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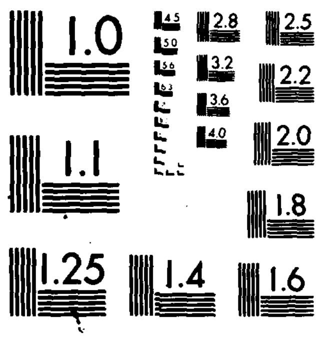

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DYNAMIC RESPONSE OF AIRFIELD PAVEMENT TO LARGE MAGNITUDE LOADS

LEVEL II

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JANUARY 1980

FINAL REPORT
JUNE 1979 — JANUARY 1980

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER ESL-TR-80-10	2. GOVT ACCESSION NO. AD-A098 796	3. RECIPIENT'S CATALOG NUMBER (9)
4. TITLE (and Subtitle) (6) DYNAMIC RESPONSE OF AIRFIELD PAVEMENT TO LARGE MAGNITUDE LOADS,		5. TYPE OF REPORT & PERIOD COVERED Final Report, Jun[redacted]79 - Jan[redacted]80
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Gerald A. Woelfl (10)	(14) AFESC/ESL-TR-80-10	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Civil Engineering Marquette University 1515 West Wisconsin Avenue Milwaukee, Wisconsin 53233	(16)	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (17) JON: 2104 2B-22 PE: 63708F
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Engineering and Services Center Tyndall Air Force Base, Florida 32403	(11)	12. REPORT DATE Jan[redacted]980 (12) 34
		13. NUMBER OF PAGES 30
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Availability of this report is specified on verso of front cover.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Pavement Response	Pavement Materials
Pavement Analysis	Runway Repair
Dynamic Loads - Pavement	Bomb Damage Repair

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The evaluation of rapidly repaired bomb damaged runways requires determining the dynamic response of pavement due to large dynamic loads. This report recommends using one of the sophisticated computer codes currently available for a conventional static analysis of airfield pavements, but with the use of appropriate dynamic material properties to predict the dynamic response of pavement. In order to select the appropriate dynamic material properties, the stress variation as a function of time is developed for pavements subjected to moving → next page
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20. **ABSTRACT (CONCLUDED)**

wheel loads. A review of the literature indicates that the elastic properties and fatigue strength of Portland Cement Concrete are relatively the same for dynamic as for static loading. The dynamic response of asphalt concrete, granular base and subbase material, and subgrade soil, however, is significantly improved relative to the response of these materials to static loads. Further, the dynamic behavior of granular material is time-independent, but for asphalt concrete and subgrade soils, especially cohesive soils, the dynamic properties vary with aircraft velocity (ie, rate and duration of loading). Recommendations for further research in this area are also given.

PREFACE

This research effort was performed under the summer faculty research program sponsored by the Air Force Office of Scientific Research and conducted by the Southeastern Center for Electrical Engineering Education. This effort was begun in June 1979 and was completed in January 1980.

The author would like to thank the Air Force Systems Command and The Air Force Office of Scientific Research for providing him with the opportunity to spend a most worthwhile summer at Tyndall Air Force Base. The author would also like to thank the Southeastern Center for Electrical Engineering Education, and in particular Dr. Richard Miller, for a well organized program.

Special acknowledgement is also due those at Air Force Engineering and Services Center at Tyndall for their cooperation and assistance, and for providing a pleasant working environment.

The author is especially indebted to Robert Van Orman, Lt Col Roger Caldwell, Capt Michael McNerney, and Phillip Nash for their continuous encouragement and guidance and for numerous helpful discussions.

Finally, the author would like to express appreciation to Marquette University, and in particular to Professor William Murphy, for encouragement and support in this rewarding endeavor.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

The design and analysis of airport pavements is based on static wheel loads. But measurements of landing gear forces during various aircraft modes of operation have shown that pavements are subjected to dynamic loads of higher magnitude than the static load. Traditionally, because of the relatively slow response of pavement materials, these higher magnitude dynamic loads were neglected in pavement design. Field observations have reinforced the use of static load for pavement design. Areas of airfield pavements subjected to static and low speed modes of aircraft operation generally show more distress than areas of runways limited to medium and highspeed aircraft operations.

The objective of the Air Force's Rapid Runway Repair program is to provide a 50 ft by 5,000 ft section of operational runway as rapidly as possible. Rapid bomb damage repair techniques are being developed to meet this objective. Because of the limited length of the repaired runway, it is unlikely that it will be subjected to static aircraft loadings. For this reason the structural design and analysis of rapid runway repairs are based on the results of field tests using an aircraft load cart at creep speeds of about 2 to 3 mph (1).

Because of the time constraints for rapid runway repair, the repaired runway section will have considerably more surface roughness than conventionally constructed airport pavements. This increased surface roughness will yield unusually high magnitude dynamic loads during various aircraft modes of operation - up to 2.5 times the static wheel load for main landing gears and even higher for the nose gear. Current research efforts in the Air Force Bomb Damage Repair program concentrate on the effects of these high magnitude dynamic loadings to the aircraft structure, aircraft payload, and pilot performance. The response of the pavement to these high magnitude dynamic loads, however, must also be investigated.

Specifically, the structural adequacy of the repaired runway subjected to medium and high speed aircraft taxi modes must be evaluated from the results of field tests using load carts at creep speeds.

The problem is: most field test programs conducted to evaluate the performance of airfield pavements have been limited to static and creep-speed loadings; field tests which have included higher aircraft speeds have been limited to relatively smooth surfaces and therefore high magnitude dynamic loads were not encountered; and, field testing on rough surfaces (bomb damaged repaired runways) has for the most part been limited to aircraft response.

The purpose of this report is to develop an approach to predict the performance of rapid runway repairs subject to high magnitude dynamic aircraft loads caused by the unusual surface roughness of rapidly repaired runways.

Because of time limitations and the broad scope of the topic, this study is confined to the following objectives:

1. Review the results of recent field tests addressing the response of airfield pavements to dynamic loads.

2. Define an analytical approach for evaluating the performance of airfield pavements subject to high magnitude dynamic loading.

3. Describe pavement stresses as a function of time due to moving wheel loads.

4. Discuss the dynamic behavior of pavement materials.

SECTION II

RECENT FIELD TESTING

Because of growing concern over detrimental effects of dynamic loads of airport pavements, the Federal Aviation Administration (FAA) sponsored a study entitled "Aircraft Dynamic Wheel Load Effects on Airport Pavements" by Wignot, et al dated May 1970 (Reference 2). The study included analysis of both aircraft and pavement dynamic responses and scaled pavement tests.

This initial FAA study raised many questions concerning the response of pavement to dynamic loads. As a result, the FAA sponsored an extensive experimental study conducted by the US Army Engineer Waterways and Experiment Station (WES) during the period from May 1971 to January 1975 and described in a three-volume report entitled "Pavement Response to Aircraft Dynamic Loads" (References 3, 4, and 5). The purpose of this study was to determine the relationship between responses of flexible and rigid runway pavements to static and dynamic loads. The study used data from instrumented B-727 and C-880 aircraft on instrumented sections of both flexible and rigid pavements.

In addition to static tests, the WES investigation dealt with a number of aircraft modes of operation. Both aircraft and pavement measurements were recorded during creep-, slow-, medium-, and high-speed taxiing, high-speed braking, high-speed braking with reverse thrust, takeoff rotation, touchdown, and turning.

For the study, gages were installed in flexible and rigid pavement test sections to measure pavement responses to dynamic loads in the form of relative displacements and pressures at various depths and locations within the pavement structure. A total of 162 gages were installed in the flexible test section, and 153 gages were installed in the rigid pavement section. A series of tests were conducted on both pavement sections during cold weather when the pavement surface layer temperatures ranged from 35° to 55°F; an additional series of tests were conducted on the flexible pavement test section during hot weather when the pavement surface layer temperatures ranged from 84° to 116°F.

The interpretation of results relied on separating the data into an elastic phase and an inelastic phase. Inelastic displacements are residual displacements remaining after the wheel had passed. If loads were repeatedly applied on the same wheel path, the pavement would become conditioned and the inelastic displacements would be permanent after a few initial repeated loadings. However, aircraft traffic loading is randomly distributed; in actual use, airfield pavements never become totally conditioned and therefore inelastic displacements are not permanent but occur continuously throughout the life of the pavement. For this reason, the WES tests used a distributed traffic pattern as does the rapid runway repair testing at Tyndall Air Forced Base, Florida.

Figure 1 summarizes the results of the taxi tests at various aircraft velocities for both rigid and flexible pavements. The maximum elastic and inelastic surface displacements are shown separately.

The elastic displacements for rigid pavement and for flexible pavement at cold temperatures remain relatively constant, being independent of aircraft speed. Elastic displacements for the flexible pavement at higher temperatures, however, decrease considerably as aircraft velocity increases for velocities below 35 knots. This elastic response of pavements relative to aircraft speed, type of material, and for asphalt, material temperature correlates well with elastic material properties. The modulus of elasticity of concrete changes little with rate of loading. The complex modulus of asphalt, however, varies with the frequency of the applied load and, therefore, with rate of duration of loading; as the frequency increases, the modulus increases. For asphalt concrete at low temperatures, frequency has much less effect on the modulus whereas at high temperatures, the modulus increases substantially with an increase in frequency. Material behavior is discussed in more detail in Section VI of this report.

Figure 1 shows that the rigid pavement had little inelastic behavior. Therefore, predicting the response of rigid pavement to aircraft at various speeds from pavement response to creep-speed loads simplifies to an elastic analysis providing the proper elastic material properties are used in the analysis.

From Figure 1, flexible pavement shows considerable inelastic behavior, especially at the higher temperature. However, since this inelastic behavior decreases rapidly with aircraft velocity, an elastic analysis, with appropriate material properties, can be used to predict the response of flexible pavements for various aircraft speeds based on the results of creep speed taxi tests. Heukelom and Klomp (Reference 6) states the Road Research Laboratory concluded that flexible roads behave elastically under vehicles moving at speeds exceeding 15 mph, and probably also at lower speeds.

The WES study showed that "... no basic aircraft ground operating mode induced pavement responses (elastic plus inelastic) greater than those occurring for static load conditions...". However, the flexible and rigid runways used for the investigation were relatively smooth. The vertical gear loads varied from .45 to 1.25 times the static load for creep

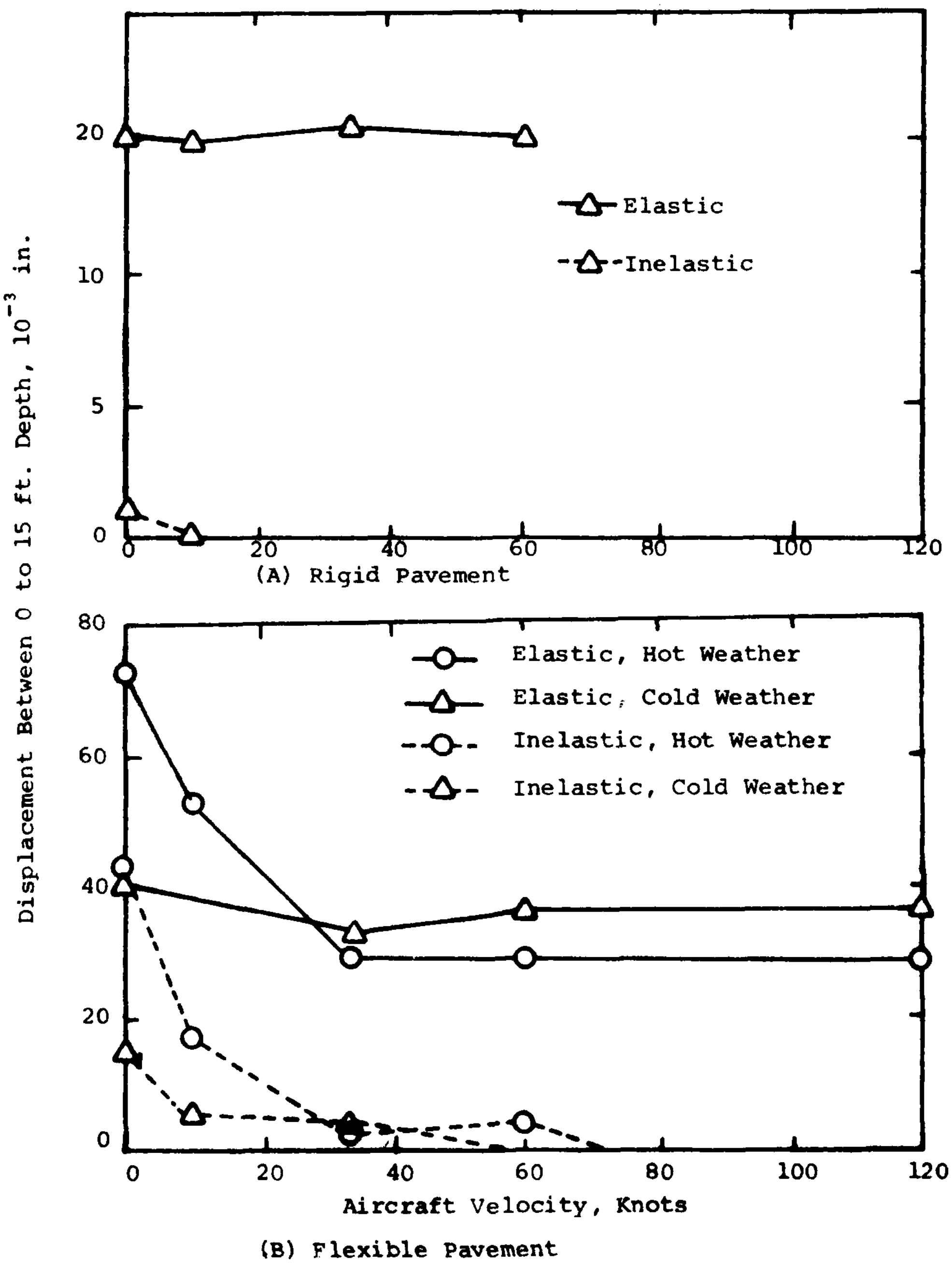

Figure 1. Maximum Elastic and Inelastic Vertical Relative Displacements Between 0 to 15 ft. Depth Verses Velocity

through high speed taxi modes for the flexible hot weather tests. For the cold weather tests, main and nose gear loads varied from .55 to 1.20 times the static load for flexible pavement and .35 to 1.25 times the static load for rigid pavement.

The Air Force is currently conducting an extensive field test program referred to as "Have Bounce" (Reference 7). The Have Bounce program utilizes instrumented F-4E aircraft operating at various speeds on runways repaired with various configurations of AM-2 mats. The repaired runway has unusually high surface roughness since the top surface of the mats are about 1 1/2 inches above the pavement surface. A short ramp is used for the transition from pavement surface to mat surface.

Preliminary data from the first phase of the Have Bounce testing program indicates that the vertical dynamic main gear loads are as much as 2.5 times the static aircraft weight because of the increased surface roughness. Nose gear loads were as high as 3 times the static main gear loads, but since static nose gear loads on the pavement are considerably less than main gear loads, main gear loads are the critical loads for design. Although the WES study did not investigate high magnitude dynamic loads, Ledbetter concludes:

> "The larger than static load response that could occur should be entirely elastic and should not be detrimental to the pavement structure except by contributing to an increase in elastic fatigue damage." (Reference 5, Page 90)

But the above conclusion is based on test results of conventionally constructed airfield pavements. Rapid runway repairs differ from conventional pavements, however, in that repair techniques do not provide for sufficient compaction of the subgrade in the repaired area. Therefore, high magnitude loads at faster aircraft speeds may produce larger inelastic displacements than inelastic displacements resulting from creep-speed load cart tests.

The high magnitude dynamic loads resulting from surface roughness are not constant but rather periodic. Preliminary data from the Have Bounce investigation showed main gear loads had a frequency between 1.8 to about 2.03 hertz. The frequency varied with aircraft gross weight but was relatively independent of aircraft velocity.

A similar type of oscillation was noted by Yang during creep-speed load cart tests at Newark Airport (Reference 8). The instrumented test pavement consisted of asphalt concrete on various granular bases. The fundamental frequency of the loading vehicle simulating a Boeing 747 ranged from 1.6 to 2.0 hertz.

A frequency of about 2 hertz was visually observed for the F-4 load cart used for rapid runway repair field testing at Tyndall Air Force Base. The F-4 load cart used at Tyndall, as well as the load cart used for the Newark testing, had no shock absorber except the damping of the pneumatic tires.

SECTION III

DYNAMIC ANALYSIS OF PAVEMENT

There are many failure criteria used in the evaluation of airfield pavements, but for structural analysis of pavement systems, material failure is the only controlling factor. It must be emphasized, however, that material failure in itself does not constitute failure of the pavement system. Material failure as pavement failure criteria may be too conservative for conventionally constructed pavements since a cracked pavement may be acceptable to the user, provided the riding surface is satisfactory. Parker, et al (Reference 9) report that rigid pavements with high-strength foundations continued to satisfactorily carry loads after cracking, but that rigid pavements with low-strength foundations developed multiple cracking and differential displacements (increased surface roughness) soon after initial cracking. Because most rapid runway repair methods being considered involve low-strength foundations, the use of material failure is probably more realistic than for conventionally constructed pavements.

From the standpoint of structural analysis of pavements, the two material failure criteria currently used are rupture failure due to a few loads of excessive magnitude and fatigue failure due to repeated loads. Because of the unusual surface roughness of rapidly repaired runways, the pavement would be subjected to repeated high magnitude loads and, therefore, pavement evaluation should be based on fatigue failure rather than rupture failure. Specifically, stresses and strains within the pavement structure should be compared with limiting fatigue values which are based on the expected number of load repetitions. Assuming inelastic pavement response plays a minor role in the dynamic response of pavements, an elastic analysis can be used to determine the pavement stresses and strains.

The problem of computing dynamic stresses and strains due to a moving wheel load has been solved for a plate on a Winkler foundation and for a plate on an elastic halfspace (Reference 2). But even with the sophisticated computational techniques currently available, the solution of the problem requires a number of simplifying assumptions regarding structural behavior and material properties.

Another approach to determine dynamic pavement response is to simplify the dynamic load by treating it as a static load and using dynamic material properties for the analysis. With this approach, more realistic results are obtained since material properties and structural behavior can be more accurately modeled. The main objection to using a static analysis with appropriate dynamic material properties is that inertia effects are ignored.

Mass and damping effects have generally been neglected in pavement design since only high speed or high frequency dynamic loads would cause inertia effects to influence dynamic pavement response.

Heukelom, Klomp, and Foster have studied the influence of mass and damping of pavement systems on the dynamic response of highway pavements (References 6, 10, and 11). They found that mass and damping hardly have any influence on the stresses which are generated in a pavement on a good subgrade (i.e., excluding peat) under actual traffic loading. Consequently, they conclude that the application of static theories is justified provided that dynamic values of the material properties are used.

The FAA-sponsored study (Reference 2) included an analysis of mass effects on airfield pavements which showed that inertia forces at taxi speeds as high as 230 mph have little influence on dynamic pavement response. The study also concludes that if the dynamic load has a frequency below about 10 hertz (aircraft taxi mode loadings generally have frequencies ranging between 1 and 5 hertz), inertia effects are negligible.

Considering the approximations made for input data required for pavement analysis, it can be concluded that variations of mass and damping effects have little influence on the accuracy of results.

In summary, the dynamic performance of pavements can be evaluated by using the expected maximum magnitudes of dynamic loads as static loads and performing a conventional static analysis using appropriate dynamic material properties. This approach makes use of finite element computer programs, such as the Air Force computer code PREDICT (Reference 12), which have been developed for pavement analysis (PREDICT has the potential for doing a complete dynamic analysis which includes inertia effects, but this part of the program has not been developed). The resulting stresses and strains from such an analysis would then be compared to limiting fatigue values which take into account dynamic loading.

SECTION IV

PAVEMENT STRESS VARIATION AS A FUNCTION OF TIME FOR DYNAMIC LOADS

Although the response of pavement is not very sensitive to mass and damping effects, the response is sensitive to material properties which, in turn, depend on duration of load and rate of loading. Before material properties can be discussed, therefore, pavement stress as a function of time must be described for a pavement subjected to a moving wheel load of oscillating magnitude.

Pavement stress variation with time can be determined by visualizing the stress distribution due to a static load as moving through the pavement with time. For example, Figure 2(B) shows the stress distribution which would be expected for horizontal stress at the bottom of a rigid pavement slab due to a static wheel load. Assume the stress distribution can be approximated with a half cosine function:

$$\sigma_x = \sigma_o \cos \frac{\pi}{\lambda} x \qquad (1)$$

for $$-\frac{\lambda}{2} < x < \frac{\lambda}{2}$$

Where σ_o = maximum stress directly under the wheel

λ = half the wave length in feet (the distance between points of inflection of the slab)

x = distance in feet

The stress distribution could be more accurately described by a Fourier series, but for purposes of this report, the above approximation is sufficient.

The half-wavelength, as defined for this report, is the distance between points of inflection of the slab and is a function of the characteristic length (plate rigidity and subgrade stiffness (Reference 8 and 13)) of the plate and the dimensions of the tire footprint. Since the dynamic response of the tire is relatively instantaneous (tire pressure remains constant) the tire footprint dimensions will be a function of aircraft landing gear configuration and magnitude of the wheel load. Trial runs using the Air Force computer code PREDICT gave values for λ of between 2 and 20 feet for an F-4 aircraft at various subgrades. The reason for such a large variation of λ is because the aircraft gross weight was varied from static weight (27 kips) to three times the static weight (81 kips). Yang (Reference 8) observed the distance between points of inflection to be 12 feet for

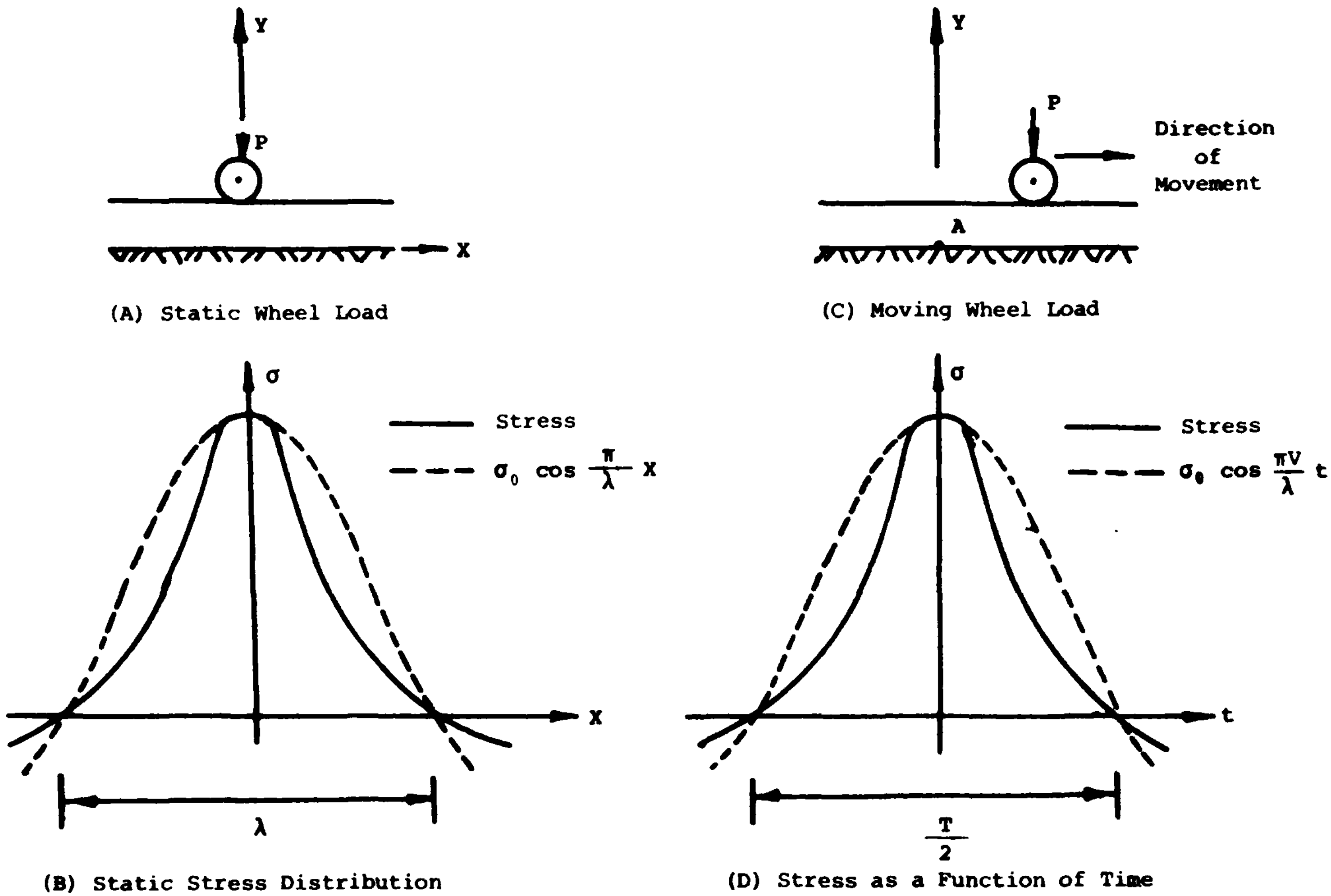

Figure 2. The Relationship Between Static Stress Distribution and Stress as a Function of Time for a Moving Wheel Load

various thicknesses of asphalt concrete pavements on different bases. Ullidtz (Reference 22) approximates the half-wavelength for flexible pavement as the footprint length plus the thickness of asphalt concrete.

The important point is that the half-wavelength, λ, and the maximum stress, σ_o, directly under the wheel can be determined from a static stress analysis of the pavement structure. As will be shown, this is all that is needed to describe the stress as a function of time.

For a moving wheel load, the static stress distribtuion can be visualized as moving through the pavement system with time; i.e., for a given point, such as point A shown in Figure 2(C), the stress will vary with time as shown in Figure 2(D). Actually, because of horizontal forces induced by moving wheel loads, the stress variation with time curve would be nonsymmetric; this effect is not included in a static stress analysis, but the problem is that the sophisticated computer codes currently available are limited to axisymmetric loading.

To transform stress as a function of distance to stress as a function of time, assume constant velocity (aircraft acceleration would cause negligible nonsymmetry in the stress as a function of time curve). Then

$$V = \frac{x}{t} \tag{2}$$

where V = aircraft velocity in ft/sec

t = time in sec

and

$$\sigma_t = \sigma_o \cos \frac{\pi V}{\lambda} t \tag{3}$$

for $-\dfrac{\lambda}{2V} < t < +\dfrac{\lambda}{2V}$

where σ_o = maximum stress as $t = 0$, i.e., when the wheel load is directly over Point A

The duration of load (for this report, the duration of the main stress pulse will be referred to as the duration of load) is simply one-half the period, or

$$\frac{T}{2} = \frac{\lambda}{V} \tag{4}$$

Only a constant load has been used, but as stated earlier, for rough surfaces the load is periodic. The stress under the wheel load, σ_o, is a function of time as shown in Figure 3(A).

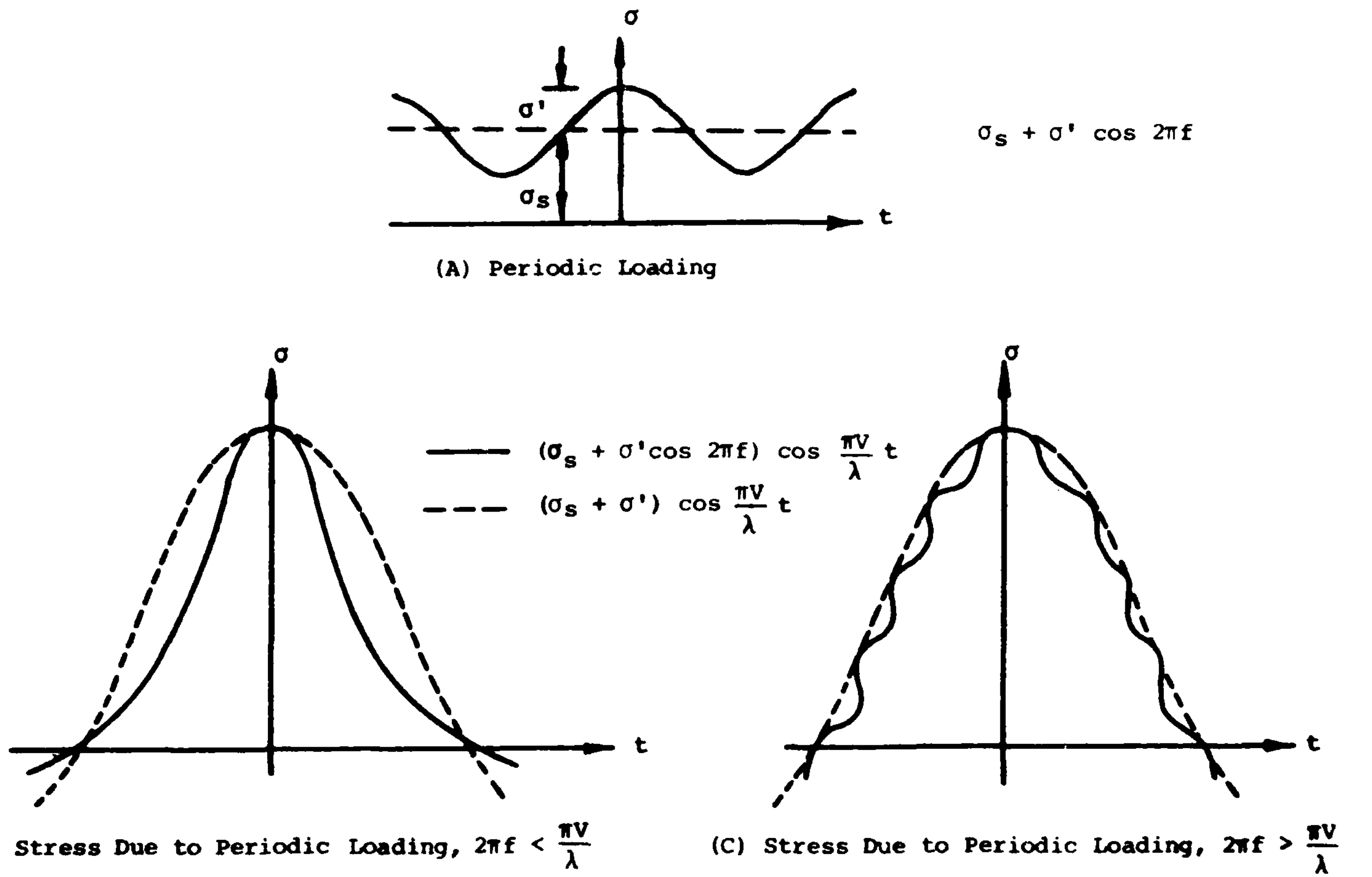

Figure 3. Pavement Stress as a Function of Time Due to a Periodic Moving Wheel Load

For the critical case when the periodic load is a maximum at t = 0, i.e., when the maximum wheel load is directly over point A, σ_o can be expressed by

$$\sigma_o = \sigma_s + \sigma' \cos 2\pi ft \qquad (5)$$

Where σ_s = stress due to static aircraft load

σ' = additional increase or decrease of stress with time

f = frequency of wheel load

The stress variation with time for point A is then:

$$\sigma_t = (\sigma_s + \sigma' \cos 2\pi ft) \cos \frac{\pi V}{\lambda} t \qquad (6)$$

$$\text{for} \quad -\frac{\lambda}{2V} < t < +\frac{\lambda}{2V}$$

Inspection of Equation (6) shows that the duration of load is the same as for Equation (3) and as calculated in Equation (4). As shown in Figure 3, the term in parenthesis in Equation (6) merely alters the wave shape of the stress as a function of time curve. For medium and high aircraft speeds, $2\pi f$ will be less than $\frac{\pi V}{\lambda}$ and the change in wave shape becomes negligible. Therefore, little error is introduced if Equation (3) is used, provided that the maximum stress resulting from the maximum magnitude dynamic load is used for σ_o i.e.,

$$\sigma_t \simeq \sigma_o \cos \frac{\pi V}{\lambda} t \qquad (3)$$

where $\sigma_o = \sigma_s + \sigma'$

To determine the rate of loading, the first derivative of stress as expressed in Equation (3) would be taken with respect to time. However, since the rate of stress application changes with time, this is not a good parameter to work with. If the waveshape and duration of loading are used for determining material properties, then the rate of loading will be automatically incorporated.

SECTION V

DYNAMIC RESPONSE OF PAVING MATERIALS

The structural adequacy of pavement subjected to high magnitude loads at medium and high aircraft speeds must be evaluated on the basis of results from creep-speed field tests. As aircraft speed increases the average rate of loading increases and duration of load decreases. The purpose of this section is to determine the influence of rate of loading and duration of load on the elastic properties and the fatigue life of pavement materials.

There is an enormous amount of literature available on the dynamic behavior of pavement materials. This section is by no means a complete review of the literature; however, it does provide a guide for selecting appropriate dynamic material properties for dynamic pavement evaluation.

1. PORTLAND CEMENT CONCRETE

Most materials when loaded have a time-dependent response, and concrete is no exception. The work of several investigators on the effects of rate of loading on the behavior of concrete was reviewed by McHenry and Shideler (Reference 14). Figure 4 shows the influence of rate of loading on the modulus of elasticity and indicates that the modulus increases with an increasing rate of loading. The lower values of moduli at slower rates of loading were attributed to creep of the concrete.

For pavements subjected to moving wheel loads, the rate of loading varies as a function of time. If the average rate of loading is approximated from the maximum stress divided by one-half the duration of loading, as expressed in Equation (4), the the expected rate of loading due to a moving wheel load would range from about 900 to 44,000 psi/sec (assuming maximum stress equals 500 psi, the half-wavelength is 5 ft, and aircraft velocity varies from 3 to 150 mph). From Figure 4, a 10 percent increase for the modulus of elasticity of PCC might be expected for high aircraft velocities. But since the rate of loading varies with time and, in fact, approaches zero at the higher stress levels, the increase in modulus as aircraft velocity increases from creep to high speed would be considerably less than 10 percent. Considering the variation of modulus of elasticity with other factors (mix proportions, aggregate properties, and type of test used to determine the modulus), the relatively small increase in modulus which could be expected as a result of high speed wheel loads is negligible.

Chou's (Reference 15) review of pavement materials indicates that Poisson's ratio of PCC has a range of about 0.11 to 0.22

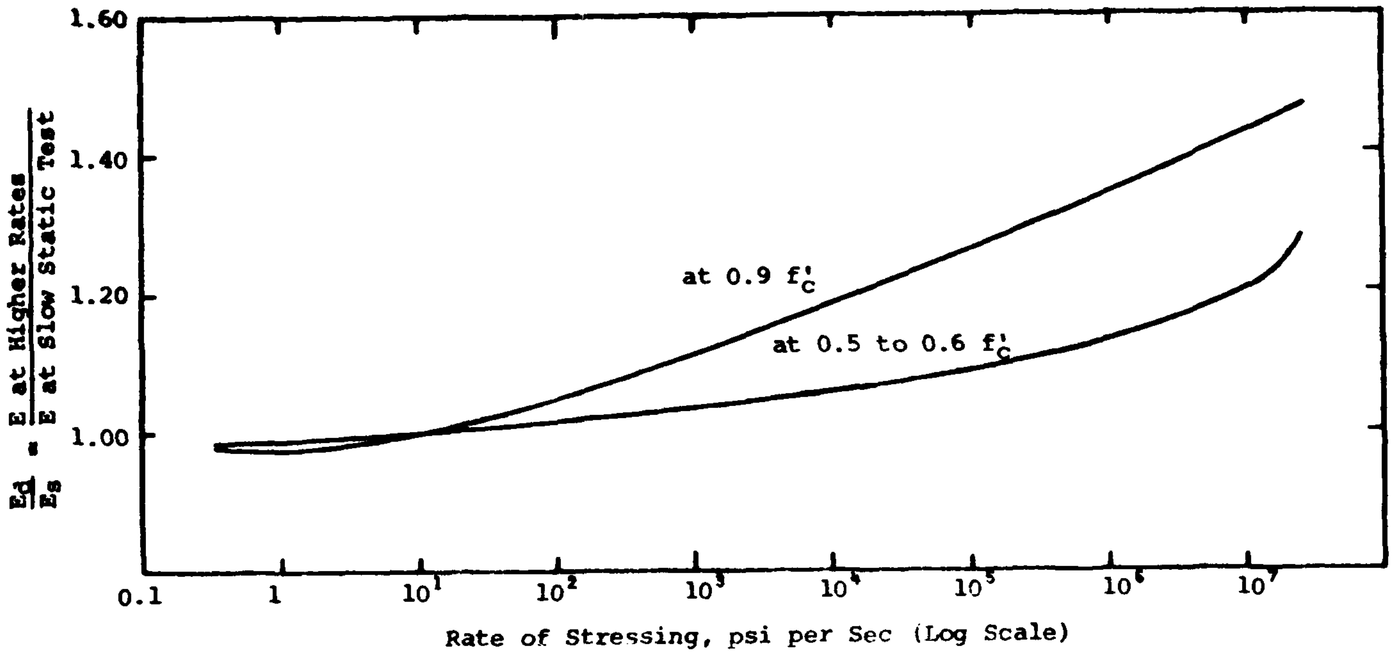

Figure 4. Effect of Rate of Stressing on the Modulus of Elasticity of Concrete [After McHenry **(Reference 14)]**

when determined from static tests, and the results of dynamic tests averaged about 0.24. Since Poisson's ratio of PCC has very little effect on the response of rigid pavements, using a value of 0.2, which is generally used for traditional static analysis, seems reasonable for dynamic analysis as well.

The compressive strength, tensile strength, and modulus of rupture of PCC increase with an increase in rate of loading. Cowell (Reference 16) found that, for a rate of loading of 100,000 psi/sec, the compressive strength increase ranged from 10 percent to 30 percent, depending on mix proportions and maturity of the concrete, as compared with the static strength. Similarly the increase in tensile strength ranged from 30 percent to 50 percent for a loading rate of 100,000 psi/sec. Results of impact tests on PCC by Lundeen (Reference 17 and 18) showed an average ratio of dynamic to static strength of 1.36 for compression, 1.74 for tension, and 2.46 for modulus of rupture. A rupture failure of concrete from high magnitude loads at medium and high aircraft speeds seems unlikely.

Since the compressive, tensile, and rupture strengths of concrete vary with rate of loading, it would seem that fatigue performance would also be time-dependent. Chou (Reference 15), summarizing the results of several studies, indicates that frequencies of the repeated load (and hence rate of loading) between 70 to 900 repetitions per minute had no effect on fatigue strength, but frequencies as low as 10 repetitions per minute may result in slightly lower fatigue lives. The load pulse associated with ten repetitions per minute corresponds to the load pulse of an aircraft at creep to slow taxi speeds.

The type of repeated loading used in fatigue tests may simulate traffic loading on highway pavements, but the type of repeated loading on airport pavements is quite different. For airport pavements subjected to aircraft taxi loads, loading is of short duration but very low frequency, i.e., the loading cycle is made up of a short load pulse followed by a relatively long rest period. Chou (Reference 15) reports of fatigue testing which included periodic rest periods, i.e., a rest period of 1, 5, 10, etc. minutes after every 4500 load repetitions. In general, it was found that rest periods were beneficial. A five-minute rest period resulted in a 10 percent increase in fatigue strength; longer rest periods did not yield any further increase in fatigue strength, but shorter rest periods did show smaller increases.

Fatigue tests which include an appropriate rest period within each loading cycle were not found in the literature. Fatigue performance may be quite different if a rest period were included in each load cycle.

In conclusion, the elastic constants for concrete to be used in an analysis of the response of pavement to moving wheel loads should be the same as those currently used for a traditional static analysis. Also, based on the current literature, no increase in fatigue strength can be assumed for concrete pavements subjected to dynamic loads. Fatigue testing should be done, however, to determine if the fatigue performance of concrete is improved when the repeated load cycle includes an appropriate rest period.

2. POLYMER CONCRETE

Since polymer concrete is a relatively new material, there is little literature available on the dynamic behavior of the material. Creep tests have shown that the behavior of polymer concrete is more time-dependent than PCC (Reference 19) and therefore the modulus of elasticity should be determined using dynamic methods. The effect of rate of loading on the modulus of rupture of polymer concrete is also needed as well as fatigue testing incorporating various load durations and rest periods.

3. ASPHALT CONCRETE

Although asphalt concrete is not currently being considered for rapid runway repairs, runways which may have to be repaired are asphalt concrete or have asphalt concrete overlays. The undamaged portions of the runway surrounding the repairs will be subjected to high magnitude dynamic loads due to increased surface roughness.

Unlike PCC, the stiffness of asphalt concrete changes dramatically with dynamic loadings. The response of asphalt concrete can be separated into a time-dependent component and an instantaneous component. For short duration dynamic loads, the response is primarily elastic.

Green (Reference 20) reports of several studies which showed that the elastic modulus of asphalt concrete wearing surfaces is highly dependent on loading frequency. For example, at loading frequencies of 1, 4, and 16 hertz, the moduli were 370,000, 570,000, and 770,000 psi, respectively. There are a number of nomographs available to determine the stiffness of asphalt concrete for various loading times (References 6, 15, and 21).

No information could be found for the effects of rate and duration of loading on Poisson's ratio. However, Poisson's ratio of the asphalt concrete surface layer has little influence on the response of flexible pavements.

The fatigue life of asphalt concrete depends on the rate of loading, duration of load, loading frequency, and the inclusion of a rest period in the loading cycle. These variables are interdependent; therefore, it is difficult to discuss the effects of each of them individually. The most recent literature review on the fatigue life of asphalt concrete is that by Decker (Reference 21).

The loading waveform used for fatigue testing has an influence on fatigue life. Decker reports that specimens subjected to a square-waveform loading had less than one-half the fatigue life of identical specimens loaded sinusoidally, whereas the use of a triangular waveform loading resulted in a 45 percent increase in fatigue life as compared to sinusoidal loading. Frequency and maximum stress amplitude were held constant for the test. The square-waveform loading has the fastest rate of loading, but the maximum stress is applied for the entire load cycle whereas it is only applied for an instant for the triangular loading. The duration of the higher magnitude portion of the load apparently dominates the behavior.

As previously pointed out, actual loading of airport pavements includes a relatively long rest period as part of the loading cycle. Decker reports on a number of fatigue studies which included a rest period within each load cycle. In general, the longer the rest period, the higher the fatigue life until a maximum beneficial rest period is reached. Further lengthening of the rest period beyond this maximum beneficial period has no influence on fatigue life. This maximum beneficial rest period is a function of stress magnitude, load period, and temperature. In most cases, the rest period included in actual aircraft loadings of airfield pavements probably exceeds the maximum beneficial rest period.

In a study to determine the effects of frequency of loading on the fatigue life of asphalt concrete, Decker reports of testing for which the ratio of load duration to rest period was held constant while the frequency varied from about 1 to 40 hertz. The fatigue life for the loading fequency of 40 hertz was almost 200 times longer than the fatigue life at 1 hertz frequency loading. However, the rate of loading increased, while the duration of load and rest period decreased as frequency increased. Because of this interdependence of variables, frequency of loading is not a good parameter to use.

The most accurate representation of stresses due to a moving wheel load was made by Van Dijk, et al (as reported by Decker). The shape of the load pulse consisted of a large tensile pulse between two small compressive pulses followed by a rest period. The length of rest period was varied, and as it increased, the fatigue life increased considerably. Again, the importance of rest periods was demonstrated.

However, to determine the influence of aircraft speed on fatigue life of asphalt concrete airfield pavements, what is needed is fatigue tests to determine the effect of load duration. The loading cycle should be similar to Van Dijk's with a constant rest period (equal to or greater than, the maximum beneficial rest period). This would best simulate actual field loadings.

In summary, there is reason to believe that the increased stiffness and fatigue life of asphalt concrete associated with medium and high aircraft speeds probably offset the higher magnitude loads due to surface roughness. However, this would have to be verified by a parametric study and possibly fatigue testing as described above.

4. GRANULAR MATERIAL

The modulus of elasticity of granular materials determined from dynamic tests is generally higher than the modulus determined from static tests. This is perhaps best illustrated by the fact that the dynamic moduli measured for soils by the nondestructive pavement test van developed by the Air Force are corrected prior to using these values for static pavement evaluation (Reference 12). Specifically, the correction for flexible pavement consists of dividing the dynamic moduli of granular base and subgrade materials by 2 to get equivalent static moduli. (The same correction is done for asphalt concrete, but for PCC the measured values are used directly since there is little difference between the dynamic and static moduli.)

Although the dynamic modulus is significantly higher than the static modulus, the dynamic modulus for clean sands and gravels appears to be independent of load duration and rate of loading. Apparently a slow deformation (creep phenomenon) develops in the course of a static test; once testing is in the dynamic range, however, the response of the material is no longer time-dependent. Allen [as reported by Chou (Reference 15)] found that the resilient response of well-graded granular materials is independent of stress duration, and concludes that any pulse duration in the range of those applied to pavements by wheel loads moving at speeds of 15 to 70 mph could be used for testing. Wignot, et al (Reference 2) also conclude that the dynamic behavior of granular materials is relatively independent of duration and frequency of loading.

Parker, et al (Reference 9) have developed a laboratory procedure for determining the resilient modulus and Poisson's ratio using a cyclic triaxial test. The procedure uses a repetitive stress similar to that encountered in a base course layer in a pavement structure under a moving wheel load. The recommended load duration of 0.1 to 0.2 second (haversine wave form) corresponds to aircraft speeds of about 30 to 120 mph (depending on λ); the recommended cycle duration of 3 seconds provides a rest period between stress pulses.

Since it is impossible to duplicate field conditions in the laboratory, field measurements for dynamic modulus and Poisson's ratio are preferred. (This is especially true for rapid runway repair since unconventional construction methods are used.) Field vibratory testing techniques for dtermining the dynamic modulus of elasticity and Poisson's ratio are referenced by Chou (Reference 15).

Vibratory testing does not directly simulate aircraft traffic loads since the latter are separate load pulses whereas the former uses a sustained vibration. Mass and damping effects have more influence for sustained vibration but become insignificant for single pulse loadings. However, Heukelom and Foster (Reference 11) have shown that the modulus measured from sustained vibrations is equal to the modulus associated with traffic loadings within 20 percent. Several investigators have shown good correlations between field-measured strains under moving wheel loads and computed strains using dynamic material properties measured from field vibratory testing techniques (References 15, 20, and 9).

Based on extensive field tests, Heukelom and Klomp (Reference 6) developed a correlation between the dynamic modulus and CBR as

$$E \text{ (in psi)} = 1500 \text{ CBR} \tag{7}$$

The use of Equation (7) is not recommended, however, since computed dynamic moduli can range from 50 percent to as high as 200 percent of the actual measured values. Chou (Reference 15) suggests that the poor correlations between dynamic modulus of elasticity and CBR is because the CBR test produces plastic as well as elastic responses. Similarly, static plate bearing test results cannot be used for dynamic evaluation of pavements.

In summary, the dynamic modulus of granular materials is relatively independent of rate and duration of loading. If possible, field testing should be used to determine the dynamic modulus and Poisson's ratio.

5. SUBGRADE SOILS

The dynamic response of cohesive and cohesionless subgrade soils is similar to granular materials in that the dynamic modulus is considerably higher than the modulus measured from static tests. For example, Parker, et al (Reference 9) reported static moduli of 1850 and 1600 psi as compared to resilient moduli of 7,500 and 13,000 psi for a high-plasticity clay and low-plasticity clay, respectively.

But cohesive soils differ from granular soils in that dynamic moduli are sensitive to rate and duration of loading. Wignot, et al (Reference 2) report test results for the complex modulus of a silty clay subgrade at different loading frequencies. At 90 percent saturation, the complex moduli of the soil were 2,000, 3,500, and 6,200 psi at frequencies of 0.16, 1.6, and 16 hertz respectively. For cohesionless soils, frequency of loading has less influence on the modulus.

Parker, et at (Reference 9) developed a laboratory test to determine the resilient modulus and Poisson's ratio for subgrade soils. The test is similar to the one briefly discussed for granular soils. Instead of using the load duration and frequency given by Parker, et al it is suggested that these be varied since subgrade soils are sensitive to frequency of loading. In this way, test results can be used to determine pavement response for different aircraft speeds.

Since the modulus and Poisson's ratio of the subgrade have such a strong influence on pavement response, field testing is preferred over laboratory testing. This is especially true for rapid runway repairs since the condition of the subgrade is so variable (uncompacted bomb damage debris). Field vibratory testing, as referenced by Chou (Reference 15) and briefly discussed for granular materials, can provide the dynamic modulus and Poisson's ratio.

SECTION VI

CONCLUSIONS

Based on the results of this investigation, the following conclusions are noted:

1. The response of stiff pavements, i.e., rigid pavements and flexible pavements at low temperatures, is primarily elastic; flexible pavement at higher temperatures exhibits significant inelastic as well as elastic behavior at slow aircraft speeds, but the inelastic behavior becomes insignificant at higher aircraft speeds. Large dynamic loads, however, may yield significant inelastic responses at higher aircraft velocities due to lack of compaction in the subgrade.

2. A static analysis can be used to obtain the response of pavement for dynamic loadings if appropriate dynamic moduli and limiting fatigue values corresponding to dynamic loading are used for material properties in the analysis. The mass and damping effects are not included using this method, but it has been shown that these effects have little influence on dynamic pavement response.

3. Based on the literature cited, the modulus of elasticity, Poisson's ratio, and the fatigue strength of Portland Cement Concrete are relatively independent of rate and duration of loading, and therefore, the usual static values for these properties would be used for a dynamic analysis. However, since the modulus of rupture of concrete is substantially higher for faster rates of loading, a rupture failure of concrete pavement due to large dynamic loads at medium and high aircraft speeds is unlikely.

4. The increased stiffness and longer fatigue life of asphalt concrete for medium and high aircraft speed loadings probably offset the larger magnitudes of these loadings occuring due to surface roughness.

5. The properties of granular base and subbase materials should be determined from dynamic testing since static tests would yield values too low for dynamic pavement analysis. The dynamic properties, however, are relatively insensitive to rate and duration of loading; i.e., the response of these materials would not be dependent on aircraft velocity.

6. The response of subgrade soil, especially cohesive soils, depends on aircraft speed. Therefore, the elastic properties of the subgrade must be determined at various loading frequencies (i.e., various rates and durations of loading) to determine dynamic pavement response associated with various aircraft speeds.

SECTION VII

RECOMMENDATIONS

1. A parametric study should be considered to determine the influence of dynamic loads of various magnitudes at various aircraft speeds on the response of pavements. Using the approach outlined in this report, one of the sophisticated computer codes (such as PREDICT) currently available can be used. Design curves can then be developed which would not only be useful for predicting pavement response for large dynamic loads but would also be of benefit in designing and analyzing rapid runway repairs for the creep-speed field test program.

2. Because of the unusual nature of the subgrade for rapid runway repairs (uncompacted bomb damage debris) and because the behavior of the subgrade plays such a dominant role in the response of pavement, field tests should be considered to determine the dynamic properties of the subgrade. Dynamic properties of the subgrade are needed to determine the response of pavement to large dynamic loads at higher aircraft speeds and also to provide for more accurate design and analysis for the creep-speed field test program. The literature survey also should be continued before specific field testing is recommended.

3. The dynamic properties and fatigue strength of polymer concrete should be investigated for fatigue testing, the load cycle should incorporate an appropriate rest period in order to accurately simulate traffic loading on airfield pavements. (Similarly, fatigue testing which includes a rest period in each loading cycle should also be done for Portland Cement Concrete.)

4. This report has not considered the influence of horizontal loads on the dynamic response of pavements. For unsurfaced bomb damage repairs, horizontal wheel loads increase with aircraft velocity, and therefore would influence the dynamic response of the repair at higher aircraft speeds.

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