Maintenance-Free Life of Heavily Trafficked Flexible Pavements

Michael I. Darter, Ernest J. Barenberg, and Jihad S. Sawan, Department of Civil Engineering, University of Illinois at Urbana-Champaign

Results obtained from a nationwide survey and analysis of the performance of 18 heavily trafficked flexible pavements are presented. The pavements surveyed are located in nine states, and interviews were held with highway engineers at each location. Results show that the major types of distress requiring maintenance for heavily trafficked flexible pavements are fatigue or alligator cracking, transverse cracking, longitudinal cracking, and rutting. The major causes are heavy traffic loadings, inadequate pavement structures, low temperature shrinkage of asphalt concrete, poor lane joint construction, aging of asphalt cement, and disintegration of cement-treated bases from deicing salts and freeze and thaw. The maintenance-free life of conventional flexible pavement depends on several factors including environmental region. For wet regions having significant freeze-thaw cycles, maintenance-free life ranges up to 10 years; for dry freeze-thaw regions, maintenance-free life ranges up to 15 years. In non-freeze-thaw wet or dry regions, maintenance-free life ranges up to 15 years. Several design recommendations are given that were found to improve the maintenance-free life of flexible pavements and whose use may be justified after the high maintenance and user delay costs of heavily trafficked highways are noted.

Many highways in urban and suburban areas are being subjected to high traffic volumes and weights, which cause rapid deterioration and premature failure of pavements. Therefore, considerable maintenance is required to keep the pavements serviceable, but scheduling of remedial and preventive maintenance is almost impossible without closing lanes and producing massive traffic jams, accidents, and delays to the traveling public. Often routine maintenance is completely neglected, thus causing even more accelerated deterioration of pavements.

The purpose of this paper is to determine the maximum maintenance-free life of conventional flexible pavements and to assess the types and causes of distress that require maintenance. This information is required for the eventual development of pavement design procedures to provide zero-maintenance pavements over much longer periods of time than currently exist. The development of design procedures for zero-maintenance pavements is currently under way at the University of Illinois through sponsorship of the Federal Highway Administration. More detailed data are available elsewhere (1). Zero maintenance, as used in this project, is defined as being related only to the structural adequacy of the pavement system. Activities such as mowing, striping, and providing skid resistance are not related to the pavement structure and, therefore, are outside the scope of this study.

The research approach to developing basic data and information from which the zero-maintenance design procedures will be developed relies heavily on information gained from extensive field visits, analytical analyses, and previous research studies.

FIELD SURVEY

A field survey was conducted of 18 heavily trafficked flexible highway pavements currently in service. Attempts were made to select projects in a variety of climatic regions so that the pavements could be evaluated over a variety of climatological conditions. The major climatic categories (wet, dry, freeze, nonfreeze) used in this evaluation are defined as follows:

1. A wet region is one in which the annual precipitation equals or exceeds the potential evapotranspiration of moisture (2) or one in which annual precipitation exceeds 76.2 cm (30 in);
2. A dry region is the opposite of a wet region;
3. A freeze region is one in which significant freezing temperatures result in pavement frost heave or frost damage. Regions that have a freezing index of 100-deg days or greater are categorized as freeze areas; and
4. A nonfreeze region is one that has a freezing index of less than 100 deg.

A project was selected in a given region by using the following guidelines:

1. Age. Longevity was the most important factor, which severely limited the number of available projects. In general, only projects with a service life of greater than 10 years were selected for this study.

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Table 1. Summary of information for Flex projects included in field survey.

Project Number	Location	Route	Date Opened	ADT Average Over Life	ADT 1974	Lanes	8.16-Mg ESAL Applications[a]	Pavement Section Material: Surface	Base	Subbase	Subbase	Subgrade	Maintenance Performed
Flex 1	Manchester, N.H.	I-93	1960	19 800	35 200	4	7.26	7.62-cm AC	6.35-cm AC	30.48-cm GRB	30.48-cm GRB	–	CF
Flex 2	New Jersey	N.J. Turnpike	1951	21 600	32 800	4	12.42	11.43-cm AC	19.05-cm MAC	16.51-cm GRB	13.97-cm SM	30.48-cm SM and S	P and SH
Flex 3	West St. Paul, Minn.	Minn-55, TS 21	1961	9 500	15 600	4	2.01	10.16-cm AC	15.24-cm GRB	31.75-cm GRB	–	A-6 CL	CF and P
Flex 4	West St. Paul, Minn.	Minn-55, TS 22	1961	9 500	15 600	4	1.91	10.16-cm AC	7.62-cm ATB	15.24-cm GRB	40.62-cm GRB	A-4 CL	CF
Flex 5	North St. Paul, Minn.	Minn-36, TS 23	1961	8 000	12 100	4	1.69	13.97-cm AC	3.81-cm ATB	22.86-cm GRB	30.48-cm GRB	A-2-4 SL	CF
Flex 6	South St. Paul, Minn.	Minn-101 TS 109	1966	10 200	14 100	4	5.21	3.81-cm AC	12.70-cm ATB	7.62-cm BTS	–	A-3	CF
Flex 7	Ottawa, Ill.	I-80	1962	11 000	18 900	4	4.70	11.43-cm AC	21.59-cm GRB	58.42-cm GRB	–	A-6	P
Flex 8	Ottawa, Ill.	I-80	1962	11 100	18 900	4	4.82	11.43-cm AC	20.32-cm ATB	10.16-cm GRB	–	A-6	None
Flex 9	Ottawa, Ill.	I-80	1962	11 000	18 900	4	4.72	11.43-cm AC	25.40-cm ATB	10.16-cm GRB	–	A-6	None
Flex 10	Ottawa, Ill.	I-80	1962	11 100	18 900	4	5.59	11.43-cm AC	30.48-cm CTB	10.16-cm GRB	–	A-6	P
Flex 11	Seattle, Wash.	I-90	1960	10 400	13 400	4	1.66	17.78-cm AC	7.62-cm GRB	45.72-cm GRB	–	LST, S and C	None
Flex 12	South San Francisco, Calif.	US-101	1955	21 250	28 000	4	8.81	12.7-cm AC	20.32-cm CTB	20.32-cm GRB	–	–	P and CF
Flex 13	San Francisco, Calif.	Calif-4	1965	19 000	28 000	4	2.27	17.78-cm AC	20.32-cm GRB	38.1-cm GRB	–	–	None
Flex 14	Los Angeles, Calif.	I-405	1965	69 000	138 500	4	3.70	17.78-cm AC	20.32-cm CTB	25.40-cm GRB	–	–	None
Flex 15	Salt Lake City, Utah	I-80	1966	21 000	19 125	4	2.75	11.43-cm AC	12.7-cm CTB	10.16-cm GRB	–	–	None
Flex 16	Phoenix, Ariz.	I-17	1964	11 100	17 000	4	4.27	7.62-cm AC	15.24-cm GRB	25.40-cm SM	–	–	CF and P
Flex 17	Atlanta, Ga.	Ga-78	1951	14 200	11 000	4	4.02	27.94-cm AC	25.40-cm GRB	–	–	C	None
Flex 18	Atlanta, Ga.	Ga-78	1968	14 000	20 000	4	2.38	8.89-cm AC	22.86-cm CTB	19.05-cm GRB	–	C	None

Notes: 1 Mg = 2.205 kips. 1 cm = 0.394 in.
AC = asphalt concrete; ATB = asphalt-treated base; BTS = bitumen-treated sand; C = clay; CF = crack filling; CL = clayey loam; CTB = cement-treated base; GRB = granular base or subbase; LST = laminated silt; MAC = asphalt penetration macadam; P = patching with AC; S = sand; SH = shoulder repair or replacement; SL = sandy loam; SM = select material.
[a]Most heavily traveled lane, one direction.

Table 2. Summary by type of distress and maintenance found on heavily trafficked flexible pavements.

Type of Distress	Projects[a]: Distressed/ Total	Maintained/ Distressed
Longitudinal cracking (lane joint in nearly all cases)	11/18	5/11
Transverse cracking (including reflective cracking)	10/18	7/10
Alligator or fatigue cracking	9/18	5/9
Polished aggregate	8/18	0/8
Rutting	6/18	1/6
Weathering asphalt	4/18	0/4
Depressions	3/18	0/3
Raveling	1/18	0/1

[a]Only the distress rated as moderate to severe as defined by Darter and Barenberg (1) is considered in this tabulation.

2. Maintenance. Only projects that have not been overlayed or seal-coated were selected. Past routine maintenance was not a consideration, and two categories of pavements were selected—those that were maintenance-free and those that received routine maintenance.

3. Traffic. Only pavements that have relatively high traffic volume were considered in the selection. Most of the projects selected were high-volume urban and rural freeways.

The individual projects included in the field survey are denoted Flex 1 through Flex 18. A detailed summary of important data for each project is given in Table 1. The 18 flexible pavements included in the field survey are located in nine states with widely ranging environmental conditions. All the projects have moderate to high traffic volumes; two-directional average daily traffic (ADT) ranged generally from 14 000 to 35 000 (one project, however, had 138 500). The accumulated 8.16-Mg (18-kip) equivalent standard axle load (ESAL) applications in the most heavily traveled lane range up to 12 million. The projects varied in age from 7 to 24 years (the mean was 14 years), and 9 of the 18 projects surveyed showed maintenance-free performance. In addition to the specific projects given in Table 1, other pavements in the various regions visited were also observed, and the general performance characteristics of flexible pavements in the region were discussed with local engineers.

TYPES AND CAUSES OF DISTRESS

Types of Distress

The types and severity of distress occurring on 18 heavily trafficked flexible pavements were determined during the field visits. A summary of types of distress found (rated moderate to severe) and maintenance applied to each flexible pavement is given in Table 2. The distress occurrence data are expressed as the ratio of the number of projects exhibiting a particular distress to the total number of projects surveyed. The maintenance applied to each type of distress is expressed as the ratio of the number of projects having the particular distress that was actually maintained to the total number of projects exhibiting the distress.

Based on data from the field survey and other research studies, including the American Association of State Highway Officials (AASHO) (now the American Association of State Highway and Transportation Officials) Road Test (3), the major types of distress occurring in heavily trafficked flexible pavements that require or receive maintenance and their level of severity are

1. Alligator or fatigue cracking. This type of distress occurs mainly in the wheel path with class 2 and 3 severity levels.

2. Transverse cracking. This type of distress occurs transversely to the longitudinal axis of the roadway and includes low-temperature as well as reflective cracking (resulting from a cement-treated base, for example) with spacing of approximately 3.05 to 9.14 m (10 to 30 ft) and possible spalling.

3. Longitudinal cracking. This type of distress almost always occurs at the lane construction joint and often occurs over more than 25 percent of the length of a project and is spalled.

4. Rutting. This type of distress occurs in the wheel paths and is normally greater than 1.27 cm (½ in) in depth to require maintenance.

Besides four major distresses previously identified on the projects surveyed, there are other types of distress that occur in varying amounts and degrees depending on construction, foundation soil, materials, environment, and the like. These types of distress include surface deterioration (aggregate polishing, bleeding, weathering and studded tire wear), swelling or heaving foundations (4), shoulder distress, depressions, and asphalt stripping (5).

Causes of Major Types of Distress

Based upon field observations and analytical studies, the causes of each of the major types of distress previously listed are given in this section.

Alligator or Fatigue Cracking

The major cause of alligator cracking is repeated traffic loading, which includes tensile stresses and strains in the bottom of the asphalt concrete surface layer if the pavement has a granular base or at the bottom of the base layer if the base course is stabilized by cement, asphalt, or lime and fly ash. If these tensile stresses and strains are of sufficient magnitude and have a sufficient number of applications, fractures will occur at the bottom of the layer and will progress upward with repeated load applications until they eventually reach the surface (6). Eight of the flexible pavements included in the field study showed moderate to severe alligator cracking. Of these eight, four had cement-treated bases and four had granular bases.

For several of the flexible pavements surveyed, an analysis was made by using elastic layered theory and Miner's fatigue damage expression (19) for the purpose of illustrating the cause of alligator cracking by predicting fatigue damage distress. Three assumptions were made in the analysis.

1. The resilient modulus and Poisson's ratio either were determined for each pavement layer and for the subgrade from laboratory tests or were estimated from the results of studies by others such as Robnett and Thompson (7), Southgate and Deen (8), and Monismith and Finn (9). Resilient modulus values for granular and fine-grained soils are stress dependent; therefore, values were selected that closely correspond to the range of expected bulk and deviator stresses in the pavements. The stiffness of asphalt concrete was determined by using the stiffness and temperature data given by Southgate and Deen (8) and was selected as a constant value for given projects corresponding to the mean annual temperature for each region.

2. The traffic loading used in the fatigue analysis is the accumulated 8.16-Mg (18-kip) ESAL applications estimated for the most heavily traveled lane of each project from the time it was opened to traffic through 1974.

3. Fatigue curves of initial tensile strain versus load applications developed by Edwards and Valkering (10) by using the controlled stress mode of testing were used for asphalt concrete. A fatigue curve of strain versus load applications for cement-treated bases (9) was used.

Calculations for three projects (Flex 7, Flex 8, and Flex 18) are discussed to illustrate the analysis. The critical radial tensile strains and stresses were computed under 4.08-Mg (9-kip) wheel load by using the linear elastic layered computer program. These values are given in Table 3 for each project. Fatigue damage was computed by using a 4086-kg (9000-lb) wheel load and the actual estimated 8.16-Mg (18-kip) ESAL applications accumulated over the life of the pavement.

Analysis for Flex 7 shows relatively large radial tensile stresses and strains (1.54×10^{-4} cm/cm) at the bottom of the asphalt concrete surface. By using the fatigue curves for asphalt concrete (constant stress mode), one determines that the number of 4086-kg (9000-pound) wheel load applications to failure is approximately 800 000. The actual estimated 8.16-Mg (18-kip) equivalent single axle load applications were 4.7 million. Hence the analysis indicates a fatigue failure. Actually, Flex 7 has extensive alligator (fatigue) cracking and is currently being overlayed.

Flex 8 is a pavement section adjacent to Flex 7 on I-80 in Illinois but has an asphalt treated base. The maximum computed tensile strain at the bottom of the asphalt-treated base is 7.04×10^{-5} cm/cm, which gives an allowable number of 4086-kg (9000-pound) wheel applications of approximately 13 million compared with 4.82 million equivalent loads actually applied. There is, as expected, no observable fatigue cracking on the surface of this pavement.

Flex 18 had a cement-treated base that showed serious fatigue failure in the field. Computed strains in the cement-treated base confirm the likelihood of this type of distress.

Similar calculations were made for 15 of the 18 flexible pavements surveyed, and the resulting data are given in Table 3. Analysis of the eight projects that have cracking indicated that excessive stresses and strains were present, and the cumulative fatigue damage for each was calculated to be greater than 1.0. In theory, these projects are expected to show fatigue distress, and such distress is apparent in these pavements. The seven projects not showing fatigue damage had cumulative fatigue damage ratios of less than 1.0. Hence the analysis appears to be reasonable (even under the assumptions made) because fatigue or alligator cracking occurred on all projects where analysis indicated potential fatigue. Conversely, for those projects where theoretical analysis did not indicate fatigue distress, such distress was nonexistent.

The cause of fatigue distress can be assumed to be one or more of the following:

1. Inadequate structural thicknesses or support for the stabilized layers to keep the tensile stresses and strains within allowable limits or both;

2. Loss of support of various layers of the pavement and subgrade as a result of excessive moisture, shear failure, and the like, which caused high tensile strains under traffic load in the stabilized layers.

3. Gradual hardening or aging of the asphalt concrete (AC) surface with time resulting in decreased fatigue life of the AC.

A general observation from the field survey is that

Table 3. Summary of fatigue analysis of 15 flexible pavements in field survey.

Project Number	Critical Layer	Critical Stress (kPa)	Critical Strain (cm/cm × 10^{-4})	n or Million Actual 8.16-Mg ESALs	N or Million Allowable 8.16-Mg ESALs[a]	$D = \sum \frac{n}{N}$	Alligator Cracking
Flex 2	APM	455	0.44	12.42	100.00	0.12	No
Flex 3	AC	1696	1.97	2.01	0.31	6.48	Yes
Flex 4	AC	993	0.52	1.91	60.00	0.03	No
Flex 7	AC	1717	1.54	4.70	0.80	5.83	Yes
Flex 8	ATB	476	0.70	4.82	13.00	0.37	No
Flex 9	ATB	372	0.55	4.72	45.00	0.10	No
Flex 10	CTB	331	0.36	5.59	10.27	0.54	—[b]
Flex 11	AC	765	0.70	1.66	13.00	0.13	No
Flex 12	CTB	572	0.50	8.81	1.66	5.31	Yes
Flex 13	AC	862	1.60	2.27	1.00	2.27	Yes
Flex 14	CTB	455	0.40	3.70	6.20	0.60	No
Flex 15	CTB	572	1.20	2.75	0.01	>100.00	Yes
Flex 16	AC	1593	3.00	4.27	0.06	71.20	Yes
Flex 17	AC	483	0.88	4.02	8.00	0.50	No
Flex 18	CTB	483	0.99	2.38	0.17	14.00	Yes

Notes: 1 kPa = 0.145 lbf/in^2. 1 Mg = 2.205 kips. 1 cm = 0.394 in.
AC = asphalt concrete; APM = asphalt penetration macadam base; ATB = asphalt-treated base; CTB = cement-treated base.
[a] According to fatigue considerations.
[b] Severe durability distintegration occurred in this CTB, and ascertaining the cause of distress is difficult.

Table 4. Rut depth data from five projects subjected to same traffic, environment, and subgrade.

Project Number	Pavement Composition: Surface	Base	Subbase	Mean Rut Depth (cm)
Flex 7	11.43-cm AC	21.59-cm CS	58.42-cm G	1.68
Flex 8	11.43-cm AC	20.32-cm ATB	10.16-cm G	1.30
Flex 9	11.43-cm AC	25.40-cm ATB	10.16-cm G	1.02
Flex 10	11.43-cm AC	30.48-cm CTB	10.16-cm G	0.96
Comp 5	7.62-cm AC	20.32-cm PCC	15.24-cm G	0.86

Notes: 1 cm = 0.394 in.
AC = asphalt concrete; ATB = asphalt-treated base; CS = crushed stone; CTB = cement-treated base; G = gravel; and PCC = portland cement concrete.

fatigue distress seems to be more prevalent in warmer climates. Let us consider Flex 4 located in Minnesota and Flex 13 located in California. The pavement structures of these two pavements are roughly equal; both have a 17.78-cm (7-in) asphalt-bound upper layer over granular subbase. The applied 8.16-Mg (18-kip) ESAL applications are roughly equal as are their ages (Flex 4 is 13 years old and Flex 13 is 9 years old). Flex 4 shows no signs of load-associated fatigue cracking (but does have temperature transverse cracking) although Flex 13 shows moderate fatigue cracking. The computed fatigue damage indicates fatigue distress for Flex 13 (D = 2.27) and no fatigue distress for Flex 4 (D = 0.03). Thus the computations support the observed distress. The reason for the large shift in the fatigue damage of nearly equal pavements is the reduced E value of the asphalt concrete for the Flex 13 pavement due to a higher average temperature, which results in higher strains and a significantly lower allowable number of loads to failure.

Nonreflective Transverse Cracking

Nonreflective transverse cracking is associated with low temperature shrinkage and occurs most frequently in the northern freeze areas of the United States where crack spacings of 3.05 to 45.72 m (10 to 150 ft) are typical. The areas visited that had this type of distress are New Hampshire (severe), Minnesota (severe), Illinois (major), Michigan (severe), New Jersey (moderate), and Ontario (severe). This distress was not observed (or was observed in minor amounts only) in the areas visited in central and southern Texas, western Washington, western California, southern Arizona, and Georgia.

Although most researchers have attributed the transverse cracking distress to the occurrence of very low temperatures, Shahin and McCullough (11) concluded that transverse cracking can be attributed to both low temperature cracking and thermal fatigue. Thermal fatigue has been shown to occur for AC in the laboratory by thermally cycling restrained beams (12, 13). A considerable amount of research has been performed to determine the causes and cures for this type of distress because it is probably the most predominant type of distress in northern regions of the United States. From the field survey, 6 out of 10 projects located in freeze areas showed transverse cracking as the most severe distress occurrence.

Reflective Transverse Cracking

Five projects containing cement-treated bases are included in the field survey. All projects except one (Flex 15) showed extensive reflective transverse cracking. The cause was definitely attributed to reflective cracking because other flexible pavements in the respective areas did not exhibit transverse cracking. Crack spacing in these sections varies as follows (1 m = 3.28 ft):

Project Number	Spacing (m)
Flex 10	6.1
Flex 12	4.6
Flex 14	15.2
Flex 18	4.6

The probable cause of this type of distress is shrinkage, which in the cement-treated base course cracks and reflects upward through the surface layer. This is a relatively serious distress that has caused maintenance to be performed in several of the projects surveyed. One project in particular (Flex 10), located in a wet freeze-thaw area, was subjected to heavy applications of deicing salts [about 5.64 Mg/lane/km/year (10 tons/lane/mile/year)] and freeze-thaw cycles (approximately 12/year). On this project, the cement-treated base disintegrated at most transverse cracks, which resulted in a depression of the AC surface and serious alligator cracking and spalling of the surface cracks.

Longitudinal Cracking

Longitudinal cracking, which existed on 61 percent of the projects surveyed, almost always occurred at the lane construction joint near the lane paint-strip marking. The basic cause in most cases is attributed to poor joint construction practices.

Rutting

Rutting occurred on 33 percent of the projects surveyed to a moderate to severe level (0.6 to 1.9+ cm) (¼ to ¾+ in). Rutting was severe [>1.9 cm (>¾ in)] on only one project (Flex 2), where some patching had been performed in the wheel path, and major (1.3 to 1.9+ cm) (1/2 to 3/4+ in) in two projects. Rutting is associated with traffic load and occurs when any of the pavement layers permanently deform under load. Most of the rutting observed at the AASHO Road Test was attributed to changes of thickness of the pavement layers.

The changes in thickness of the pavement layers were concluded to be due primarily to lateral movement of the materials but sometimes to increased density (consolidation). Five projects included in the field study were subjected to the same traffic on I-80 in Illinois. Rut depth data from these pavements are given in Table 4. Flex 7 with crushed stone base has the most rutting, and Comp 5 (a composite pavement) with a portland cement concrete base has the least rutting. These projects are 12 years old and have carried approximately 5 million ESAL applications. A considerable amount of the rutting in Flex 7 appears to have occurred in the crushed stone base or the gravel subbase. Also, by comparing Flex 8 and Flex 9 with Flex 10, one can conclude that some rutting has occurred in the asphalt-treated bases. The rutting of Comp 5 also indicates that a significant amount of rutting is occurring in the AC surface.

MAINTENANCE-FREE LIFE OF CONVENTIONAL FLEXIBLE PAVEMENTS

Conventional flexible pavements are defined according to typical past and current design and construction practice. Pavement compositions vary widely, but typical ranges are as follows: asphalt concrete surface of 7.62 to 15.24 cm (3 to 6 in), a nonstabilized or stabilized granular base of 20.32 to 30.48 cm (8 to 12 in), and a granular subbase ranging from 10.16 to 50.8 cm (4 to 20 in).

Field Performance

Results from the field survey of 18 flexible pavement projects showed 9 with maintenance-free performance. These 9 pavements ranged in age from 8 to 23 years with an average traffic loading of 0.34 million 8.16-Mg (18-kip) ESALs/year in the most heavily traveled lane. Traffic loadings ranged from 0.40 to 0.54 million 8.16-Mg (18-kip) ESALs/year for flexible pavements having average daily traffic ranging from 30 000 to 138 500.

A summary of project data from the field survey grouped by environmental region is given in Table 5. The summary includes the maintenance-free life, major distresses requiring maintenance, and maintenance performed. The following maximum maintenance-free lives are summarized from these data from each environmental region for the actual traffic loading applied:

Environment	Maintenance-Free Life (years)
Wet and freeze	5 to 23+
Wet and nonfreeze	7 to 23+
Dry and freeze	9
Dry and nonfreeze	10 to 11+

Factors Affecting Maintenance-Free Life

The major factors that affect the maintenance-free life of flexible pavements include traffic, environment, materials, construction, and variability. These factors are only briefly discussed in this section to summarize their effect on maintenance-free life.

Traffic

The effect of repeated traffic loadings on maintenance-free life is particularly important for the heavily trafficked flexible pavements. Structural deterioration under repeated loads is, in most cases, the primary factor that limits the life of conventional flexible pavement. Pavement structural distress under repeated traffic loadings is in the form of fatigue (alligator) cracking or permanent deformation of the pavement layers or both. The fatigue analysis presented previously for flexible pavements illustrates the significant effect that traffic loadings have on distress frequency and subsequent maintenance requirements. A plot of accumulated fatigue damage, D, as summarized in Table 3, is shown versus the cracking index for each pavement in Figure 1. Cracking index here includes class 1, 2, and 3 alligator or fatigue cracking. As fatigue damage becomes greater than approximately 0.6, the various projects exhibit a greater incidence of fatigue cracking. Another interesting aspect of this plot is that all projects having accumulated fatigue damage greater than 0.6 have either received maintenance for fatigue cracking or were in need of immediate maintenance at the time of the survey. All projects having fatigue damage of less than the 0.6 (except one) were maintenance free insofar as fatigue distress was concerned. These results illustrate the importance of traffic loading on the maintenance-free life of flexible pavements.

Environment

Several environmental factors affect the maintenance-free life of flexible pavements including freeze and thaw, low temperature shrinkage, cyclic thermal fatigue, excess moisture, and swelling soils. In certain regions of the United States, these environmental factors become the dominant factors in affecting maintenance-free life of flexible pavements. For example, the low temperature cracking of asphalt concrete surfaces is of particular significance in freeze regions in reducing maintenance-free life to less than 5 years, and the swelling soils in portions of Texas and other states limit the maintenance-free life to generally less than 10 years.

Materials

Several material properties affect the maintenance-free life of flexible pavements including factors such as asphalt aging (or hardening and brittleness), asphalt stripping, degradation of aggregates, freeze and thaw, and durability with use of deicing salt of cement-stabilized aggregates. In specific environmental regions and certain localized areas, these factors will control the maintenance-free life of flexible pavements. The factor having the greatest overall affect is asphalt aging. This phenomenon will reduce fatigue life and increase low temperature cracking development in freeze regions. The effect of asphalt aging in reducing the maintenance-free life of a flexible pavement varies depending on type of asphalt, film thickness, voids, climate, and the like. The disintegration of cement-treated aggregate bases in freeze regions due to freeze and thaw and particularly to use of deicing salts is believed to seriously limit maintenance-free life in these regions to less than 10 years (for Flex 10 pavements).

Construction

The major errors or deficiencies that occur during construction and affect maintenance-free life are factors such as built-in roughness of the surface, lack of material quality control, inadequate thicknesses of layers, inadequate compaction, and poor construction of the lane paving joint. These have significant effect and greatly reduce the maintenance-free life of flexible pavement. For example, longitudinal joint cracking occurred on more than half of the projects surveyed on multilane pavements. This, by itself, could reduce maintenance-free life to less than 5 years on an otherwise maintenance-free pavement.

Variability

There are many variations and uncertainties associated with load, materials, and climate that can cause local-

Table 5. Maintenance-free life of flexible pavements.

Project Number	Environment	Annual Maintenance-Free Life of Project (years)	Average Million 8.16-Mg ESALs per Year	Distress That Required Maintenance	Maintenance Received
Flex 1	Wet and freeze	5 to 15+[a]	0.52	TC, LC	CF
Flex 3		5 to 10	0.15	TC, ALC, LC	P, CF
Flex 4		5 to 14+	0.15	TC, LC	CF
Flex 5		5 to 14+	0.13	TC	CF
Flex 6		5 to 9+	0.65	TC	CF
Flex 7		5	0.39	ALC	P
Flex 8		13	0.40		
Flex 9		13+	0.39		
Flex 10		8	0.47	TC, ALC	P
Flex 2		23	0.54		P[b]
Flex 11	Wet	15+	0.12		
Flex 17		23+	0.17		
Flex 18		7	0.40	ALC	—[c]
Flex 15	Dry and freeze	9	0.34	ALC	—[c]
Flex 12	Dry	10	0.46	ALC	P, CF
Flex 13		10+	0.25		
Flex 14		10+	0.41		
Flex 16		11	0.43	ALC	P, CF

Notes: 1 Mg = 2.205 kips.
ALC = alligator cracking; CF = crack filling; LC = longitudinal cracking; P = patching; R = rutting; TC = transverse cracking.
[a] Lower value is maximum zero-maintenance life of project due to transverse crack filling.
[b] Received minor amount of maintenance.
[c] Needs immediate maintenance.

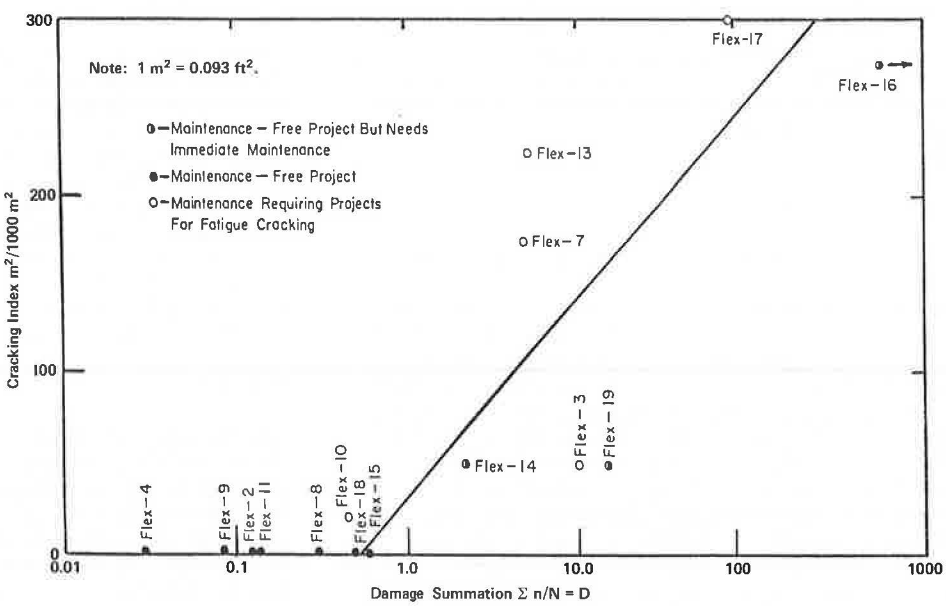

Figure 1. Accumulated fatigue damage versus cracking index for flexible pavements included in field survey.

Table 6. Estimated maximum maintenance-free life of flexible pavements in years.

Environment	Crushed Stone Base			Asphalt-Treated Base			Cement-Treated Base		
	Actual[a]	Computed[b]	Determined by Experience[c]	Actual[a]	Computed[b]	Determined by Experience[c]	Actual[a]	Computed[b]	Determined by Experience[c]
Wet and freeze (regional factor = 1.0)	<5 for Flex 1 <5 for Flex 7	1	<5	7+ for Flex 8 7+ for Flex 9 <5 for Flex 6 18 for Flex 2	14	5 to 15	<5 for Flex 10	4	<5
Wet (regional factor = 0.7)		3	<5	2+ for Flex 11 6+ for Flex 17	20	10 to 15	<4 for Flex 18	6	5 to 10
Dry and freeze (regional factor = 0.9)		1	<5		16	5 to 15	3 for Flex 15	4	<10
Dry (regional factor = 0.5)	3+ for Flex 13 <4 for Flex 16	3	5 to 10		27	10 to 15	<8 for Flex 12 5+ for Flex 14	7	5 to 10

Notes: Layer thicknesses are 12.7 cm (5 in) of AC surface; 25.4 cm (10 in) of base material (either crushed stone, asphalt-treated base, or cement-treated base); and 25.4 cm (10 in) of gravel-sand subbase. Subgrade is similar to that at the AASHO Road Test (AASHO classification = A-6, unified classification = CL, and California bearing ratio = 2 to 4).
[a] Actual project maintenance-free life at 0.7 million 8.16-Mg (18-kip) ESALs/year for those projects where actual traffic is less than 0.7 million/year.
[b] Computed life to serviceability index of 3.5 from AASHO equation C-12 (18).
[c] By field surveys.

ized distress requiring maintenance. These have been identified and analyzed by several researchers (14, 15, 16, 17). These variations include those occurring along a pavement (internal strength, resiliency, durability) and differences between parameter values assumed in design (load, strength, and the like) and those attained "as constructed." These variations can reduce maintenance-free life significantly by causing localized failures.

Expected Maintenance-Free Life

The expected life of conventional flexible pavement was estimated by

1. Use of best available predictive models,
2. Actual project life based on data from the field survey, and
3. Estimate of project staff based on general performance found in the various climatic regions.

The predictive model derived from the results of the AASHO Road Test and included in the AASHO Interim Guide as equation C-12 (18) is used to estimate maintenance-free life of flexible pavement by using the serviceability performance approach. A limiting serviceability value of 3.5 for zero-maintenance conditions is used as recommended elsewhere (1). If this criterion is used along with the AASHO predictive equation, the maintenance-free life may be roughly estimated for certain pavement designs including crushed stone base, asphalt-treated base, and cement-treated base that are located in different environmental regions.

A summary of estimations of the maintenance-free life of various designs is given in Table 6. Two conclusions related to the life estimates given in Table 6 can be drawn.

1. The three sets of estimates in each cell are generally in agreement with each other. For example, consider a flexible pavement with a cement-treated base located in a dry, nonfreeze region. Two projects (Flex 13 and Flex 15) are located in this region with approximately the same structure and provide estimates of actual life of <8 and >5 years respectively. The computed life is 7 years, and the life estimated by the project staff is 5 to 10 years. The relatively short life estimated for the crushed stone and cement-treated bases compares well to the performance of sections of similar composition at the AASHO Road Test. For example, AASHO Road Test section 333 had 15.24 cm (6 in) of AC surface, 2286 cm (9 in) of crushed stone base, and 40.64 cm (16 in) of gravel-sand subbase and lasted only 2 900 000 8.16-Mg (18-kip) ESALs to a serviceability of 3.5. Hence its maintenance-free life would be approximately 4 to 5 years as a major freeway pavement, which is comparable to the estimates given in Table 6.
2. The expected maximum maintenance-free life of conventional flexible pavements located in the four environmental regions is as follows for asphalt-treated base, which provided the best performance:

Environment	Expected Maintenance-Free Life (years)
Wet and freeze	5 to 15
Wet and nonfreeze	10 to 15
Dry and freeze	5 to 15
Dry and nonfreeze	10 to 15

The shorter life of 5 years as indicated for flexible pavements located in freeze regions is due to expected low temperature cracking of the AC surface.

CONCLUSIONS

The conventional design for flexible pavement that has shown the longest maintenance-free life under heavy traffic includes an asphalt concrete surface course of 10.16 to 12.70 cm (4 to 5 in) thickness, an asphalt stabilized base course of 20.32 to 25.40 cm (8 to 10 in) in thickness and a granular subbase. This design, if properly constructed, should provide maintenance-free life ranging from 5 to 15 years in cold regions, and 10 to 15 years in warm regions under heavy traffic [0.7 million 8.16-Mg (18-kip) ESALs/year].

Observations from the field survey and information gained during the interviews indicate several design modifications that would significantly increase the maintenance-free life for flexible pavements.

1. Thickness of the stabilized layers of the pavement structure should be significantly increased to reduce potential fatigue damage.
2. Mix design should be done with the specific environmental region in mind. In the wet and freeze and dry and freeze regions, greater attention should be given to the low temperature ductility of the mix to minimize the cold weather cracking of the AC surface. At the same time, the stability of the AC surface material and the asphalt-treated base must be maintained at a high level to minimize the rutting distress.
3. Only asphalt cement having a low susceptibility to hardening should be used.
4. Construction procedures must be reviewed and modified to eliminate the longitudinal cracking along the lane construction joints. Longitudinal cracking along these cold joints is a potential cause for premature maintenance of flexible pavements.
5. Realistic drainage criteria to minimize the spring damage must be developed and applied.

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