degree to which any theory corresponds to real conditions. Therefore, I consider that the simplified method of the "equivalent beam" with modifications reported by me at last year's conference in Brussels *(Ref. 9)* represents a practical, feasible approach to a final solution of the design problems for this type of structures.

REFERENCES

1. Terzaghi, Karl. "General Wedge Theory of Earth Pressure," Transactions, American Society of Civil Engineers, 1941, pp. 68-97.
2. Tschebotarioff, Gregory P. "Einfluss der 'Gewoelbowirkung' auf die Eiddruckverteilung," *Bautechnik-Archiv,* Heft 8, Ernst u. Sohn, 1952, 55.33-45.
3. Blum, H. "Einspannungsverhaeltnisse bei Bohlwerken," W. Ernst u. Sohn, Berlin, 1931.
4. Tschebotarioff, Gregory P. "Large-Scale Earth Pressure Tests with Model Flexible Bulkheads," Final Report to the Bureau of Yards & Docks, U. S. Navy, Princeton University, January 1949, 272 p.
5. Rowe, Peter W. "Anchored Sheet Pile Walls," Proceedings Institution of Civil Engineers, London, Vol. I, Pt. 1, 1952, pp. 27-70; 616-619.
6. Tschebotarioff, Gregory P. and Johnson, Edmund, G. "The Effects of Restraining Boundaries on the Passive Resistance of Sand," Report to the Office of Naval Research, U. S. Navy, Princeton University, June 1, 1953.
7. Rowe, Peter W. "Sheet Pile Walls in Clay," Proceedings, Institution of Civil Engineers, London, Vol. 7, pp. 629-654, July 1957.
8. Tschebotarioff, Gregory P. and Ward, Edward R. "Measurements with Wiegmann Inclinometer on Five Sheet Pile Bulkheads," Proceedings, Fourth International Conference on Soil Mechanics and Foundation Engineering, London, 1957, Vol. II, pp. 248-255.
9. Tschebotarioff, Gregory P. Discussion of Section V: "Stability of Sheet-Pile Bulkheads," Proceedings, Brussels Conference 58 on Earth Pressure Problems, Brussels, Sept. 1958, Vol. III, pp. 229-233, 243.

Critical Elements of Design and Construction of Heavy-Duty Flexible Pavements

WILLARD J. TURNBULL, *Chief,*
U. S. Army Engineer Waterways Experiment Station,
Vicksburg, Miss.

The increase in weight of aircraft has made it necessary to devote special attention to the design and construction of flexible pavements that will perform satisfactorily under these unprecedented aircraft loads and operational characteristics.

The load on a single wheel of an aircraft can now be as high as about 60,000 to 70,000 lbs. The number and alignment of the wheels vary with the gross weight and type of aircraft. In order for the wheels to carry such loads without using excessively large tires, the inflation pressures of the tires must be much higher than those required in the past. Tire pressures are now approaching 300 psi and this intensity of contact loading makes it necessary to give special attention to the upper portion of the pavement.

In addition to the great increase in load weights and tire inflation pressures, the operational characteristics of the aircraft while on the ground must be considered. Almost all recently developed aircraft can be steered by mechanical means, which results in operation of the newer aircraft in a path much narrower than that of the older aircraft which are steered by rudder alone. Such concentrated traffic, referred to as channelized traffic, has the effect of deteriorating the pavement in a shorter period of time than traffic distributed over a wide area. While certain areas receive the concentration of channelized traffic, other areas are subjected to lesser or even quite light traffic, or only to traffic of aircraft not loaded to maximum weight.

Basic Design Requirements

A flexible pavement is constructed in layers of material placed on a subgrade. Each layer must have adequate strength to resist the stresses imposed on it. As the intensity of stress is highest at the surface and decreases with depth, it follows that each layer must have a higher strength value than the layer immediately below it. Stated in another way, a layer of a given strength must have a certain thickness of a higher-strength material above it to provide adequate protection from imposed loads.

In addition to adequate shear strength in the entire pavement structure, a high degree of compaction in all layers must be obtained to insure that additional densification does not occur under the traffic of heavy aircraft. The high degree of compaction not only is essential to insure the maximum strength of the various layers but also is quite essential to insure satisfactory surface smoothness during the life of the pavement. Differential compaction can produce an undesirable surface condition which will have detrimental effects on the operation of heavy aircraft. Aircraft with bicycle-type landing gear are especially sensitive to roughness and unevenness of runway surfaces.

A high compaction effort is required in the field on base courses in order to meet the design requirements. After this initial density has been obtained, the surface of the layer of base course in question is subjected to about 30 coverages of a very heavy rubber-tired roller having a tire pressure ranging from 90 to 150 psi to insure that a uniform and high degree of compaction has been obtained and that no isolated uncompacted areas exist. This latter procedure is referred to as "proof-rolling."

Generally speaking, the densification of the base course shall be at least 100 per cent laboratory modified AASHO (American Association of State Highway Officials) density. Quite often it is found that with the addition of proof-rolling, the density will be as high as 104 per cent of modified AASHO density.

A considerable amount of information has been obtained on heavy-load prototype traffic in the field, and this information indicates that it is not unusual for a base course to exist at 105 per cent modified AASHO density as a result of compaction by traffic. The degree of compaction of the subbase course usually should be as high as that of the base course, and proof-rolling on at least the surface of the top layer of the subbase course is required.

Below the subbase course in the subgrade, the compaction requirement decreases until at a depth of about 5 to 6 ft below the pavement surface a compaction of 80 to 90 per cent modified AASHO density is required.

The surface smoothness requirements are quite rigid in that surface deformities must be such that they will not produce more than ⅛-in. variation under a straightedge 12 ft in length. Proper initial densification is essential to insure not only that this high degree of surface smoothness exists at the time the pavement is constructed but also that it is maintained during the life of the pavement as the base and subbase materials are subjected to possible further densification by traffic.

The effect of the blast (and heat) and the spillage of fuel from jet aircraft must be considered in the design of pavement surfaces; this, of course, is in addition to the ordinary requirements that the bituminous concrete surface wearing course must be resistant to wear and weather. In areas subjected to repeated blasts, such as maintenance areas and the ends of runways, portland cement concrete is generally used. Parking areas which are subjected to some fuel spillage and occasional blast are constructed of either portland cement concrete or rubberized-tar flexible pavements. The rubberized-tar pavement has somewhat higher resistance to blast and is much more resistant to fuel spillage than asphaltic concrete.

Other Design Considerations

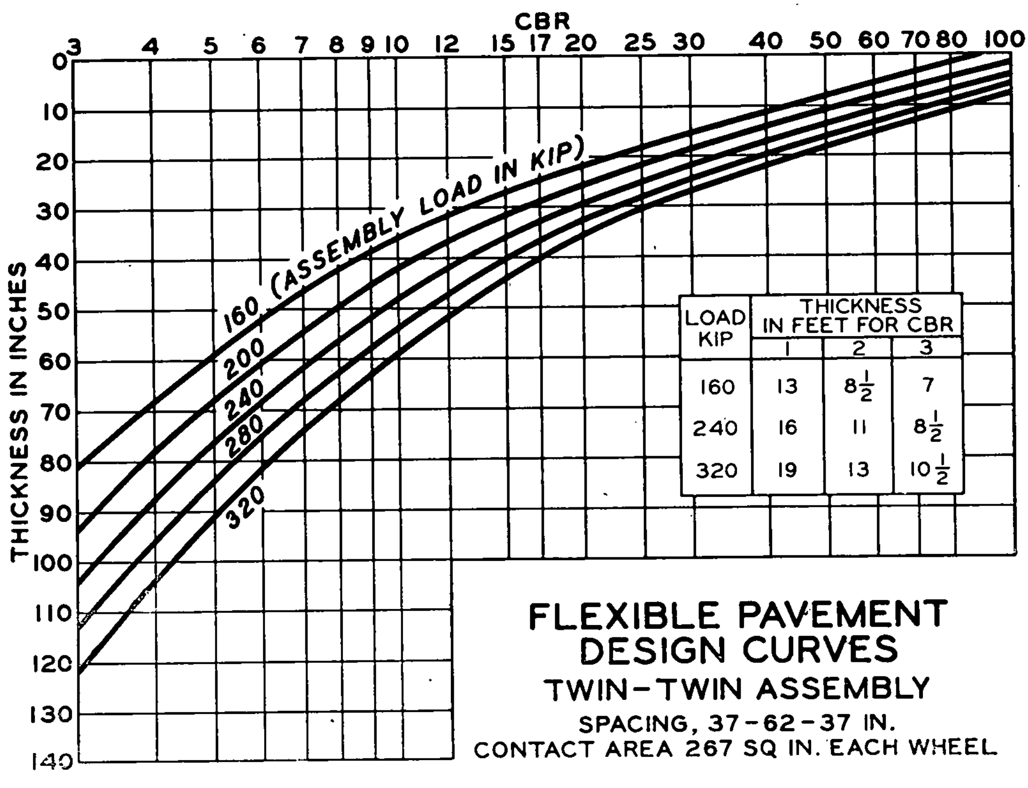
It has been found desirable to place layers of a base course or a subbase course by means of mechanical spreaders to insure a layer of uniform thickness. This uniformly thick layer tends to produce more uniform compaction and also gives much greater insurance of meeting grade limitations and thus producing a pavement surface which initially meets and will maintain smoothness requirements.

The quality of the aggregates used in bases and subbases must be such that the aggregates will meet ordinary soundness and durability requirements. It has been found that the denser-graded material with a maximum size not greater than 2 in. is the most desirable. Probably the most critical quality requirement of a base or subbase material is the plasticity index. It is essential that the base course layer be nonplastic, that is, have a plasticity index not over 5. The plasticity index of subbase materials may be slightly higher, but under no conditions should it be over 12.

The design requirements of the materials below the upper subbase are not discussed here because it is evident that the basic design principles allow the use of lower-quality materials at the greater depths. The quality and strength of the materials at any given depth in the pavement determine the total thickness of material above the given layer. Similarly, the degree of compaction of the lower subbase course and subgrade materials decreases with depth.

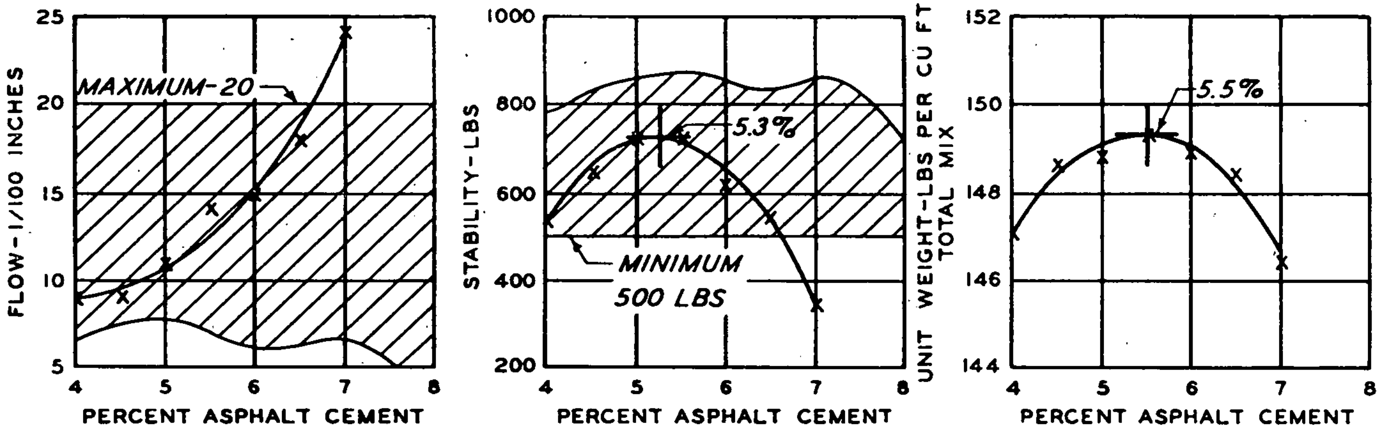
Design Methods

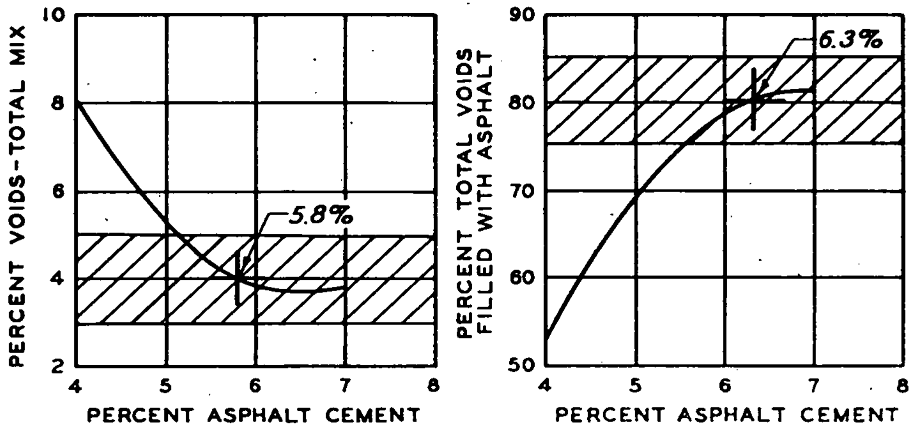
The U. S. Army Corps of Engineers utilizes the California Bearing Ratio (CBR) system *(Fig. 1)* in the over-all design of a flexible pavement structure. The strength of each type of material is determined by means of the CBR test. By means of test sections and by observations of pavements of airfields, the Corps of Engineers has developed a relationship between the CBR of a material and the thickness of pavement required above it to protect the layer from the imposed loads.



LOAD KIP	THICKNESS IN FEET FOR CBR 1	2	3
160	13	$8\frac{1}{2}$	7
240	16	11	$8\frac{1}{2}$
320	19	13	$10\frac{1}{2}$

FIGURE 1





TEST PROPERTY	SELECTED ASPHALT CONTENT-PERCENT
STABILITY	5.3
UNIT WT-TOTAL MIX	5.5
VOIDS-TOTAL MIX	5.8
VOIDS FILLED WITH ASPHALT	6.3
AVERAGE	5.7

TYPICAL CURVES
TEST PROPERTIES VS
ASPHALT CONTENT

ASPHALTIC CONCRETE

FIGURE 2

The Marshall procedure *(Fig. 2)* is used for designing bituminous concrete surfaces of flexible pavements. The bitumen content for light-duty pavements and for the portions of heavy-duty pavements that receive relatively light traffic is determined by the conventional Marshall test. This bitumen content is decreased for the areas of pavement subjected to channelized traffic of heavy aircraft. This latter is necessary because of the high compaction effects of the intensive traffic of heavy airplanes and the nonfeasibility of increasing the laboratory compaction effort to duplicate this high densification produced by prototype traffic.

The objectives of the Marshall method of design of bituminous surfaces are to insure that the mixture has sufficient voids to prevent plastic movement (flushing) when the pavement is consolidated under prototype load and that the bitumen content is high enough to insure good durability and weathering characteristics of the pavement.

It has been found by experience that these criteria can best be met when a sound and well-graded aggregate is used. Assuming the use of high-quality materials, it is considered that the proper proportioning of the asphaltic cement is the most critical feature in the design of satisfactory bituminous mixtures. Basically, the Marshall method is developed so as to furnish the maximum asphaltic content in a mix which will not flush under traffic.

Heavy-load bituminous pavements are constructed with conventional machinery and equipment. Recently it has been found that the use of medium-heavy pneumatic-tired rollers, in addition to steel-wheel rollers, is of considerable benefit.

Equipment and Procedures

In the last few years, real "break-throughs" have occurred in compaction equipment development and/or procedures, the principal ones being as follows:

(a) Heavy rubber-tired rollers (90 to 150 psi) weighing 32 tons and above produce a high degree of compaction in bases and subbases. The 32-ton self-propelled equipment is particularly efficient in operation.

(b) Medium-weight rubber-tired rollers (90 to 150 psi) weighing 16 to 32 tons are very efficient for compaction of asphaltic concrete. High densities are easily obtained. The self-propelled feature is particularly effective and efficient.

(c) The use of asphaltic mixture spreaders for upper subbase and base course layers has proved particularly effective in furnishing true grade, thus insuring a smooth surface and improving uniformity of compaction.

(d) Proof-rolling with heavy rubber-tired rollers when properly specified and executed is very useful in producing satisfactory heavy-duty flexible pavements.

The large size of all the pavement facilities at a heavy-duty air base means that large quantities of earth must be moved during the course of construction. To move such large quantities of earth, high-performance earth-moving equipment must be used. The equipment must carry a large pay load, travel rapidly, and be capable of close control both in loading and unloading operations.

Summary

It is believed that if proper cognizance is given to the basic design considerations discussed, as well as to the other design considerations noted in this paper, a satisfactory heavy-duty flexible pavement can be designed by utilizing the CBR method for the over-all pavement and the Marshall method for the bituminous concrete. However, good equipment and construction procedures are necessary to insure that specification requirements are met and satisfactory pavements constructed.

Insofar as load-carrying capacity is concerned, it is considered that flexible pavements are entirely satisfactory for the interior portions of runways of heavy-duty airfields. Further, it is believed that, exclusive of blast and fuel-spillage areas, satisfactory flexible pavements can be designed for the heavier-traffic areas of runways and taxiways. However, some additional field and laboratory research is needed in this area.