Condition Surveys for Pavement Structural Evaluation

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Two types of condition surveys for pavement structural evaluation, decision surveys and design surveys, are defined. The decision survey is examined further by using the results of a recent survey conducted among state and other selected highway agencies. Emphasis is placed on the amount and types of distress mechanisms that influence maintenance decisions. The criteria that nondestructive equipment should meet to assist in conducting such surveys are stated, and the effectiveness of the two methods used to collect pavement condition information is compared. A related statistical sampling study that uses Dynaflect is shown, and promising developmental techniques for measuring stiffness and cracking of pavements are presented.

The decision to rehabilitate a pavement is usually made well in advance of the time when that pavement becomes functionally distressed. The functional performance of a pavement is defined by its riding and safety quality (1), which are indicated more or less reliably by various profilometer and skid resistance measurements (2). Deterioration of the functional condition of a pavement is preceded by or occurs at the same time as a deterioration in its structural condition (3), its loss of strength and stiffness, its cracking, and other measures of distress. This known relation between structural distress and functional decline is used by many highway agencies to determine which segments of a highway network must have maintenance or rehabilitation work.

There are two major purposes for evaluating the structural condition of pavements: to furnish information for design and to provide data for rehabilitation decisions. The first of these purposes required detailed information either for the design of new construction or for determining the amount of rehabilitation (overlays, seal coats, reconstruction) that will be required. Data for the second of these purposes, rehabilitation decisions, will not need to be so detailed but they should be consistent in ranking the distressed condition of all pavement sections in a highway network.

The two main purposes of pavement structural evaluation require two kinds of condition survey: a detailed survey for design data and a rapid survey for decision data. Because each of these surveys has its own unique objectives, it is not surprising that each should also have its own criteria for what determines an acceptable survey. In general, the decision survey is interested in a quick but comprehensive view of everything that is going wrong with the pavement. It is primarily interested in the distressed condition of a whole section of pavement, and its objectives are better served if its assessments of the level of distress are consistent from one section to the next. As such, the decision survey forms only a part of what is called the sufficiency survey in current highway practice. A sufficiency survey also may consider factors such as safety, geometry, traffic, and obstructions (4).

The design survey is concerned with the structural adequacy of the pavement section to carry future anticipated loads. It is an attempt to gather data on thickness, stiffness of layers, material properties, and crack spacing to determine the thickness of planned overlays or the depth of a pavement to be reconstructed. The design survey is intended to be broader in scope than the structural evaluation commonly used in current highway practice. The structural evaluation is usually associated with deflections and pavement layer moduli. In addition to these data, a design survey may gather other kinds of data such as those on crack spacing, which are required in some overlay design procedures (5).

In an ideal case, there should be some correlation between the results of these two surveys. The decision survey should indicate reliably which sections need work, and the design survey should tell how much work is needed. The common tie between these two survey systems is distress. The greater the distress is, the more urgently the pavement needs attention and, in general, the more extensive the rehabilitation will be.

Although both types of surveys are important, this paper will be primarily concerned with the decision survey because of its importance in making maintenance and rehabilitation decisions. Several aspects of these surveys will be investigated:

1. Importance of the decision survey in making

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rehabilitation decisions;

2. Relative weights given to various forms of distress and thus the most important forms of distress to measure;

3. The most effective ways to apply measurement equipment in determining the current pavement structural condition; and

4. Promising development methods of measuring stiffness and cracking, which are shown to be the most important indicators of pavement structural condition.

PAVEMENT CONDITION SURVEYS

A letter was sent to the highway departments in most states and territories and selected Canadian provinces requesting information on their pavement condition rating system currently in use or projected for use in the immediate future. Fifty-eight agencies were contacted, and 44 responses were received or had previously been made available. The agencies included not only those in the states and selected Canadian provinces but also one in a county in Washington and two in cities in Texas.

Most of the agencies contacted responded by furnishing extensive information on their rating methods. However, some agencies cannot be treated adequately because of one of the following reasons: (a) sufficient information was not sent to permit a complete examination of the rating system; (b) development efforts were under way for a new system; or (c) the agency did not reply to the questionnaire. As a consequence, whatever information provided was used to the greatest extent possible.

Five general items were derived from the replies.

1. Thirty-four agencies are using or are adopting rating systems.
2. Twenty-four agencies are using a composite numerical rating score.
3. Twenty agencies are using ratings or rating scores in maintenance decisions.
4. Thirty agencies are using rating systems for flexible pavements.
5. Eighteen agencies are using rating systems for rigid pavements.

Of the states and agencies for which information was available, a total of 16 either currently use or plan to use mechanical devices to assist in obtaining pavement ratings.

1. Sixteen use roughness measuring devices.
2. Eight use skid measuring devices.
3. Three measure deflections by Dynaflect.
4. One measures deflections by Benkelman beam.

These types and amounts of mechanical devices are used for decision surveys and should not be confused with the number of mechanical devices used in design survey procedures. Many agencies use the types of devices shown but do not necessarily use them in a rating system.

CHARACTERISTICS OF PAVEMENT CONDITION SURVEYS

These condition survey methods represent valuable experience in determining the most important kinds of distress. As a consequence, they were analyzed in detail from the following points of view:

1. Percentage of pavement condition rating determined by various types of distress, as opposed to traffic, safety, skid, geometry, obstructions, and other nondistress items and
2. Percentage of the condition rating determined by each form of distress, such as cracking, rutting, raveling, patching, and the like.

Item 1 shows how important the maintaining agencies consider distress, and item 2 determines the forms of distress considered most important in these rating scores.

Distress Versus Nondistress Items

The approximate percentage of the pavement condition rating score that is determined by distress is given in Table 1. Of the 24 agencies using numerical ratings, only 18 can be listed because of available data. The percentages range from 17 percent (Arizona) to 100 percent (Maine). No geographical pattern is evident from the distribution of the percentages. On the average, 49 percent of the rating score for flexible pavements and 40 percent for rigid pavements is accounted for by distress. Because the remaining percentages account for such items as roughness, traffic, geometry, and the like, it is readily apparent that distress considerations are a significant, though highly variable, part of the individual rating systems.

Importance of Various Kinds of Distress

Figure 1 shows the percentage of the pavement rating score that is represented by each of the forms of distress. The types of distress listed are self-explanatory except for the type listed as general. This category is used to group those forms of distress listed by the various agencies under generalized headings such as structural adequacy.

The amount that individual types of distress influence the overall rating can be examined in two ways: (a) by determining the average for those agencies that actually use the type of distress and (b) by averaging over all agencies. The latter is considered the most informative because, if an agency does not include a given type of distress, it indicates that the distress is considered unimportant.

Based on the latter averaging procedure, the general category accounts for an average of 13 percent of the overall pavement rating score for flexible pavements and 17 percent of the overall pavement rating score for rigid pavements. Of all of the specific types of distress, cracking is the most heavily weighted (17 percent for flexible pavements and 7 percent for rigid pavements). The next most important forms of distress for flexible pavements are rutting (5 percent) and patching (3 percent). The next most important forms of distress for rigid pavements are spalling (5 percent) and faulting (3 percent). Deflections average 3 percent for flexible pavements but are not considered as distress in this analysis.

It is apparent from this study that cracking is the major distress variable used in making maintenance and rehabilitation decisions. Deflections, roughness, and skid number are being measured, but the most heavily weighted type of distress (cracking) is not being measured by mechanical devices or instruments. Visual methods are the main techniques used currently but, in the future, as larger percentages of the highway budget are spent on maintenance and rehabilitation activities, it is anticipated that there will be a corresponding need for an increased use of measuring equipment to achieve faster and more consistent measurement on a larger percentage of the nation's highways. This need can be met by some existing equipment and some that are still in the conceptual stage, the most promising of which use nondestructive testing techniques. In the next section of this paper, the criteria that must be met by this equipment, the most efficient ways of using it, and some promising developmental techniques for measuring stiffness and cracking will be discussed. As noted previously, stiffness (or structural adequacy) and cracking are the most heavily weighted factors in making maintenance and rehabilitation decisions.

EQUIPMENT CRITERIA FOR MEASURING PAVEMENT STRUCTURAL CONDITION

Highway technology has produced a significant number of nondestructive pavement evaluation techniques. Some of these are production models that are used daily by various highway agencies. Others are still in the development stage and, although their principles of operation are known and the data they produce can be used in several ways, few of them produce data that can be analyzed to produce material properties of the pavement layers. A detailed description of this survey of equipment, their principles of operation, their capabilities of producing analyzable data, and their advantages and disadvantages for applications in pavement evaluation is available elsewhere (6).

The kinds of data that must be collected in the two kinds of surveys are different, a reflection of their different purposes. Decision surveys are concerned with distress, and design surveys are concerned with material properties, crack spacing and severity, and the response of a pavement structure to imposed loads or environmentally induced stresses. The types of data that each of the surveys may assemble can be broken down. A decision survey may assemble data on

1. Deflections,
2. Stiffness,
3. Cracking,
4. Rutting,
5. Roughness, and
6. Skid resistance.

A design survey may assemble data on

1. Deflections,
2. Cracking, and
3. Layer moduli.

The measurements made in a decision survey are of major interest because the results of a decision survey are a major factor in maintenance and rehabilitation decisions.

USE OF MEASUREMENTS IN A DECISION SURVEY

There are two methods of conducting a decision survey, a mass inventory or a statistical sampling study, and each has its own merits. In a mass inventory, one makes many measurements along the pavement to discover the location of the weak points most in need of repair. The pavement section with the greatest density of weak points in the roadway network presumably would receive maintenance attention earlier than one with a lower density. In a statistical sampling study, one makes sufficient measurements to determine a reliable statistical distribution of the pavement variable being measured. The pavement sections with the poorest average and greatest spread (as measured by the standard deviation) presumably would receive the earliest rehabilitation efforts. In either method, the objective is to establish rehabilitation priorities among several candidate sections in a roadway network.

The merits of the mass inventory methods as opposed to statistical sampling methods will be discussed as they are applied to deflection or stiffness or both and to cracking.

Decision Surveys of Pavement Stiffness

The California traveling deflectometer and the Lacroix deflectograph are the best known mass inventory devices for measuring pavement stiffness. They are capable of making between 1000 and 4000 measurements/day while covering approximately 17.7 to 22.5 km (11 to 14 miles) of road. The data that are produced are a collection of stiffness numbers that may or may not be well correlated with Benkelman beam data and may not mean the same thing on one pavement section as they do on another. What these devices give is an estimate of how stiff the pavement is at one location relative to the pavement at adjacent locations along the same length of road. This approach can pinpoint places for spot patching.

In the statistical sampling study, the emphasis shifts toward collecting data that can be analyzed to determine elastic moduli, coefficients of subgrade reaction, or other similar material properties of the pavement while obtaining a reasonably reliable statistical distribution of pavement stiffness numbers. These numbers may or may not represent material properties. In some cases, various measurements taken within a Dynaflect basin, such as surface curvature index (SCI), base curvature index (BCI), and Dynaflect maximum deflection (DMD), are used as a measure of pavement stiffness (7). In other cases, elastic moduli may be calculated from the measurements of surface deflections (8). Because this approach is slower and makes fewer measurements per day, it loses the detail that can be achieved with the mass inventory methods. Nevertheless, the statistical sampling approach still achieves the major objective of the survey, which is to collect data from which rehabilitation decisions can be made. Furthermore, it has the advantage that the data can be analyzed to determine the distribution of material properties along the length of a pavement.

In net balance, the adaptability of the statistical approach that uses slower equipment with analyzable data is expected to demonstrate more cost-effective long-range benefits.

Statistical Sampling Study Using Dynaflect

A study of the statistical approach was conducted by using Dynaflect data, which were measured every 0.8 km (0.5 mile) over a 161-km (100-mile) length of rigid pavement on I-45 between Houston and Dallas. A series of two computer programs were written to analyze the data. The first is the analysis program that used Westergaard's equations for the deflections of a point load on a rigid pavement resting on a liquid subgrade (9) to determine the elastic modulus E of the concrete and the subgrade modulus k of the subgrade. The equation for surface deflections w is of the form

$$w = (P/kl^2)\, f(x/l) \tag{1}$$

where

P = size of point load,
x = distance away from point load,
l = radius of relative stiffness = $[Eh^3/12k(1 - \mu^2)]^{1/4}$,

Table 1. Percentage of pavement condition rating score determined by distress.

Agency	Flexible Pavements	Rigid Pavements	Agency	Flexible Pavements	Rigid Pavements
Arizona	17.0	17.0	Nebraska	40.0	0.0
California	73.2	—	New Mexico	40.0	40.0
Florida	50.0	—	North Dakota	75.5	—
Georgia	37.5	—	Tennessee	50.0	50.0
Indiana	22.0	22.0	Texas	80.4	88.5
Kansas	44.0	50.0	Virginia	48.0	42.0
Louisiana	30.0	30.0	Washington	50.0	50.0
Maine	100.0	—	King County, Washington	37.5	—
Maryland	40.0	40.0			
Minnesota	50.0	50.0			

Note: In general, distress measured by ride meters is not used in the computation of percentages.

Figure 1. Breakdown of Table 1 data.

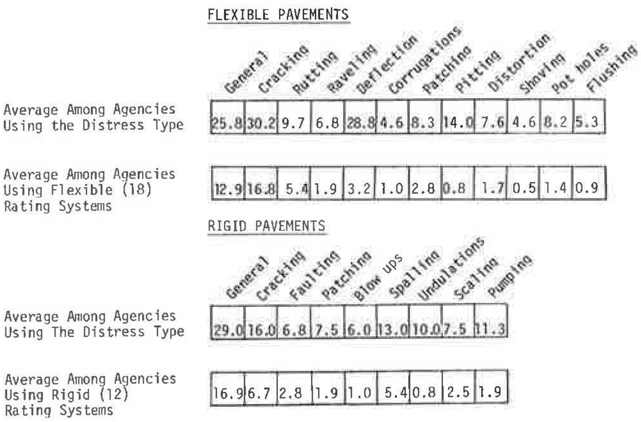
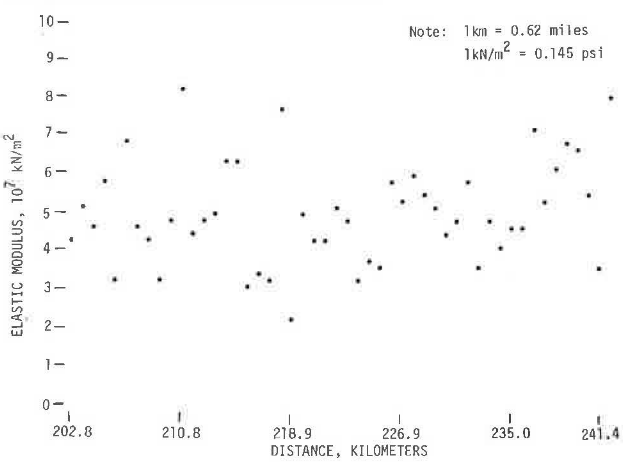


Figure 2. Variation of concrete elastic modulus along 40 km (25 miles) of I-45 between Houston and Dallas.



μ = Poisson's ratio of the concrete, and
f = a decreasing function of x/1.

The technique used chooses E and k by trial and error to minimize the sum of the squared errors between predicted and observed deflections. The second program determines the statistical properties of the calculated E and k value along the road. This program then drops out data in a specified pattern so that 90 percent, 80 percent, 70 percent, and smaller size samples can be used to calculate the same statistical properties, which include the mean, standard deviation, skewness, and kurtosis of the distribution. By finding the smallest size of sample that produces about the same statistical properties, one locates the minimum sampling rate for a pavement survey.

Figure 3. Variation of subgrade modulus along 40 km (25 miles) of I-45 between Houston and Dallas.

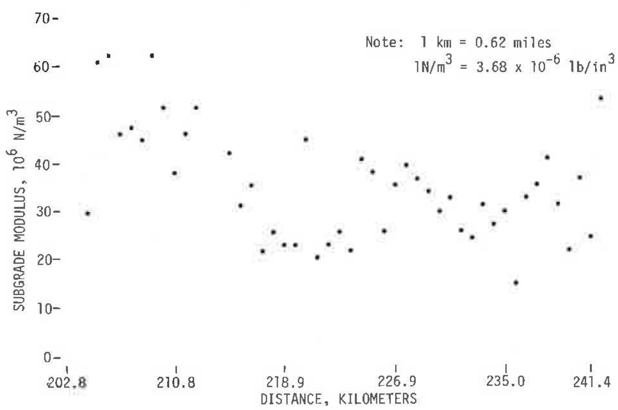


Table 2. Statistical properties of elastic modulus distribution.

Sample Size (%)	Mean (GN/m^2)	Standard Deviation (GN/m^2)	Skewness (GN/m^2)	Kurtosis (GN/m^2)
100	47.2	11.1	-1.05	-5.4
80	46.6	11.2	-1.06	-5.8
50	46.6	11.4	-2.07	-4.8
30	46.5	11.9	-1.33	-3.2
10	46.2	12.1	-1.93	-6.7

Note: 1 N/m^2 = 0.00145 lbf/in^2.

Figure 2 shows a typical distribution of the elastic modulus of the concrete pavement over a 40-km (25-mile) length of pavement. The values of E range between about 21 and 83 GN/m^2 (3 and 12 million lbf/in^2). The higher values are undoubtedly in error probably because of an underestimate of the thickness of the pavement or because of the presence of a stiff subbase material that has the same effect on the analysis as underestimating the thickness of the concrete. This is confirmed, to some extent, by Figure 3, which shows the values of the subgrade modulus over the same length of road. The larger values of E are in roughly the same location as the larger values of k, which indicates the possible presence of a three-layer pavement that is insufficiently well modeled by the two-layer Westergaard equation.

The statistical program then sampled the calculated data and produced the statistical measures of elastic modulus given in Table 2. The total number of samples considered was 180. Skewness measures the distribution of the data around the mean, and kurtosis measures how peaked the distribution is. A value of zero in each case is a property of the normal distribution curve.

The 50 percent sample, representing a measurement every 1.6 km (1 mile), gives values that are nearly identical with those of the 100 percent sample. Even the 10 percent sample, computed from only 18 measurements, gives acceptably close values of the mean and standard deviation. This 10 percent sample represents a measurement made every 8.0 km (5 miles). A similar determination was made for the subgrade modulus distribution. Although this is not suggested to be standard practice, it does show that relatively infrequent measurements can produce acceptable statistical measures of pavement properties. Furthermore, it indicates that a study such as this can sometimes greatly reduce the amount of data required for making decisions on rehabilitation and at the same time produce data that are sufficiently accurate for the design of overlays and other forms of pavement rehabilitation.

These considerations demonstrate that the speed of operation of deflection or stiffness measuring devices, or in fact any kind of device, is relatively unimportant as long as the equipment can be used effectively as part of a statistical sampling survey.

Impulse and Impedance Methods

Among the methods of determining pavement stiffness are the Phoenix falling weight deflectometer (PFWD) and the impulse testing techniques developed at the Cornell Aeronautical Laboratory (CAL) and the Washington State University (WSU) as well as the vibration testing impedance technique developed in South Africa at the National Institute for Road Research (NIRR). All of these devices are capable of making measurements that can be analyzed provided that both input force and output response are measured as a function of time. The WSU device measures vertical accelerations as the pavement output response with time; the NIRR device measures vertical velocities as the output response; and the CAL and PFWD devices measure displacements with time. Because of the way they operate, these devices are well suited to a statistical sampling survey. The vehicle-mounted WSU device is even capable of collecting data on a mass inventory basis. Szendrei and Freeme (10), referring to the NIRR device, define the pavement impedance function $Z(\omega)$ as the ratio of the Fourier transforms of the input force and the output velocity response.

$$Z(\omega) = \left[\int_{t=-\infty}^{t=\infty} f(t) \exp(-j\omega t)dt \Big/ \int_{t=-\infty}^{t=\infty} v(t) \exp(-j\omega t)dt \right] \quad (2)$$

where

$f(t)$ = input force as function of time,
$v(t)$ = output velocity response as function of time, and
ω = frequency in radians per second.

By using the derived impedance function $Z(\omega)$ and other such derived data, namely, the exponential rate of saturation and the phase retardation with distance, one can calculate the deflection response of a pavement surface to a moving load. As long as the pavement deflects reasonably linearly overall, which it does even for fairly heavy highway loads (10, 11), the calculated response can be expected to be reasonably accurate. The same impedance function could be derived from the WSU measurements by means of the following relation at every point where acceleration $a(t)$ is measured:

$$Z(\omega)/j\omega = \left[\int_{t=-\infty}^{t=\infty} f(t) \exp(-j\omega t)dt \Big/ \int_{t=-\infty}^{t=\infty} a(t) \exp(-j\omega t)dt \right] \quad (3)$$

Thus approximately the same analysis techniques developed in South Africa could be used to analyze data

Figure 4. Typical GM profilometer data showing a cracked pavement profile.

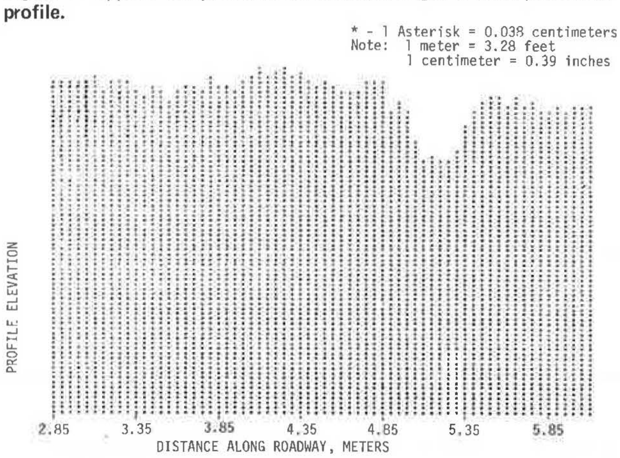
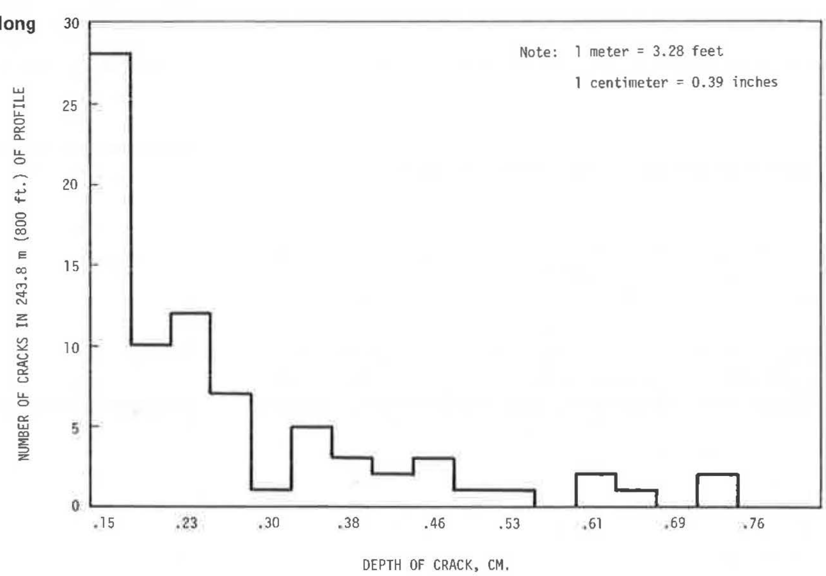


Figure 5. Frequency distribution of crack depths along I-20 between Midland and Odessa, Texas.



from the WSU device. This would permit a calculation of the deflection response of a pavement to any selected moving load.

Both the CAL and the PFWD measure output displacement response at only one point immediately beneath the load. Therefore, use of their data to make moving load predictions would be impossible. However, as shown by Szendrei and Freeme (10), these measurements are sufficient to predict the deflection response of a pavement to an impulse load, which, in itself, is a reasonable indication of the overall stiffness of a pavement.

The results of these measurements, data reduction, and Fourier transformation is an analytical measure of overall pavement stiffness that can be determined quickly and can be expected to be sensitive to changes in pavement stiffness, either with time or with distance. This makes this device potentially useful in a statistical sampling survey.

Crack Counting With GM Profilometer

The General Motors (GM) profilometer is capable of making very accurate detailed measurements of pavement profile in the right and left wheel paths. Usually the analogue measurements made by the profilometer are converted to digital data, and a profile elevation is given every 5.149 cm (2.027 in) along the roadway. The entire process is described in detail elsewhere (12, 13). A computer plot of typical profilometer data is shown in Figure 4 where each asterisk represents an elevation change of about 0.038 cm (0.015 in). The numbers marked at the bottom of the figure are the distances in meters from the beginning of the profile, which was measured along a test section of badly cracked flexible pavement on I-20 in Texas Department of Highways and Public Transportation District 6. The cracking along this length of pavement is apparently caused by thermal shrinkage of the base course.

The large dip centered on distance 5.25 m (17.22 ft) is a crack that is about 0.71 cm (0.28 in) deep. The really significant feature of this crack is the depression on each side of it. As expected from analysis (14), a shrinkage crack in the base course will draw down the pavement on each side of it for a considerable distance, which in this case is about 0.46 m (1.5 ft). The characteristic V shape of a crack makes it a visually distinctive feature in a profile of a flexible pavement. A crack in a rigid pavement where the surface course is a brittle material will be much more abrupt. In either case, the crack may become accentuated with time as fines are pumped out of the base course. Distortion around the crack will always point toward the most active layer—the layer that has caused the crack.

The observation of the V shape around a crack led to the development of a special profile filter that distinguishes a V shape and stores in computer memory the location of the center of the crack. The profile filter first smooths the profile by averaging the 5 points centered around a given point and then manufactures an even smoother profile by averaging 30 points around the given point. A crack is defined by a difference in elevation between the 5-point averaged and the 30-point averaged profiles. The 30-point averaged profile provides a relatively smooth datum with which to compare the 5-point profile while following the general slope of the pavement fairly faithfully. The 5-point averaging was done to eliminate extraneous material from the profile.

The crack-counting filter found that there are two cracks in the space shown in Figure 4:

1. A crack of severity 4 [0.15 cm (0.06 in)] at 3.50 m (11.48 ft) and
2. A crack of severity 19 [0.71 cm (0.28 in)] at 5.25 m (17.22 ft).

A frequency distribution of the cracks found within a 243.8-m (800-ft) distance is shown in Figure 5. A total of 78 cracks were found with this filter, which gives an average crack spacing of just over 3 m (10 ft). A field survey of this same section of pavement indicated that the visible cracks occur on the average of 3.7 m (12 ft), a reasonably close match.

Although the difference between a 3-m (10-ft) and a 3.7-m (12-ft) crack spacing may be only a statistical error, it does suggest that the crack-counting filter found some 11 out of 78 surface profile features that resembled cracks but may not have been.

There are two possible interpretations of this finding.

1. The crack-counting filter is in error and should use a greater difference in elevation as a crack criterion. An elevation difference of 0.20 cm (0.08 in) would give an average crack spacing of about 4.9 m (16 ft).
2. The crack-counting filter has found some cracks that are as yet invisible.

It is impossible at this stage to say which of these interpretations is correct. This determination will require further field investigation. Analytical results such as those of George (14) show clearly the mechanism of pavement depressions forming above where cracks in the base course have not yet broken through the surface. Whether such a depression will always indicate the presence of an invisible crack is another question that remains to be determined.

That the crack-counting filter is a convenient, automatic, and rapid method of determining cracks from GM profilometer data can certainly be concluded. The filter may have a hidden potential for detecting invisible transverse cracks and may be very useful in statistical sampling surveys.

SUMMARY AND CONCLUSIONS

Pavement structural evaluation is a major consideration in pavement condition surveys that are widely used in making maintenance and rehabilitation decisions. Although each highway agency has developed its own rating system independently, there is broad agreement on the most significant indicators of pavement condition. Equipment to measure some of these indicators is being used routinely but there is some controversy about the best way to use the equipment in sampling the condition of the roadway and a lack of development of equipment that can reliably measure cracks. Several innovative ways of using existing equipment have been tried, and the results are presented in this paper. The major conclusions of this study are as follows:

1. Most highway agencies are conducting pavement condition surveys for flexible and rigid pavements;
2. Most agencies with pavement condition rating methods use these systems in making maintenance decisions;
3. Car ride meters are now the most widely used methods of measuring riding quality;
4. Cracking is the most heavily weighted distress indicator in the rating systems and as yet is not measured by instrumentation, and general structural adequacy is also a major factor in the rating systems;
5. The GM profilometer combined with a crack-counting filter shows promise as a possible crack-measurement device;
6. The most rapid, reliable method of gathering

data for a decision survey will use a statistical sampling technique; and

7. Impulse and impedance methods of measuring pavement stiffness must have further development in data reduction and analysis techniques, but they show promise of being a rapid, reliable indicator of pavement stiffness; currently used devices for measuring pavement deflections can produce reliable measures of pavement stiffness but also can be analyzed to give material properties of the pavement layers.

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