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16. ABSTRACT

Asphalt in quantity is used for two purposes in connection with hydraulic construction. One is the protection of banks which might erode or slump; the other is the prevention of loss in permeable formations. Both purposes are sometimes combined. The characteristics needed for the two purposes are somewhat different.

Since in the past, asphalt has primarily been used in road construction, there is a tendency to suppose that principles of mix design which have been found suitable in that field can be applied with little change to hydraulic problems. This view is erroneous. While an asphaltic canal lining and a high type road mix are both asphaltic concretes, the best mix for the one is hardly in any case the best for the other, and in some cases may be the worst.

The characteristics which are to be taken into account in a given case are:

Impermeability.
Mechanical Stability.
Flexibility.
Durability.

Of these, only the last is an ever-present consideration. For stream treatments, and for canals in impermeable formations, impermeability does not enter. For the bottoms of canals and horizontal blankets in stream beds, mechanical stability is not a serious problem. For banks or formations where undercutting is not to be expected, and where no great subsidence or distortion of banks by shrinkage, swelling, etc.,

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HYDRAULIC APPLICATIONS OF ASPHALT

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INTRODUCTION

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Since in the past, asphalt has primarily been used in road construction, there is a tendency to suppose that principles of mix design which have been found suitable in that field can be applied with little change to hydraulic problems. This view is erroneous. While an asphaltic canal lining and a high type road mix are both asphaltic concretes, the best mix for the one is hardly in any case the best for the other, and in some cases may be the worst.

The characteristics which are to be taken into account in a given case are:

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Of these, only the last is an ever-present consideration. For stream revetments, and for canals in impermeable formations, impermeability does not enter. For the bottoms of canals and horizontal blankets in stream beds, mechanical stability is not a serious problem. For banks or formations where undercutting is not to be expected, and where no great subsidence or distortion of banks by shrinking, swelling, etc. is expected, flexibility is a minor consideration. However, it is hard to imagine a condition where durability is not important.

It is not planned here to try to set forth the special problems of an engineering and physico-chemical nature which can be encountered in designing an asphaltic treatment, for a fixed condition, within a narrow range of available aggregates and asphalts. However, the fundamental and generally applicable principles, without which successful design is seldom possible, are quite simple. These principles will be briefly discussed, with special reference to the four abovementioned characteristics.

PRESENT STATE OF THE ART

Some of these applications of asphalt are actually considerably beyond the experimental stage. Asphalt has been widely used in Europe for some years for this purpose. In Hamburg is a ship model towing basin, lined with 1 inch of asphaltic concrete, which in three years observation, including evaporation records, showed no leakage of water whatever. The Kiel Canal has extensive asphaltic revetments, and swimming pools, etc, lined with asphaltic concrete are quite common. In Holland and Germany there are extensive asphaltic revetments on the seawalls of the North Sea and the Zuyder Zee, and many ship and barge canals are lined for miles with these materials. In Africa large dams have been successfully faced with bituminous mixes, and canals in Portugal have been lined with them. In Southern California there is much use of asphaltic concrete mats for flood channel linings, including extensive applications by the U.S. Engineers on the Los Angeles River, and in the same region there are a number of reservoirs lined with asphaltic mixes of various types, usually with local soils and gravels (1). The U.S. Bureau of Reclamation and the Asphalt Institute have cooperated in large scale trial sections of canal lining (2). The use of asphalt on the Mississippi River by the U.S. Army has been very extensive, employing huge plants in some cases (3). Asphalt is thus not an untried material. However, it is true that failures have occurred, and that some of these successful installations have been so by good fortune, rather than by knowledge of the materials on the part of those who have used them. Asphaltic engineering grew up by cut-and-try methods over a number of years, and it is only during the last few years, even in its older branch, that of asphalt road engineering, that it has been put on a scientific basis comparable to that of Portland cement, for instance.

Hence wide fields of its use are still to be considered semi-experimental; there are many possible improvements in both economy and quality, and trials to be made of methods not yet used. Many successful projects can be considered experimental in the sense that those responsible for them do not have a full understanding of the reasons for their own success.

THE NATURE OF ASPHALT

Petroleum asphalt cement is the residual product of the distillation of petroleum, next to coke. All asphalts tend to lose durability as they approach the stage of coke, whether this be due to distilling too far, or to overheating in mixing. Some however may be reduced much farther than others without serious damage.

In its chemical nature, asphalt is a very complex mixture of hydrocarbon molecules of variable but undetermined sizes and formations; it usually contains other materials such as sulphur, fine mineral particles, waxes, various acids, etc. By processes of solution and distillation, it can be divided into materials of various natures (oily fractions, resins, heavy molecules called asphaltenes, etc.) of whose chemical constitution but little is known. It is known however that the heavier molecules are very complex, containing thousands of atoms.

A common but over-simplified picture of asphalt is that of heavy solid molecules suspended in liquid of an oily nature. Some asphalts appear to conform quite closely to this; in other cases the better conception is that of a series of particles packed together and graded rather closely as to sizes, partly adhered to one another, and partly separated by viscous oil. Such particles are usually quite elastic in nature, as is the structure formed by their combinations. In deformation the common asphalts act as though they were molasses with which a number of short rubber bands or coiled springs had been mixed. Their deformation properties are definitely a combination of liquidity and elasticity. In general, the elasticity increases at the expense of liquidity, as the number and sizes of the heavy molecules increase. This increase takes place with increasing distillation, and is also due to oxidizing either in manufacture, in mixing with a mineral aggregate, or in exposure to weather effects. Owing to the elastic properties of the structure, most asphalts have a yield point; but the static load which they will carry is so slight in comparison with the yield points of other engineering materials, that it can be considered negligible. Mechanically, the most workable conception is that of a stiff, sticky liquid, or rather soft glue.

Asphalts from different crude oils vary widely, and even sometimes vary when made from crudes from different parts of the same field. Further variations take place between different refineries. There are variations, from the point of view of the chemist and physicist, which are reflected little if at all in the action of the asphalt in combination with other materials; and there are variations in combination, for which the chemist has not yet discovered satisfactory reasons. Considerable progress has been made in learning the effect of the different fractions upon the nature of the asphalt, and to some degree properties can be controlled by synthetic recombinations of the fractions.

It is impracticable to go into such questions in a discussion intended for the engineer in general construction practice, for the whole question is as complex as is the technology of Portland cement.

For trade purposes, asphalt is divided into grades, or ranges of consistency. A 50/60 asphalt, for instance, is one into which a standardized needle will penetrate from 5 to 6 millimeters in 5 seconds, under a load of 100 grams, at 77°F. The hardest asphalt cement normally used for roads has been 20/30, the softest, 150/200.

The "liquid asphalts" as distinguished from asphalt cements, are oils or cutback asphalts of still softer consistency.

ASPHALT IN COMBINATION

When asphalt is combined with a mineral aggregate, a number of effects arise which could not possibly be found by study of the asphalt alone. The strength of a mixture varies systematically with the consistency of an asphalt from a given source; but it also varies with the source of the asphalt, its treatment in manufacture, the method of mixing and placing the combination, and, most of all, with the properties of the aggregate itself.

So far as asphalt is liquid, the mix strength is vitally affected by the speed of testing. However, the changes do not conform to the conception of a pure liquid; in that case the material could not carry a static load, because a liquid at negligible rate of deformation offers negligible resistance. In an asphalt-aggregate combination, there is a residual strength which is unaffected by speed, but for some reason is considerably correlated with the stiffness of the asphalt. In a really liquid material this would be quite contradictory. The residual binding power appears to be due to certain molecules of high cohesive power, possibly with certain orientations toward the aggregate; to surface tension effects, etc. The binding power of a thick film between two particles is low; that of a thin one, high. Thus the proper aim, in respect to mechanical strength, is to use as thin a film between surfaces as is possible while getting complete coverage of the surfaces. However, this tends to destroy durability when carried too far, and thus a compromise is often necessary. Other interrelated factors can best be dealt with under the four characteristics previously mentioned - impermeability, mechanical stability, flexibility, durability. These will be treated separately under asphaltic concretes and sealing membranes.

ASPHALTIC CONCRETE

Impermeability.

It is erroneous to conceive of an asphaltic concrete as an aggregate structure whose voids are filled with asphalt. If this were the case, impermeability would be no problem, since for all practical purposes any unbroken film of asphalt is itself impermeable. Unless there is an excess of asphalt, tending to render the concrete unstable, this condition is not approached. In mixing, the asphalt is rolled up as a covering film on the individual larger particles, the film incorporating in itself the very fine materials, which act as a stiffener and stabilizer for it. As it comes from the mixer, the normal concrete mix is thus like stones rolled in dough. When compacted, the particles are forced against each other, partly penetrating their individual films, but leaving a cementing residue of film between them, excess asphalt being forced into the voids between the particles. These voids are practically never entirely filled even in rich mixes, and thus, unless specially designed for impermeability, channels remain, through which water can penetrate. Basically, the principle of securing impermeability in this case is the same as in soil science; close grading and the elimination of large pores.

Most road mix gradings are not satisfactory. Several grading curves have been worked out which give generally satisfactory results; particularly those of Kind and Behringer (4)*, of Chas. H. Lee as developed for rolled fill dams (5), and the upper fineness limit of Hveem's curves (6), the above in order of effectiveness. The Hveem curves were not designed for maximum impermeability, nor the Lee curves for asphalt mixes. The Fuller curve is unsatisfactory.

Also, the percentage of asphalt which should be used to secure maximum impermeability is practically always greater than that for maximum strength, resulting in less than maximum strength.

It is recommended to seal coat the lining with an asphaltic spray, which, when properly applied, renders it highly impermeable regardless of whether the asphaltic concrete itself is impermeable. However, since ordinary cheaply applied seal coats are subject to easy mechanical injury, and often deteriorate with time, requiring occasional freshening, it is good practice and an additional factor of safety to have the concrete as impermeable as practicable with available materials.

In testing for impermeability, absorption should not be confused with permeability. The correct test for permeability is the application of water pressure to one side of a sample, the other side of which is open to the air. Permeability is then measured by the flow through the sample.

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* As this publication is not generally available, the grading is given herewith:

Grading	Material and percentage
0. to 0.09 mm.	Limestone filler 20 to 25.
0.09 to 0.2 mm.	River sand, 65 to 50, proportionally graded.
0.2 to 1 mm.	
1 to 3 mm.	
3 to 7 mm.	Crushed limestone, 15 to 20.
7 to 10 mm.	" " 0 to 5.

This mix has less fines and more middle sizes than the other two. Kind and Behringer secured as low as 2% voids with it; we have secured 5% with a grading within the same limits.

Mechanical Stability.

An asphaltic concrete lining is held in place on a slope by the column action transmitted through it from the bottom of the canal or reservoir, and by the bond between it and the subgrade soil. The former action in a well designed mix appears to be considerable, since such a lining will not only carry its own weight but will also hold in place the surface of a bank soil which would ravel down into the canal if unsupported. In tests to determine whether a mix is stable enough for a given situation, consideration has to be given to the maximum temperature expected at such times as the lining is not submerged, and the test should be at that temperature. In very hot regions this will be around 180°F. At such temperature the interlock of the aggregate becomes very important, if normal types of paving asphalt are used, since their binding power is very low at this point. Marked reduction of temperature is secured by whitewashing or similar treatment. If steel reinforcing is used, in hot climates, damage can result from differential expansion of the steel, which may tend to break the lining into blocks. Except in flood control work at points where undercutting is expected, there appears to be little need for reinforcing.

The types of grading given for maximum impermeability are also suitable for maximum stability, but need close control of the asphalt and filler content. In general, any aggregate source and grading which has been found suitable for road work will be sufficiently stable for bank linings, provided it can meet the other requirements. Under traffic, a road mix is sometimes consolidated until the material is over-oiled and instability results. This does not happen in hydraulic work, where a much more critical (close-graded) type of aggregate can be used. An asphaltic concrete lining is usually placed at temperatures higher than will be experienced in practice; and as the asphalt also hardens somewhat as time goes on, it can be taken as a general principle that a mix which can be placed on a bank without slumping at the time, will stay on it unless movemont takes place in the soil. This is not necessarily the case with cold-placed types.

Flexibility.

Where flexibility is a factor, asphaltic materials have an overwhelming advantage. They not only can take deflections without injury which would shatter concrete, but if actually cracked, will tend to heal themselves because of the fluidic constituents of the asphalt. However, such a factor becomes important only where undercutting or severe distortion of the bank is expected. In any application where experience shows cement concrete satisfactory, flexibility need not be considered. If it is desired to adjust for flexibility, this can easily be done by beam tests at the minimum temperature expected in service, and by comparing the permissible deflection with those expected in practice.

An interesting study of a series of tests in connection with experimental sections was given by the Asphalt Institute. (2).

Durability.

Asphaltic linings have three enemies whose effects appear only with the passage of time: weathering, weed growth, and the stripping of asphalt from the aggregate in the presence of water. Freezing and thawing trouble is also possible, but not seriously so.

Weathering: Practically all asphalts harden with time. There is considerable difference in the degree to which they harden, and also much difference in the effect of a given amount of hardening. This is also largely determined by the nature of the mix. The thicker the films, the greater is the asphalt content, the fewer are the voids, and the less the hardening. At high asphalt contents, it is rather a question of whether a properly selected, properly treated asphalt will ever deteriorate enough to damage the work. There are roads some forty years old, in which the asphalt has become very hard, but which show no signs of deterioration. While some asphaltic roads laid with improper materials or methods have had short lives, there are few records of durability of cement concrete roads, so far, to equal those of the best asphaltic roads.

It should not be forgotten, however, that it is possible to build either a road or a canal lining of asphalt in such manner that it will fail very quickly. No chances should be taken with installations made without informed engineering service, or with materials not definitely known to be suitable, any more than corresponding chances would nowadays be taken with cement concrete work. The predetermination of the durability of an unknown asphalt is a most complex physico-chemical problem, for which methods are only now being scientifically established. Some present tests are completely misleading. Meantime, there are types of asphalt readily available which have been proven by satisfactory service records, and only these should be used until further knowledge is acquired.

In general it has been found in road work that an asphalt which has fallen to 20 or 30 penetration has a high probability of failing. However, some will fail at 40, and others will harden to 10 or 15 without bad results. This also depends somewhat on climate. Obviously, the softer the original asphalt, the less danger, so that as soft an asphalt should be used as will produce the necessary mechanical stability. This also has advantages in the economy of handling. In the U.S.B.R. sections previously mentioned (2), asphalt of 150/200 penetration was used; an unprecedented softness for such work.

It should be recognized that it is not altogether the mere fact that the asphalt has become hard that produces failure, but rather that certain constituents are lost which causes it to lose binding power. This loss is roughly parallel with hardening, and there seems to be a critical point - different with different asphalts - at which the effect becomes noticeable.

Failure of a lining by weathering takes the form of progressive cracking. A failing pavement cracks or ravels, or both.

Weed Growth: Where weed prevention has not been properly taken into consideration, asphaltic linings, and untraveled asphaltic roads, have sometimes been penetrated, and even broken up. How far this may happen with the newest type of close-graded asphaltic concrete is not yet known. Bulb weeds and willow roots are probably the worst enemies, but both have been successfully controlled. Methods of prevention form a large subject in themselves; but a few may be mentioned which have been successful in known cases: creosote spray, salt layers, sodium chlorate, acid extracts, and thin layers of cement mortar. Sodium chlorate inserted in punched holes about 18" apart seems to have been especially effective. This subject needs more research and observation.

Water Stripping: Wherever oil and water are together in the presence of a stone surface, there is a fight for possession of the surface. All stone is easily wetted by water, and, when surface dry, by oil if the oil is not too stiff to flow over the surface. In general it is difficult to get an oil to force water from a stone surface and occupy the surface itself, but it is often easy to get water to force the oil from the surface unless the oil has first been thoroughly applied to a dry stone. There is a very great difference between the affinities of different aggregates for water, and those which have the least attraction for water have the most for oil. Available aggregates should be tested for affinity for water, and available oils and asphalts for power to adhere to stone in the presence of water. Special chemical methods can be used to improve the situation where the available materials are adverse. Some of these are treatments of the aggregate, and some are treatments of the asphalt. Some of them are so effective that they will cause the oil to displace water from the stone, some work even better with the stone actually wet rather than dry; but the best safeguard is still to mix a hot, dry aggregate with hot asphalt after getting the best aggregate available, from the point of view of stripping.

Failure through this cause is due to the material absorbing water, which causes swelling, stripping, softening, and disintegration to a greater or less degree. If a good seal coat is used, the danger of stripping is much minimized.

Freezing and Thawing: Asphaltic concrete is quite resistant to this effect, owing to its non-rigid nature. When made to an impermeable design, this is especially the case. A problem somewhat allied to this is abrasion by ice or boulders (in flood channels), and pulling by ice. In actual practice, asphaltic concrete has shown excellent quality in this respect. Cement concrete flood channels which were eroded by boulder and gravel flow have been relined with asphaltic materials and have given excellent service. Adhered ice comes loose very quickly because the asphaltic material absorbs heat rapidly with any temperature rise. None of these factors appears more of a problem than with cement concrete, and in some cases less.

SEALING MEMBRANES

Where a high-cost, mechanically resistant material is not necessary, advantage can be taken of the fact that even a very thin film of asphalt is impermeable for these purposes. It is a fact that a 1/16" layer of asphalt (0.25 gallon per square yard) sprayed on a firm surface and maintained in such manner that it remains mechanically intact, will carry, by actual experiment, pressure of over 100 feet head of water without flow. Such a layer can be applied for a fraction of a cent per square foot. The problem lies in producing and maintaining such a layer on a slope. For dependability, it is necessary to increase the quantity applied considerably, at least to 0.5 gal. per square yard, or about 1/8" thick, and this is probably too little. When this is done, however, it will sometimes be hard to spray it in one application without having it flow and develop irregular thickness. A membrane of asphalt exposed to the air and without the reinforcement of an internal mineral skeleton, will tend to crack. The indicated solution is to build up a dependable membrane by successive applications of thin sprayed layers and sand. This involves skill and experience on the part of the operator, but no special difficulty.

There exist some cases of successful seal membranes on this general principle, some of them of surprisingly unscientific nature, but a wide and useful field of experiment exists here. We can set forth at the present time only the results of preliminary laboratory studies, which need to be carried into larger-scale experiments on actual canals and reservoirs.

Mechanical Stability: In such an application, only a very thin layer of pure asphalt will remain on the slope without flow; the practicable thickness depends upon type and consistency of asphalt, prevailing high temperatures, etc. Such a layer is not only susceptible to weathering effects, but is easily damaged mechanically, and often tends to peel. Such a membrane should give excellent service if protected by an earth overlay. (If such an overlay is to be alternately wet and dry, it should have a low shrinkage ratio. A material which flakes and curls tends to be especially disastrous to thin asphaltic membranes.) However, as pure asphalt is a lubricant under certain conditions, the overlay in this case must support itself on the slope by column action transmitted from the foot of the slope. Whether a specific material will lie over an asphaltic membrane of this kind, in a given canal section, without slumping, can only be determined for the case in question. However, membranes of even more lubricative properties have been used under overlays in some cases without producing slumping.

In other cases, the overlay can be keyed to the soil underneath, through the membrane, by rolling coarse, open-graded sand into the membrane at the time of placing. This also enables the construction of a thicker membrane.

Several problems of application are involved here. If a cold sand is rolled into the sprayed layer, even while the latter is quite warm, little adhesion between the sand and the asphalt will take place, the sand being only mechanically included. Thus if some of the sand particles are forced entirely through the asphalt, water may easily follow along the unadhered contact between sand and asphalt, causing leakage and also some tendency to disintegration of the membrane. If it is economically practical to use hot sand, this difficulty is largely overcome. It can also be overcome by passing a flame brush over the surface after rolling the sand in, care being taken not to burn the asphalt. (Burning is indicated by smoke from the surface.) A compromise method is to roll the sand into a thin asphalt layer (about 1/4 gal. per sq. yard), then spray an additional layer on top, of just enough material to secure thorough sealing, without making it thick enough to create a lubricating layer. The second spray adheres to the sand, and moreover its heat partly remelts the first spray and causes it to adhere also to a large extent. A membrane of this construction will be 1/4" thick or better, and if made of asphalt of the proper consistency, will be quite tough and resistant to mechanical damage. In many cases it will need no overlay.

Consistency of Asphalt: The harder the asphalt, the tougher the membrane will be. However, the harder it is, the more danger there is of reducing durability, as has been noted; and the more difficult it will be to spray. On the other hand, a very soft material lacks toughness, is easily ruptured by water pressure, or driven into pores of the soil, etc. The heaviest road oil, SC-6, has been found unreliable, while asphalt cement of 85/100 penetration has been found quite satisfactory. Since in many asphalts a change of penetration from 85/100 to 50/60 has been found to embrace some critical point at which durability is noticeably decreased, the use of a material harder than 85/100 for this purpose is not generally to be recommended. The range is thus from 85/100 to 150/200, the latter being the softest asphalt cement usually obtainable. For most conditions, 150/200 for sprayed membranes is probably verging toward the unduly soft side.

Bank Slumping: Sometimes a sandy canal bank which is satisfactorily stable at the time of construction will dry out during a period in which it is not used, lose cohesion, and slump behind a membrane, destroying it. In other cases, stability is lost by saturation through rain water, capillary water, etc. This will happen with materials more of the clay type. Where either of these forms of instability may be expected, an unsupported membrane should not be used. A high-type lining, or a membrane with a heavy overlay, is indicated. This type of slump should not be confused with the slow surface migration characteristic of many soils on a slope, and which is effectively deterred by even a thin facing.

Penetration Membranes: Where the bank soil is quite open, it is possible to penetrate it with successive sprays of very light rapid-curing liquid asphalt. This is made by dissolving in gasoline or a similar solvent.

slab may be dragged into a truck when cool, or rolled on a drum. (Drums as small as 18" diameter have been used.) The drum method is quite convenient in placing, as the top edge of the slab is held at the top of the bank while the drum is rolled down the bank with the aid of hold-back ropes. According to soil stability, slope of bank, etc., the top of the slab may be anchored by leaving the mesh projecting, and attaching to metal stakes. If the soil is deleterious to metal, a good anchorage can be secured by bringing the upper edge of the membrane beyond the break of the bank into a shallow trench, and backfilling over it. In many cases an anchorage is not needed. Openings between slabs can be filled with mastic poured by hand. Little field use of this method has yet been made, but a very similar principle has been followed by the U.S. Army Engineer Corps on the Mississippi River, where enormous installations of flexible mats have been made by casting on the decks of barges. After each slab has been cast, the barge is hauled sidewise from the bank, leaving the edge anchored to the top of bank, while the slab slides off the deck into the river and adjusts itself to the contours of the bottom. (3)

The principles of impermeability in such membranes are the same as discussed under asphaltic concrete, where that type of mix is used; but such a mix requires compaction in the form. If mastic (fine-grained mix with an excess of asphalt) is used, no compaction will be necessary, and flexibility will be very high, but mechanical stability will be considerably lower than in the case of asphaltic concrete. A mastic is of such consistency that when hot it can be poured like a heavy liquid.

By the use of special mineral fillers, or special asphalts, it is possible to construct membranes of extremely high quality as to flexibility, toughness, durability, impermeability, etc., for use where extra cost is justified. Some of these compositions are similar to those used in asphaltic

The solvent evaporates rapidly after spraying, leaving the base, which ultimately becomes of about the same consistency as the original asphalt. However, such a membrane cannot be made impermeable by a single spraying, and at least several days would be required for the solvent to evaporate after each application. Too heavy an application delays the evaporation.

Membranes on Canal Bottoms: Since no problem of mechanical stability exists in the matter of impermeabilizing the bottoms of canals, a simple spray of asphalt of 1 gal. per sq. yard, in two applications, protected from weathering and mechanical damage by an inch or two of soil, should be sufficient. There appears to be no necessity of carrying an asphaltic concrete lining across the bottom, and thus substantial saving should be effected, over the full-section construction which is sometimes used. Even where cement concrete is preferred for the bank linings by engineers in charge, there seems to be no reason why the bottom should not be treated merely with an asphaltic membrane. For stability of the slopes, the bank lining should be carried somewhat below the bottom of the canal, and the membrane should be applied afterward.

Pre-Cast Membranes: The maximum use of the flexibility of asphaltic mixes occurs in membranes which are made up at a central plant in sections of definite size, and transported to the site of placing. For the construction of such membranes, a floor of the proper size is constructed, having side forms whose height is one-half the thickness of the membrane. The mix is placed on the floor and screeded to the form height. (If a rolled mix is used, allowance is made for reduction in thickness, and the forms are removed before rolling.)

After laying the first half of the membrane, wire mesh is placed over it, followed by a second lift of side forms, and the operation repeated. This places the reinforcement exactly in the center of the membrane. The floor tiles, floor coverings for docks and factories.

The thickness of pre-cast membranes usually considered is about 2 inches. Laboratory studies indicate that with proper equipment and workmanship, and controlled proportioning, fully satisfactory membranes of 1 inch thickness can be constructed. However, the thinner the membrane, the more dependent it will be on soil friction, top anchorage, etc. for its stability on a slope.

Organic Reinforcement: Some experiments have been made with coarse, loosely woven cotton cloth, burlap, or paper, as reinforcement for thin membranes. A few road sections have been laid in this manner, and also some canal sections. While the initial results appear to be quite satisfactory, there is always danger of bacterial attack with any organic material, and the durability of such materials is not established. Fundamentally, if they are used, care should be taken to secure their complete enclosure in the asphalt. Also, care must be taken as to temperature, because in field work asphalt is often raised to temperatures destructive to organic materials.

The demands upon reinforcement in canal applications are not mechanically severe, but a low coefficient of expansion is desirable. There are probably some untried possibilities in this line.

CONCLUSION

We have endeavored to show, first, that successful use of asphaltic materials in hydraulic applications is already established; second, that the basic principles of design and use of such materials are well determined; third, that in applications which are still experimental or semi-experimental, enough foundation has been laid so that further extensions need not be made entirely in the dark.

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