RIGID PAVEMENT DESIGN FOR AIRFIELDS

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BACKGROUND

Immediately preceding the entry of the United States into World War II, the U. S. War Department generated a requirement for approximately 100 million square yards of pavement at more than 300 airfields throughout the country. Because the geographic location of the Corps' Division and District offices was well suited to the management of this work, responsibility for design and construction of military airfields was transferred from the Army Construction Quartermaster Corps to the Corps of Engineers in late 1940. The assignment was accepted by the Chief of Engineers but with some misgivings. The airfields were to be completed within a 30-month period. Aircraft loadings had escalated three to five times over those dealt with by either airfield or highway pavement designers up to that time. The engineering staff of the Corps was much more experienced in design and construction of river and harbor navigation structures and in flood control than in airfield pavements.

As an initial action, the Chief of Engineers directed a review of all existing design and construction methods with the aim of selecting, developing, and applying a simple, practical, and uniform method of design for guidance throughout the Corps. The objectives of the system were:

a. To obviate the use of untried methods.

b. To ensure adequate performance.

c. To eliminate variation occasioned by cost differentials of local and competitive materials.

d. To avoid reductions of pavement thickness or quality in order to balance cost.

e. To establish procedures for further development of design methods through tests, investigations, and study of actual pavement behavior.

WESTERGAARD ANALYSIS

The review of design methods for both rigid and flexible pavements was undertaken by the engineering staff of the Office, Chief of Engineers, assisted by a Board of Consultants. While the evaluation of design methods for flexible pavements presented a considerable problem because of the several methods in vogue for highway design throughout the country, the rigid pavement design selection process was relatively simple.

Dr. H. M. Westergaard's[1,2,3] method of rigid pavement design was fairly universal in its application throughout the United States and was quickly recommended to the Chief of Engineers as the most advanced procedure for determining critical stresses in concrete slabs under load. In 1941 with the support of the Department of the Army investigational funding, the Corps' Ohio River Division Laboratories initiated a series of static and dynamic loading tests on nine specially prepared slabs of various designs and on an existing 7-in. lightly reinforced apron pavement at Wright Field, Dayton, Ohio. Simultaneously flight tests were conducted at Dayton Municipal Airport, Vandalia, Ohio, using a B-26 medium bomber to investigate "impact" loadings on landing. In early 1942 towed traffic tests on existing rigid pavement sections were initiated at McDill, Maxwell, Godman, and Hamilton Army Airfields. A full presentation of the results of these early

rigid pavement tests will not be given here since they have been treated in a number of technical papers and reports over the years.[4,5] Certain key conclusions will be discussed, however, because of their influence on the design of military airfields for many years.

SUBGRADE MODULUS

At the time of the Wright Field Slab Tests, the need for design guidance within the Corps was urgent. Design and construction of a vast number of military airfields was in progress throughout the United States and overseas by Corps of Engineers' personnel. While the Westergaard method of design had been adopted, some important facets had never been treated in Dr. Westergaard's publications. No specific test method had been advanced for the assignment of the subgrade modulus, k , to the pavement foundation; analysis of stress at slab edges and corners had not yet been developed; and the effect of stress repetitions, pavement fatigue considerations, dynamic loadings, slab size, load transfer at joints, and joint design had not been treated. Thus the Chief of Engineers was disseminating test results and tentative design information almost as soon as the tests were completed.

In Dr. Westergaard's first Highway Research Board publication in 1926 entitled "Stresses in Concrete Pavements Computed by Theoretical Analysis," he stated that ". . . by assuming the reactions of the subgrade to be vertical only and to be proportional to the deflections of the slab . . . the analysis is reduced to a problem of the mathematical theory of elasticity." He further assumed the modulus of subgrade reaction, k (a measure of the stiffness of the subgrade), ". . . to be a constant at each point, independent of the deflections and to be the same at all points within the area which is under consideration;" this was despite his acknowledgment that tests of bearing pressures ". . . indicated a modulus, k , which varies considerably depending upon the area over which the pressure is distributed. Yet, so long as the loads are limited to a particular type, that of wheel loads on top of pavement, it is reasonable to assume that some constant value of the modulus, k , determined empirically will lead to a sufficiently accurate analysis of the deflections and stresses."

Except to state that the subgrade modulus ". . . may be determined empirically--for a given subgrade by comparing the deflections found by tests of full-sized slabs with the deflections given by the formulas . . . ." Dr. Westergaard never suggested a test method for determining the k value. This lack of definition has through the years caused Corps' researchers and, we believe, many others considerable concern. Referring to Dr. Westergaard's ". . . wheel loads on top of pavement . . . ." analogy, surely the geometry of a Model T Ford automobile on a 5- or 6-in. concrete slab in 1926 would bear little resemblance to a 360,000-lb C-5A 12-wheel loading gear on a 20-in. concrete slab today. Yet the Corps, in every major rigid airfield pavement test program carried out since 1941, has found the procedures for determining the subgrade modulus developed in conjunction with the Wright Field Slab Tests to be essentially representative of the values obtained by the load-deflection tests of full-size slabs or the so-called volumetric k . The only exception to this pattern is the high k value obtained on moderate base course thicknesses which generally must be adjusted downward to match full-size slab performance.

In the Wright Field tests, nine test slabs, ranging in thickness from 6 to 10 in., were instrumented for strain and deflection and loaded to failure at the slab center. The subgrade modulus, k , was computed from these loading tests as suggested by Westergaard to be between 152 and 214 lb per cubic inch. A separate series of plate bearing tests were then performed on the same subgrade using 8-, 12-, 18-, 24-, 30-, 48-, and 72-in. plate sizes with the k value computed at 0.05-in. deflection of the plate. Test results are presented on Figure 1 and show a range of values from 720 lb per cubic inch for the 8-in.-diam plate to 118 lb per cubic inch for the 72-in.-diam plate. Values obtained from plate tests in the 18- to 48-in.-diam range compared favorably with the slab load test results. For practical purposes the 30-in.-diam steel plate was selected as reasonably representative of subgrades under concrete airfield pavements. The test method was later modified to measure the plate deflection under a uniform 10-psi loading and to employ stacked plates to minimize plate bending particularly on higher strength foundation soils. This made the field test procedure simpler without significantly affecting results. Corrections for plate bending were applied and a method developed

for assessing a "soaked" value of k through comparative loadings on saturated and unsaturated subgrade specimens in laboratory consolidation test equipment.

The Corps accepts the general criticism relating to a plate bearing test in which a pavement foundation is represented as a heavy liquid rather than an elastic, layered elastic, or elastoplastic system. Dr. Westergaard himself later referred to the subgrade modulus as an "empirical makeshift justified by usable results." In his 1933 and 1939 papers, Dr. Westergaard according to Pickett, Gerald, and Ray[6] incorporated in his analysis a "plausible estimate" of what the correction should be to bring his formula for maximum stress for interior loading into agreement with what would be obtained if the assumed subgrade had been replaced by a "deep elastic solid."

Responding to the continual growth of military aircraft during the 1940's and 1950's and the attendant increase in pavement thickness, the Corps has repeatedly questioned and subjected to test the continued applicability of the standard 30-in. plate bearing test. Perhaps the reason for its apparent range of application is that rigid airfield pavement slabs usually exhibit initial or first structural cracking within a very narrow range of deflection, which is in the order of 0.05 to 0.15 in. It appears probable that the 30-in. plate under the relatively low 10-psi loading gives an accurate index of foundation support within that deflection range for slabs directly on subgrade. The standard subgrade modulus is probably an improper value for concrete pavement systems that give acceptable performance at larger deflections, such as prestressed, continuously reinforced, and flexible pavement overlays on a concrete base slab. In these latter cases, the Westergaard analysis itself is useful only with considerable modification or through totally empirical correlation.

IMPACT LOADINGS

The flight tests at Dayton Municipal Airport indicated that impact loadings on runway pavements during landing operations were "normally" only 40 to 80 percent of the static load, averaging about 65 percent. The pilot of the B-26 aircraft with instrumented main landing gear shock struts produced some "hard" landings by "flying the airplane into the ground." Impact loadings up to 210 percent of static were recorded, but it was concluded such landings would be extremely rare in military aircraft operations.

Investigators at Wright Field borrowed a landing gear "drop test" device from the Wright Air Development Center to produce impact loadings on the test slabs. Impact loadings were achieved by dropping a single aircraft wheel loaded statically to 10,000 lb from heights up to 24 in. Philippe[4] concluded that "the character and speed of impact of a landing aircraft produce stresses that do not differ from those produced by a statically equivalent force."

The performance of the Wright Field test slabs under static interior slab loadings were fully consistent with the Westergaard stress analysis. Load tests at the corners and edges of slabs, however, showed conclusively that appreciably lesser loads produced initial structural crack failure. These findings were further supported by the traffic tests at Maxwell, McDill, Godman, and Hamilton Army Airfields where the towed wheels loaded near the computed interior slab capacity produced immediate slab failure essentially shattering and deforming the pavement at the corners and edges of the slab after only a few passes. Unfortunately a reasonable analysis of stresses at the corners and edge of slabs had not been developed. Thus the first Rigid Airfield Pavement Design Manual of the Corps of Engineers was published in 1943 based upon interior load equations. A "design factor" of 1.75 established empirically on the basis of tests conducted to that date was incorporated in the design curves to accommodate both the observed differences in allowable edge and interior loads and the behavior of the concrete slab in fatigue resulting from repetitive loadings over the desired pavement life.

ACCELERATED TRAFFIC TESTING

Between 1943 and 1949 a number of changes were made in the Corps of Engineers' rigid airfield pavement design posture. These changes resulted from a continual growth in aircraft weight, accelerated traffic tests of thickner pavement systems initiated in

response to the increasing loads, new analytical procedures developed by Dr. Westergaard[7,8] to handle large elliptical tire-contact areas, multiple-wheel configurations, edge- and corner-slab stresses and load transfer at pavement joints, and small-scale model tests designed to validate certain aspects of the Westergaard stress analyses.

Again the results of these activities are well documented in the technical literature.[9] A few comments are appropriate regarding the manner in which the changes are occurring and the impact on the thinking of those responsible for the development of pavement design procedures.

During the early war years, the aircraft systems producing the most critical loadings were the B-17 and B-24 bombers, weighing approximately 75,000 lb and producing single-wheel loadings of about 33,000 lb with 100-psi tire inflation pressure. In 1942, development of the 125,000-lb B-29 bomber was initiated with a forecast of 60,000-lb single-wheel loads. The production model of the B-29 came out with a twin-wheel main landing gear carrying the 60,000-lb loading but not before considerable rigid pavement testing had been initiated in response to the single-wheel version at Lockbourne Army Airfield, Columbus, Ohio. In late 1944 before the completion of the Lockbourne No. 1 test track, which contained 52 pavement test items to be traffic tested with 20,000-, 37,000-, and 60,000-lb single-wheel loads, development of the 330,000-lb B-36 bomber aircraft was initiated with anticipated single-wheel loadings of 150,000 lb on a 110-in.-diam tire and 100-psi tire inflation pressure. The Lockbourne No. 2 Experimental Mat was constructed containing 97 highly instrumented test items.

While the XB-36 prototype aircraft was equipped with the large single-wheel main landing gear, the production model came out in 1946 with a four-wheel twin-tandem main-gear assembly. This was the Corps' first real consideration of multiple-wheel landing gear and resulted in the construction and testing of the Lockbourne No. 2 modification containing 33 rigid pavement items. It is interesting to note that the reason for changing the main landing gear on the B-36 from a single-wheel to a twin-tandem configuration was simply that aircraft designers found that the twin-tandem wheels would occupy less space in the aircraft than the large single wheel with little difference in weight penalty. Although the change would permit a reduction in airfield pavement thickness, this consideration played no part in the modification of the aircraft. Because performance in the air of the bomber aircraft and indeed all military aircraft developed through the early 1950's was the paramount consideration, the concept of paying some air performance penalties in the aircraft design in order to achieve greater ground flotation thus permitting either less-expensive pavement systems or achieving greater flexibility in selecting airfields capable of supporting the aircraft operations was not seriously advanced until about 1951.

The entire Lockbourne test series was perhaps the most comprehensive ever undertaken by the Corps. These tests involved a range of gear loading from 20,000- to 150,000-lb on single-wheels from 25,000- to 60,000-lb twin wheels and up to 150,000 lb on a four-wheel twin-tandem assembly; tire inflation pressures ranged from 60- to 200-psi; natural low-bearing capacity lean clay subgrade, thin-to-medium thicknesses of base course, and very thick base courses to represent high-strength foundation soils; slabs were tested of plain concrete, concrete with temperature steel reinforcing near the surface, various levels of structural steel reinforcing, bonded and unbonded concrete overlays of concrete base slabs; joint types included undoweled and doweled expansion joints, undoweled and doweled contraction joints; thickened edge and doweled construction joints; and keyed construction joints with and without tie bars.

One of the more meaningful aspects of the accelerated traffic testing at Lockbourne was the data developed on pavement cracking after observation of initial structural distress. Tests were routinely continued until the slabs were broken into very small pieces, in the range of 6 to 10 sq ft in area. See Figure 2. Since the Westergaard equations can only predict initial cracking, this traffic testing practice was most helpful in later years in establishing empirical rates of breakup in the slab between initial and ultimate failure and to identify the properties of the concrete and foundation that had the greatest influence on pavement behavior in this range of performance.

LOW FIRST-COST PAVEMENT SYSTEMS

It was during the Lockbourne tests that President Truman signed legislation making the United States Air Force a separate service. This placed the Air Force in the position of budgeting for airfield construction, establishing loading and operational safety standards, funding design research and investigations, establishing pavement performance requirements, and approving new developments in pavement design methodology. Two important decisions were made by the Air Force in the late 1940's which affected military airfield pavement design for many years. The first was that competitive pavement types would be judged on a "low first-cost" basis. The second was that "permanent" pavement systems would be designed for a 20-year operational life with minimum maintenance.

The first decision tended to suppress consideration of steel reinforcing in rigid pavements or any extensive subgrade or foundation stabilization treatment because of the generally higher initial cost of such systems. The second decision placed the definition of failure for rigid airfield pavements on a first-crack criteria in order to minimize crack sealing and maintenance after construction.

By the end of the 1940's, the Corps had developed and published rigid pavement design criteria with a proven record of performance for plain concrete pavements, reinforced concrete pavements, and concrete overlays of concrete base pavements with and without bond breaking courses. The pavement design methods were capable of handling single- and multiple-wheel aircraft gear loadings up to 150,000 lb and with tire inflation pressures up to 200 psi. The design procedures properly accounted for a normal distribution of traffic determined by extensive investigation on the various pavement features of an airfield and permitted designs for any desired pavement life from 6 months to 20 years.

PAVEMENT DESIGN FOR HEAVY BOMBER AIRCRAFT

During the 1950's, rigid airfield pavement research in the Corps of Engineers was directed primarily at accommodation of high-performance jet aircraft. The new military fighter and bomber aircraft systems of that period were characterized by significant increases in weight, gear loads, tire inflation pressure, take-off and landing distances, and pavement smoothness requirements.

Two strategic bomber aircraft caused airfield pavement designers the greatest concern in the 1950's. The first was the B-47 which first made its appearance in 1951. The design gross weight was initially 175,000 lb and did not seem to present a particular problem when compared to the 330,000-lb gross weight of the B-36 for which a number of successfully performing airfields had been designed and constructed in the late 1940's. Within two years the B-47 "grew" to a gross weight of 230,000 lb producing a rear twin-wheel loading of 120,000 lb and tire inflation pressures of 225 psi. The aircraft landing gear design departed from the conventional tricycle arrangement. Both twin-wheel main gears were placed directly under the fuselage with the rear twin wheels trailing the forward by some 36 ft. Additionally the forward main gear was "steerable," a factor which was not recognized immediately by pavement designers as being significant.

The second heavy bomber of the period was the B-52 which went into production in 1954. This aircraft was again equipped with a bicycle arrangement of main landing gear, each of which had four wheels abreast or a twin-twin configuration. The rear main gear trailed the forward by 95 ft. The B-52 ultimately produced a gross weight of 520,000 lb, having a rear main gear loading of 265,000 lb with 285-psi tire inflation pressure.

The earliest investigational efforts sponsored by the U. S. Air Force in response to the upcoming jet bomber systems was initiated in the late 1940's at Lockbourne. Engineers anticipated that the construction of Strategic Air Command (SAC) bases would involve extensive overlay and rehabilitation of existing military airfield pavements throughout the country. Nine test items consisting of a range of thicknesses of flexible pavement overlay of concrete base slabs were constructed and traffic tested at the Lockbourne facility. In 1950 a more elaborate test program including both rigid and flexible overlays was undertaken at the Sharonville General Services Depot near Cincinnati, Ohio. Between 1951 and 1953 some 51 overlay test items were traffic tested at Sharonville.

These overlay investigations established the basis for the Corps of Engineers' flexible-over-rigid overlay design and construction criteria[10] and further validated the rigid-over-rigid overlay criteria developed in the Lockbourne No. 2 Experimental Mat test series. One of the more important peripheral aspects to the flexible overlay investigation was the development of an empirical analysis for predicting the rate of breakup of a concrete pavement slab after the first crack. Data taken from all Lockbourne tests and the older test series at McDill, Maxwell, and Godwin were studied to develop the pattern presented in Figure 2. This information proved to be essential in establishing Corps' requirements for flexible overlays. The thickness of flexible overlay chosen in design is that which limits breakup of the base concrete slab during the pavement service life to a condition just short of individual pieces losing all aggregate interlock with contiguous pieces and failing by "punching shear" into the subgrade. The rate of breakup, as shown in Figure 2, is primarily related to the quality and strength of the subgrade soil, thus placing much more emphasis on subgrade bearing capacity than is inherent in the Westergaard analysis of initial cracking failure.

As the construction program for SAC bases to support B-47 operations unfolded, it became obvious that the concern of military airfield pavement researchers with the development of overlay design procedures was unwarrented. The operational planners in the Air Force decided that the new jet bomber aircraft should have a runway-taxiway-apron system laid out and dimensioned to specifically meet the needs of this strategic bomber system. Few, if any, existing military airfields met or even approached requirements for runway and taxiway width and length and none provided an apron configuration permitting a parking pattern with refueling and maintenance service for rapid maneuver during alert operations. As a consequence, a construction program was initiated calling generally for new pavements for the B-47.

When the heavier B-52 began to replace the B-47 in the mid-1950's, it looked once again as though extensive overlay construction would be in order. It was found, however, that removal and replacement with new pavements of the center 25 ft in the 75-ft-width taxiways and the center 75 to 100 ft in flexible and rigid pavement runways was usually more economical than overlaying all pavement features, raising the existing grades, disrupting surface drainage patterns, and constructing new shoulder and overrun areas. Approximately 100 million square yards of new and replacement pavements were designed and constructed by the Corps during the 1950's in direct response to providing airfield facilities for the B-47 and B-52 bomber aircraft.

One of the most significant changes in rigid pavement design criteria during the 1950's resulted from the ability of aircraft pilots to control the ground traffic operations to a much narrower pattern than had been associated with the older aircraft systems that were not equipped with positive "steering" of either the nose or main landing gear. Other changes of note were made to properly account for the rocking motion of the bicycled geared aircraft which produced dynamic impact loadings on runway and taxiway pavements and required a more rigorous specification for runway smoothness.

CONDITION SURVEY PROGRAM

In the late 1940's the Chief of Engineers instituted a condition survey program at selected airfields throughout the U. S. The program was designed to gather detailed pavement performance data at active Air Force facilities; to establish the aircraft type, weights, traffic frequency and volume, and ground-operational patterns from traffic records maintained by Air Force operational elements; to study construction control test records; to summarize weather and climatological data at the airfield; and to validate, modify, and update pavement design procedures on the basis of these investigations as warrented. In the writer's opinion, the condition survey program was one of the most meaningful that could be undertaken by those responsible for pavement design research.

The following represent only a few of the major findings and actions taken which resulted from the condition survey effort:

a. An early finding was that under any condition of overload, the taxiways and runway end sections show the earliest distress. Initially, this resulted in arbitrarily

reducing the pavement thickness of the center portion of runways by 10 percent. Later when coupled with comprehensive traffic-distribution studies, the finding permitted the identification of four distinct traffic areas on heavy-load airfields for runway ends and taxiways, warm-up pads and connecting taxiways, runway interiors and aprons, and runway edges.

b. Limitations on joint design were recorded wherein expansion joints were eliminated on rigid military airfield pavements; doweled construction joints were specified for the most critical traffic areas on heavy-load airfields; key-joint dimension investigations were initiated as highly controlled model tests in the laboratory. The condition surveys further established that even the most costly joint-sealing materials lost their surface-water-sealing effectiveness after only two or three years and served primarily thereafter only to preclude dust and debris from entering the joint. The program also assisted in establishing the relative effectiveness of contraction joints, the optimum depth of dummy groove, the optimum time of sawing the dummy groove, and specifications for curing at sawed joints.

c. The results of the surveys were used in establishing slab dimensional criteria and instructions for partial slab repair and replacement.

d. The Corps' specifications for concrete paving operations and pavement curing to prevent ultimate distress, such as shrinkage cracking, map cracking, and scaling, resulted from the condition survey program.

e. The program uncovered the critical problem of slight departure from design grade in pavements designed for heavy jet bomber aircraft, such as the B-47 and B-52, and assisted in establishing specification smoothness requirements to eliminate "porpoising" of the aircraft, a rather violet rocking mode of the aircraft occurring during high-speed takeoff runs and taxiing operations.

f. Information obtained in the condition survey program showed conclusively that the Westergaard based designs produced pavement thicknesses that were unnecessarily conservative for rigid pavements on high-strength foundations, with subgrade modulus, k, values above 200. The design procedures were modified in this foundation strength range to permit more than one crack as criteria for failure and incorporated in the design curves as a shift in the position of the k lines to yield reduced design pavement thickness requirements.

CHANNELIZED TRAFFIC

Perhaps the most dramatic finding associated with the condition survey program was in the spring of 1954 when longitudinal cracks were discovered in 90 percent of the slabs in the primary taxiway system at Lake Charles, Louisiana, after only one full year of B-47 bomber operations. Since all other pavement features were performing well and the quality of construction fully met specifications, the cause of the taxiway distress was not readily apparent. Additional condition surveys carried out at SAC bases throughout the U. S. within the following 12 months revealed that taxiways of both rigid and flexible pavements were showing similar distress at some 13 facilities. In early 1955 and as a direct result of these findings, the Chief of Engineers initiated a traffic-distribution investigation, which showed that aircraft equipped with steerable landing gear confined 80 percent of all wheel load traffic into a 75-in. width on taxiways and runway ends. The result was that the number of stress repetitions being applied in one year of operation exceeded the design life of these particular pavement sections. New criteria were developed to properly account for the increased volume of traffic or channelized traffic and the areas affected designated as Type A.

Two test sections, each consisting of three items, were constructed on a low-strength and a high-strength foundation at Sharonville and the extrapolated design thickness for Type A traffic areas were verified up to 30,000 coverages. One of the more significant aspects of the channelized traffic problem was that these taxiway pavements designed by Corps' criteria and by engineers in a number of Corps' offices throughout the country, failed under the design loading and at very near the design traffic volume. While failure to anticipate the channelization of traffic and the resulting failures were an embarrassment to the Corps (prompting a Congressional investigation[11]), it was of some

consolation to realize that our design and construction procedures were apparently well founded and represented neither an under design nor undue conservatism.

As a result of the channelized traffic investigations, the Corps and the U. S. Air Force agreed to some conservatism in the interpretation of data relating to stress repetitions versus design thickness. In 1956 the shape of the initial cracking curve was modified upward on a semilog plot of design thickness versus coverages for coverages beyond 5000. See Figure 2. This action produced about a 6 percent thickness safety factor at 30,000 coverages. Since the basis for design of Type A traffic areas was later established at 10,000 coverages for SAC airfields, few pavements were provided the full 6 percent cushion. Nonetheless many Corps' investigators have felt a simple straight line extension of the initial crack line on the semilog plot beyond 5000 coverages more nearly represented the traffic test results. It is probable that the assigned 15 percent increase in design gear loading resulting from the forward rocking motion of bicycle geared bomber aircraft during high-speed breaking, represents the greatest conservatism in present Corps of Engineers' rigid pavement criteria, since this factor was applied to all traffic areas on B-52 airfields.

PRESTRESSED CONCRETE PAVEMENT INVESTIGATIONS

Between 1955 and 1957 the Corps' extrapolated rigid pavement design methodology was developed for such loadings as the B-36 and B-47 to accommodate the B-52. This was done with reasonable confidence despite the fact that, for the first time, no validation was carried out through accelerated traffic tests. The new designs particularly for the Type A traffic areas were calling for concrete pavement thicknesses in the range of 22 to 27 in. In many parts of the country pavements of such thicknesses were extremely difficult to place with existing construction equipment. Problems developed in the logistics of merely getting up to 6 cu yd of concrete per running yard of pavement into a 25-ft lane, not to mention vibrating, screeding, finishing, and applying curing compound before initial set. The difficulties were further magnified in areas such as the southwestern U. S. where hot, arid climates accelerated curing to the point where only nighttime placement under a fog spray was possible. Under such conditions, the timing for sawing of dummy grooves at contraction joints to prevent random uncontrolled transverse cracking was quite difficult to establish.

In anticipation f the development of a supersonic replacement for the B-52 bomber system, engineers began to actively consider thinner pavement systems that would be capable of carrying a 700,000-lb aircraft, such as was forecast for the B-70 bomber and would produce a four-wheel twin-tandem main landing gear loading of 325,000 lb with tire inflation pressures in excess of 300 psi.

Since the required unreinforced concrete pavement thicknesses for the anticipated B-70 loadings would be generally in excess of 30 in., the construction problems experienced in the B-52 pavement construction program could only become more severe. Based on a review of all potential pavement types, the primary candidate for a thinner, more constructable system became prestressed concrete pavements. Through a comprehensive series of small-scale model tests, a design approach for prestressed pavements was advanced in 1955. These tests demonstrated very early in the program that criteria based solely on elastic behavior in a prestressed pavement would be unduly conservative. Consequently a tentative design procedure[12,13] was developed that permitted the formation of partial plastic hinges (i.e. tensile cracking in the bottom of the slab resulting from positive radial moment), which in turn cause a redistribution of moments and under increased loads or traffic volume the ultimate buildup of negative radial moments at the top of the slab. The design loading then becomes that combination of load and traffic volume which produces a negative radial moment of sufficient magnitude to induce initial cracking in the top of the slab. See Figure 3.

This prestressed concrete pavement design approach gained partial field validation at Sharonville in 1957 where nine full-scale test items were constructed on low-strength subgrades and trafficked under heavy twin-tandem gear loadings. The design procedure adopted by the Corps was established with some built-in conservatism because further investigations were considered essential to properly position the criteria for a full range of load repetitions and high-strength foundation soils. Conservatism was further believed warrented because ultimate failure of prestressed pavements are relatively

dramatic and occur with little advance warning. The failure is characterized by a complete disintegration of the concrete surfacing generally over elliptically shaped areas of 4 to 8 ft across the minor axis. The volume of traffic is quite small that causes the progression of initial surface cracking into a complete failure. For airfield pavements prestressing is recommended in both the longitudial and transverse direction. Compression joints where transverse prestress acts across longitudial construction joints are not an apparent source of weakness in the system.

PERIOD OF LIMITED RESEARCH

In 1957 additional rigid pavement test items were constructed at Sharonville for investigation under the 325,000-lb twin-tandem gear loading. Only six items were traffic tested and consisted of plain concrete on grade, partially bonded and fully bonded rigid-over-rigid overlay pavements, and one sandwich item composed of a plain rigid slab over an asphaltic concrete over a plain rigid base slab. Traffic testing of reinforced rigid overlays of plain concrete base pavement and plain concrete over a lean-mix concrete base were not carried out because the pavement investigational program funding was curtailed in 1958 by the U. S. Air Force.

A summary of the Corps rigid pavement research efforts through 1958 is presented in Reference 14. Except for minor modification, the design posture remains today essentially as it was in 1958. As will be discussed later, certain improvements in design methodology will become highly desirable and perhaps essential in the future. Work on these improvements has been initiated but is proceeding slowly because of low research funding priority.

Between 1958 and 1968, the Corps carried out only minor investigations relating to rigid pavement design and construction. Basic research efforts in random wire-reinforced concrete pavements were undertaken by the Corps' Construction Engineering Research Laboratory, but these were generally limited in scope to mix design and physical property studies. Some additional work was accomplished at the Waterways Experiment Station during this period in the development of nondestructive testing equipment procedures for both rigid and flexible pavement evaluation.

VERY HEAVY MULTIPLE-WHEEL-LOAD INVESTIGATIONS

In 1968 the Department of the Air Force, the Department of the Army, and the Federal Aviation Administration undertook joint sponsorship of a major two-year investigation to determine the adequacy of existing airfield pavement design methods for such heavy, multiple-wheel aircraft as the military C-5A and the commercial 747. For rigid pavements, the primary finding was that the Corps' version of the Westergaard analysis gave an accurate assessment of stress conditions in the slab and pavement thickness requirements. The procedures needed modification for pavement joint design. Specifically the keyed construction joint was found to give unsatisfactory performance when employed on pavement systems having low-strength foundations.

As a consequence of the Very Heavy Multiple-Wheel-Load Investigation, design criteria for Air Force facilities were modified to eliminate keyed construction joints in Type A traffic areas on airfields designed for the C-5A. For 747 airfields (or other commercial facilities having a design aircraft loading over 200,000 lb) the Federal Aviation Administration revised design criteria to permit the use of keyed construction joints only on cement-stabilized foundations.

The investigational program also indicated that pavement smoothness problems might occur on rigid pavements subjected to the operation of very heavy multiple-wheel aircraft when constructed on low-strength foundations. Even on pavements evidencing no structural distress, the operation of these 700,000-lb plus aircraft can cause an overall slab displacement on soft foundations that could prove objectionable. The Corps recognizes the potential problem but has not taken specific action. We feel the phenomenon should be further investigated even though it is not believed to be critical with respect to either C-5A or 747 operations. These aircraft are not particularly sensitive to low orders of pavement roughness in their operations.

In the early 1970's the Corps' airfield pavement research activities became characterized by multi-agency sponsorship. A broad scope of technical investigation, centered around the development and refinement of nondestructive pavement evaluation equipment the exploitation of various analytical techniques to study pavement performance. Little effort was devoted to full-scale accelerated traffic testing, but those tests that were carried out were, to our mind, highly significant. In a series of low-budget, limited-scope investigations sponsored primarily by the Chief of Engineers, it was demonstrated that present design and analytical methods for rigid and flexible pavements were quite conservative in predicting the performance of certain complex multilayered pavement systems. A number of these systems incorporating a range of materials, stabilization treatments, and even reinforced earth concepts below the pavement surface gave truly phenomenal performance under very heavy aircraft loading.

PRESENT RESEARCH ACTIVITIES

In reflecting upon the results of these apparently anomalous pavement tests, the Waterways Experiment Station pavement research staff undertook an in-depth evaluation of the state-of-the-art in all airfield pavement design, of the avenues offering the greatest potential gains in future research activities, and an assessment of the research time and effort required to make these gains. These were incorporated in a comprehensive five-year research plan, which has guided many of our efforts over the past few years. From the standpoint of airfield pavement design, the following is a summary of significant conclusions resulting from this evaluation.

a. The Corps' design methods for both rigid and flexible pavements, though empirically based, are considered valid for plain and reinforced jointed concrete pavements; for flexible pavements that do not incorporate chemical stabilization or materials reinforcing concepts in the base, subbase, and subgrade; and for simple overlays composed of these specific material types.

b. These same empirically developed design methods are not suited to the assessment of performance in systems that depart in concept from the Corps' definitions of "rigid" and "flexible" pavements.

c. Improved procedures are considered essential to the analysis of performance of pavement systems that would incorporate multiple-pavement layers, chemically or structurally stabilized foundation layers, continuously reinforced or prestressed concrete when employed in conjunction with layered foundations.

d. Promising procedures are available for application to analysis of stresses and deformations in complex layered systems. By making prudent use of the wealth of model and full-scale traffic test data available in the Corps and other agencies, such procedures, to some degree, have an available validation base. If improved analytical procedures can be made to accurately explain what we already know with some confidence, the procedures can be better trusted to respond to more complicated systems.

e. Two factors tend to complicate the selection of an optimum analytical procedure.

(1) Physical property input. Probably the most powerful analytical tools available would involve the adaptation of two- or even three-dimensional finite element codes capable of responding to nonlinear stress-strain behavior of materials, volume change characteristics, and such anomalies as joints and cracks in the systems. Unfortunately, the basic research effort required to develop test procedures and equipment capable of producing these constitutive physical properties is both time-consuming and costly and would thus delay immediate exploitation by pavement designers. Despite this constraint, we feel that the finite element procedures offer the highest promise of fully and rationally explaining the behavior of complex pavement systems and should be pursued by pavement design researchers in the future.

(2) Definition of failure. The distress in a pavement system that constitutes "failure" is a complex and essentially undefined variable in itself. It depends not only on the degree of cracking, deformation, and roughness in the pavement system but equally upon the operational capabilities of the using aircraft. Some aircraft systems can operate satisfactorily and safely over relatively rough pavements; some can not.

In attempting to forecast future requirements for airfield pavement design and construction both in the military and commercial sector, we feel that major emphasis must again be placed on major rehabilitation of existing systems. While requirements for entirely new runway, taxiway, and apron systems will undoubtedly continue, the upgrading of existing pavements that have been in service for long periods of time or that must support new aircraft systems of the future will be given increasing consideration by planners. One can relate this emphasis economically to the large investment in existing terminal facilities and airfield service structures and to the restrictions on development of new real estate from the standpoint of both economic and environmental considerations. It is possible that ultimate rehabilitation of the Interstate Highway System resulting from requirements for extended service life or increases in traffic volume and loading will also accentuate the need for rehabilitation rather than entirely new construction.

As pointed out in previous discussions, the applicability of the Corps' rigid pavement design methods to the multilayered systems that would result from extensive overlays is limited at best. We, therefore, place a high priority on development of analytical procedures capable of responding to these needs.

In the process of improving the rigid pavement design procedure, the question arose as to what basic response model should be used. The decision was made to use an elastic-layered response model as proposed by Burmister.[15] In particular the computational procedure used is a computer program (BISTRO) prepared by Peutz, et al[16] that employs certain numerical techniques to solve the basic equations proposed by Burmister.

By changing response models, implications are that the present model (often referred to as the Westergaard idealization)[8] which defines the pavement as a thin elastic plate on a dense liquid (Winkler) foundation is inadequate and that the model selected is the best available. These implications are not entirely true. Our intent is to gain an analytical capability for design of rigid pavements founded on or incorporated in complex multilayered systems. To approach this objective at this point in time, we feel that it is important to adopt a readily usable model and to correlate the output with our present system before attempting more complicated applications. This led us to the selection of the elastic-layered response models. In taking this step, we are not indicting the Westergaard based method; we are simply acknowledging its limitations.

The use of the elastic-layered model permits the pavement to be represented as a series of layers rather than representing the support characteristics of all layers beneath the concrete slab with the modulus of subgrade reaction, as measured with a plate load test with a 30-in.-diam plate. This should present a more accurate representation, especially when stabilized layers of various quality and thickness are involved. The representation with the layered system should also prove advantageous where there is a change in the subgrade (to a softer or stiffer strata) at relatively shallow depths.

The characterization of each layer with elastic constants obtainable from laboratory tests makes procedures for material optimization and cumulative damage feasible. A number of materials can be tested in a number of conditions much easier and at less expense in the laboratory than in the field with a plate bearing test. In addition, layer thickness can be varied with the elastic-layered model.

One weakness of the elastic-layered model is that joints and discontinuities in the slab cannot presently be considered. The pavement is represented as elastic layers of infinite horizonal dimension on an elastic half space. The Westergaard model permits the computation of the stress at the edge of a finite-dimensioned slab and, as such, permits the representation of stress conditions at a joint or crack. In developing a working application of the elastic-layered analysis considerable dependance will be placed on the correlation between the performance of the pavement and the limiting parameter from the response model that is used to establish the design criteria. The criteria used in conjunction with the elastic-layered model will be criteria established by a compatible correlation and the neglect of joints may not prove to be a serious fault, provided certain minimum joint requirements are met.

SUMMARY

The Westergaard analysis of stresses in concrete airfield pavements has served the Corps of Engineers exceptionally well for more than 30 years. The results of research and investigational efforts including accelerated traffic testing, model studies, field condition surveys, and programs for developing field and laboratory test procedures have played a significant role in refining and modifying the basic Westergaard analysis into an accurate and well-validated design tool. Based on the performance of almost 100,000 sq yd of concrete pavements on military airfields, we are convinced the Corps' design procedures will result in satisfactory pavements that are neither unduly conservative nor underdesigned.

While at some periods in the Corps' design research programs the desirability of changing to a possibly more versatile elastic or an elastic-layered analysis may have been attractive, such action would have required a funded effort that our military sponsors have been unwilling to support. Further for the relatively simple unreinforced pavements at Army and Air Force airfields, it is doubtful that a new design base would be demonstrably cost effective. The pavement thickness and configuration produced by a new design procedure would be very like that resulting from the Westergaard based design.

Because of this lack of interest by our sponsors in developing entirely new design methods, the research and engineering staff of the Corps has treated each new requirement, such as increases in aircraft weight, gear load, number of wheels, and traffic volume, as an extension to the existing design methodology. This approach was usually essential in order to perform the necessary investigations in a time frame responsive to rather short-range construction programs.

Within the past few years, the Corps' pavement research family has once again been confronted with circumstances that indicate an advantage to changing our basis of design. New sponsors, such as the Federal Aviation Administration, desire serious consideration of layered-pavement systems, stabilized bases, and extensive use of reinforcing. The need for complex rigid overlay pavements on present military airfields may be required within the next few years. The Westergaard analysis does not respond well to the design of these pavement types. We have, therefore, embarked upon a course of developing and validating a layered-elastic analysis that will replace both our present rigid and flexible pavement design methods and that we hope will permit us to better address more complex pavement types.

Within the coming years, we hope to achieve an improved ability to design airfield pavements of continuously reinforced concrete, prestressed concrete, concrete overlays, and rigid pavements on chemically stabilized foundation layers with at least the same confidence we presently design plain "rigid" and "flexible" type pavements. It is our desire to base this new posture on well-validated analytical procedures and with a minimum of empirical correlation.

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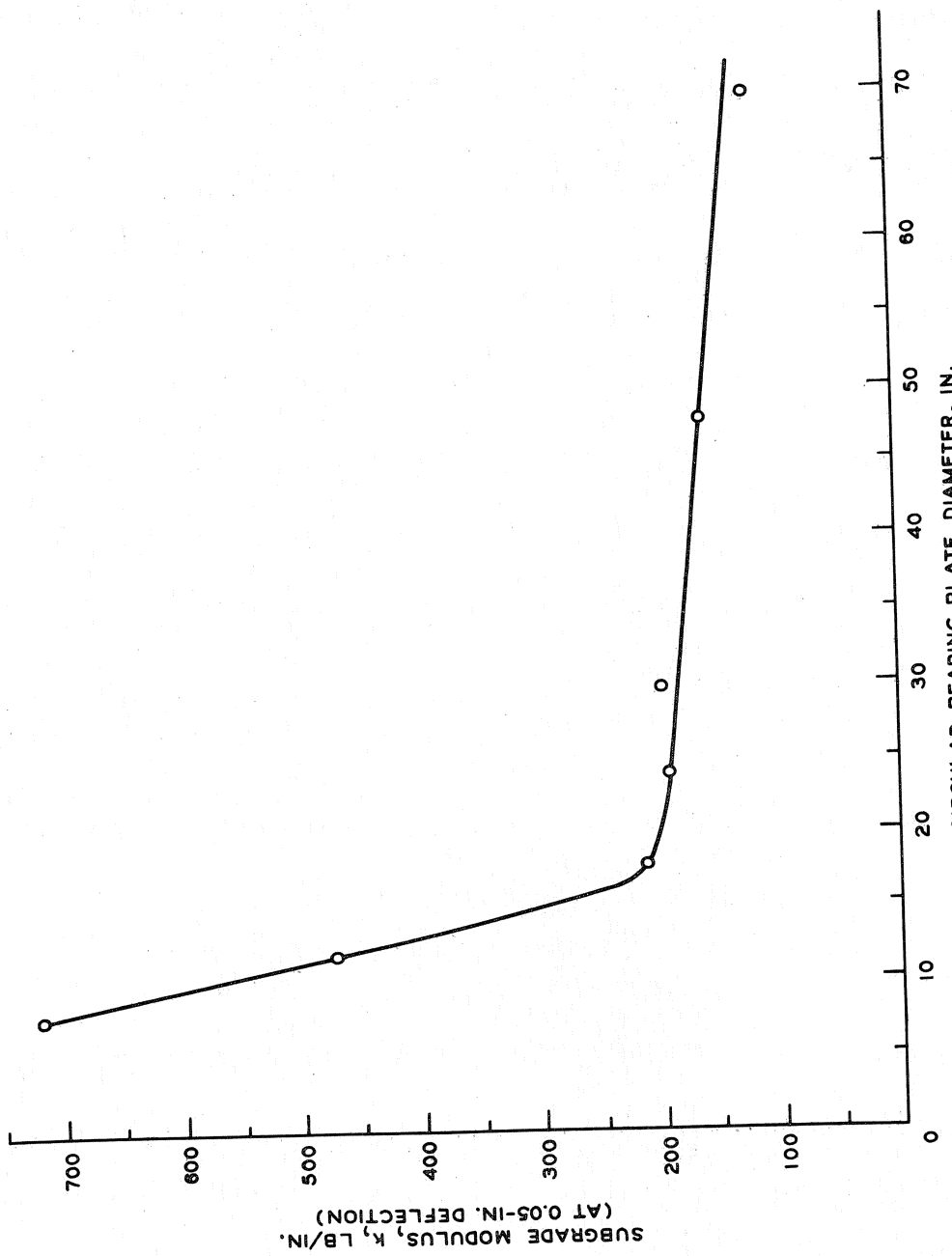


Figure 1. Results of subgrade modulus tests at Wright Army Airfield, Ohio, 1942, using bearing plates of various diameter, U. S. Army Engineer Ohio River Division Laboratories

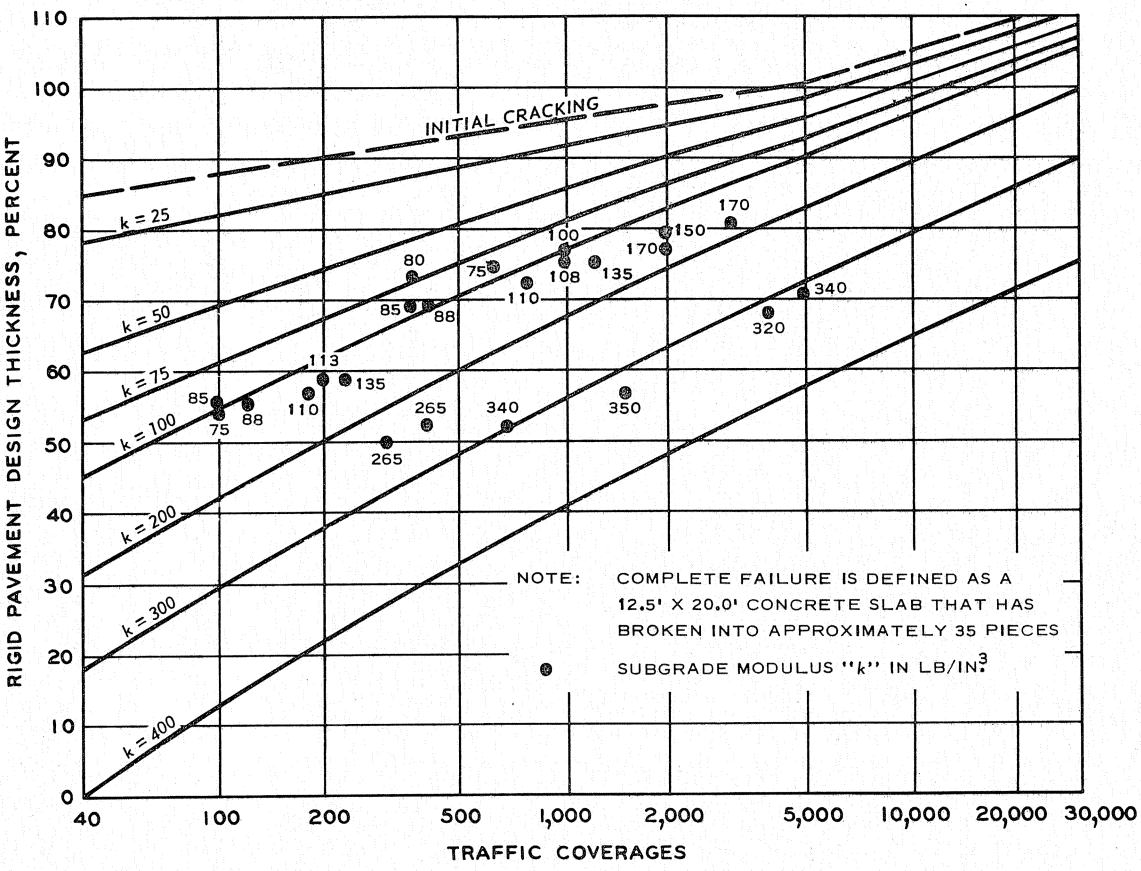


Figure 2. Percent design thickness versus traffic coverages at complete failure for tricycle-type landing gear on airfield pavements

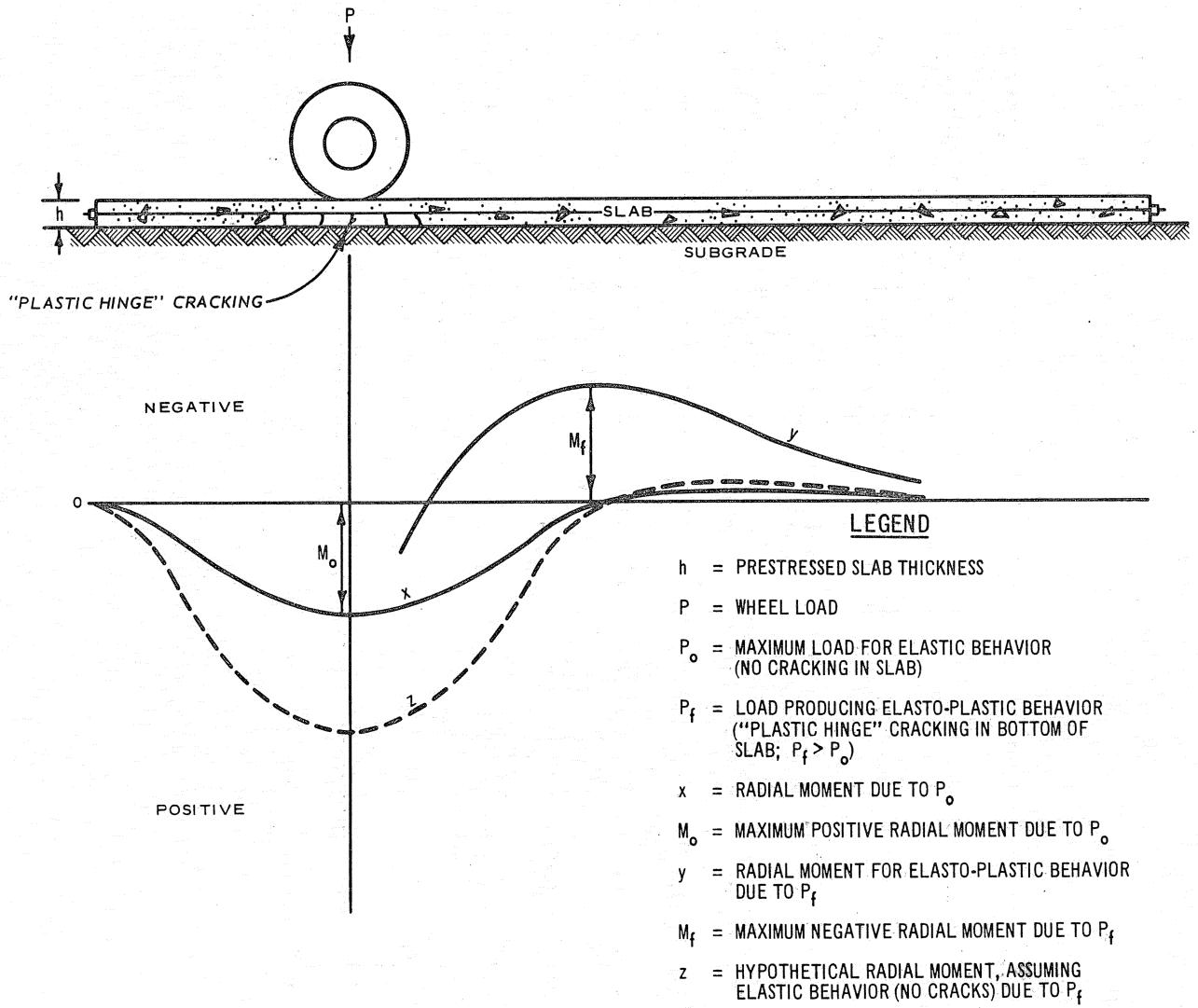


Figure 3. Radial moments for prestressed concrete pavements