in plastic state).
2. Stresses due to volume change of the concrete produced by change in moisture content (concrete in rigid or elastic state).
3 Stresses due to volume change in the concrete due to change in temperature
4 Stresses due to differences in temperature and moisture contents in the various parts of the slab
5 Stresses due to non-uniform subgrade support

[2] As used in this report the terms "Shrinkage" and "Swell" denote volume changes due to variation in moisture content, while the terms "Contraction" and "Expansion" signify volume changes due to variation in temperature

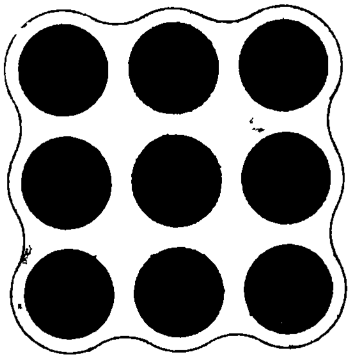
6 Stresses produced by traffic loads in slabs having uniform support

7 Crystal pressure due to the growth of frost or other crystals productive of concrete disintegration

In order to understand these explanations, therefore, one must have some conception of (a) the physical character of shrinkage and swell as contrasted with that of contraction and expansion, (b) the effect of uniform as contrasted with the effect of non-uniform subgrade support on the bending stresses in slabs, and (c) the mechanics of disintegration

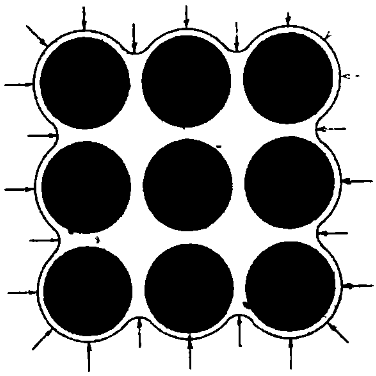
VOLUME CHANGES DUE TO MOISTURE VARIATION DIFFER RADICALLY IN CHARACTER FROM THOSE PRODUCED BY TEMPERATURE VARIATION

The extent of cracking due to volume change of concrete depends upon the magnitude of the forces stressing the fibers and the degree to which the fiber deformation is restrained



A—Mortar Newly Mixed

Water Entirely Surrounds Inert Particles of Sand and Cement (Circles) and Completely Fills the Pores between Them. Thus Surface Tension Exerts No Consolidating Force



B—After Losing Moisture

Water Recedes in the Pores and Similar to a Taut Skin Draws the Inert Particles Closer Together and in This Manner Reduces the Volume of the Mortar

Figure 5 Shrinkage of Plastic Mortar

In spite of the fact that both shrinkage and contraction tend to shorten concrete fibers the force productive of shrinkage, as it affects the mortar matrix, is opposite in character to that causing contraction Likewise, the restraint of fiber deformation differs in the two cases

Figure 5 illustrates the shrinkage of plastic mortar

When first mixed, the mortar consists of solid particles of cement and sand separated by pores completely filled with moisture, as shown in the left view. As the evaporating moisture recedes in the pores, as shown in the right view, surface tension, like a rubber skin that is gradually being drawn tighter, continues to force the mortar particles closer together in the same manner that evaporating moisture shrinks soils, until the increasing resistance of inert particles to further consolidation combined with the increasing rigidity of the hardening cement glue just balance the consolidating force

The external pressure required to compress a mortar to this extent is not known Laboratory tests on soils similar in grain size to mortars indicate that the minimum pressure necessary to produce consolidation equivalent to that produced by capillary pressure on drying may equal approximately 50 pounds per square inch or three and one-half tons per square foot of external surface [3]

Under extreme test conditions, this pressure, may cause a rich mortar to shrink as much as 18 inches per hundred feet, and several inches quite readily under ordinary conditions

The higher the water-cement ratio, the greater the separation of the cement colloids; consequently, the less will be the cohesion between them and as a result the lower will be the strength

Figure 6, furnished by the Highway Research Board Proceedings, 1930 (3), illustrates the relation of the moisture loss (upper curves) to the shrinkage of small mortar slabs According to Figure 7, which shows the relation between rate of shrinkage and age, the change of the mortar beams (Figure 6) from the plastic to the rigid state was completed at the age of about 175 minutes for the reinforced and about 200 minutes for the plain concrete, as shown by the sharp break in the curves.

Figure 8 illustrates the shrinkage of rigid mortar

When wet, rigid mortar, on the right, loses moisture, the water recedes in the pores, as in those of the plastic mortar, until there remains, as shown on the left, only the "solidified" or "adsorbed" water referred to in the beginning of this discussion as that which causes dried soil to exist as cakes instead of dust. This type of water cannot be evaporated and has surface tension greatly exceeding that of normal water.

[3] The magnitude of the force productive of shrinkage depends upon the potential shrinkage properties of the mortar and the rate of moisture loss from the slab The potential shrinkage properties of the mortar depend, in addition to the degree of solubility of the cement, upon those characteristics of the cement and fine aggregate which control the moisture content required to produce a workable mortar and the porosity of the mortar after hardening The potential shrinkage property is just as definite a property of the mortar as the compressive or tensile strength and like them can be determined by test in the laboratory A modification of the subgrade shrinkage tests may serve this purpose The rate of moisture loss depends upon the climatic conditions during curing, the method of curing and the absorptive properties of the subgrade

Due to this high surface tension, the rigid glue bands are compressed and the slab may be shortened as much as one inch per 100 feet, and the normal modulus of rupture (that of the mortar with pores filled) may be increased as much as 20 per cent or slightly more An external compressive force of 2,500 pounds per square inch ($E = 3,000,000$), would be required to produce a similar shortening of the slab.

Filling the pores subsequent to drying reduces the capillary pressure to zero and causes the mortar to both swell and diminish in modulus of rupture Thus the shrinkage and the swell of rigid concrete are, to a certain extent, reversible phenomena and, consequently, as shown

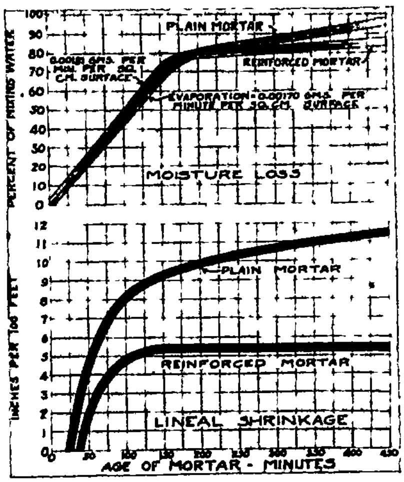


Figure 6. Relation of Moisture Loss to Shrinkage of Small Mortar Slabs

by Figure 9, produce alternate shortening and lengthening with alternate wetting and drying of slabs (8)

Part of the swell, however, due to reasons at present unknown, may become permanent under certain conditions of continued saturation. Figure 10, for instance, furnished by W. K. Hatt and R. E Mills (14), shows that small beams saturated for 200 days and then dried for three years were longer by about 0 37 inch per 100 feet than similar beams saturated but seven days before an equally long drying period

Figure 11 illustrates the phenomenon of contraction.

When lowering temperature of rigid concrete, left view, causes molecular consolidation, the inert fragments grow smaller in diameter and the glue bands tend to shorten, as shown in right view. This causes the linear dimensions of the slab to diminish and the glue bands to become stretched, in effect, and thus be placed in tension. This should reduce the modulus of rupture and, in spite of evidence to the contrary, Figure 12, for a particular set of tests, shows such to be the case. Here a reduction of modulus of rupture of 17 per cent occurred with a temperature drop of 40°F. Experiments of the University of Texas (University of Texas Bulletin No. 2825, July, 1928) furnished contradictory evidence, and those of the Japanese Investigator, Uchida (Rikwagaha Kekyijo Ihio, Vol. 2, p. 285, 1920), furnished corroborative evidence of the above.

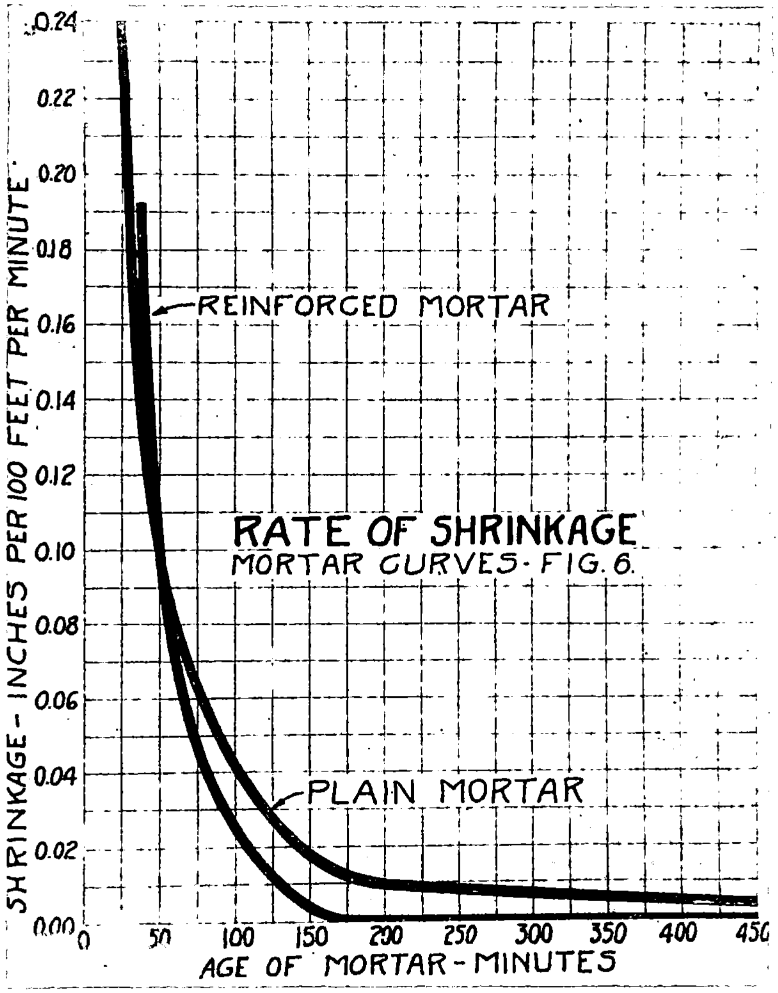
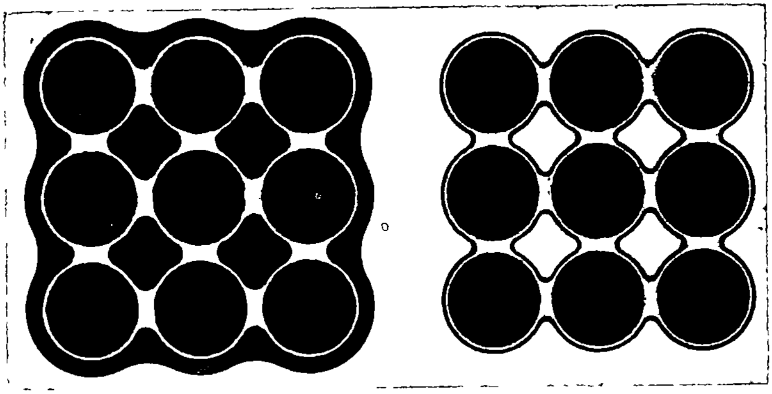


Figure 7. Relation between Rate of Shrinkage and Age

With a thermal coefficient of 0.0000055, the corresponding contraction equals the shortening produced by a compression of more than 500



A—Wet Rigid Mortar

Inert Particles (Circles) Coated and Connected with Colloidal Glue Bands Pores Entirely Filled with Moisture, Surface Tension Exerts No Consolidating Force

B—Dry Rigid Mortar

Films of "Solidified" Moisture Cover—and Like Tightly Stretched Rubber Coatings—Tend to Shorten All Exposed Glue Band Surfaces Thus Reducing the Mortar Volume

Figure 8 Shrinkage of Rigid Mortar

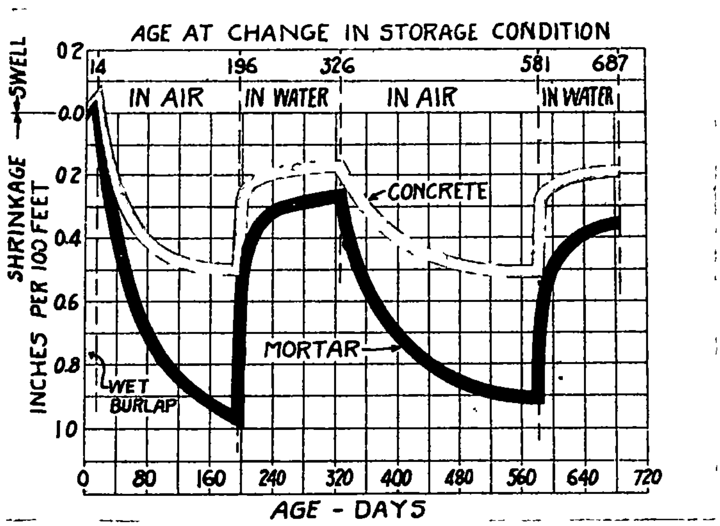


Figure 9 Shrinkage and Swell of Rigid Beams 4 by 7 by 48 Inches

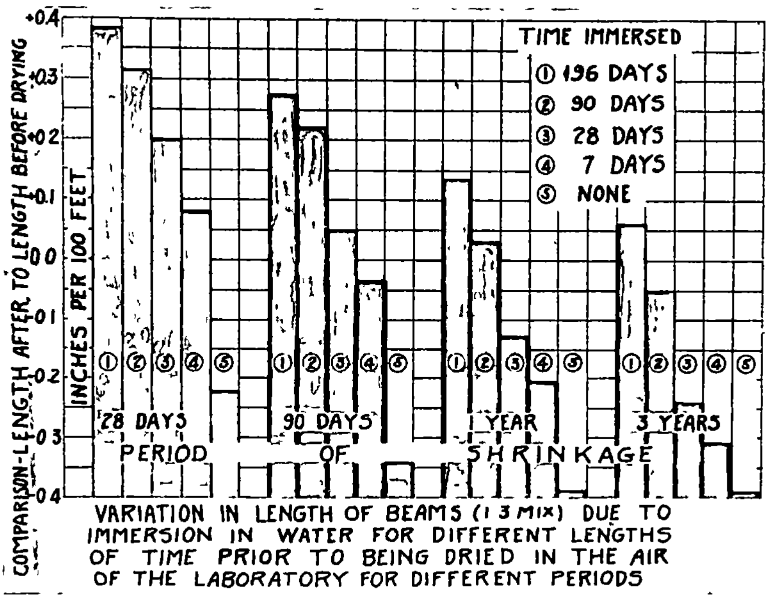
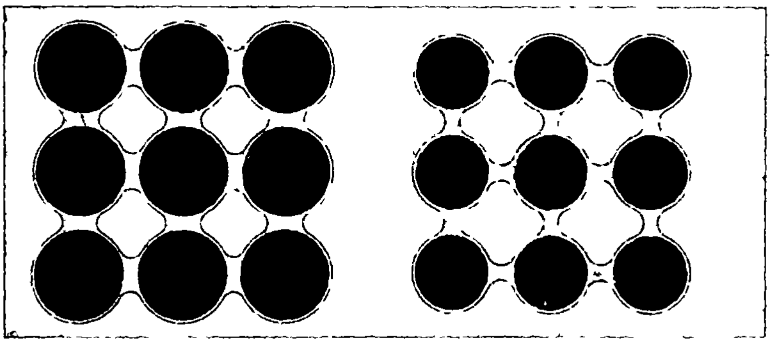


Figure 10



A—Before Temperature Drop

Inert Sand and Cement Particles Held Rigidly in Position by Cement Glue Bands. Stress in Glue Bands Assumed to Equal Zero

B—After Temperature Drop

Consolidation of Molecules Causes Inert Particles to Become Smaller and the Glue Bands to Tend to Shorten This in Effect Stretches the Connecting Bands. Draws the Inert Particles Closer and Reduces the Mortar Volume

Figure 11. Contraction of Rigid Mortar

pounds per square inch, as compared with the minimum of 50 pounds per square inch in the plastic state and the 2,500 pounds per square inch due to surface tension in the rigid mortar

Thus it can be seen that under extreme conditions a rigid slab may shorten very appreciably due to either shrinkage or contraction. An increase in the modulus of rupture would be expected, however, if the shortening were due to shrinkage and a reduction in at least some instances if the shortening were due to contraction Thus the terms " shrinkage " and " contraction " serve to identify two radically different phenomena and therefore should not be used synonymously

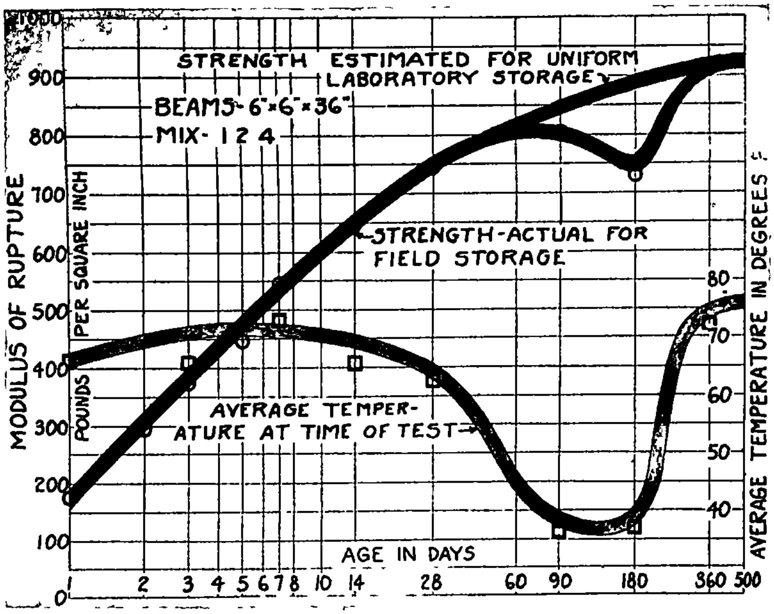


Figure 12 Strength as Influenced by the Condition of the Concrete When Tested

The maximum of about one-fourth inch to which the corners of slabs 18 to 20 feet wide may curl upwards, due to the drop in temperature from day to night is reduced to about one-sixteenth inch by the installation of a longitudinal center joint [4]

[4] Stress produced by differential temperatures in slabs is disclosed by the formula (10)

$$S_c = \frac{E e_t T}{2(1-u)}, \text{ wherein,}$$

S_c = Tensile stress in the top of the slab

e_t = Coefficient of contraction and expansion

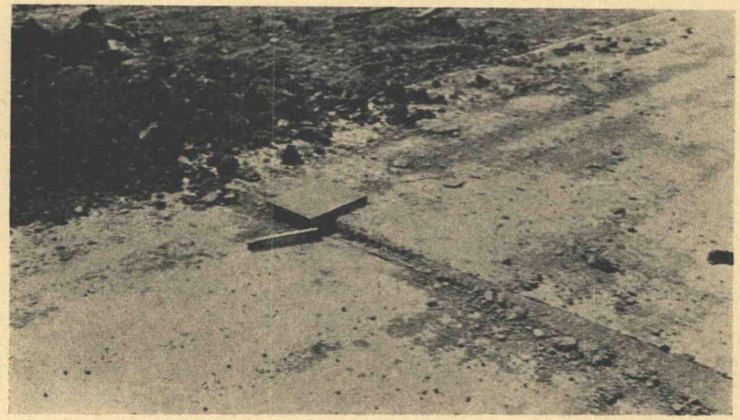
E = 0 0000055 per degree F

T = Temperature difference between top and bottom of slab (20° to 40° F)

u = Poisson's ratio for concrete = 0 15

A third type of warping, shown in Figure 13, not reversible in character, curls slab ends and edges upward permanently as much as one to two inches and thus produces serious traffic hazards and the excessive stresses leading to slab destruction (9, 10). This type, in so far

A—Badly Warped Pavement in Mississippi. Both Ends and Sides Curled Upward Permanently



B—Faulting at Joint Caused by Unequal Warping of Pavement Slabs—Texas

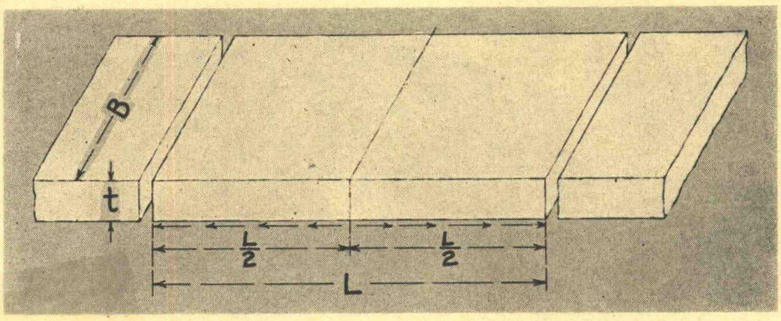
Figure 13. Examples of Detrimental Pavement Warping

as has been observed, is confined to slabs laid on soils of particular character and the reasons for its occurrence have not been completely explained.

So much for the causes of volume change. Let us now consider the effects of restraining volume change.

SHRINKAGE OF PLASTIC CONCRETE

Restraint of slab shortening is twofold in effect. First, it causes a crack to occur wherever the cumulative tension exceeds the resistance of the slab and thus distributes the shortening in a number of cracks throughout the length instead of allowing its accumulation at the ends of the slab. Second, it reduces the extent to which the parts of the slab between cracks shorten and thus causes the summation of crack width and end movement of the restrained to be less than that of unrestrained slabs.



Let $L =$ Spacing of transverse joints in feet
$B =$ Width of concrete slab in feet
Then $f \frac{L}{2} BW =$ Force required to slide a slab of $\frac{L}{2}$ length and
$12\ BtS =$ Tensile strength of slab—provided
$S =$ Allowable tension in concrete—lbs. per sq inch
$f =$ Coefficient of subgrade friction
$t =$ Thickness of slab in inches
$W =$ Weight of concrete—pounds per square foot

Cracking occurs when increasing length of slab causes the accumulating restraint of movement ($f \frac{L}{2} BW$) to just equal the tensile strength of the slab ($12\ BtS$). At this time the length of slab is disclosed by the formula $L = \frac{24tS}{fW}$

Figure 14. Effect of Subgrade Restraint upon Slab Length

Theory published in Public Roads (11) and shown in Figures 14 and 15 amply demonstrates how spacing of cracks depends upon the degree of restraint. Thus according to Figure 15 cracks which form when the tensile strength of the concrete equals but 20 pounds per square inch may be spaced 80 feet apart if the subgrade has a low coefficient of friction ($f = 2.0$). The effect of restraint for reducing the amount of slab shortening between cracks will be disclosed as the discussion proceeds.

In order to demonstrate the effect of restraining early shrinkage, let Figure 16-A represent a slab of plastic mortar, 100 feet long, six inches thick, without weight, not restrained in movement, and capable of losing moisture from all locations at equal rate Furthermore, let it be assumed that no shrinkage will occur when moisture loss is prevented and that the slab when cured in the air will shrink in accordance with the plain mortar curve, Figure 6 Accordingly, the shrinkage will amount to 4.5 inches at the age of 50 minutes and this will be localized at the ends of the slab as shown in Figure 16-B because of the absence of subgrade friction and other restraining influences When, however, no water escapes from the bottom of the slab and the rate of escape from any other location varies as its dis-

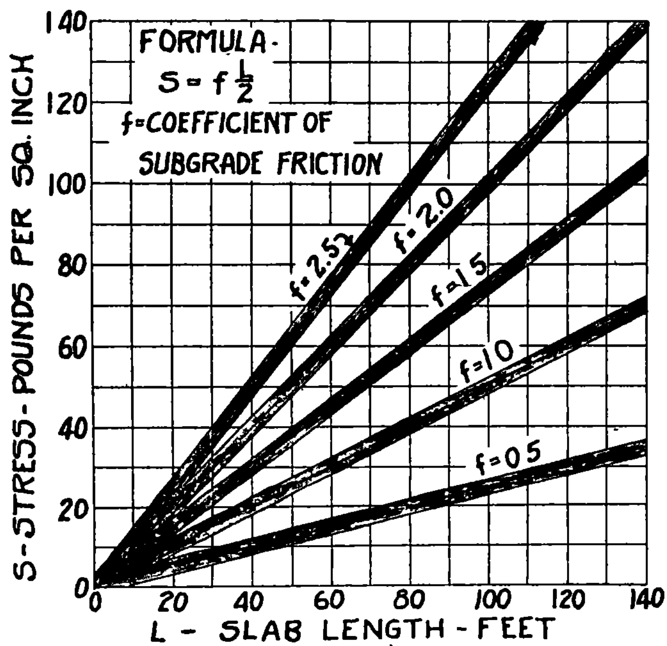


Figure 15 Stress as Related to Slab Length and Subgrade Friction

tance from the top, a curved slab such as shown in Figure 16-C is produced with ends elevated due to the assumed absence of weight

Due to its weight, however, the slab cannot curl as shown in Figure 16-C, and consequently stress is produced in the top of the plastic slab which causes it to become map-cracked in a manner similar to that illustrated in Figure 17 According to measurements it is interesting to note that the cracks in this particular case have a width which in 100 feet of slab would amount to 11 8 inches Furthermore, an upward curling of the edges of 0 72 inch would be required to prevent the formation of the cracks in this slab, which is four inches thick and four feet long

When, in addition to the weight of the slab, subgrade friction is introduced, the effect is to influence the occurrence of cracking in the following manner:

The lower the coefficient of friction, the longer will be the individual slabs, the greater will be the shrinkage in each slab, the wider will be the cracks and the closer will the summation of crack widths approach the 4 5 inches shown in Figure 16-B As the coefficient of

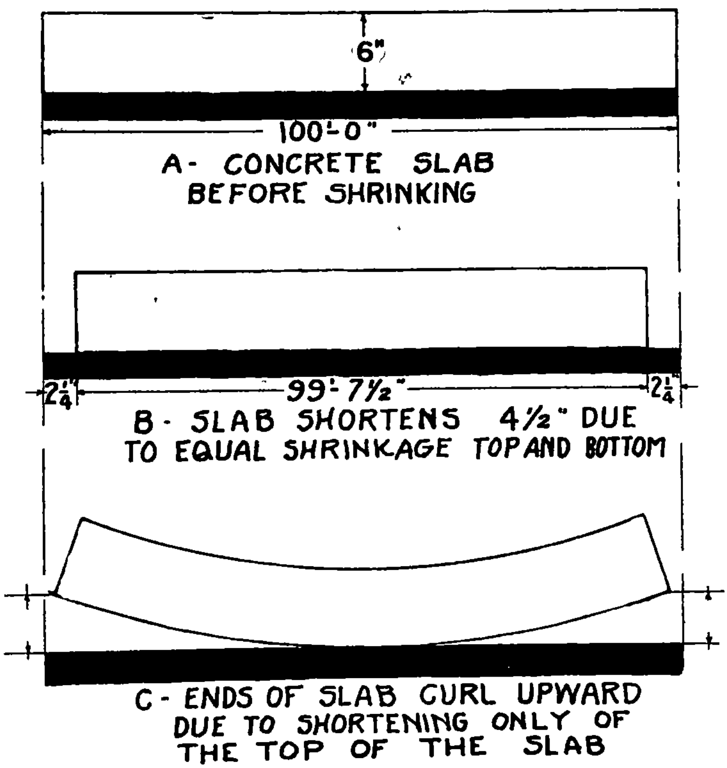


Figure 16. Effect of Shrinkage upon the Shortening and Warping of Road Slabs

friction increases, however, the cracks increase in number, their width decreases, there is less shortening of slabs between cracks, and the sum of crack widths becomes much smaller than the 4½ inches shown in Figure 16-B The effect of different degrees of form roughness on the shrinkage of plastic material is disclosed by Figure 18. Here the lineal shrinkage of the clay slab in the form with the rough sanded bottom was but 62 per cent of that of the slab in the form with the smooth and greased bottom

The effects of large aggregates of two types for restraining the shrinkage of concrete slabs are illustrated in Figure 19. Let that shown in Case 1 be either loosely arranged or of such shape and of such surface texture as to furnish but little resistance to further consolidation. Let that shown in Case 2 be either compactly arranged or of such shape and surface texture as to resist further consolidation.

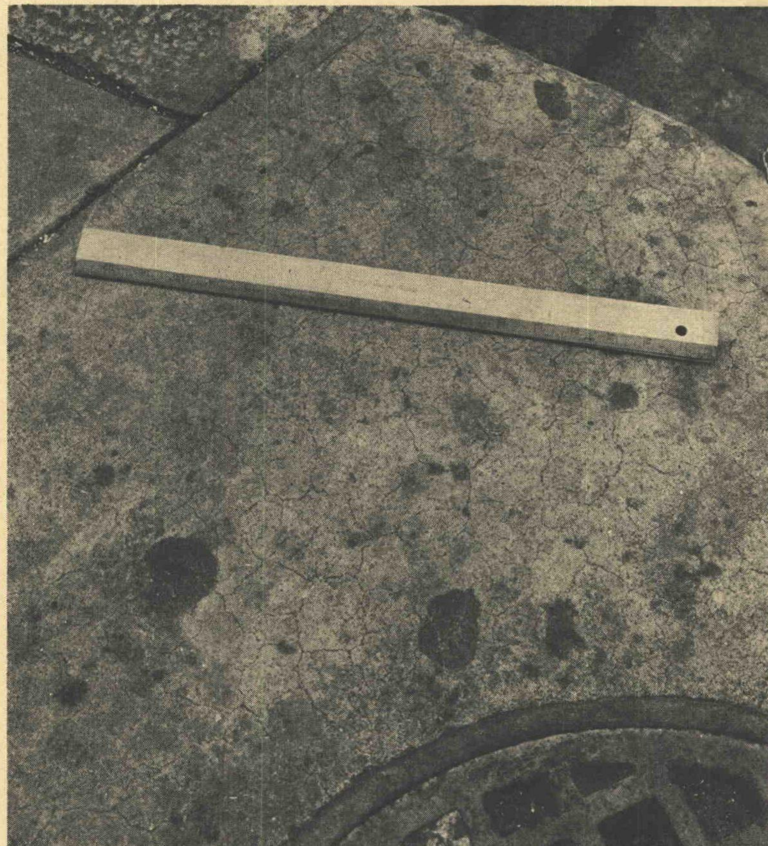


Figure 17. Map Cracking

During shrinkage the particles of loosely arranged material move closer with appreciable shortening of the slab as shown in Case 1. The particles, Case 2, in contrast, cannot move closer together and consequently this slab does not shorten appreciably.

In practice it has been observed that under apparently equal conditions of design, construction, and environment, concrete containing one type of aggregate may crack appreciably more than concrete containing a different aggregate (13). And this, according to what precedes, indicates that character of aggregate may exert an important influence upon the shrinkage of concretes and mortars.

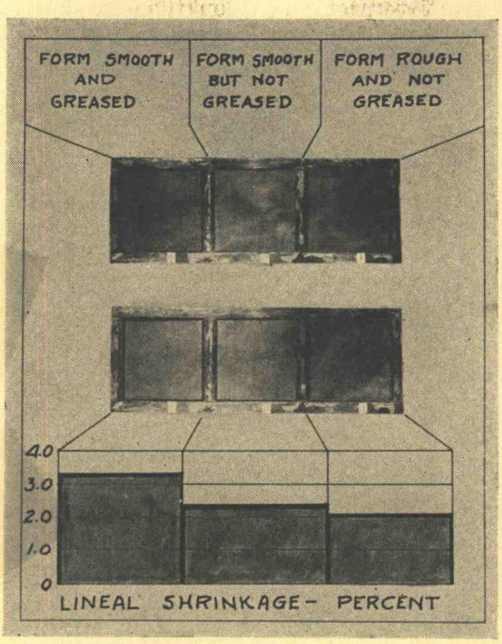


Figure 18. Effect of Form Roughness upon the Shrinkage of Plastic Material

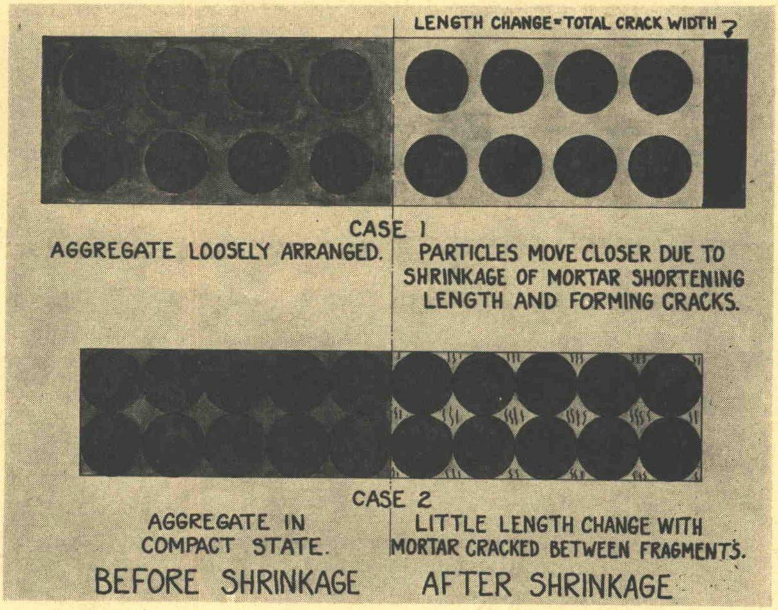


Figure 19. Effects of Large Aggregates upon Shrinkage

The influence of reinforcement on the shrinkage of plastic materials (in this case clay) is shown in Figures 20 and 21. Slabs Nos.

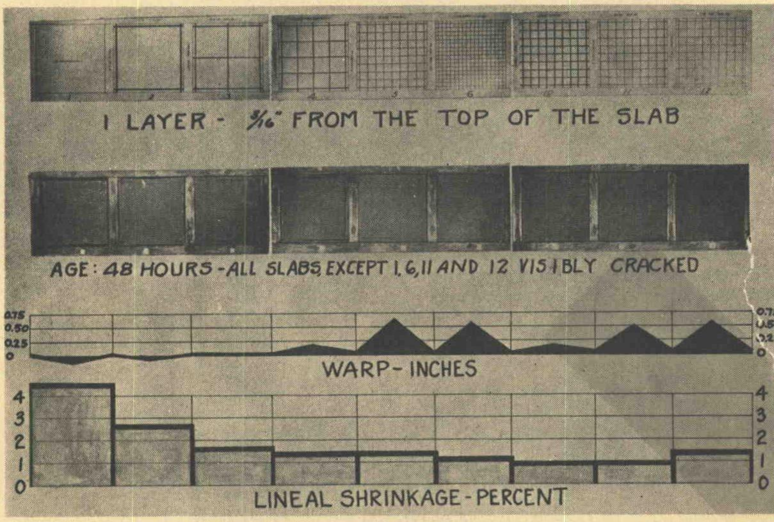


Figure 20. Effect of the Weight and Spacing of the Reinforcing Members on the Shrinkage and Cracking of Plastic Materials

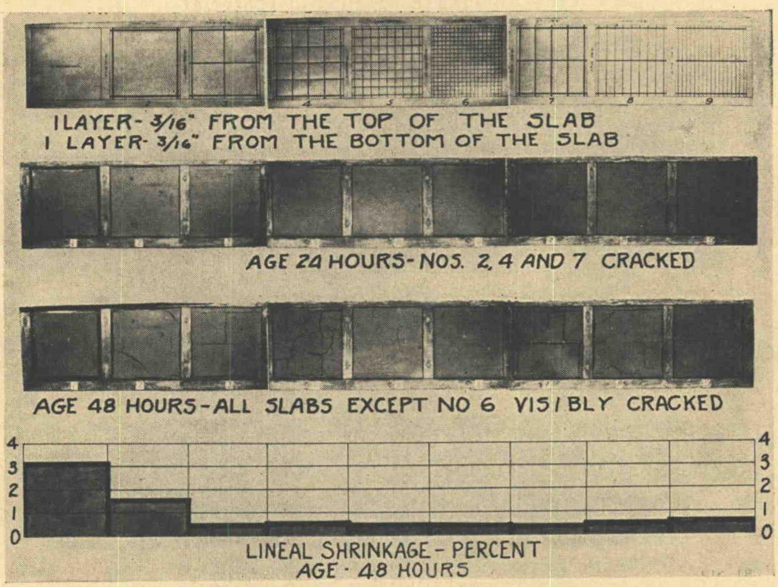
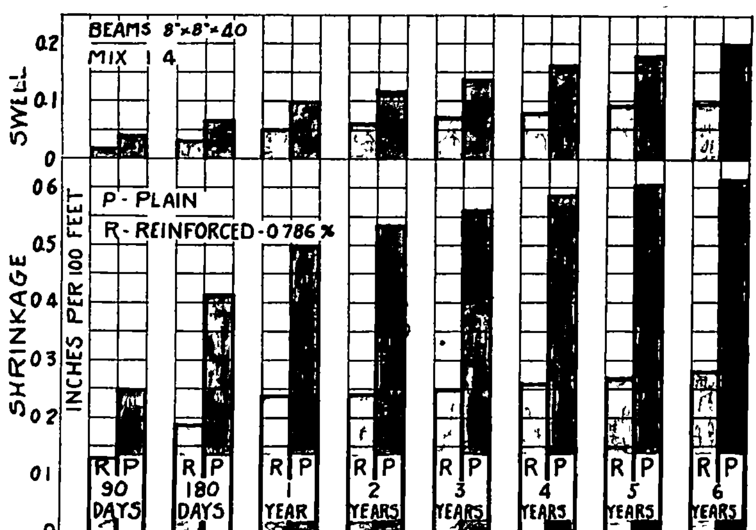


Figure 21. Double Layer Reinforcement: Its Effect on the Shrinkage and Cracking of Plastic Materials

1 to 6, inclusive, show that as the number of wires were increased from 2 to 17 in each direction without much change in cross-sectional area of metal (see Table I), the lineal shrinkage of the reinforced slabs

consistently diminished from 58 to 26 per cent of that of the plain slab (No. 1). Also, it will be noted that slabs Nos. 10 and 11, with the same number of wires, were restrained equally in spite of the fact that slab No 10 contained more than five times as much weight of reinforcement as slab No 11

While the 17 wires in slab No 6 furnished the greatest reduction in shrinkage, they at the same time accomplished this benefit without causing cracking such as developed in slabs Nos 2 to 5, inclusive



RELATIVE SHRINKAGE AND SWELL OF PLAIN AND REINFORCED BEAMS STORED IN-AIR AND WATER.

Figure 22

The downward curling of the edges shown in Figure 20, due to the fact that only the top fibers were restrained from shortening, is in accordance with the foregoing discussion

By placing the reinforcement in both top and bottom as in the slabs Nos 2 to 6, inclusive, Figure 21, the warping is completely eliminated and the shrinkage further reduced

Likewise, cracking in slab No 6, with the wires spaced closest together, is again absent Thus the importance of distribution instead of the weight of wires in the restraint of plastic materials is disclosed.

SHRINKAGE AND SWELL OF RIGID CONCRETE

Figures 22, 23, and 24 illustrate how steel reinforcement reduces the movement of slabs due to shrinkage and swell Figure 22, furnished by W K Hatt and R E Mills (14), shows a relative expansion in water and a relative shrinkage in air of concrete beams 8 by 8 by 40 inches, both plain and reinforced In each case the change in

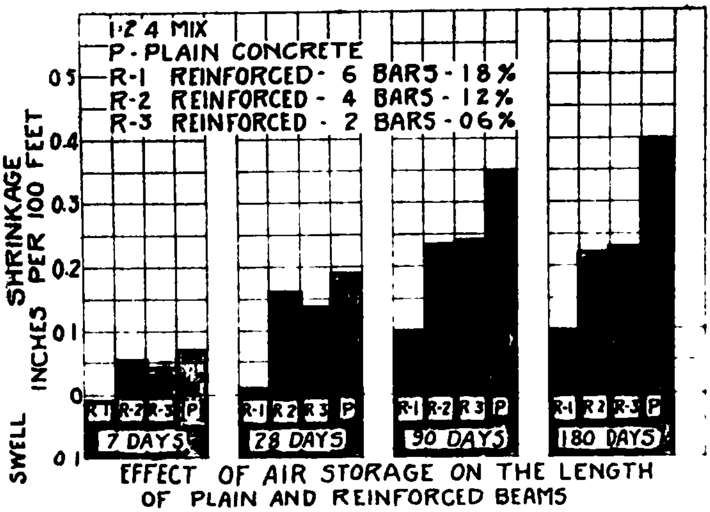


Figure 23

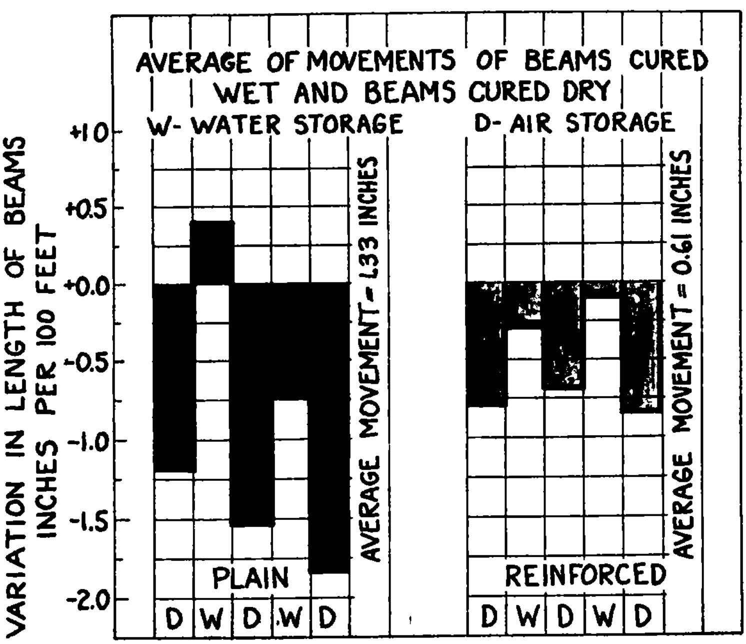


Figure 24 Effects of Storing Alternately in Air and Water for Short Periods, on the Lengths of Both Plain and Reinforced Mortar Beams

length of the reinforced beams, it will be noted, was but about 40 per cent of that of the plain beams. Figure 23, furnished by A. T. Goldbeck and F. H. Jackson (15), also shows that reinforcement reduces the amount of movement and, in addition, shows that increasing the weight of the reinforcing increases the benefit in this respect.

Consequently, in the shrinkage of rigid concrete as contrasted with the shrinkage of plastic concrete, weight or cross-sectional area of the reinforcement becomes an important factor.

As would be expected from Figures 22 and 23, lengthening and shortening of slabs due to alternate wetting and drying would also be reduced by steel reinforcement, and this is shown in Figure 24, suggested by the 1930 Highway Research Board Report.

TABLE I

EFFECT OF THE DISTRIBUTION OF REINFORCEMENT ON THE SHRINKAGE OF CLAY SLABS, FIGURES 17 AND 18

Slab No.	Number of Wires Each Direction	Area of Metal—Per Cent Each Direction	Lineal Shrinkage in Per Cent of That of the Non-reinforced Slab	
			Wires 3/16 inch from the Top of Slabs Figure 17	Wires 3/16 inch from both top and Bottom of Slab Figure 18
			Per Cent	*Per Cent*
1	None	None	100	100
2	2	0.22	58	50
3	3	0.14	37	15
4	5	0.11	30	19
5	9	0.13	30	17
6	17	0.16	26	15
10	9	1.01	22	
11	9	0.19	22	
12	9	0.08	33	

Restraint of either expansion or swell may be due to insufficient joint space or to frictional restraint of subgrade or to reinforcement. The first sets up flexural or column, as well as compressive stresses in the slab, whereas the latter two produce only the compressive stresses. Compression of the first type is illustrated in Figure 25, suggested by H. F. Clemmer (12). Here the pavement constructed at a temperature of 40°F. without expansion joints was compressed by expansion as much as 361 pounds per square inch when the temperature equaled 100°F.

Figure 26, furnished by A. T. Goldbeck and F. H. Jackson (15), shows the difference in shrinkage on the plain and reinforced sides of a beam. Where at the age of about 100 days the movement on the plain side of the beam was about 0.9-inch per 100 feet, that on the

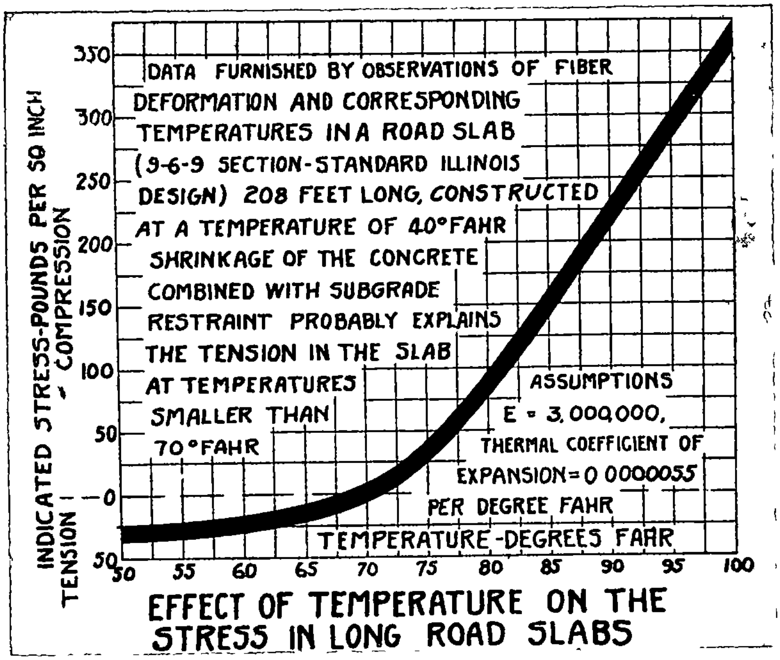


Figure 25

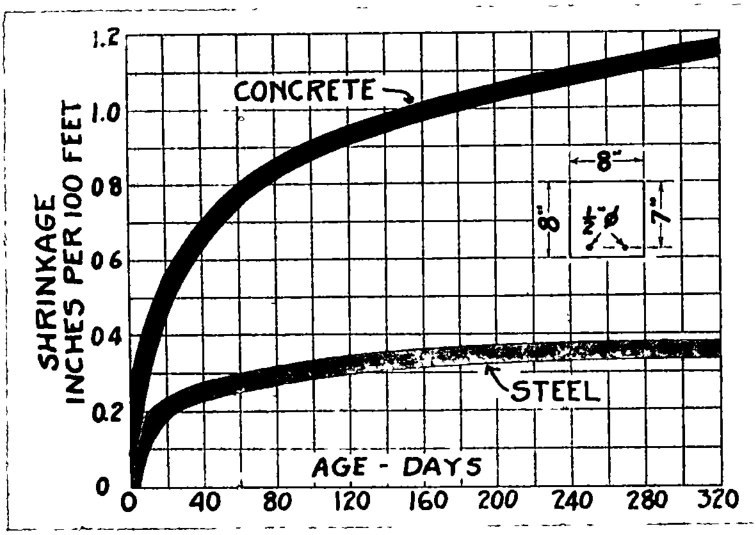


Figure 26. Relative Shrinkage of the Plain and Reinforced Sides of the Same Concrete Beam

reinforced side was but 0.3 per 100 feet This shows how reinforcement may serve to reduce warp in slabs When, for instance, the top dries out and the bottom remains wet, the shortening in the top exceeds very appreciably that in the bottom and consequently there is a tendency for the slab edges to curl upward If this difference in fiber shortening were as much as 0.6-inch per 100 feet, then, according to Figure 26, steel in sufficient amount placed in the top surface could entirely prevent the warp

The coefficient of contraction and expansion of steel differs but little from that of concrete, therefore short concrete slabs are restrained by reinforcement but little when contracting and expanding. Under these conditions the steel assists instead of retards the movements and may thus be utilized to so bind fragments of slabs as to prevent visible cracking For this purpose the steel is assumed to furnish all of the tension necessary for moving the slabs.

The following formula (11) serves to disclose the amount of steel required for this purpose

$$A = \frac{fLW}{2S_1} \text{ in which}$$

A = Area of steel in square inches per foot of slab width.
f = Coefficient of subgrade friction.
L = Spacing of transverse joints in feet for longitudinal steel and width of slab for transverse steel
W = Weight of concrete in pounds per square foot
S_1 = Allowable tension in steel in pounds per square inch.

When the transverse steel does not extend through the longitudinal joints, L equals the width of the individual slabs When the transverse steel extends through the longitudinal joints L equals the width of the pavement

In contrast to the lack of restraint due to reinforcement in short slabs, continuous steel used in very long slabs restrains the contraction of concrete in amounts increasing with the weight of the reinforcement This is illustrated in Figure 27, which shows the relation between drop in temperature, summation of crack width, and amount of reinforcement, as suggested by the performance of long reinforced slabs at the Arlington Experiment Farm (16).

According to available theory, the restraint of neither the shrinkage nor the contraction of slabs by subgrade friction is of much practical significance after the concrete attains appreciable strength.

Thus according to Figure 15, a pavement having a tensile strength of 100 pounds per square inch at the time of breaking may have a crack spacing of either 100 or 400 feet, depending on whether the coefficient of subgrade friction is very high ($f = 2.0$), or very low ($f = 0.5$) In either case, the spacing far exceeds any deemed detrimental in pavements

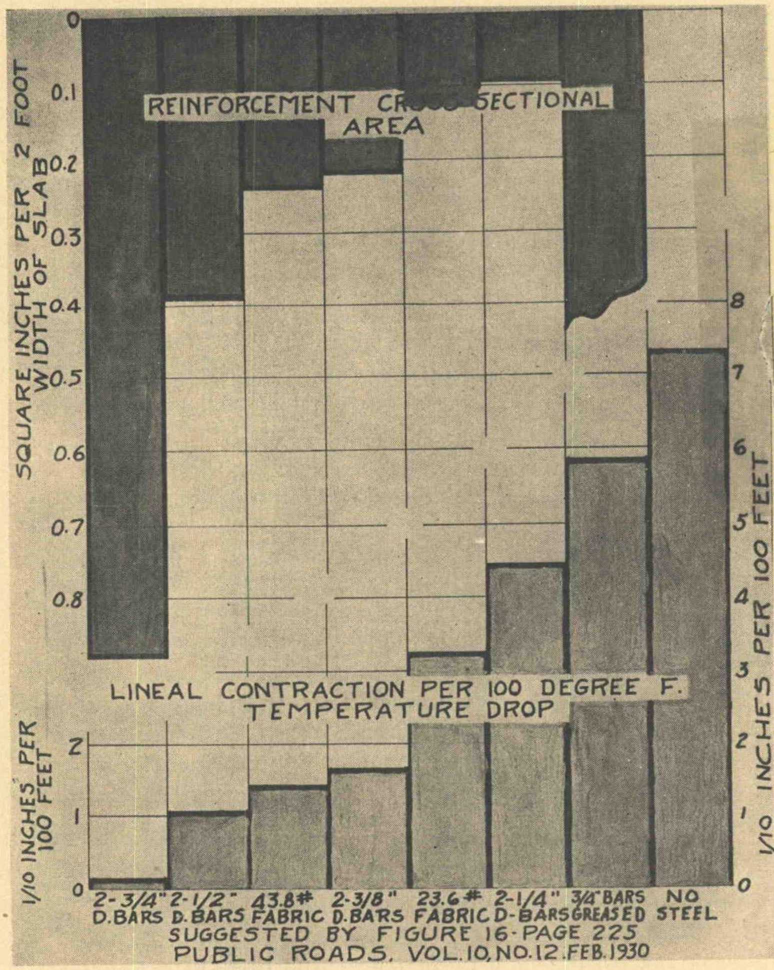


Figure 27. Performance of Long Concrete Slabs

SLAB STRESSES AFFECTED DIFFERENTLY BY NON-UNIFORM AND UNIFORM SUBGRADE SUPPORT

The extent of cracking produced by non-uniform support is different from that produced by load in uniformly supported slabs. Likewise, the correct preventive measure is different in each case. This is very clearly illustrated by a theoretical analysis furnished by Dr. H. M. Westergaard (17). According to this analysis, for instance, a wheel load which causes a uniformly supported slab of any appreciable length (30, 40, 100 feet, etc.) and thickness to crack will continue to produce cracking in such slabs until the resulting fragments become very small—say three to five feet in length.

Cracking in rigid slabs caused by their attempts to adjust themselves to variations in the subgrade support, in contrast to the cracking which occurs in uniformly supported slabs, divides the slabs into lengths depending upon the supporting conditions

Thus, when the number of transverse cracks increase with the pavement age in such a manner as to suggest that the resulting slab fragments will be but 3 to 6 feet long, a deficiency of slab strength is indicated.

Generally, thin road slabs (4 and 5 inches thick) constructed during the early stages of highway development, when not supported by sand and gravel and similarly stable subgrades, cracked in this manner. It is obvious that increasing either the slab thickness or the stability of the subgrade should serve to reduce occurrence of this type of cracking, which may be caused by the slab's inability to distribute the wheel loads over sufficiently large areas of the subgrade.

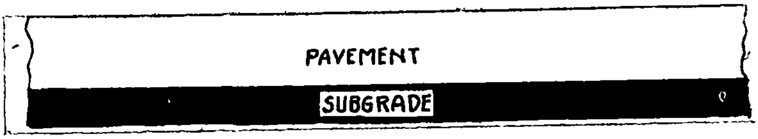
When in contrast to the cracking in the 4 and 5 inch slabs the number of cracks as found in slabs 6 inches or more thick, increases with the pavement age at a rate suggesting that the ultimate slab length will be from 15 to 20 feet, the cause cannot be attributed to deficiency of slab strength Therefore, increase in slab thickness is not the proper remedy for this type of cracking, which among other things may be due to non-uniform support Furthermore, Dr. Westergaard's theory shows that under certain conditions increasing both the slab thickness and the stability of the subgrade may actually increase instead of diminish the tendency to crack due to non-uniform subgrade support The preventive measures under these conditions, therefore, are crack control and reinforcement instead of increased pavement thickness

Figure 28 illustrates the conditions under which increase in both slab thickness and subgrade support may serve to either increase or diminish slab stress

When a slab, placed on a perfectly uniform subgrade, Figure 28-A, is loaded, the deflection and consequently the stress diminishes as either or both the thickness of the pavement and the stiffness of the subgrade increases When, however, a slab placed on a subgrade furnishing non-uniform support, Figure 28-B, is loaded, increased subgrade stiffness and increased thickness may cause increased stresses

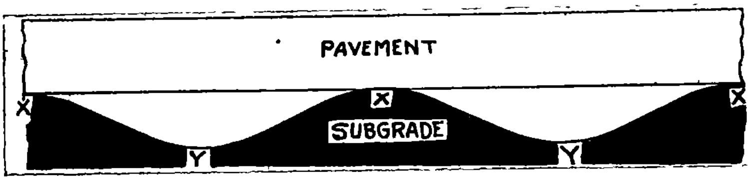
In Figure 28-B a load will cause the soil at X to compress and the pavement to deflect until it receives support from the subgrade at Y An increase in the stiffness of the subgrade will cause a decrease in the amount of compression at X and consequently an increased deflection of the pavement over Y, resulting in increased stresses Furthermore, for equal deflections, stress increases with increase in slab thickness in spans of the same length Therefore, both a thin and a thick pavement will be deflected an equal amount before receiving support from the subgrade at Y, but for this equal deflection the thick slab will have to be stressed the greater amount.

Reinforcement may serve to reduce the number of cracks due to bending stress in several ways It may increase the modulus of rupture as much as ten per cent when slabs are cured dry (14) and very much more when it serves to restrain the swell of slabs due to wetting (2), it increases by as much as ten per cent (8) the amount which slabs may stretch before showing visible cracks and by preventing the separation of visibly cracked slabs diminishes the faulting of slabs productive of high impacts Thus its benefit is twofold, to increase the load carrying capacity of slabs and to reduce the loads which the slabs must accommodate



A Uniform Subgrade Support

1. The firmer the subgrade, the smaller becomes the slab deflection for constant load and slab thickness
2 The thicker the slab the smaller becomes its deflection for constant load and degree of subgrade firmness



B Non-Uniform Subgrade Support

1 The softer the subgrade the more it compresses at "X", therefore the less the slab deflects in order to touch the subgrade at "Y," with constant slab thickness and load

Figure 28 Effects of Subgrade Support and Slab Thickness upon Slab Stress

It is during the bending of rigid concrete that the significance of the difference between shrinkage and contraction is important with respect to the use of reinforcement. If, for instance, shrinkage placed the slab fibers in tension instead of compression, restraint of the movement due to shrinkage would very appreciably increase this initial tension and thus cause the modulus of rupture of dried reinforced samples to be appreciably less than that of dried plain concrete samples

According to the Arlington tests (2) however, thoroughly dried slabs of appreciable age, both plain and reinforced, were approximately equally resistant to impacts (2) And, as noted above, the reinforced beams in the Purdue tests (14) even when cured under dry conditions, were stronger, by as much as ten per cent, than plain concrete beams. This benefit was especially noticed in the early ages and diminished gradually to practically negligible amounts as the concrete became older.

It is possible that, as the beams shrank with age, those without reinforcement shrank in greater amount and consequently became relatively stronger than those restrained from shrinkage by the reinforcement This relative increase in the strength of the plain beams apparently just about equalled the ten per cent higher strength of the reinforced concrete beams initially Consequently the compression furnished by shrinkage prevents the restraint of the steel from penalizing the dried reinforced slabs

THEORETICAL CONCEPTION OF DISINTEGRATION

There are, apparently, three different types of concrete disintegration, chemical, part chemical and part physical, and physical The purely chemical type, which involves base exchange, can be expected to begin where the concrete is in contact with the detrimental chemical and progresses from this location into the slab Thus softening of the concrete due to sulphate action would be expected to begin at the bottom of road slabs and progress upward

In the physico-chemical type, the active chemical is either carried into the slab in solution by capillarity, or dissolved by contained moisture from some location within the slab It is then deposited at some location on the interior of the slab or where evaporation occurs at the surface

The purely physical type of disintegration may be of two kinds—the crystallization of water due to frost and that of dissolved chemicals due to the evaporation of the liquid carrier

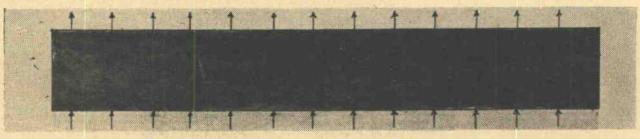
Thus the purely physical disintegration of the second type, in contrast with the chemical action which progresses upward, can be expected to begin at the top of the slab and progress downward as shown in Figure 29

All types of disintegration which depend upon the movement of capillary moisture through the slab, its evaporation from the surface, or its crystallization by frost in the interior of the slab are influenced largely by the permeability and this is controlled, not by the percentage, but by the character and distribution of the pores in the slab. Especially detrimental in this respect are certain types of fissures.

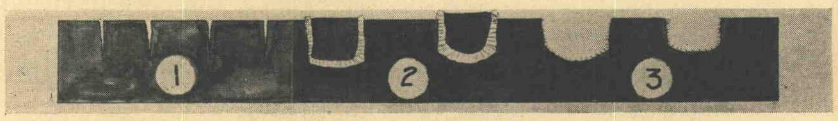
The growth of crystals (Figure 29) in these fissures causes the slab to expand and the concrete to weaken When this expansion exceeds the allowable joint space provided for this phenomena compression in the slab gradually increases until it ultimately causes failure due to crushing of the concrete fibers

It must be remembered, also, that particles of water smaller than a certain size fail to freeze even at very low temperatures, whereas, particles larger than this amount freeze at normal freezing temperature. Thus it can be seen if the pores of the concrete are so small that the contained water is unfreezable, expansion due to frost action is eliminated. If, in contrast, water particles in fissures, fine cracks, and large pores exist in freezable size, they tend to expand nine per

Water evaporates from top of slab causing chemical to crystallize within or on top of the slab
Rate of evaporation may equal 0.00012 gms. per min. per sq. cm.

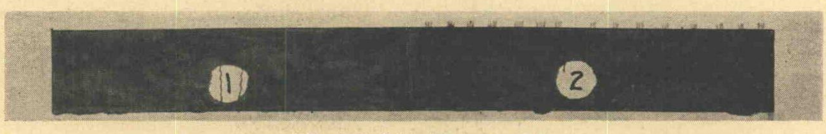


Water carrying chemical in solution enters bottom of slab. Rate as high as 0.0019 gms. per sq. cm.



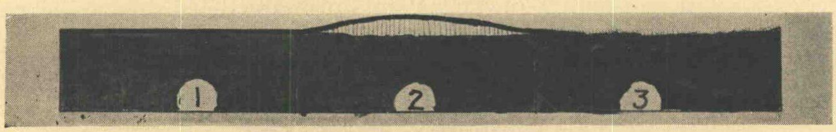
Case I. Air Cured Mortar

1. **Fissures form in surface of slab during curing**
2. **Crystals form in fissures**
3. **Thus forcing out mortar between fissures leaving holes**



Case II. Highly Porous Mortar

1. **Fine fissures probably extend from top to bottom of slab**
2. **Due to uniform rate of capillary flow crystals form on top of slab**



Case III. Water Cured Mortar

1. **Dense skin forms on top of slab**
2. **Crystals form beneath skin**
3. **Skin scales on top of slab**

Figure 29. Crystal Growth in Mortar Slabs

cent in volume upon solidification and in addition, may draw to themselves, during freezing, the otherwise small unfreezable particles and grow at their expense.

Likewise, it can be seen that a slab totally immersed would be free from physical disintegration due to chemicals in solution. Similar slabs, but partly immersed, however, permit the penetration of the detrimental solution in the immersed portion, and the evaporation of the liquid carrier from the surface not immersed and thus furnish the conditions productive of crystal growth.

Information now available does not justify recommending reinforcement for preventing disintegration. Research data, however, do indicate that steel reinforcement like any other factor influencing the

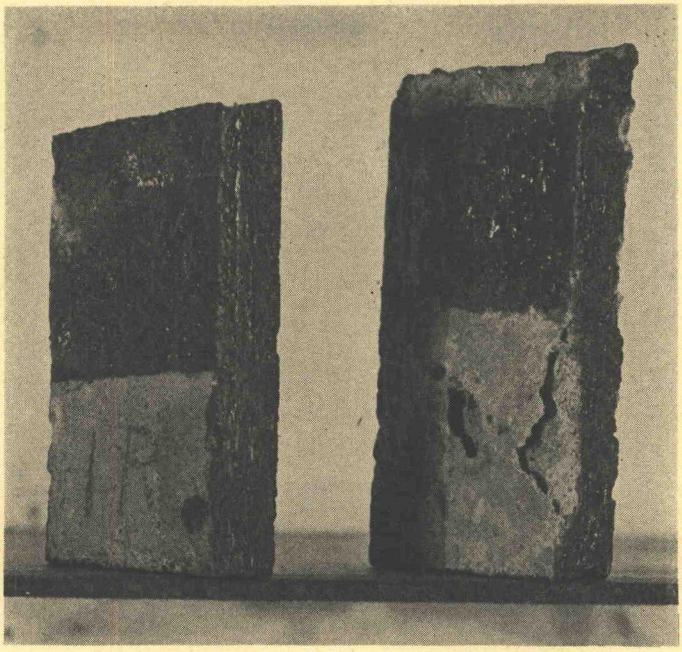


Figure 30. Effect of Reinforcement on the Rate of Detrimental Crystal Growth

A. Reinforced mortar beam, no evidence of crystal growth
B. Plain beam. Top scaled off and edges slightly pitted. Both beams were tested side by side in the same sulphate solution for the same period of time.

manner in which pores occur, must of necessity, exert an influence on both the physico-chemical and the purely physical disintegration. (See Figure 30). Furthermore, the reduction of shrinkage and its uniform distribution in plastic concrete, and the possible decreased permeability of concrete vertically (3) due to the incorporation of well distributed reinforcement, all contribute to producing a concrete which should be more resistant than plain concrete to disintegration.

BENEFITS OF STEEL REINFORCEMENT AND CONSIDERATIONS CONTROLLING ITS USE SUMMARIZED

BENEFITS

The benefits furnished by well distributed steel reinforcement begin at the time of its incorporation in the plastic concrete; continue during the hardening period; become especially important at alternate changes in slab moisture; at alternate changes in slab temperature; when differential subgrade movements produce non-uniform slab support, and when slabs on wet uniform subgrades are loaded

During the shrinkage of plastic concrete it serves to reduce the extent of transverse and longitudinal movement of plastic concrete, to distribute uniformly throughout the length and breadth of slabs that movement which does occur, and to reduce, according to indications, the vertical permeability of slabs In this manner it serves to reduce the amount of cracking of plastic concrete and tends to increase the uniformity of the concrete existing at different locations in the slab

During the shrinkage and swell of rigid concrete it reduces the extent of swell due to wetting, and of shrinkage due to drying the concrete and thus serves to reduce the amount of cracking due to the alternate wetting and drying of concrete slabs

During the contraction and expansion of concrete it serves to hold fractured slabs together and thus decreases the widths of the cracks due to the contraction of concrete This benefit may be utilized with a knowledge of the subgrade friction to predetermine the length of slab which can be maintained free of contraction cracks

During warp it reduces the magnitude of movement due to swell, shrinkage and flow of concrete, and therefore, when properly placed in the slab should serve to reduce the warping produced by these phenomena

During the bending of slabs due to non-uniform subgrade support it allows greater stretch of the concrete before the appearance of visible cracks and, within limits, prevents the separation of cracked slab fragments These benefits utilized with intelligent crack control, permit the determination of the length of slabs which can be maintained free of cracks due to non-uniform subgrade support

During the bending of slabs due to load it tends to reduce the magnitude of impacts due to wheel loads because reduction in faulting produces smoother pavements and tends to increase very appreciably the modulus of rupture of slabs laid on wet subgrades.

During disintegration the possibility of a beneficial influence is indicated, but research has not yet furnished information on the practical significance of this benefit, or on the weight and distribution of metal required for this purpose

RECOMMENDED USE

Reinforcement should prove beneficial in all slabs, but is especially required in all slabs comprised of concrete of the high shrinkage varieties; all slabs laid on wet subgrades, and, as has been suggested (18), in slabs laid on subgrades as follows, Group A-4 subgrades subjected to frost heave, all Group A-5 subgrades, poor Group A-6 subgrades, all Group A-7 subgrades, all Group A-8 subgrades and all subgrades in which there exists a conspicuous lack of uniformity in support (Groups B-1, B-2 and B-3)

IMPORTANCE OF EFFECT ON PLASTIC CONCRETE

Special attention is called to the possible benefits furnished by steel reinforcement during the shrinkage of the plastic concrete In this connection Figure 2 and other data (3) show that the shrinkage of small reinforced mortar slabs at the age of two hours was but 20 to 50 per cent of that of similar slabs not reinforced

Whereas, increasing the roughness of the base very appreciably (Figure 18) reduced the shrinkage about 38 per cent, adding well distributed single line reinforcement (Figure 20) reduced the shrink-age of plastic clay 74 per cent and double line reinforcement (Figure 21) reduced it 85 per cent

The restraint of movement furnished by the reinforcement is constant at all locations and, therefore, tends to equalize the shrinkage on areas of the subgrade having different coefficients of friction and in portions of the pavement having different shrinkage properties

Figure 31 illustrates the manner in which this uniform resistance to movement influences the occurrence of cracks The bottom layer of mortar, 1 inch thick, was laid on a very smooth base, and as can be seen, it was very badly cracked On this was placed a layer of 2-inch mesh wire fencing and a top inch of mortar of the same character as the bottom was deposited As can be seen, no visible cracks of any kind exist in the top layer This cracking of the bottom layer and freedom of cracking in the top layer of mortar laid on mesh reinforcement is a common experience for those employed in the water-proofing of bridge floors.

If the strength of concrete is a function of the density and if this in turn is controlled by the relative shrinkage of the concrete, the reinforced slabs because of the more uniform shrinkage referred to should possess a more uniform strength throughout their length than plain slabs of the same character If this be true, the maximum strength should be lower and the minimum strength higher in the reinforced slabs

Since beams or slabs will break where the concrete is weakest, the suggested higher minimum strength could account for the increased strength observed by W. K. Hatt (8) in concrete beams cured in air in which small amounts of welded fabric were incorporated.

Furthermore any benefit of steel for increasing the durability of concrete can be explained only on the basis of its influence for either decreasing the permeability of concrete vertically on for reducing the occurrence of detrimental shrinkage fissures—in each case a benefit afforded only when the concrete is in the plastic state.

Likewise only its effect on the plastic concrete furnishes the possibility that the reduction of shrinkage afforded by steel reinforcement

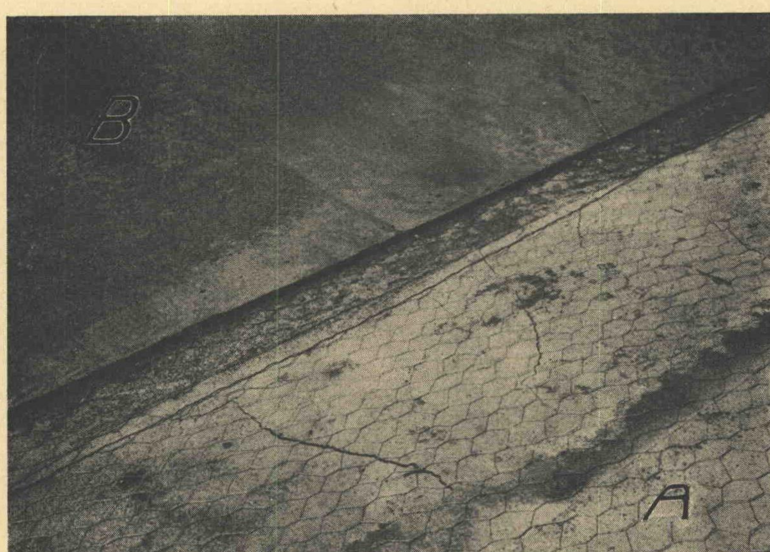


Figure 31. Effect of Wire Netting on the Shrinkage Cracking of Mortars

A. Bottom inch of mortar (badly cracked) laid on smooth bituminous treated burlap. Wire netting spread ready to receive the top layer of mortar

B. Top layer of mortar, one inch thick, free from cracks

may make usable aggregates which would be otherwise unsuitable on account of shrinkage properties.

The importance of shrinkage on the occurrence of cracks in pavement slabs is disclosed by theory, experiment and experience.

According to Figure 15, closely spaced transverse cracks caused by subgrade friction occur before the concrete has attained appreciable strength. Furthermore, results reported in the Proceedings of the Highway Research Board (3), indicate that the shrinkage of the mortar during the hardening period may be as much as six or more times the contraction of 0.72-inch per 100 feet, which would be expected should the temperature drop 100°F.

There is plentiful evidence of the effect of this shrinkage on cracking. During the construction of small test specimens at Arlington several years ago, shrinkage cracks occurred above the reinforcing bars In the Columbia Pike experiments, cracks occurred above the reinforcing bars which, in the light of present knowledge, would seem to have been caused by shrinkage of the concrete. Furthermore, during the construction of dummy joints it is common to find a well developed crack occurring under the constructed groove in the pavement when the steel forms are removed within an hour or so after the concrete is deposited on the subgrade This applies to both longitudinal and transverse cracks

Thus one sees that its ability to reduce cracking due to the shrinkage of plastic concrete may account very largely for the benefits furnished by small amounts of well distributed reinforcement in concrete roads

DESIGN AND PLACEMENT OF THE REINFORCEMENT

AMOUNT

Due to the very low strength of concrete when first laid, and the fact that at this time restraint of movement is most needed, distribution of steel is far more important than cross-sectional area Consequently but small amounts (0 05 per cent or less each direction) may be required to properly restrain and distribute the shrinkage of plastic concrete

As the need for restraining the shrinkage and the swell of rigid concrete increases, the amounts of steel required also increase And, while research has not yet disclosed the actual amounts required for this purpose, it has indicated that a considerable percentage might be required Thus amounts varying from 0 6 per cent to 1 8 per cent were required to furnish the restraint illustrated in Figures 22 and 23

The formula, page 295, may serve to furnish an estimate of the amounts required to prevent the appearance of contraction cracks in slabs of known length and the opening of center joints and grooves Thus, for instance, 0 153 square inch per foot of width (0 18 per cent) of longitudinal steel would be required in a slab 7 inches thick and 40 feet long, laid on a dry loam subgrade with an assumed coefficient of friction equal to 2 0.

To prevent faulting of slabs the steel must be present in amount sufficient to furnish the shear strength required to distribute loads across cracks and joints Tie bars, whose purpose is merely to hold slabs together may have a cross-sectional area indicated by the formula referred to above, and should be imbedded at least 40 diameters

DISTRIBUTION OF REINFORCEMENT

The spacing of reinforcement members required to furnish particular benefits may vary from a maximum of about two feet *c* to *c* to a minimum of possibly four inches or even less

According to H M Westergaard (19), the maximum spacing of dowels to serve as shear bars is about two feet *c* to *c* Since the members of all wire fabrics and bar mats which prevent the faulting of slabs must serve as shear bars, the spacing of such wires and bars apparently should not exceed this amount and a smaller spacing may be desirable

In this connection, L W Teller notes that in the Arlington Impact Tests (20) the ability of the reinforcement (0 5 and 1 0 per cent) to hold fractured slabs together increased as the spacing of the members was decreased The members in these mats were spaced 40, 20, 10¼, 7⅝ and 3¾ inches *c* to *c*, respectively

Generally, the necessity of great distribution of the steel increases with the extent to which the concrete is apt to shrink when plastic When, for instance, experience in particular localities with given materials and methods of construction, discloses by the absence of both shrinkage fissures and close spacing of transverse cracks in pavements that important shrinkage of the plastic concrete does not occur, the spacing of the reinforcement members should be determined on the basis of their ability to tie the slabs together and prevent faulting

As the number and character of shrinkage fissures and the close spacing of cracks in pavements (and laboratory investigations) indicate more and more that important shrinkage is apt to occur in the plastic concrete, the greater becomes the necessity for distributing the steel

Whereas a spacing of 12 inches or more *c* to *c* may be satisfactory in concretes which shrink but little in the plastic state, a spacing of six inches *c* to *c* may be required in concretes of normal shrinkage properties Furthermore, future research is apt to disclose the desirability of spacings as small as four inches or less *c* to *c* for reinforcement members to be incorporated in those concretes expected to shrink in exceptionally large amounts Equal spacing of members in both directions also seems desirable under these conditions

The presence of cracking in slabs Nos 2 to 5, inclusive, Figures 20 and 21, and its absence in slab No 6, suggests that the determination of both the weight and the distribution of reinforcement required to furnish the greatest restraint of shrinkage, with the least tendency to visibly crack the slab, has all the essentials of a very intricate problem

The importance of weight of reinforcement, in this respect, is indicated by W K Hatt's (8) researches He finds, for instance, that when reinforcement in a structural amount of ¾ to 1 per cent prevents the natural shrinkage of concrete, it tends to produce surface fissures, and that mesh or fabric reinforcement 0 26 to 0 33 per cent, in contrast, aids to preserve the integrity of concrete surfaces

It has also been pointed out that shrinkage cracks similar to those in the clay slabs, Figures 20 and 21, occurred directly above reinforcement members of appreciable weight in both the Arlington and the Columbia Pike investigations Similar cracking has been observed elsewhere Therefore not only the spacing of members, but also the amount of steel in a particular layer seems to be important Consequently precaution against the occurrence of shrinkage fissures suggests that reinforcement when required in appreciable amount, possibly 0 5 per cent or more, in concretes of the high shrinkage variety, should be distributed in two layers instead of one layer

Generally, single line reinforcement should be placed close to the tops of slabs whenever there exists a tendency for them to warp upward due to the restraint of movement of bottom fibers by subgrade friction, and the greater shortening of the top fibers on account of the fact that water is apt to escape from the bottom of the slab at a slower rate than from the top

As both the smoothness and the dryness of the subgrades increase, it seems logical to lower single layer reinforcement toward the center of the slab On smooth wet subgrades where the tendency for the slab bottoms to swell exceeds that of their tops to shrink, single layer reinforcement might well be placed below the neutral axis

Double line reinforcement should be used wherever experience or subgrade investigation indicates the possibility of either conspicuous non-uniformity of subgrade support due to frost heave or permanent pavement warping of the detrimental type

While the foregoing is generally applicable alike to both pavement slabs and bases, attention is called to one essential difference in the requirements of these two structures

For the sake of general appearance, cost of maintenance, and purposes of load distribution, pavement slabs should be as large as they can be made without danger of cracking The actual width of crack or joint between full sized pavement slabs is of little or no importance

The prime consideration in the design of bases, in contrast, is the prevention of cracks wide enough to cause a visible crack in the overlying wearing course The maximum allowable width of these base cracks is not now known It is somewhat larger, however, than the 0 0015 inch width which causes cracks to become visible in pavement slabs It seem entirely possible by the use of reinforcing and closely spaced planes of weakness to control base cracks to such an extent that they will not be reflected by cracks in the wearing surface

" The idea of increasing the number to reduce the widths of cracks has been advocated by J H Walker, M Inst C E It is a distinguishing feature of the English 'Anchorete' and 'Plumcrete' concrete roads " (23)

CONCLUSION

The foregoing amply discloses that both the decision as to the necessity for using reinforcement in road slabs and the determination of weight and distribution are not matters which can be settled by a set of simple instructions applicable for all cases, but instead depend upon climatic and subgrade conditions, in addition to the physical characteristics of the concrete in each particular case

Research has been liberal in its disclosures as to the benefits which may be furnished by reinforcement, and the qualitative explanations as the reasons for these benefits Quantitatively, however, its disclosures are of value primarily as a basis for a rational method of attack on, not only the factor of reinforcement, but the entire problem of design and construction of concrete

BIBLIOGRAPHY

1 Hogentogler, C A , 1925 Economic Value of Reinforcement in Concrete Roads Proc Fifth Annual Meeting, Highway Research Board, Part II

2 Hogentogler, C A , 1928 Steel Reinforcement in Concrete Pavements Proc Eighth Annual Meeting, Highway Research Board

3 Hogentogler, C A , and Willis, E A , 1930 The phenomenon of Shrinkage and Its Influence Upon the Integrity and the Durability of Concrete Pavements Proc Tenth Annual Meeting, Highway Research Board

4 Terzaghi, Charles, 1926 Simplified soil tests for subgrades and their physical significance Public Roads, Vol 7, No 8, October 1926

5 Terzaghi, Charles, 1927 Principles of Final Soil Classification Public Roads, Vol 8, No 3, May 1927.

6 Keen, B A , 1931 The Physical Properties of the Soil Longmans, Green and Company, New York

7 Anderegg, F O , 1929 The Mechanism of Corrosion of Portland Cement Concrete With Special Reference to the Rôle of Crystal Pressure Proc A C I , Vol 25, 1929

8 Hatt, W K , 1926 Extensibility of Concrete Proc A C. I

9 Watkins, W I , and Aaron, Henry, 1931 The Soil Profile and the Subgrade Survey Public Roads, Vol 12, No 7, September 1931.

10 Woodward, E C , 1930 The Development and Occurrence of High Joints in Concrete Pavements Proc Texas Section, A S. C. E , October 1930

11 Goldbeck, A T , 1925 The Interrelation of Longitudinal Steel and Transverse Cracks in Concrete Roads. Public Roads, Vol 6, No. 6, August 1925

12 Clemmer, H F , 1930 Design and Curing of Cement Concrete Pavements Canadian Good Roads Convention, Reported In The Canadian Engineer, Vol 59, No 13, September 23, 1930

13 Jackson, F H , 1925 Condition of the Ohio Post Road After Ten Years of Traffic Public Roads, Vol 6, No 4, June 1925.

14. Hatt, W K., and Mills, R E , 1928 Physical and Mechanical Properties of Portland Cements and Concretes Bulletin No 34 Engineering Experiment Station, Purdue University, November 1928

15 Goldbeck, A T , and Jackson, F H , 1917 The Expansion and Contraction of Concrete and Concrete Roads U S Department of Agriculture Bulletin No 532 October 13, 1917

16 Teller, L W , and Bosley, H L , 1930 The Arlington Curing Experiments Public Roads, Vol 10, No 12, February 1930

17 Westergaard, H M , 1929 Mechanics of Progressive Cracking in Pavements Public Roads, Vol 10, No 4, June 1929

18. Hogentogler, C A , and Terzaghi, Charles, 1929 Interrelationship of Load, Road and Subgrade Public Roads, Vol 10, No 3, May 1929

19 Westergaard, H M , 1928 Spacing of Dowels Proc Eighth Annual Meeting, Highway Research Board

20 Teller, L W , 1924 Impact Tests on Concrete Pavement Slabs Public Roads, Vol 5, No 2, April 1924

23 Walker, J H Jointless Concrete Roads and Walls Good Roads, Vol 7, No 10, October 1, 1931

DISCUSSION ON REINFORCEMENT IN PAVEMENTS

ABSTRACTED

Mr R D Bradbury, *Director, Wire Reinforcement Institute* In calling attention to the ability of even small amounts of embedded steel to cause concrete to elongate without cracking to a far greater extent than can be accounted for in the basis of the relative moduli of elasticity, Mr Hogentogler has dealt with a phase of structural design which offers a most important field for analytical research Although agreeing with the general principle that cracks and joints in concrete pavement should be rendered shear resistant, Mr Bradbury does not subscribe in all cases to the general statement that · "To prevent faulting of slabs the steel must be present in amount sufficient to furnish the shear strength required to distribute loads across cracks and joints" This is for the reason that bonded reinforcement holding cracks tightly closed acts simply in tension, the shear resistance being furnished by the high frictional resistance between the rough jagged faces of the crack

The structural action of reinforcement in tending to retard actual cracking is not so clearly apparent, although it is evident from experimental data that extensibility under direct stress and flexibility under bending, as measured by the appearance of first crack, may under certain conditions, be materially increased by the introduction of even small amounts of well-distributed reinforcing steel

Breed [1] found that 0 13 to 0 25 per cent of wire fabric increased the extensibility of 3 to 5 days old dense concrete briquettes 11 to 16 per cent as measured by the load required to produce the first crack under direct tension Hatt [2] has found, with beam specimens 14 days old reinforced with 0 30 per cent of wire fabric, increased flexibility ranging from seven per cent for water curing and 19 per cent for air curing to as much as 60 per cent in the case of certain poorly made and cured concrete Although Hatt's investigations seemed to indicate that the beneficial effect of reinforcement in producing increased flexibility was confined to early ages, being much less pronounced at 28 days than at 14, still, in Germany, Otzen [3] has found that 0 37 per cent of wire fabric in fairly large-size slab specimens three months old increased the extensibility of the concrete 21 per cent as measured by the load required to produce first crack under direct tension

For a given percentage of steel it seems logical to conclude that the amount of increase in the ability of the concrete to extend without cracking is largely a question of the relationship between the tensile strength of the plain concrete and the elastic properties of the steel as governed principally by yield point It would then follow that with concrete of the same tensile strength the amount of increased extensibility to be expected would be governed by the elastic properties of the particular grade of steel used This is clearly apparent from the Otzen tests which showed an increased extensibility of 21 per cent in specimens reinforced with cold-drawn wire, whereas an increase of only two per cent was obtained in the specimens reinforced with hot-rolled bars, notwithstanding the fact that the bars had a recorded yield point as high as 47,000 pounds per square inch This marked difference can be accounted for only on the basis of the difference in the elastic properties of the two classes of steel, the bars having a definite yield point whereas the cold-drawn wire, of course, had no distinct yield point throughout practically its entire tensile range

[1] Fifth Annual Proceedings, Highway Research Board, page 118

[2] American Concrete Institute, Proceedings 1926 Also Fifth Annual Proceedings, Highway Research Board, page 112

[3] Die Betonstrasse, August 1931, page 163

Although, in the usual procedure of practical design, reinforcement in concrete pavements is commonly proportioned wholly on the basis of holding cracked slab units together, still ample evidence exists to indicate that it performs another important function in protecting concrete quality by increasing its ability to withstand elastic elongation While this function of steel reinforcement may not be readily usable in design procedure, it may, nevertheless, be quite important and can be relied upon to constitute an additional safeguard to the integrity of concrete pavements by protecting the quality of the concrete during the hardening period when the slab is most susceptible to the formation of incipient crack fissures

Mr A. L. Gemeny, *U S Bureau of Public Roads* Mr Hogentogler's assumption that the bond stress is uniform throughout the length of the bar is not in accordance with the conclusions of Mr W H Glanville, who states in Technical Paper No 11 of the Building Research Board of Great Britain, that the entire compression in a bar caused by shrinkage in volume change is due to the bond stress within one foot of each end of the bar This conclusion was drawn from a carefully conducted series of observations made on test pieces 6 by 6 inches in cross section with varying percentages of reinforcement.

Mr. H F Gonnerman, *Portland Cement Association* It has been found in tests made on plastic mixtures in the Portland Cement Association laboratory that they have behaved similarly over the first three to five hours to those shown for the 24 hour period by Mr Hogentogler After that time however the clays keep on shrinking while the rate of shrinkage of the concrete, due to the setting and hardening, becomes very slow When cement-water paste and concrete mixtures were kept covered with a moist covering during the plastic period the shrinkage could be entirely prevented, indicating that by keeping concrete wet during the hardening period this shrinkage can be eliminated and reinforcement will not be needed for that purpose.

Mr C A Hogentogler, *U. S Bureau of Public Roads* On Figure 7 the shrinkage is plotted against the time. The greatest rate of shrinkage is at the instant the concrete is deposited on the subgrade Then there is a slowing up until a very appreciable change at the age of about one and one half hours indicates a change from the plastic to the rigid state Therefore, if something were used in the concrete to prevent as much as possible the loss of water until the burlap is used, it might prove very beneficial