and of the research work being done by Purdue University and other great technical and scientific universities throughout the country.

If we are to progress in our paving work, research and investigation must go forward. All engineers continually discover where errors have been made in design and construction by themselves and others. Often these errors cause inconvenience or danger or reduce the life of the construction. It is usually true that only by investigation and research can methods of economically avoiding these errors be developed—often after months of experimental work. The Highway Research Board of the National Research Council is doing fine work in correlating the investigational and research work of universities, state highway departments, and many other agencies throughout the country and is also itself doing a great deal of such work.

Designing and supervising highway engineers must necessarily depend upon these research agencies and upon such investigators as Dean Potter, Dr. Hatt, and Prof. Hollister and their staffs for the facts which enable them to proceed intelligently, economically, and safely with their work.

The Bureau of Public Roads has been and is doing a wonderful work in the development of rational methods of comparative design. Perhaps it may be said that their primary purpose is the proper disbursement of the Federal Aid road and bridge funds. But I believe that the value of the Bureau, in a far greater degree, lies in the work it has done and is doing in securing proper drainage, proper locations, proper alignment, proper grades, proper pavement design to carry the loads and withstand the elements, and proper and carefully supervised construction.

PROPER USE OF REINFORCING STEEL IN CONCRETE PAVEMENTS

By R. D. Bradbury, Engineer-Director, Wire Reinforcement Institute, Washington, D. C.

A recent nation-wide survey of concrete pavement design practice, made with special reference to structural details as prescribed by the various state highway departments, reveals the rather significant fact that, under certain conditions, 41 of the 45 states covered by the survey utilize steel in some form or another as a specified feature of concrete pavement design. This marked recognition of steel as a necessary adjunct to the concrete pavement is further emphasized when it is noted that the annual programs of those few states that do not use steel of any kind in pavement slabs aggregate less than 4 per cent of the total yearly state mileage of concrete pavements. Although this would indicate an almost universal recognition of the general principle that steel in some form is essential to the successful adaptation of concrete as a surfacing material for highways, still one must not infer that highway designers are by any means in full accord as to either the extent or the basis of its use. On the contrary, there exists a marked diversity of opinion among highway designers, not only regarding the extent to which steel is required in pavement slabs, but even as to the proper type and character of detail when used for a definitely intended purpose.

Current design practice thus indicates that steel is used in concrete pavements in widely varying amounts, in various forms, and for numerous structural purposes. In referring to the various items of pavement steel, we accordingly encounter such terms as "reinforcement," "tie bars," "marginal bars," "corner bars," and "dowels," each term indicating in a way the significance of each specific form or arrangement with reference to its intended structural function. Reinforcing steel as used in concrete pavements may thus be divided into two general classifications: (a) distributed reinforcement, and (b) accessory steel. The term "distributed reinforcement" is intended to imply an arrangement of distributed or fabricated members introduced in such a way as to provide a complete tensile strengthening of the entire slab; whereas "accessory" steel would include such items as tie bars, marginal bars, corner bars, and dowels, all of which are utilized as isolated members for the purpose of strengthening only certain edges, joints, or localized sections of the slab.

DISTRIBUTED REINFORCEMENT

Purpose. Distributed reinforcement, which will be referred to simply as reinforcement, is considered to consist of a series of longitudinal and transverse members assembled into sheet or mat form and so positioned as to comprise a complete network of steel bonded with the concrete and distributed throughout the entire area of each individual slab. The fundamental purpose of such an arrangement of distributed steel is not actually to prevent the formation of incipient crack fissures but to delay the appearance of visible cracks and to hold closely together all fissures that may develop in the slab as a result of any cause whatsoever. By arresting further development of microscopic fissures reinforcement will delay the appearance of eye-visible cracks and for all practical purposes will thereby serve to reduce cracking of the slab. The ultimate function of reinforcement in concrete pavements, therefore, is to prevent the progressive opening of cracks if they do occur, thereby holding cracked sections closely together, permitting transfer of load across the crack, maintaining evenness of surface, and safeguarding the strength and integrity of the pavement as a whole, even though its original slab dimensions may subsequently become subdivided by cracking into units of any possible size or shape.

Basis of Design. Distributed reinforcement, as commonly employed in pavements, is not utilized in amounts sufficient to produce a strictly balanced reinforced beam section. To do so would necessitate the use of such large quantities of steel as to render the concrete pavement prohibitive in cost. Furthermore, experience has indicated that such high percentages of steel are not necessary in pavement slabs. Research, investigation, and practical pavement experience have conclusively shown that the structural requirements of the concrete pavement can be adequately and more economically met by utilizing a safe bending-strength value for the plain concrete section and introducing only a moderate amount of distributed steel to protect pavement integrity and to accomplish a more effective means of crack control.

The modern conception of concrete pavement design, therefore, with particular reference to the use of reinforcement, is first to provide adequate slab thickness for transverse bending as determined by a safe fatigue value for modulus of rupture of the plain concrete without relying upon any steel to increase the direct moment of resistance of the section; and then to provide distributed steel only in sufficient amount merely to prevent crack opening under lateral contraction, thereby holding to microscopic dimension any crack which may occur from any cause whatsoever.

By utilizing a safe fatigue value for modulus of rupture of plain concrete of the quality commonly used in concrete pavements, both experience and theoretical analysis indicate that an edge thickness of approximately 9 inches, based upon the plain concrete section alone, is in general sufficient safely to withstand a maximum wheel load of approximately 8,000 pounds. Both experience and theoretical analysis also indicate that the interior portion of the slab may have a thickness equal to about seven-tenths of the edge thickness provided all joints are properly doweled and adequate steel is distributed throughout the slab to hold closely together the faces of any crack that may subsequently occur regardless of the cause. This results in what is known as the thickened-edge type of pavement section. The general acceptance of this type of pavement section is indicated by the fact that it is specified as a standard type of design by approximately 85 per cent of the states.

In this connection it may be pointed out that, from the standpoint of logical analysis, the thickened-edge type of pavement slab is not structurally consistent unless the slab is reinforced throughout the distributed steel. The reasoning by which the central portion of the slab can be made only seven-tenths as thick as the edge is based upon the assumption that either the interior portion of the slab will remain intact or that a wheel load placed at a crack in the central portion of the slab will be transferred from one side to the other and distributed approximately equally on the two crack edges.

Everyone recognizes the fact that, no matter how carefully pavements may be designed, they are susceptible to erratic cracking due to many unforeseen and unaccountable causes. It would thus appear that any proper design should certainly anticipate the probability of a crack occurring ultimately at any place in the slab. If there is no physical means provided for connection of the two edges forming such a crack, then the crack produces two independent edges each of which is no different structurally from the exterior edge of the pavement, and consequently the central portion of the slab would require the same thickness as the exterior edge. If, however, the two edges forming the crack are held tightly together so that, when a load is applied at one side of the crack, the two edges will function simultaneously rather than independently, then the amount of load on each edge is decreased and the requirement for slab thickness is less than at the free exterior edge. Distributed reinforcement is the only means by which erratic cracks can be made shear resistant or, in other words, capable of transferring load. It is thus evident that if distributed reinforcement is omitted, the thickened-edge type of pavement section is not logical from the standpoint of consistent structural analysis.

Amount of Steel. When a pavement slab contracts as the result of any physical or climatic influence, all cracks and joints will tend to open as a result of a shortening of the unbroken sections between cracks. When steel reinforcement is introduced for the purpose of holding cracks closely together when contraction occurs, it simply means in effect that steel must be provided in sufficient amount actually to drag a given slab unit against the force of subgrade friction. This conception of the function of reinforcement has established the so-called "subgrade-drag" theory, which is probably the most rational basis for proportioning steel reinforcement in concrete pavements. By this analysis the maximum force tending to produce crack separation in any given slab is readily determined from the known size and weight of slab and coefficient of subgrade friction. By utilizing a properly allowable working stress for the particular grade of steel used, the amount of sectional area of steel required either longitudinally or transversely is thus determined by a very simple mathematical expression. On this basis of design, with joints at reasonable spacings, moderate amounts of well distributed reinforcement—amounts much less than would be required to create a balanced reinforced section—will provide adequate resistance to crack separation under normal subgrade conditions.

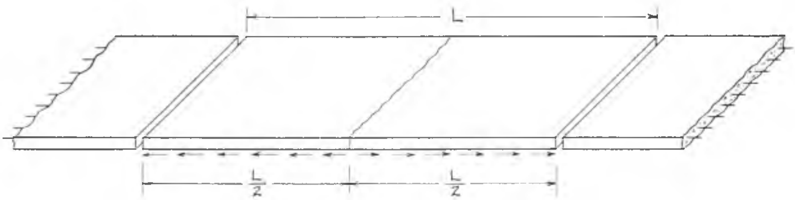

Fig. 1. Illustration to accompany formula based on subgrade drag theory.

Formula Based on Subgrade-Drag Theory—Requirements for Reinforcing Steel as Determined by Subgrade Friction. (Fig. 1.)

A_s = sectional area of steel in sq. in. per foot width
L = length of slab in feet (distance between free joints)
w = weight of slab in lb. per sq. ft.
c = coefficient of friction between slab and subgrade
f_s = allowable tensile stress in steel in lb. per sq. in.
Maximum pull on steel per foot width of slab,

$$F = \frac{w c L}{2}$$

resistance of steel per foot width of slab,

$$F_r = A_s f_s ;$$

hence,

$$A_s = \frac{w\ c\ L}{2\ f_s}$$

Note: The value of "c" varies from about 1.0 to 2.0. For average conditions a value c = 1.5 is frequently used.

The value of "f_s" should not exceed 50 per cent of the yield point for the particular grade of steel used.

In determining the value of A_s by the formula above, w and L are, of course, known for any given case, while it is necessary to assign suitable values to c and f_s.

Experiments have shown that the coefficient of subgrade friction varies from less than 1.0 to about 2.0, depending upon the kind of subgrade; the value c = 1.5 being frequently used for average subgrade conditions.

An allowable working value for f_s will depend upon the particular class and grade of steel used. Reinforcing steel is effective in holding cracks closely together only so long as the yield point of the steel is not exceeded. Obviously, for a class of steel wherein the yield point occurs at a very high point in its tensile range, a higher allowable working stress (f_s) can be safely used than for a steel having a lower yield point, even though both steels may have the same ultimate tensile strength. The American Society of Municipal Engineers recommends an allowable tensile stress of 20,000 pounds per sq. in. for hot-rolled bars and 25,000 pounds per sq. in. for cold-drawn wire.

In practice, however, reinforcement is not always designed on this strictly theoretical basis. Indications are that selection of both distribution and amount of steel is frequently based arbitrarily upon the experience and practice of those states that have long used reinforcement. This experience indicates that a total weight of distributed reinforcement of from 42 to 65 pounds per 100 sq. ft. appears to give generally satisfactory results under average conditions as represented by the service condition of large mileages of concrete pavement. The predominant weights as now used among the various states fall within the range of 45 to 55 pounds per 100 sq. ft. although amounts as low as 35 pounds and as high as 75 pounds are used in a few instances.

Distribution of Steel. Formerly the total weight of reinforcement was considered as the important index of reinforcing requirements, secondary consideration being given to the question of distribution. It is now generally recognized that, for a given total weight of reinforcement per 100 sq. ft. of pavement surface, the distribution of that steel throughout the slab is of vital importance. If such reinforcement is intended to prevent the lateral separation of adjacent slab sections, it is obvious that the amount of total steel must be distributed longitudinally and transversely to the pavement in general relation to slab dimensions.

Distribution of steel involves not only the distribution of relative amounts longitudinally and transversely but also the feature of spacing of members in either the longitudinal or transverse group. Experience and research, notably the extensive pavement survey conducted in 1925 by the Highway Research Board and also the Arlington Impact Tests, have indicated that the intended function of reinforcement is more efficiently performed by small members closely spaced than by large members widely spaced. It would thus appear that the closest possible spacing of members would be the most desirable. Spacing of members, however, is limited by practical considerations of construction, the minimum being almost universally limited to 6 inches, although a spacing of 4 inches is occasionally used. It is considered desirable, therefore, from the standpoint of reinforcing efficiency to confine the spacing of longitudinal members as closely to 6 inches as possible and to restrict the spacing of transverse members to not more than 12 inches or 16 inches.

Location in Slab. As to the proper elevation at which reinforcement should be placed in the slab, this should not be judged with respect to tension caused by transverse bending.

The primary purpose of distributed reinforcement is merely to prevent the lateral separation of adjoining slab sections, and for this purpose the most natural position would probably be at the center of the slab. However, from the standpoint of both appearance and maintenance the surface of the pavement is of primary concern; and it is therefore generally considered advisable to locate the reinforcement as near as possible to the top surface. The prevailing practice accordingly is to place distributed reinforcement about 2 inches below the surface of the slab. If double layer reinforcement is used, one layer is placed about 2 inches below the surface and the other 2 inches above the subgrade. Double layer reinforcement, however, is used to a very limited extent, only two states using it exclusively and two others using it occasionally under special conditions.

Installation. The procedure by which sheet reinforcement is installed in concrete pavements during construction is important. From a structural standpoint it is important that the reinforcement occupy its required position in the slab and that the method by which it is installed will not be such as to tend to impair the quality of the concrete. From an economic standpoint it is important that the method of installation be such as will not entail unnecessary expense or tend to delay paving progress.

There are two basic methods by which sheet reinforcement may be installed in concrete pavements. One is to support the sheet of reinforcement at its required elevation by means of some type of supporting device and deposit concrete through the suspended reinforcement, thereby pouring the full thickness of slab in one operation. The other is first to deposit concrete on the subgrade, give it a rough strike-off to the proper elevation, lay the sheets of reinforcement on this struck bed of concrete and cover with additional concrete to the required pavement surface. This latter method is known as the strike-off method and is most generally used. (Figs. 2 to 5.)

The installation of sheet reinforcement by means of any supporting device has numerous disadvantages and objections. This method requires the placing of reinforcement just after the paver moves to a new position, a time when installation of the reinforcement may very easily cause delay in paving operations. By supporting the reinforcement above the subgrade before any concrete is poured, it becomes necessary for the shovel men to walk on the reinforcement, tending to bend it out of position. Furthermore, when a supporting device of the sled type is used the longitudinal members of the sled, as they are withdrawn from the concrete, cause aggregate separation in line with the sled runners, thus tending to produce planes-of-weakness in the slab.

The strike-off method has none of these objections. It permits the placing of reinforcement just before the paver moves

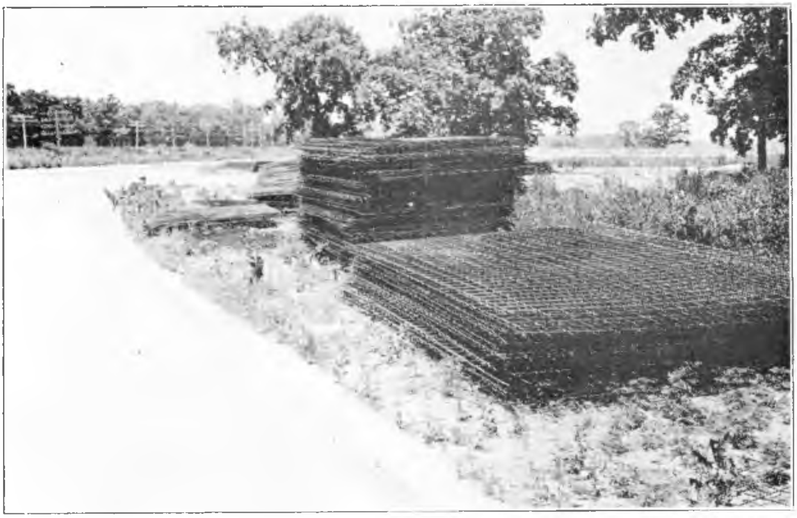

Fig. 2. Roadside stock pile of welded wire fabric. Illustrating convenient storage and handling of reinforcement when finished in flat, rigid sheets.

Fig. 3. Striking off concrete preliminary to installing sheet reinforcement. Concrete has been deposited on the subgrade and given a preliminary strike-off at an elevation 2 inches below final pavement surface.

Fig. 4. Placing sheets of reinforcement. The flat sheets of reinforcement are being placed on the rough-struck bed of concrete.

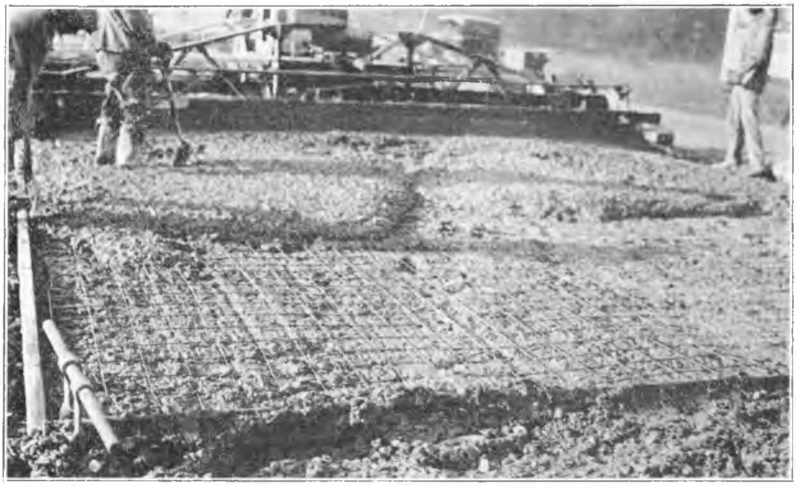

Fig. 5. Covering with concrete. Cover batches of concrete have been deposited on top of the reinforcing sheets and the finishing machine is screeding the final surface of the pavement.

to a new position, a time when no auxiliary pit operations are going on and when an abundance of labor is available. By the strike-off method, the reinforcement is supported on a level bed of concrete which offers adequate support to the sheet so that it can even be walked upon if necessary, and the sheet is always located in its exact position without danger of being bent or distorted out of shape.

The whole problem of installation of sheet reinforcement from the standpoint of economical operation of the job thus becomes merely a question of the best means of making the preliminary strike-off. This can be done in any one of several ways. A hinged plate on the front screed of the finishing machine may be used, although this method is not always desirable since it is necessary for the finisher to maneuver to the right position at the right time to make the strike-off. The most practical method on the usual highway paving job is to make the strike-off by means of a separate strike-off template. This may be operated by hand, or it may be operated from an auxiliary power shaft on the paver by means of cables attached to the template, or it may be operated by means of the cables attached to the finishing machine.

This latter method is the latest development in paving methods with respect to making the strike-off, and experience indicates that it is an ideal method. The available pulling power of the finishing machine is utilized to pull the strike-off template ahead by backing the finishing machine away, the work being done at a period during paving operations when delay is least likely to be caused, and done by the finishing machine wherever it may happen to be at the time when a strike-off is required.

ACCESSORY STEEL

Tie Bars. Tie bars are individual bars extending through either a preformed or dummy joint and bonded throughout their entire length. Tie bars are utilized for the specific purpose of preventing lateral separation of adjacent slabs usually along a longitudinal joint. Tie bars are often referred to as dowels. This appears to be a rather inappropriate term to apply to such members since tie bars are not as a rule depended upon for doweling action but are utilized simply as a means of holding adjoining slabs together at a joint which is usually provided with some other mechanical means for supplying the doweling action. Where the joint is of either a tongue-and-groove or a dummy type, shear resistance, or in other words doweling action, is attained by virtue of the interlock of adjoining slab faces. The function of the tie bar therefore is simply to hold the two slabs together, thus maintaining interlock, the bar serving merely as a tie member in tension and not as a dowel in shear.

The diameters commonly used for tie bars are ½-inch, ⅝-inch, and ¾-inch round with spacing varying from 20 inches to 60 inches. The most prevalent arrangement consists of ½-inch round bars 4 ft. long, spaced 5 ft. on centers, this arrangement being used by 18 of the 31 states using tie bars across longitudinal joints.

Theoretically the amount of steel required in tie bars should be determined on the basis of subgrade drag, taking into account the weight of slab, coefficient of subgrade friction, and width between free slab edges. When analyzed in this respect for average conditions, the usual arrangement of ½-inch round bars on 5 ft. centers is questionable from the standpoint of a conservative working stress in the steel. This arrangement appears to have developed in an arbitrary fashion and, in spite of the prevalence of its use, is open to question from the standpoint of conservative design. Tie bars are bonded members and are usually specified as deformed bars. The length of bar should be sufficient to develop through bond the necessary anchorage in each adjoining slab.

Marginal Bars. Marginal bars are individual bars independent of any bar mat or other system of distributed members and located adjacent and parallel to the edges of the slab. Marginal bars are obviously utilized for the basic purpose of strengthening slab edges. Nevertheless current practice with respect to details of design appears to indicate considerable uncertainty as to just what structural function such members are intended to perform. Marginal bars are specified by 14 states, the inconsistency of their adaptation being illustrated by the fact that 7 states require that the bars be bonded, whereas the other 7 specify that they shall be free to slip. If a marginal bar is bonded with the concrete it will serve as a tie member across any crack which may form transversely to the bar. If the bar is made bondless, it cannot serve as a tie bar but must function simply as a continuous dowel.

Marginal bars as commonly used are apparently not intended to provide any appreciable beam strengthening of the slab edge since they are universally located at the center of the slab depth where their resistance to transverse bending is practically nil. Their function if bonded, therefore, would necessarily be principally one of preventing lateral slab separation at any edge crack that may form. However, in performing this function they are not as efficient with respect to the slab as a whole as would be the same amount of steel distributed across the entire slab width. With no longitudinal tie steel other than marginal bars, it is evident that in resisting crack separation due to contraction it becomes necessary for the marginal bars to drag the slab entirely by its two corners. Experience has shown that this concentration of steel along slab edges may, under certain conditions, actually promote cracking rather than reduce it owing to the tendency to pull off slab corners as a result of the large tensile force thus concentrated at each edge of the slab. Undoubtedly the same amount of steel distributed across the entire slab width in the form of small members closely spaced rather than large units concentrated merely at the slab corners would be far more efficient in serving the basic purpose of preventing slab separation.

If marginal bars are made bondless so that they may function only as continuous dowel bars, even this effect is not lost when they are replaced by an adequate amount of distributed reinforcement. Marginal bars in acting as continuous dowels no doubt tend to assist in transferring load across edge cracks. The efficiency of this action, however, is purely a question of transverse rigidity of the bar rather than tensile strength and in any event the effect of doweling action is necessarily confined to the immediate vicinity of the bar. Smaller units of steel distributed across the entire slab width will more efficiently accomplish the same purpose but in a different way. When distributed steel is used, doweling action, or in other words transfer of vertical load, is accomplished by reason of the high frictional resistance of the cracked concrete faces, the steel serving not as rigid dowels in shear but simply as tie members in tension holding the faces of the crack in close contact. Furthermore, this action is not confined alone to the edges of the slab but is equally effective across the entire slab width.

Since marginal bars are not usually needed to provide adequate beam strength of the section and since any purpose they may serve either as lateral tie bars or as continuous dowels can otherwise be accomplished in a more efficient manner, it would appear that marginal bars are unnecessary when the slab is reinforced throughout with a proper amount of distributed steel.

Marginal bars, at one time considered a vital feature of design, are observed to be used at present by only 14 states. The common practice when used is to place one ¾-inch round bar about 6 inches from the slab edge and at the center of the slab depth. Other diameters such as ½-inch and ⅝-inch are occasionally used, in some cases one bar and in some cases two bars being employed.

Marginal bars are also used to some extent as transverse bars adjacent and parallel to transverse joints with the intended purpose of strengthening slab ends. This practice, however, is not prevalent, being followed by only 7 states.

Corner Bars. Corner bars are comparatively short members placed within a corner as formed by the intersection of a transverse joint with a longitudinal slab edge. A corner bar may be merely a straight member placed so as to bisect the corner angle; or it may be a member bent into either a right-angle or hairpin shape and placed symmetrically with respect to the slab edges forming the corner. Corner bars are sometimes used at all transverse joints but more generally at expansion joints only. Sizes commonly used are ½-inch and ⅝-inch round. At one time corner bars were quite generally used, but at present their use is extremely limited, being included in the requirements of only 7 states.

From the standpoint of structural design, protection of slab corners involves two distinct problems. One is to provide sufficient steel so located as to cross the probable corner crack, which potentially is a diagonal crack extending across the corner at an angle of approximately 45 degrees with respect to the slab edge and located about 3 feet from the extreme slab corner as measured along the longitudinal edge or transverse joint. Such steel will serve the purpose of holding the corner segment closely to the parent slab if such a crack develops from any cause whatsoever. Obviously small members closely spaced would be far more efficient in this regard than either a single or hairpin bar. It is thus apparent that, if the slab is provided with distributed reinforcement, such reinforcement is particularly efficient in holding corner cracks closely together.

The other problem, with respect to a cracked corner, is to protect the integrity of the corner segment itself. If a corner crack occurs, the small corner segment thus developed is particularly susceptible to disintegration under traffic, owing to the small size of the unit and the acute angles resulting from its triangular shape. Secondary corner cracks are easily developed in the piece itself, thus tending to accelerate disintegration of the corner segment. A single bar thus offers very little protection to the corner piece itself as compared with distributed reinforcement, which provides steel in both directions throughout the small corner segment, thus serving to protect it against otherwise rapid disintegration. Greater reliance may therefore be placed upon distributed reinforcement to protect corners than can possibly be expected from either single or hairpin corner bars. Several states employ additional strengthening of this kind at corners and along slab ends by utilizing extra short sheets or mats of distributed reinforcement, placed adjacent to all transverse joints, a practice which appears to be gaining in favor.

Dowels. Dowels are short individual bars which extend through transverse expansion or contraction joints and are rendered free to slip within at least one of the slabs which they connect. While dowels are thus short bars crossing joints, they are, however, definitely distinguished from tie bars by reason of the fact that they are introduced for an entirely different purpose. The slip feature of dowel bars is essential since they must not restrain lateral movement caused by expansion and contraction of the slabs which they connect. Their function is to provide rigid members connecting adjoining slabs for the purpose of making the joint shear resistant, that is to say, render the joint capable of transferring vertical load. Dowel bars, therefore, do not function as tension members but purely as shear members carrying vertical shear by virtue of their stiffness and rigidity rather than by reason of their tensile capacity.

Slip dowels are used across expansion joints by 26 states and also across contraction joints by 6 states. Details of design vary from ½-inch round bars on 30-inch centers to ¾-inch round bars on 48-inch centers, the most common arrangement being ¾-inch round on 30-inch centers followed closely by ⅝-inch round on 24-inch centers and ¾-inch round on 36-inch centers.

Dowel bars must be rendered bondless in one of the slabs which they connect; also dowels crossing expansion joints must be provided with end clearance pockets so that they will not interfere with free movement of the slabs when the joint tends to close. Dowels crossing contraction joints should also be rendered bondless in one of the adjacent slabs in order that the joint may be free to open under contraction. When contraction joints are of the dummy type, end clearance pockets are not necessary since such joints are constructed as closed joints.

Unusual care must be exercised in the installation of dowels since it is essential that they be set parallel to the pavement surface and also parallel to the axis of the roadway. If dowels are not given proper alignment, they will tend to bind upon movement of the slabs, thus interfering with free slab movement, which results in a tendency to buckle the dowel and probably cause cracking of the slab ends.

The structural efficiency of slip dowels as commonly used is now being seriously questioned by many designers. At best the dowel is a rather dubious means of maintaining slab alignment and transference of load, particularly at expansion joints where comparatively wide openings occur. Play of the dowel in its bondless socket accompanied by high intensity of bearing on the concrete adjacent to the joint edge tends to permit vertical movement which, together with a certain amount of bending in the dowel itself, results in a questionable efficiency with respect to the transference of an adequate proportion of load applied to one edge only. It is thus evident that if the dowel is to function with any degree of efficiency, at least a comparatively close spacing is required and it is decidedly questionable whether the customary spacing of 30 to 36 inches is sufficiently close to provide proper dwelling action across an appreciable width of the slab.

While certain recent tests have indicated that dowels as commonly designed are decidedly inefficient in transferring load, still it may be said that these particular tests involve rather meagre and incomplete data and cannot be taken as conclusive evidence that the dowel is worthless. Other tests have indicated that dowelling action in the immediate vicinity of the dowel itself is comparatively efficient, transference of as much as 38 per cent of the load as compared with a possible 50 per cent being observed. It would thus appear that slip dowels should not be hastily discarded simply because of supposed or even observed inefficiency since they constitute the only simple means at the disposal of the designer for providing against independent deflection of adjoining slabs at those joints where lateral movement must take place. Strengthening of slab ends accomplishes only part of the problem. By adequate strengthening the integrity of slab edges may be safeguarded, but the independent movement of slab edges vertically can be prevented only by some means of mechanical dowelling across the open joint. It would thus appear that the present criticism of slip-dowels should not lead to a hasty abandonment of their use but rather prompt an improvement in dowel details by the use of adequate diameters, hard grades of steel, closer spacings, and, above all, exacting standards of construction in the field.

CONCLUSION

In summarizing the general purpose and utility of distributed reinforcement, it must be realized that reinforcement of this type, as adapted to the design of concrete pavements, is no longer an experiment. From an engineering standpoint, its structural function and limitations are now clearly understood and it can be proportioned in amount and distribution on a thoroughly logical and consistent basis of design. From the standpoint of practical experience, its structural effectiveness and economic value have been fully substantiated. In serving the primary function of holding incipient crack fissures closely together regardless of their cause, properly proportioned reinforcement of the distributed type not only protects the integrity of the entire slab unit but also renders unnecessary the localized strengthening of slab edges and corners, otherwise less efficiently accomplished through the use of marginal and corner bars. Distributed reinforcement used in conjunction with joints, properly designed and spaced, thus affords the most logical means of assuring effective crack control; and, after all, it is really crack control rather than actual crack prevention that constitutes the basic problem of concrete pavement design.

In those states where large mileages of reinforced pavement have been built over a long period of years, experience, as revealed by actual pavement condition, has indicated that definite structural and economic benefits are derived through the use of reinforcement. In this connection it is significant to note that no state that has used reinforcement extensively over an appreciable number of years has ever abandoned its use. On the other hand, numerous states that have used it in a limited way in certain projects and over certain adverse subgrade conditions have, as a result of their experience, adopted it as a standard feature of design in all concrete pavements. At least two states, after some years of partial use, have within the last year adopted the reinforced pavement exclusively.

As to the extent of use of reinforcement among the various states it is observed that at the present time 28 states specify distributed reinforcement of the wire mesh or bar mat type, some using it in their entire programs, others using it only in certain projects or at designated locations. Of these 28 states, 14 use distributed reinforcement in all concrete pavements and at least 6 others in from 25 per cent to 50 per cent of their yearly concrete mileage. It is conservatively estimated that approximately 30 per cent of the total concrete pavement mileage being built at the present time is reinforced, and definite indications are that this percentage is increasing every year.

Reinforcement is often considered as a feature of design to be utilized only in connection with severe frost conditions or unfavorable subgrade. While it is no doubt of decided advantage in protecting pavements against the effects of these unfavorable conditions, still the presence of such conditions does not by any means constitute the sole advisability of its use. Reinforcement is a precautionary measure of protection to the integrity of a pavement slab. Regardless of upheavals due to frost or unequal settlements due to subgrade, it serves a necessary and useful purpose in maintaining the integrity of slab units even where frost and subgrade conditions are favorable and should accordingly be viewed as an essential feature of design rather than an added precaution to be taken only when abnormal conditions are encountered.

Under the most favorable subgrade conditions concrete pavements are subjected to lateral contraction both during the setting period and subsequent changes in temperature. There is ample evidence of the fact that incipient cracks or fissures develop during the earlier ages of the pavement which, although microscopic at first, are at least subject to subsequent development to the point of becoming elements of major structural weakness. A well proportioned reinforcement distributed throughout the entire surface area of the pavement is undoubtedly the most practical and economical means of safeguarding pavement integrity and prolonging its useful life.