parent, therefore, that only partial composite action existed, and the conclusion drawn was that the bond between the steel beams and the concrete slab had broken Friction, and perhaps the bearing of the slab against the tops of the floor beams, must have been responsible for whatever composite action existed. When stresses were computed on the bases of full, partial and no composite action, it was found that 30 9 percent composite action existed during the run which produced the maximum recorded stress of 6,170 psi

Since the tops of the floor beams extended into the concrete slab, gages were placed only on the bottoms of the lower flanges The recorded tensile stresses ranged from 56 1 percent of the computed stress for Truck A, to 89 9 percent for Truck 7A. Inasmuch as the recorded tensile stresses are less than the computed values, it is likely that some composite action existed, as in the case of the stringers.

Figure 14 also deals with stresses in the stringers, but the values of maximum, minimum and average tensile stress are averages of all the runs made by the particular vehicle indicated For Truck A, the maximum stress was 167 9 percent of the average, while the minimum was only 45.5 per cent of the average Similarly, for Truck 7A, the maximum was 207.6 percent of the average and the minimum only 14 7 percent. These comparisons indicate that the distribution of the wheel loads to the stringers was extremely limited, the stringer nearest a wheel carrying the greater part of its load The reason for this may be ascribed to the fact that the stringers are fairly rigid, the ratio of their span length to depth being only 13.83.

PREFABRICATED BITUMINOUS MEMBRANES AND METAL NETWORKS AS LOAD SPREADING DEVICES

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SYNOPSIS

Sometime in 1942 when the Allied plan for an assault in Europe was taking shape, the military engineer was confronted with the problem of devising ways and means to build all-weather fighter and light bomber runways in the anticipated combat zones Effective use of the air arm was dependent on the presence of numerous fields right behind the advancing forces As the range of the armed fighter was limited, no reliance could be had on fields hundreds of miles back

The main difficulties confronting the engineer were First, that World War II was a war of movement and the old time front became a fluid zone, sometimes hundreds of miles in depth. Construction of emergency airfields had to conform to the fluctuation of the battle zone, as a combat field built today may well be two hundred miles in back within a week This meant that a runway had to be built in a matter of days instead of months Second, materials for standard base and paving work are seldom available near the construction site, and even if available, it would have still proved impossible to assemble the required equipment and transport to supply and consolidate thirty to forty thousand tons of aggregate within a few days Even then, a hastily built gravel or macadam runway would have been of limited use without a waterproof and dustproof surface

Standard designs and materials therefore, were out of the question, and the Command looked to the engineer to develop some entirely new method and material wherewith to provide the air arm with what might be termed an advancing front of fighter runways This was accomplished by the development of Prefabricated Bituminous Surfacing, better known as P B S

The importance of P B S as a material and process is not only that it provided the Allies with numerous airfields and many miles of roads under conditions where standard methods would have been entirely inoperative, but that it gave a practical demonstration of how a prefabricated surfacing, ranging in weight from 10 to 30 lb to the square yard, took the place of base and pavement structures hundreds of times more massive per unit area covered The disparity of weight

versus supporting value of the prefabricated surfacing and the standard base and pavement, brings to the fore the possibility that this wartime experience may provide a new approach to road and runway design. Considering that after years of technological effort, the only counter measure to the constantly increasing traffic loads is more massive and more costly construction, it is imperative that emergency runway and road construction during World War II be thoroughly analyzed with the view of evolving designs that might give a highway combining durability with low cost

The purpose of this paper is to direct attention to the fact that during World War II, the allied forces developed certain methods, materials and devices for emergency construction of roads and runways that were entirely different from the conventional or the standard. The principal differences were:

First, that the road or runway had no base structure other than the natural soil.

Second, that these emergency roads and runways had none of the accepted pavements or wearing courses ordinarily built upon site. Thin prefabricated membranes, metal networks, metal plates and combinations of all these served the dual purpose of base and wearing course.

Third, that prefabricated surfacing varying in weight from 10 to 30 lb. per sq. yd. was placed directly on natural soil and carried traffic loads that ordinarily would have called for thick base and pavement structures.

What follows is an account of these developments and an attempt to explain what has occurred and how the various prefabricated surfacings and combinations of these surfacings functioned, with the possibility that these wartime experiences may indicate an entirely new approach to the problem of load distribution. If thin low weight prefabricated surfacings over unstable soil supported heavy military traffic, which otherwise would have required heavy base and pavement structures, it is indeed important to find out exactly how it has done so. Admittedly the prefabricated surfacing was intênded for temporary use The fact, however, remains that most of the emergency roads and runways both in Europe and South East Asia outlasted the campaign periods.

By prefabricated surfacing is meant not only the prefabricated bituminous surfacing, known as P.B S but everything used during the war to assist traffic over unstable terrain, from the oldtime chicken wire, to the U. S Pierced Steel Plank and to the final and the most effective development, combinations of P.B.S. and metal grill reinforcing.

A brief digression into history will make the whole subject more intelligible if only to show why standard materials and established methods were not applicable to emergency construction in forward areas during World War II. Concentration on mass production of planes was brought about principally by the realization that the air arm was to be the decisive factor in the war. Those directly concerned with aerial operations, however, were soon confronted by the problem that while speed of production of planes increased manifold, the methods, materials and time required to construct an airfield remained the same. By the end of 1942 the disparity in rate at which planes were coming off the assembly lines and the time required to build airfields became a major problem. It was quite obvious that no amount, size or capacity of equipment could overcome the fundamental time consuming factors in standard runway construction, such as the need for masses of material most if not all of which are hardly ever obtainable on site. The main worry was how to insure an ample number of fighter and light bomber runways within the combat zones. World War II was very unorthodox, not at all like World War I, which had a front line that was stable for long periods. In World War II, the oldtime front became a fluid zone, sometimes hundreds of miles in depth, and a fighter runway located within such front might be three or four hundred miles in the rear within relatively a few days As the air arm was the Allies main reliance, development of methods of construction was required that would produce all-weather runways within a matter of days, not months The principal requirement for Western Europe was runways for fighters and light bombers that would be operative for at least three weeks in continuous wet weather. The problem in South East Asia was much greater, as the same road or runway was required to last through five to six months of monsoon downpours that convert every flat or low area into a lake or quagmire.

This problem was solved by the development of Prefabricated Bituminous Surfacing known as P.B.S. and the solvent plasticizing method of application. The details of wartime P.B.S. and its behavior both in Western Europe and South East Asia are dealt with more fully in a paper presented to the Association of Asphalt Paving Technologists in February, 1950. Only several salient facts that preceded and led to this development are mentioned here.

In 1941, some private individuals in England developed and demonstrated a mobile impregnating machine designed to surface soil runways with asphalt impregnated fabric. The method, however, was found to be too cumbersome, uncontrollable, too wasteful of material, and entirely unreliable for safe operation in forward areas. Why they did not adopt the simpler U. S. Cotton Roads' practice is hard to say; but even this method, where the fabric was bituminized by spraying, the surfacing of a soil runway would still have required assembly, in the front areas, of fabric, bitumen, spray trucks, melting kettles, cover material, and experienced operators, the absence of any of these items making it impossible to proceed with surfacing.

Impregnation on site was soon discarded in favor of the P.B.S. method suggested by the author while serving as Technical Advisor to the Canadian Overseas Forces and developed and demonstrated by the Royal Canadian Engineers. Prefabricated Bituminous Surfacing was a jute fabric, variously known as hessian or burlap, impregnated with 100 penetration asphalt and coated with 220 F. to 260 F. S. P. oxidized asphalt. As a material, therefore, P.B.S. was very similar to rolled surfaced roofing except that fabric was substituted for paper felt. Where P.B.S. did differ from standard roofing was in method of application. Ordinarily, rolled roofing is cemented to the

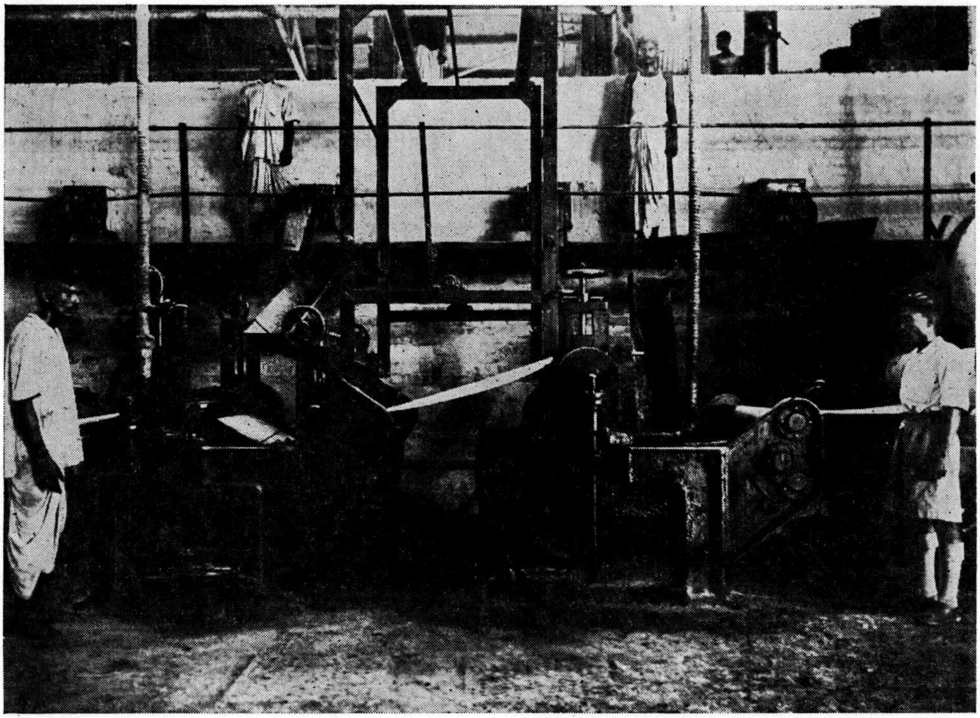


Figure 1. P.B.S. Plant India View of Saturating and Coating Units

roof deck by use of either a hot or cold applied adhesive, such as 170 F. to 180 F. S.P. oxidized asphalt, liquid asphalt, or emulsion. Strips of P.B.S. were cemented to each other during placement onto the soil by just wetting the sheet with a solvent, such as gasoline or, still better, mixtures of gasoline and light fuel oil. The solvent rapidly plasticized or softened the surface of the coating asphalt and converted it into an adhesive, much the same as the gum on a postage stamp is made adhesive by wetting with water. This development reduced construction of an emergency runway to grading, compacting, and surfacing the soil with P.B.S. Figures 1 to 5 illustrate the manufacture and placement of P.B.S.

It is no exaggeration to say that the P.B.S. process solved the problem of constructing all-weather soil runways in forward areas. The purpose, however, is not to discuss the merit or demerit of P.B.S. as a wearing and waterproofing course over dry stable soil, but rather how P.B.S. by itself and in combination with other devices enabled traffic to negotiate wet and highly unstable soil areas, starting with the metal networks and other devices for spanning unstable soil, as these were developed and used much before P.B.S. ever made its appearance.

Consider a load spreading device known as chess-paling, used to get tanks over unstable terrain. Chess-paling acted as a supplementary track, extending the tanks' surface contact area and reducing the unit load below the supporting value of the unstable soil. Provided the chess-paling mat did not pull out from under the caterpillar tracks the load was

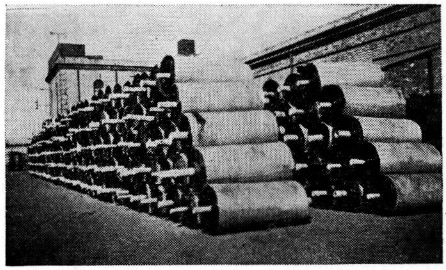


Figure 2. P.B.S. India Ready for Shipment

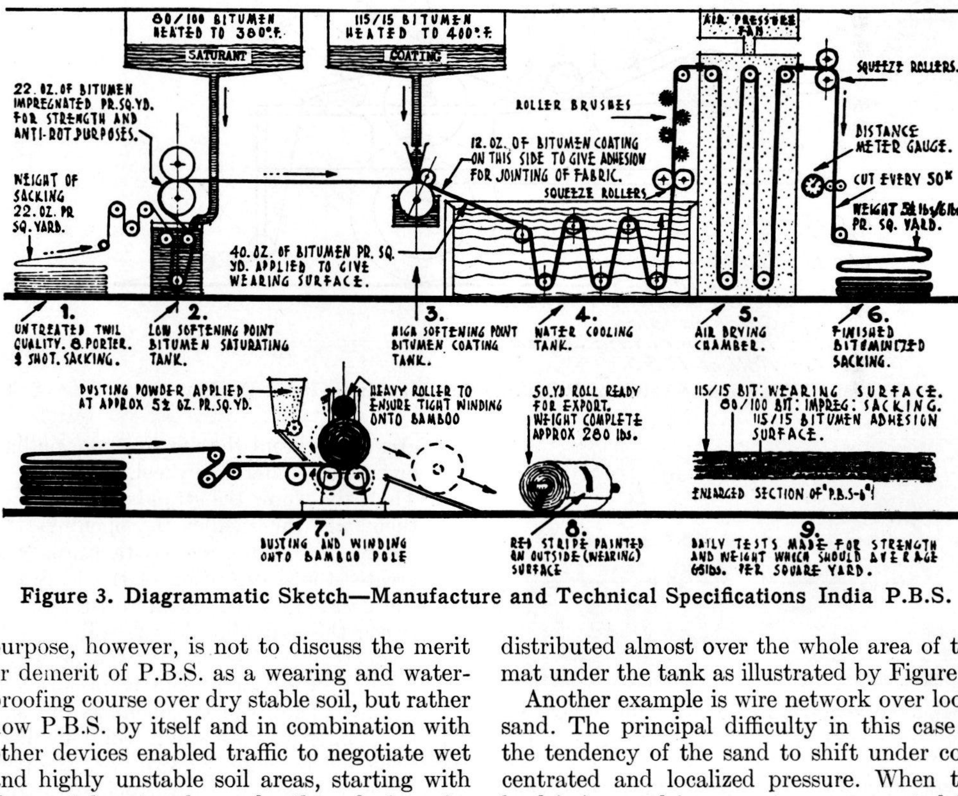


Figure 3. Diagrammatic Sketch—Manufacture and Technical Specifications India P.B.S.

distributed almost over the whole area of the mat under the tank as illustrated by Figure 6.

Another example is wire network over loose sand. The principal difficulty in this case is the tendency of the sand to shift under concentrated and localized pressure. When the load is imposed in separate nonconnected increments, such as a man walking, progress may be slow yet possible. A vehicle's progress, however, is retarded and finally blocked by the fact that the wheels impose a concentrated and continuous load on the shifting sand The wheels must constantly climb onto the increasing mound of sand in front of it. Lack of traction is only part of the story Another is overconcentration of load, due to the fact that each wheel acts independently of the others. The remedy is to spread the total load over so great an area that the unit load is not sufficient to cause any material shifting and building up of sand in front of the wheels. A wire or similar network brings this about by distributing the load more evenly over the entire area under the vehicle instead of just over the tire imprint areas The wheels act as continuous points of anchorage, constantly keeping the section of the network under the vehicle in taut condition so that any tendency

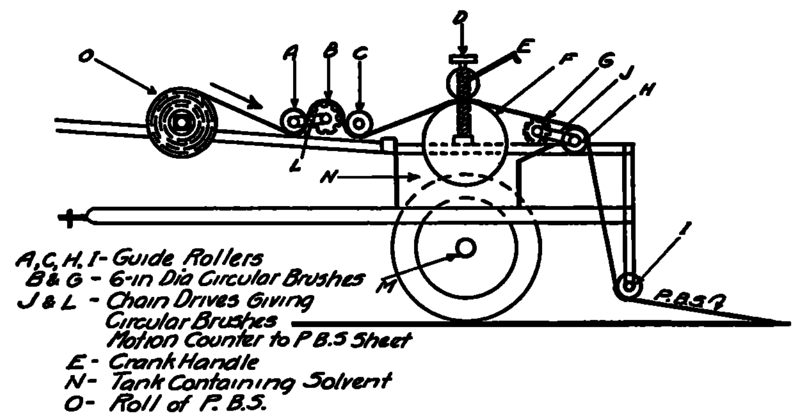


Figure 4. Sketch of P.B.S. Laying Machine—India Design

Figure 5. Laying P.B.S. by Machine—India

to subsidence of one wheel immediately imposes a stress which is resisted by the whole mat under the vehicle Subsidence of the total network is in turn resisted at all points where the network strands are in contact with the sand In other words, the whole network under the vehicle becomes something like the ordinary snowshoe The same mechanism applies to virtually all the metal load spreading devices from the flimsy chicken wire to the heavy pierced steel plank used over sand as well as over waterlogged clay soil. Figure 7 illustrates the principle of load distribution by metal-grill mat However, all these load spreading devices have the same limitations. The effectiveness, for instance, of a wire net depends on the following:

1. That it is of such pattern and construction that its strands will not unduly stretch, extend, pull or fail under the stresses to which it is subjected.
2. That the frictional resistance between the network and the soil is sufficiently great to prevent the netting from pulling or bulging under the wheel.
3. That, the closer the strands, the more of them and the smaller the openings the greater will be the real contact area, the greater the distribution of the load and the greater the frictional resistance between the network and the soil

One can readily observe that the principal deficiency of all the metal contrivances is lack of continuity They all have openings through which a plastic or loose sandy soil can flow When the soil is or becomes plastic, the network is only of temporary utility as it rapidly sinks out of sight under passing traffic

Under such conditions the most obvious remedy would have been to use metal sheets or better, planks tightly locked together with as few openings as possible or still better, no openings at all. But here the question of weight comes into the picture with the likelihood of the remedy being worse than the disease Actually, the attempts to improve the metal network proceeded along the line of increasing stiffness, an outstanding example in this direction being the American Pierced Steel Plank. The steel plank acted the same as a wooden plank over mud Piercing of plank was merely to reduce its weight while retaining appreciable resistance to bending.

On the other hand, piercing the plank reduced its effectiveness, as it reduced the surface contact area and above all, permitted loose sand and plastic soil to flow through the openings and build up on top of the plank.

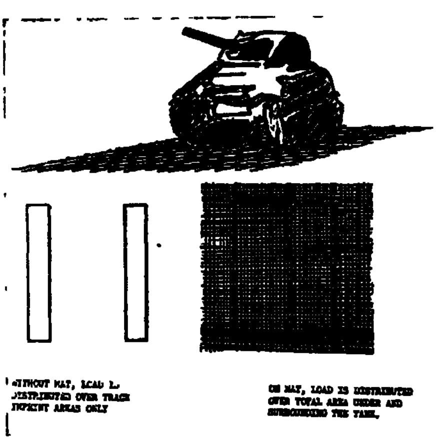
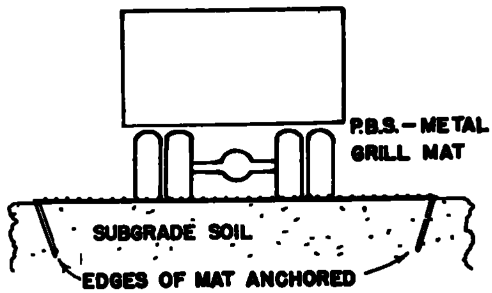


Figure 6. Tank on Chess-Paling Mat

The principal limitation, therefore, of all the metal contrivances as used was lack of continuity and tightness Surface water rapidly reduced the consistency of the soil to mud which in turn flowed freely through the metal grill or plank openings All these metal load spreading devices, therefore, remained of limited utility until P B S provided an effective and low weight seal By placing the P B S membrane directly on the waterlogged soil and the metal grill over it, the membrane made an automatic seal as the plastic soil pressed on the P B S and held it firmly against the metal rods or planks

Thus, prefabricated metal load spreading devices have gone through several stages. The first stage was the use of loose networks. Observing that the wire networks corrugated, extended and went out of shape too readily under traffic, the engineer proceeded to rectify this deficiency along structural lines by stiffening the networks with steel rods. The next step was to use something similar to concrete reinforcing This was more effective than wire netting reinforced with steel rods, but it meant increased weight per unit area covered. A grillwork of steel rods, however, did not pull, extend or wrinkle under the wheels to



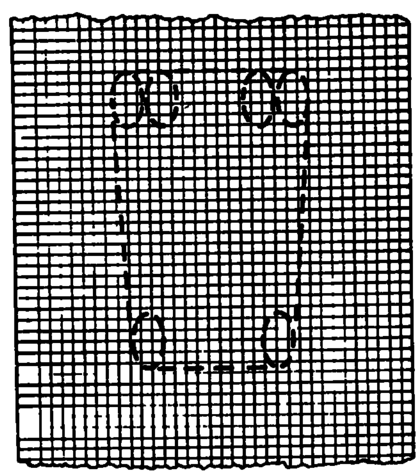


Figure 7. Vehicle on P.B.S.-Metal-Grill Mat

anywhere near the same extent as a reinforced wire network Further developments in metal load spreading devices proceed along the same line, tending towards stiffer members and closer spacings, terminating with the U S Pierced Steel Plank weighing about 50 lb per sq yd.

The discovery that a strong waterproof membrane like P.B S. placed under a metal network will automatically seal the openings and block the flow of soil, changed the situation entirely. A combination of a light metal reinforcing and P.B.S. weighing 16 to 20 lb. per sq. yd., proved a more effective load spreading device over unstable soil than the 50-lb. per sq. yd. Pierced Steel Plank (See Fig. 8).

In the European and South East Asian war theatres, combinations of P.B.S. membrane and metal reinforcing was used extensively to get military traffic over sections of broken roads and quagmires. Early in 1945, when

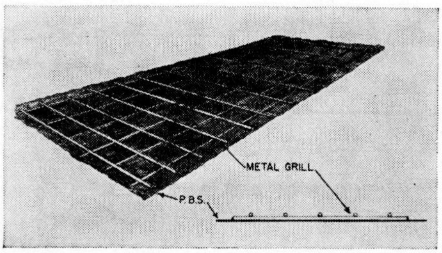


Figure 8. Reinforced Prefabricated Bituminous Surfacing (R.P.B.S.)

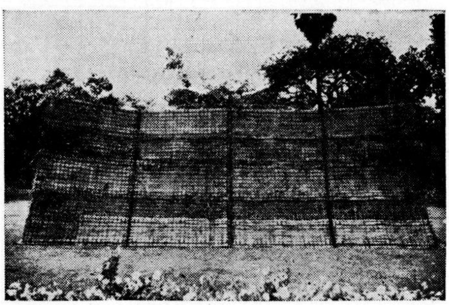


Figure 9. Top View of Reinforced P.B.S. Mat for Use over Tidal Mud Flats

plans were afoot for landing operations in Malay and Indonesia, the author demonstrated the feasibility of prefabricating P.B.S. metal grill panels that could be assembled into continuous mats on site and spread or projected over otherwise impassable tidal mud flats. Figures 9, 10, 11, and 12 are views of assembled sections of such mats and terrain over which these mats were tested. The consistency of the soil ranged from something like soft putty to fluid mud. After 96 passes by a 14-ton military lorry, the pressure of the fluid mud on the unloaded sides of the mat was great enough to bend the reinforcing parallel to the line of traffic. That, however, does not mean that the mat might not have stood many more passes.

At this point it is to be emphasized that the P.B.S. process was intended as a waterproof wearing course, over dry and compacted clay soil without any reinforcing. P.B.S. construction specifications called for proper compaction of soil before surfacing. As all offensives in the past have been planned to

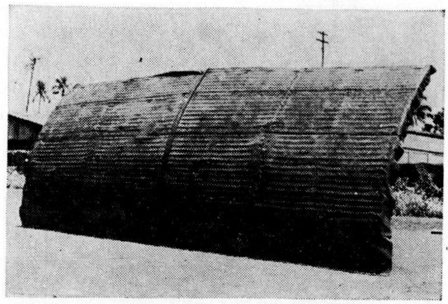


Figure 10. Prefabricated Reinforced P.B.S. Mat, View Showing P.B.S. Affixed to Reinforcing

Figure 11. Prefabricated P.B.S. Mat over Quagmire after 96 Passes by 14 Ton Military Lorry

commence in spring and terminate or be materially reduced before the start of the wet season, it was felt that there would be ample dry ground to grade, compact and surface with P.B.S.

But nothing ever works exactly according to plan, so, while P.B.S. construction specifications called for proper compaction of soil before surfacing, in practice a properly compacted soil runway was the exception rather than the rule. In South East Asia there was no such thing as properly compacted soil under the P.B.S. runways or taxiways except on several experimental projects. There was not the time, the trained personnel, and above all the equipment. The runways in Burma were built directly behind the advancing forces. The Burma campaign was in most instances a series of thrusts by air from hastily built airfields, by river and by sea. No sooner were the Japanese dislodged from some area, than the engineers sought out for construction of runways the most level section available, which was usually low lying rice, or as commonly known, paddy fields. They then knocked off the bumps and covered it with one or two layers of P.B.S. depending on time, availability of material, and other considerations. Under these conditions, the engi-

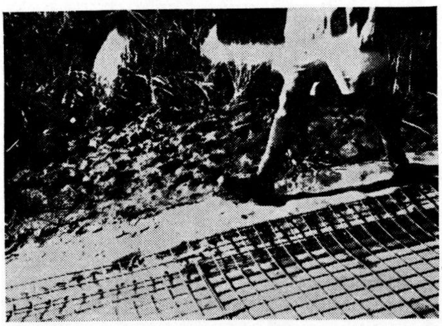


Figure 12. View above Water Level. The Pressure of the Fluid Mud Bent the Grill Longitudinally to Line of Traffic

neer tried to disturb the dry soil crust as little as possible. Those who by necessity, or accident, had cut appreciably into the dry soil, found themselves with a real problem on their hands—how to reconsolidate a layer of clay dust with inadequate equipment and a limited water supply. A river or lake might be only five miles from the job, but to get to it required cutting through the jungle or building a road over a swamp.

One can readily appreciate that the soil under most of the P.B.S. remained in its natural state of porosity, if not worse. As the emergency airfields on the Arakan, and particularly in Burma, were usually located in areas that were for the most part in flooded or waterlogged condition for months during the monsoon downpours, it is but reasonable to assume that the soil under the P.B.S. was often in saturated state. Actually the author found many a combat runway where the soil was of the consistency of putty. Yet, wherever the P.B.S. sheets were properly cemented together and the soil under the membrane was not fluid mud, there were no failures. This much is certain, that the soil under the P.B.S. on a number of runways and taxiways in heavy use by fighters, light bombers, and transports had a moisture content considerably above the optimum.

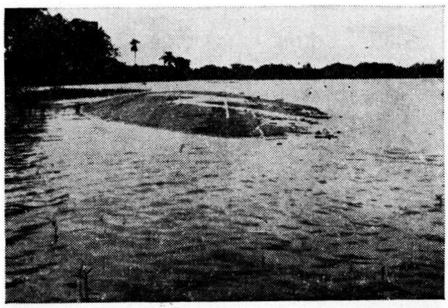


Figure 13. Flooded P.B.S. Taxiway. Note How Air, Forced Out of Subgrade by Rising Watertable Inflated the P.B.S.

Figure 14. Flooded P.B.S. Taxiway. Closeup of Inflated P.B.S. Mat

The only explanation that occurs to the author is that the load on the P.B.S. mat automatically distributed itself over so great an area that the pressure exerted on the soil was below its supporting value, even though the soil might have been in saturated or almost saturated state. Figures 13, 14, and 15 illustrate monsoon conditions on a P.B.S. taxiway near Calcutta. Figure 13 was taken after several weeks of tropical downpours. Figure 14 is a closeup of the inflated mat. As the double layer of P.B.S. was virtually vapor tight, the air pressure was great enough to support a man walking or standing Figure 15 is a view of the taxiways sometime after the flood receded. The soil under the mat was virtually in saturated state, yet the taxiway supported a variety of fighters and light bombers

On this particular taxiway, the engineers made a real effort at soil compaction, and yet the soil remained sufficiently porous for the air to be readily forced out of it by the rising water table.

When the planning of production of P B.S. in India was first started, the possibility of a membrane spreading the load over a greater area than the tire imprint was not thought of. At that time (1943) the author was very apprehensive lest the soil under the P B S. be-

Figure 15. Taxiway in Operation after Flood Subsided

come thoroughly saturated and fail even under fighters right in the middle of a campaign. The author, therefore, recommended adoption of the system of soil construction as proposed by Prevost Hubbard, of cutting off subgrade moisture by covering the grade with a film of asphalt or some such means, and consolidating over the waterproof seal, a layer of compacted soil with a suitable waterproof surfacing on top and sides. Soil was to be used as a base material and in P.B S. an excellent seal was available, as it was strong enough to stand up under the strain of compaction. General Headquarters India hailed it as the method of building heavy-duty airfields, but lack of equipment, time, and personnel made it impossible to engage in this form of construction except on several critical sections of road and taxiways At one vital airfield for instance, the heavy brick taxiway began to fail and about half of it was reconstructed by consolidating a layer of soil 18 in. thick over a P B S seal and completing with a P B S wearing surface. This section gave satisfactory service while the original brick section had to be constantly reinforced with additional layers of brick Figure 16 shows the details of this type of construction.

The significance of this is not that a soil in a dry and compacted state makes an excellent base material, but that it suggests new forms of construction and new techniques by which a membrane may serve as the principal means of spreading the load over a subgrade The original idea was that the layer of dry and sealed soil would distribute the load in the same manner as a layer of gravel, stone, or concrete The P B S was to function primarily as a seal and as a wearing course. At that time the possibility that all that might be required was a layer of soil thick enough to hold or anchor down the P B S membrane on the subgrade and keep it in taut condition was not considered. Actually, the tensile strength of a double layer of India P B S. was greater than the stress imposed on it by traffic no matter what form of distribution was assumed What the thickness of the soil layer should have been was not determined, but surely it would not have been 18 in —it might well have been only 3 in. Considering the problem from this angle, the utility of a layer of soil on top of P B S. would be mainly as an anchorage or rather as a means of holding the light flexible membrane in taut condition and to prevent it from pulling or wrinkling under a load Failure could then occur only if the load was greater than the bursting strength of the P B.S. membrane. Distribution of load by the layer of soil then becomes a minor consideration and thickness of the soil layer would be determined, not on the basis of load supporting value, but rather, on the weight of soil required to hold down the membrane and prevent it from wrinkling or distorting under traffic loads

Nor is soil the only material that may be used as an anchorage layer over membranes. A layer of bituminous surfacing may be fully as effective and, in some instances, more economical, as a bituminous surfacing is in itself waterproof and makes an excellent wearing course

As mentioned before, P.B S. was primarily designed for compacted soil runways and taxiways It is obvious, however, that if clay soil surfaced with P B.S will make a satisfactory all-weather runway and taxiway, it will also make a satisfactory road In Western Europe ously discussed P.B.S membrane seal, dubbed by some military engineers as the mud-pack, took care of the critical soil areas on roads or airfields Besides this, the European war

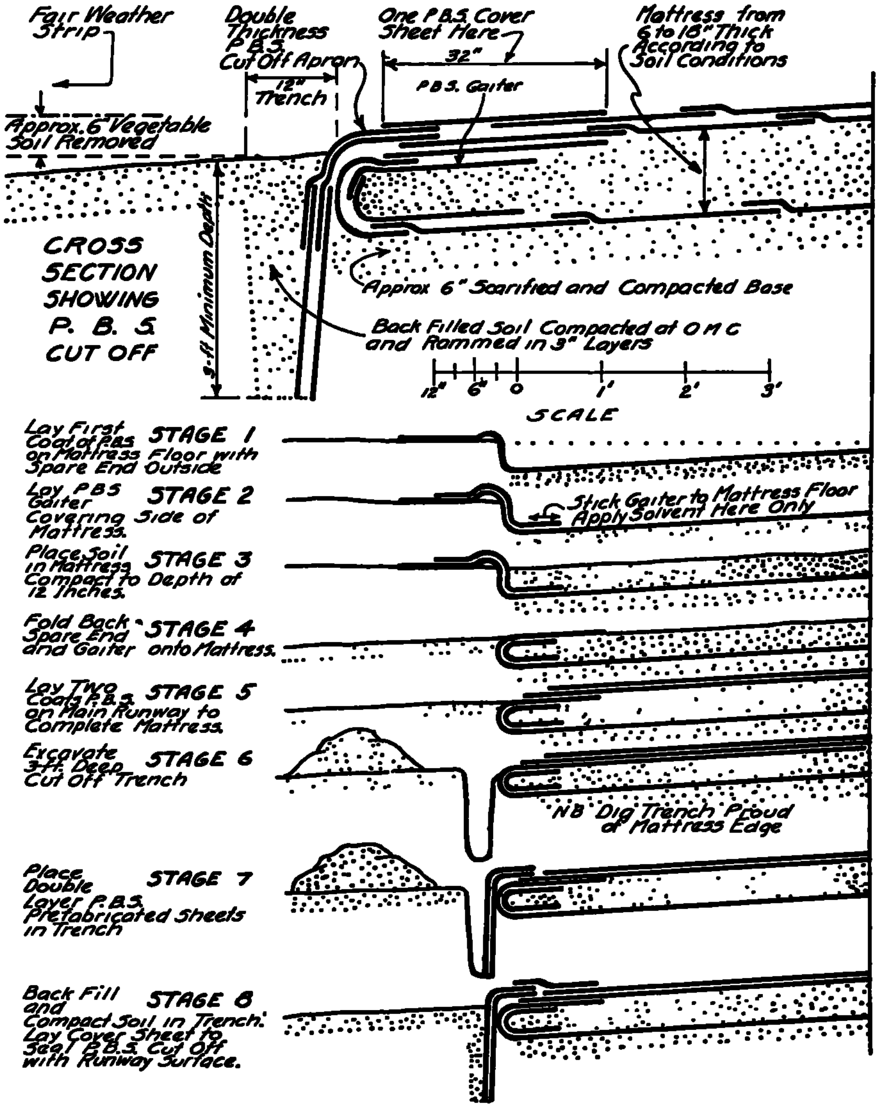


Figure 16. P.B.S. Runways. Cross Sectional View of Soil Base Construction

the demand was principally for combat runways; roads were a minor worry, as Northern France, the Low Countries, and Western Germany were intersected with dense networks of roads with massive base structures of ancient origin. The development of the previ- theatre never had enough P.B.S. even for airfield surfacing, in spite of some twelve large roofing plants concentrating on the manufacture of P B S in the United States and Britain.

The need for combat airfields in South East

India and Burma was if anything greater than in Western Europe, but aside from the need for airfields, these areas had no roads worthy of mention. There is no reliable record of P.B.S. road work in South East Asia; a reasonable estimate would be that the total was well over 350 miles. Some of the air trooping centers, such as Avadi, Karachi, and others, were surrounded or interlaced with networks of P.B.S. surfaced roads. The Tamu-Kalewa Highway, however, built during the 1944–1945 Burma campaign, is an outstanding example of wartime P.B.S. road construction. This road, referred to in official records as the life line of the 14th Army in Burma, was virtually all natural soil grade over rice or paddy fields, jungle swamp, and along mountainsides, with nothing more than a P.B.S. surface over the soil. The grade in some instances was over 10 ft. above surrounding levels and was protected against erosion with a double layer of P.B.S. The total length of the road was 125 miles. Figures 18 to 20 illustrate this type of road work.

Figure 17. Construction Scene on Tamu-Kalewa Road in Burma

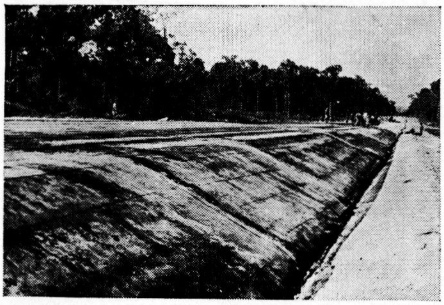


Figure 18. Surfacing Compacted Soil Road with Double Layer of P.B.S.

The jungle may have reclaimed a goodly portion of this road, but irrespective of its present condition, the Tamu-Kalewa Highway gave excellent service for well over a year and supported traffic loads that would have taxed the bearing capacity of first class base and pavement structures. Traffic on the first 60 miles completed averaged 2000 vehicles per day, mostly heavy supply lorries, including numerous transports carrying 70-ton tanks and much motorized artillery. As the Burma campaign increased in intensity supplies flowed steadily over this jungle highway with nothing between the vehicle's wheels and the natural clay soil but a thin P.B.S. mat.

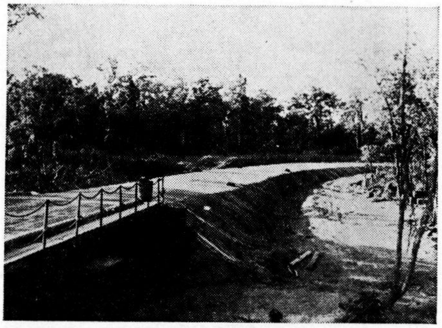


Figure 19. Tamu-Kalewa Road—Burma Protective P.B.S. Covering over Soil Grade against Erosion During Monsoon Floods

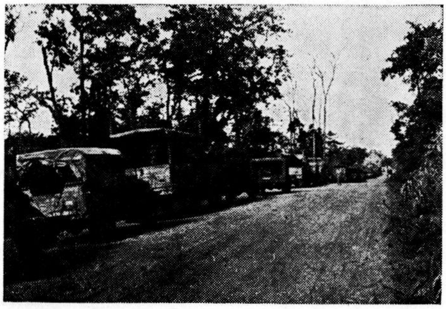


Figure 20. Military Traffic on the Tamu-Kalewa Road, Burma

It is reasonable to assume that the soil on a goodly portion of this mileage was only partially consolidated and therefore must have softened considerably with infiltration of capillary moisture during the 5 to 6 months' period of monsoon downpours. Again, the question arises how thick a conventional base or pavement would have been required over the new soil grade to carry all this traffic for months on end. The total thickness of the P B S. mat was hardly over one-third of an inch, and its weight at no time exceeded 16 lb to the square yard. The author's experience, extending well over 30 years, indicates that a 4-in. thick, standard pavement, rigid or flexible, would not have stood up for a week under the heavy traffic carried on the P.B.S. Tamu-Kalewa Highway during the Burma campaign of 1944–1945.

SUMMARY

The foregoing is an outline of the development of prefabricated bituminous surfacing and an attempt to explain how the P.B.S. membrane by itself, and in combination with metal reinforcing of one type or another, functioned. The explanation is admittedly theoretical, that is theoretical from the standpoint that the explanation is not based on quantitative and qualitative values It is primarily based on the proposition that since the bearing capacity of the soil was for the most part inadequate to support the traffic load, it must have been the prefabricated mat that made up this deficiency. This in turn could have occurred in no other way except by the mat reducing the unit load below the bearing capacity of the soil under it. It must be recognized that in most instances a soil, no matter how saturated, still has some supporting value Covering the plastic soil with a mat evidently spreads the total vehicular load in contact with the soil over a vastly greater surface area than can ever be brought about by any accepted means.

Thus, what was accomplished with membranes during World War II is entirely different from anything that could ever have been done with layers of aggregate and standard pavements. It is therefore very likely that established tests and engineering terminology, built up on the basis of standard materials and methods of construction, may not apply to thin flexible membranes. Membranes may be in a different realm, the investigation of which may require entirely different tests, measurements, and terminology. Since membranes can be had with a bursting strength greater than the strain imposed on it by traffic loads, it becomes a question of how to arrive at a basis for evaluating the behavior of a membrane over cohesive soil in various stages of instability. With positive data to hand, the idea of membranes may be combined with established practice, or it may form the basis for entirely new designs But even if the behavior of the afore described mats were to be analyzed by established means, the only conclusion would be; that the reason P.B.S. mats stood up under conditions that would have disintegrated heavy base and pavement structures, is that it combined the three most desirable properties—tensile strength, flexibility, and a high degree of immunity to temperature change A P B S. mat, especially when reinforced, has high enough tensile strength to stand any strain developed by modern traffic, even if the soil under it may be in saturated condition The same P.B.S mat will stand almost any degree of deflection without failing. Finally, the tensile strength of a P.B S. mat is not affected by wide fluctations in temperature.

No other pavement combines these characteristics. Hence, the reason why all other pavements have to be so complicated in design and above all, so massive

ACKNOWLEDGMENT

Acknowledgment is made to Mr. R S. Colquhoun (Late Major Royal Indian Engineers) for photographs of construction scenes on the Tamu-Kalewa Highway; to Mr Prevost Hubbard; and Dr N W McLeod for helpful criticism and suggestions

DISCUSSION

Prevost Hubbard; Mr. Baskins paper provides much food for thought in connection with the future design and construction of highways and airport runways In view of the ever increasing total loads, which must be visualized, any method of reducing unit loads is well worthy of careful consideration and study. This, of course, has long been realized in connection with methods taken to increase vehicle contact areas by the use of larger tires, balloon tires, dual tires, caterpillar treads, etc. All of these methods are, however limited by the dimensions of the vehicle It would seem that use of a high tensile strength membrane, at or near the surface of a pavement, actually performs a similar function and extends the effective contact area of a vehicle well beyond its dimensional limits

The term "distribution of load" has, I believe, been rather loosely used to designate two quite different phenomena, that is—reduction of the unit load transmitted to the surface of the pavement; and distribution of the transmitted surface load throughout the underlying support. To make this distinction perfectly clear in this very brief discussion I have used the term *deconcentration of load* to apply to reduction of unit load transmitted to the surface, without any reference to distribution of load throughout the underlying support.

a common phenomenon but, I believe, its significance has been generally disregarded The mass below this depression has been moved downward. This represents work done just as though the direct contact area had been expanded to conform with the outside depression plus the original contact area, the sum of which I have labeled as the *effective contact area* In other words, the average unit load has been decreased by the tensile strength of the plastic soil at or near the surface, as indicated by the slightly shorter vertical line As with such material, its tensile strength is relatively low and its ability to stretch is very limited, the surface will ultimately crack near

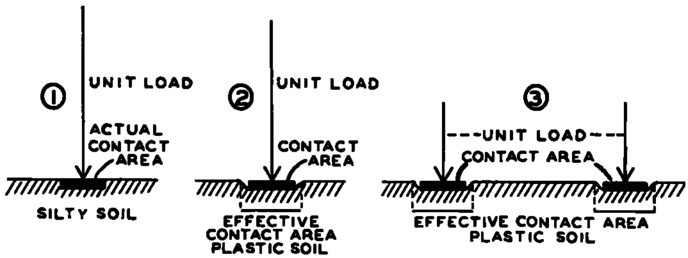


Figure A. Deconcentration of Total Load By Increasing Vehicle Contact Area. (Same Total Loads, 1, 2, 3)

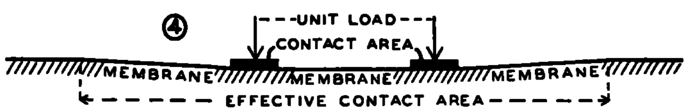


Figure B. Deconcentration of Total Load By Increasing Effective Contact Area By Means of Membrane. (Same Total Load as in Fig. A)

With this in mind, I have prepared a single illustration to demonstrate how and why a high tensile strength flexible membrane may increase the effective vehicle contact area.

Figure A-1 shows a load applied to the surface of a mass of cohesionless material such as silt or fine sand With a given total load, the unit load transmitted to the surface is a direct function of the area of surface contact In this case the intensity of the unit load is indicated by the length of the vertical line above the contact area

Figure A-2 illustrates what happens when the same total load is transmitted through the same direct contact area to the surface of a plastic soil possessing some tensile strength With deflection, a saucer shaped depression forms around the direct contact area This is

the periphery of the direct contact area and further deconcentration of load will cease

Figure A-3 merely illustrates how the unit load may be cut in half by doubling the effective contact area of a vehicle The comparison is upon a linear basis

Figure B shows what may possibly be accomplished in further deconcentration of load by the use of a high tensile strength flexible membrane placed upon the surface The effective contact area is greatly enlarged and the unit load accordingly decreased, as represented by the short vertical lines This does not mean that the load per square inch under the effective contact area provided by the membrane is exactly the same as under the direct contact area, but it does mean that the average unit load has been materially decreased.

Of course there is nothing new in the use of reinforcement in highway construction and, in a sense, the membrane placed even upon the surface may be considered as a form of reinforcement. However, because of its complete continuity, its adaptability for use with flexible or non-rigid types of construction offers a comparatively new field of scientific research There is a need for accurate measurements of the effectiveness of a membrane placed upon or slightly below the surface of a flexible pavement; a study of the relative effectiveness of various combinations of materials in the formation of membranes; and particularly a study of the durability of different membranes under actual service conditions. If membranes are found to be economically effective in highway and runway construction their use will result in a decrease in the required thickness of the ordinary types of base and subbase construction but not as a substitute for such construction.

THE RATIONAL DESIGN OF BITUMINOUS PAVING MIXTURES

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SYNOPSIS

The use of the triaxial test and the Mohr diagram for designing the strength or stability of bituminous mixtures on a pounds per square inch basis is outlined in quantitative terms A method for calculating the amount of lateral support provided by the pavement material adjacent to the loaded area is included. The influence of the viscous resistance of bituminous mixtures on their stability is described The effect of the frictional resistance between pavement and tire and between pavement and base on the stability of bituminous pavements is discussed The influence of braking stresses on the design of bituminous mixtures is considered. Stability equations and design charts are included

An engineer becoming acquainted for the first time with current engineering practice in the field of pavement design for airports and highways, must be surprised to learn that our approach to the design of rigid pavements is entirely rational throughout, that is, on a pounds per square inch basis, while flexible pavement design is largely empirical.

For rigid pavement design, the thickness of slab required can be obtained from the Westergaard equations. In addition, there are well established principles for designing portland cement concrete mixtures of any specified compressive or flexural strength in terms of pounds per square inch.

For flexible pavement design, on the other hand, there is the greatest divergence of opinion concerning the overall thickness of base and surface required, and the method to be employed for determining it That this problem of the overall thickness of flexible pavements is highly controversial at the present time, is quite evident from articles and discussions on this topic that have appeared in the technical press in recent years.

When it comes to designing bituminous mixtures of any specified strength, the stability tests in most common use, Hubbard-Field, Marshall, and Hveem Stabilometer, are not able to measure the strength of bituminous mixtures in terms of shear or any other fundamental property on a pounds per square inch basis. They are strictly empirical tests.

Empirical methods have a serious drawback in that it is dangerous to extrapolate their results to cover conditions beyond those under which they were established With empirical methods also, it is difficult to avoid either overdesign or underdesign In addition, in every engineering field there should be the ultimate objective of establishing rational methods of design, in which the strengths of all materials employed are utilized on a unit strength basis

In the absence of a more fundamental approach, these empirical tests have served usefully in the past to provide some indication of the relative stabilities of bituminous mixtures However, the fact that the number of such methods continues to increase is proof of the current dissatisfaction of highway and airport engineers with the inadequacies of these empirical tests. In addition to the three methods already named, the Texas Punching Shear, Florida Bearing Value, Modified Hubbard Field, Campen's Bearing Index, Un-