Impulse Index as a Measure of Pavement Condition

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A rapid method of measurement of pavement structural condition has been developed that is adaptable to automatic data acquisition from a moving vehicle and yields numerical data suitable for computer manipulation. A hand-carried version has been developed that measures parameters indicative of structural condition and computes an evaluating number called the impulse index. To determine the impulse index, an impulse of energy is delivered to the pavement with a hammer blow. Two transducers are used to monitor the acceleration of the pavement very close to the impact point and the attenuation of the energy as it propagates through the pavement. The outputs of the accelerometers are manipulated electronically to compute the impulse index. Comparisons of Benkelman beam deflections and impulse index measurements for the same locations on a wide variety of types of pavement and pavement conditions are presented in graphical form for easy comparison. A high degree of correlation was found between the impulse index and Benkelman beam deflections. This impulse index is much faster to obtain and requires only lightweight, highly portable equipment.

This project was initiated to develop a method of nondestructive testing of highway pavements that would be more economical and faster than existing methods. A system was desired that would ultimately be adaptable to operation from a moving vehicle and in which the data would automatically be acquired and recorded in computer-compatible format such as on magnetic tape. If the system can be made to operate fast enough, the pavement condition of the entire highway system can be logged at planned intervals, yielding the state of deterioration as well as the rate of deterioration of every increment of highway pavement. Such a log would be a valuable aid in highway management and in documenting budgetary requirements and establishing priorities of maintenance.

PAVEMENT STRUCTURAL LINEARITY

Earlier tests performed at Washington State University indicated that the structural parameters of pavement are sufficiently linear over a broad enough range so that the energy or force used in deflection or impulse testing need not be as great as in previously accepted methods. These findings are consistent with those of other investigators (1, 2). The direct consequence of this reasonable linearity is that nondestructive pavement testing equipment need not be large and heavy. The impulse index results reported in this paper were acquired by using a driving function of approximately 9 J (6.5 ft·lbf). The total weight of the impulse index equipment is currently about 25 kg (55 lb), and it can be made even lighter.

IMPULSE DRIVING FUNCTION

The advantages of using an impulse driving function rather than a steady-state sinusoid were also explored. Textbooks on linear circuit theory (3, 4, 5) present the theoretical background that shows the necessity of using a broad range of frequencies when system response is investigated. Use of single frequency excitation carries the risk that response will be very dependent on the locations of the S-plane poles of the system transfer function with respect to the poles of the single frequency driving function. A unit impulse, on the other hand, contains an equal amount of all frequencies, and the response of a system to a unit impulse is determined only by the parameters of the system under test and not by a response to a specific single frequency selected for a driving function that may or may not coincide with self-resonant frequencies of the system under test.

A true unit impulse is, of course, not actually attainable, but a pulse of finite height and width can be substituted provided that the width is much narrower than the period of the highest frequencies of interest.

IMPULSE INDEX

Tests were conducted on various pavements by using an impulse of energy for system excitation. Various characteristics of the response of the pavement to such excitation were examined for correlation of parameters with known pavement condition. The result of the research was the development of a system that uses a hammer blow for excitation and two accelerometers on the pavement surface. One accelerometer is placed as

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near to the point of impact as possible and the second accelerometer is positioned a fixed distance away [46 cm (18 in) was found to be a convenient and suitable distance]. The output from each accelerometer is electronically processed so that its absolute magnitude is determined and then integrated with respect to time. If we designate the resulting quantity as R and the unprocessed output of the accelerometer as a, then

$$R = \int |a| \, dt \tag{1}$$

This quantity R from each accelerometer can be used for plotting a profile of the pavement response basin, which is loosely referred to as a deflection profile under impulse loading.

For convenience, the quantity from the accelerometer nearest the hammer has been designated R_1 and the quantity from the second accelerometer is designated R_2. A relation was developed that reduces the profile information into a single number, designated impulse index.

Experiments on flexible pavements indicated that the attenuation of energy propagated through better pavements was less than that for poorer pavements. The ratio of R_1/R_2 provides a form of measure of this attenuation. Poorer pavements also yielded higher values of R_1 than did better pavements. If we take both of these observations into consideration, the impulse index is generated as follows:

$$\text{Impulse index} = (R_1/R_2) \times R_1 = R_1^2/R_2 \tag{2}$$

High values of impulse index correspond to weakened pavement, and low values correspond to sound pavement. Further details on impulse index are available elsewhere (6).

VEHICLE OPERATION

The total time required for an impulse index measurement is a fraction of a second. To acquire the data from a moving vehicle is therefore feasible. A test vehicle that demonstrates one possible approach to mechanizing the automatic acquisition of impulse index data has been constructed (7). The transducers and a hammer pin are mounted in a continuous belt that contacts the pavement in a manner similar to that of the tread of a tracked vehicle. The end support wheels for the belt are approximately 6 m (20 ft) apart. As the vehicle travels down the highway, the belt lays the transducers and hammer pin on the pavement where they are stationary with respect to the pavement until the vehicle advances far enough so that the belt travels up and over the near support wheel. At 50 km/h (30 mph), the transducers would be on the pavement for nearly 0.5 s, ample time to make an impulse index measurement. A measurement is made with each complete revolution of the belt. Two belts side by side could be used, if desired, to monitor both wheel tracks of the lane.

Additional development is required to make the operation of the vehicle smooth and satisfactory at highway speeds. Before proceeding with further development of the vehicle, it was determined that a thorough evaluation of the validity of the impulse index as a measure of pavement condition would be required.

HAND-CARRIED IMPULSE INDEX COMPUTER

To acquire sufficient data for a thorough evaluation of the validity of the impulse index as a measure of pavement condition, demonstrate the system, and perform spot checks, a suitcase-sized hand-carried version of the impulse index computer was assembled. The device includes the hammer, two transducers, and the necessary electronics, batteries, and readout meters. A block diagram of the device is shown in Figure 1. Figure 2 shows the device in operation. In use, the device rests on the pavement, the hammer is raised to its limit and dropped, and the meters give R_1, R_2, and impulse index values. The results in the remainder of this paper were acquired by using the hand-carried impulse index computer.

COMPARATIVE DATA FOR PAVEMENT SECTIONS WITH KNOWN HISTORY

Some interesting locations on I-90 were examined. At milepost 122 in the eastbound lane east of Ellensburg is a joint in the top lift. The top lift west of the joint had been laid only 2 weeks before these tests were conducted. The top lift east of the joint had been laid 2 years earlier. Both of these regions would have the same traffic history. The impulse index was measured about 30 m (100 ft) on each side of the joint in the top lift. Measurements were made in the outside wheel track, lane center, and inside wheel track in the extreme right hand lane of both areas. Figure 3 shows a graph of the data. In Figure 3, the lower impulse index values were obtained where the top lift had been in place for only about 1 week. The higher values of impulse index were obtained about 60 m (200 ft) to the east where the top lift had been placed several years ago.

A low reading of impulse index signifies better pavement condition than a higher reading does. Several things can be noted from Figure 3. The region with the brand new overlay registered the lower value of impulse index. Note that the wheel track registers the highest (most distress).

I-90 AND YAKIMA FREEWAY INTERCHANGE RAMP

Tests were made on the ramp from eastbound I-90 to southbound Yakima Freeway. This ramp has been in service for several years although the top lift had not been previously applied. The paving project was under way while the tests reported here were made. The top lift had just been applied in the passing lane a few hours earlier and had not yet been applied in the extreme right lane. Measurements were made after one lane had just received the top lift and the other lane had not. Figure 4 shows a graph of the impulse index measurements from the usual six places. The lane that had the top lift applied had lower impulse index values.

IMPULSE INDEX AND BENKELMAN BEAM COMPARISONS

District 1 Sites

Nine sites located in Skagit and Snohomish Counties in the western part of the state of Washington were selected for tests to compare impulse index measurements with Benkelman beam measurements (7). These particular sites were selected because the district 1 personnel were already scheduled to make Benkelman beam tests at those sites under a program designed to determine future load limits under freeze-thaw conditions. The sites are identified in Table 1.

At each test site, nine positions were marked off at 7.5-m (25-ft) intervals. One Benkelman beam set was used and it was operated by the crew from district 1. The pointer of the beam was projected through the space between the dual wheels of the truck to a point 1.2 m (4 ft) ahead of the axle centerline. The truck was driven slowly ahead and the maximum deflection was recorded. The position on the pavement of the pointer of the Benkelman beam was marked before the beam was moved. The truck provided a rear axle load of 6800 kg (15 000 lb).

Eight impulse index measurements were made at each test position. The instrument was rotated 45 deg between each measurement and positioned so that the hammer would impact at the point where the tip of the Benkelman beam had rested.

Figures 5 through 13 show comparisons for each of the nine positions. The eight impulse index readings taken at each test position are averaged and graphed along with the Benkelman beam reading for each position. A separate graph is presented for each test site, but the scale is identical for all graphs. One unit of impulse index corresponds rather consistently with 0.08 cm (0.03 in) of Benkelman beam deflection for the region of operation examined. It can be observed from these graphs that the Benkelman beam measurement and the

Figure 1. Block diagram of impulse index computer.

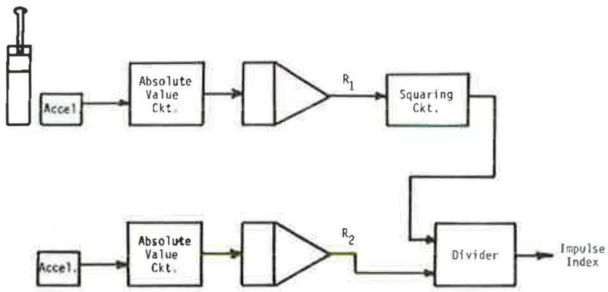

Figure 2. Impulse index computer in operation on Wash-270.

Figure 3. Impulse index profile of I-90 at milepost 122.

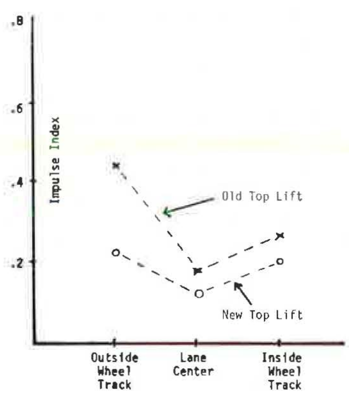

Figure 4. Impulse index profile for I-90 and Yakima Freeway.

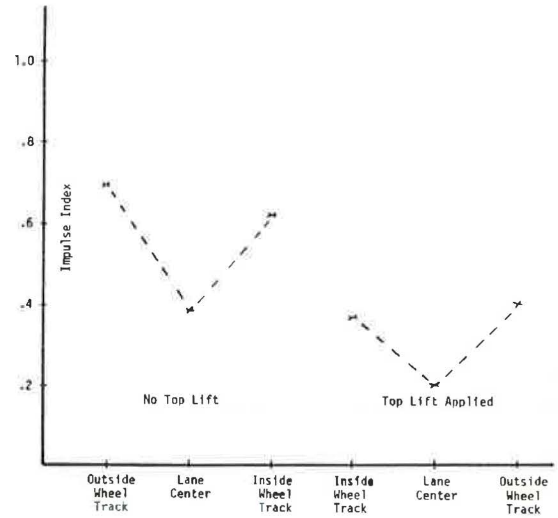

Figure 5. Benkelman beam and impulse index of district 1, test site 1.

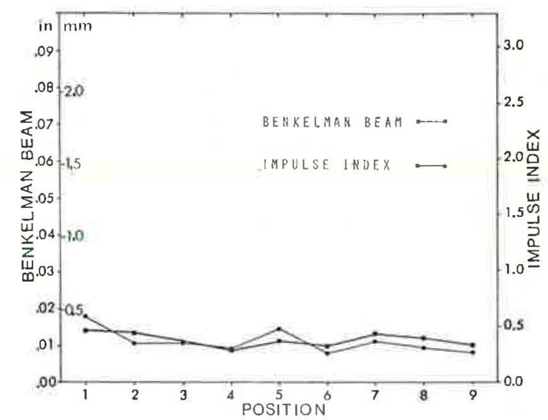

Table 1. District 1 sites.

Site	Route	Milepost	Direction	Location	Surface
1	Wash-20	6	Eastbound	South of Anacortes	0.11-m AC, 0.12-m CTB, 0.08-m sand
3	Wash-20	18.6	Westbound	West of Lyman	0.11-m RS, 0.09-m AC, 0.11-m SRB, 0.24-m SSGB
4	Wash-20	21	Westbound	East of Lyman	0.15-m RS, 0.11-m AC, 0.198-m SRB, 0.15-m SSGB
6	Wash-9	27	Southbound	South of Arlington	0.08-m AC, 0.08-m CSTC, 0.18-m GB, 0.21-m SSGB
7	Wash-9	17	Southbound	South of Marysville Jct.	0.12-m AC, 0.06-m CSTC, 0.27-m SSGB, 0.21-m SSB
8	Wash-204	1.1	Westbound	East of Everett	0.12-m AC, 0.18-m SG, 0.24-m SSB
9	Wash-9	13	Southbound	South of Wash-204 Jct.	0.14-m AC, 0.05-m CSTC, 0.15-m SGB, 0.21-m SG
10	Wash-2	10	Eastbound	East of Snohomish	0.12-m AC, 0.03-m CSTC, 0.3-m SGB, 0.15-m SSG
11	Wash-2	19	Eastbound	West of Sultan	0.27-m AC (5 layers), 0.03-m CSTC, 0.06-m SSGB, 0.3-m SG

Notes: 1 m = 3.28 ft.
AC = asphalt concrete; CSTC = crushed surfacing top course; CTB = cement-treated base; GB = gravel borrow; RS = resurfacing; SG = sand and gravel; SBG = sand and gravel borrow; SRB = selected roadway borrow; SSB = silty sand borrow; SSGB = silty sand and gravel borrow.

impulse index correlate fairly well on a point-by-point basis.

Pullman Area Sites

It can be observed from the Benkelman beam deflection as well as from the impulse index that the district 1 sites yielded fairly low deflections. In an effort to obtain comparisons over a wider range of pavement condition, some additional sites were selected in the vicinity of Pullman (8). The locations and pavement profiles of Pullman sites are given in Table 2. The procedure for obtaining the impulse index for these sites was modified. Only four readings were taken at each position at 90-deg rotations instead of eight readings at 45-deg rotations as with the district 1 tests.

The Benkelman beam technique was also slightly modified. The pointer of the beam was placed between dual wheels for the reference. The truck was then driven ahead 6 m (20 ft), and the pavement rebound was re-

Figure 6. Benkelman beam and impulse index of district 1, test site 3.

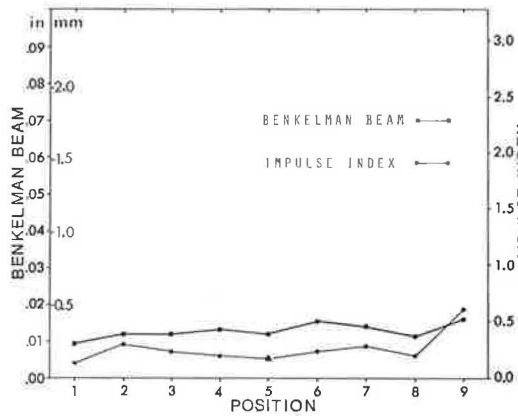

Figure 7. Benkelman beam and impulse index of district 1, test site 4.

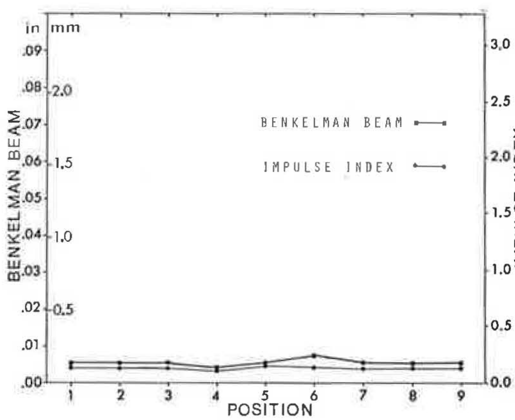

Figure 8. Benkelman beam and impulse index of district 1, test site 6.

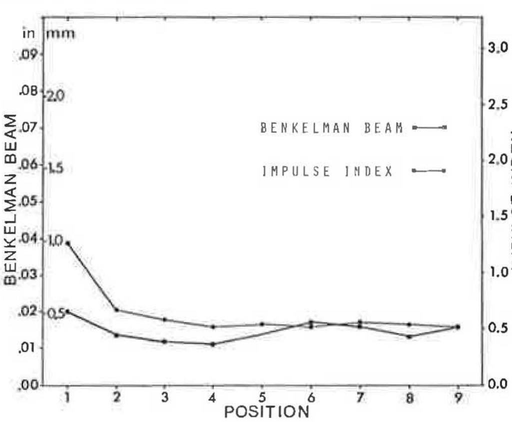

Figure 9. Benkelman beam and impulse index of district 1, test site 7.

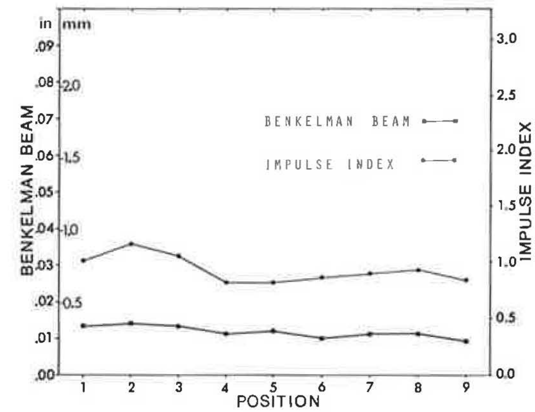

Figure 10. Benkelman beam and impulse index of district 1, test site 8.

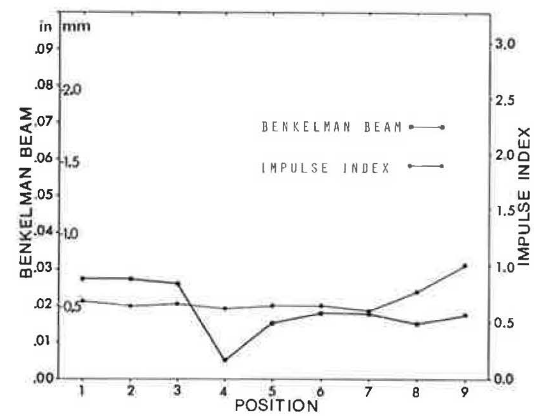

Figure 11. Benkelman beam and impulse index of district 1, test site 9.

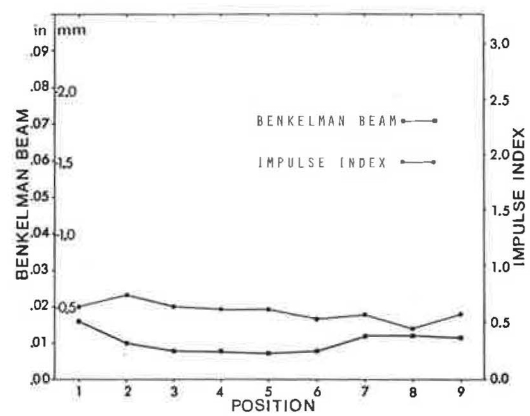

Figure 12. Benkelman beam and impulse index of district 1, test site 10.

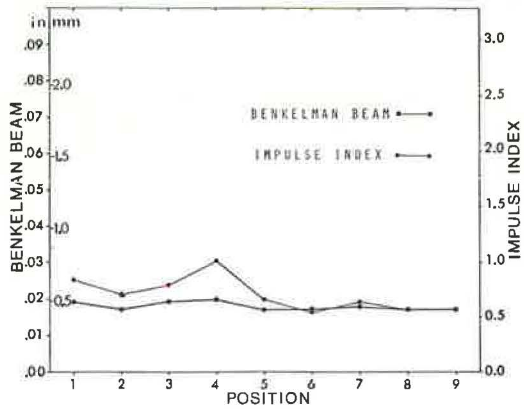

Figure 13. Benkelman beam and impulse index of district 1, test site 11.

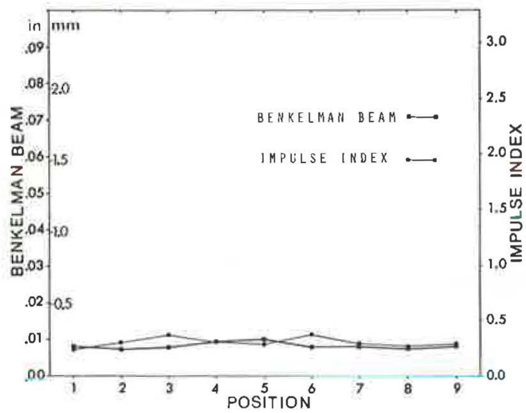

Figure 14. Benkelman beam and impulse index of Pullman area, test site A.

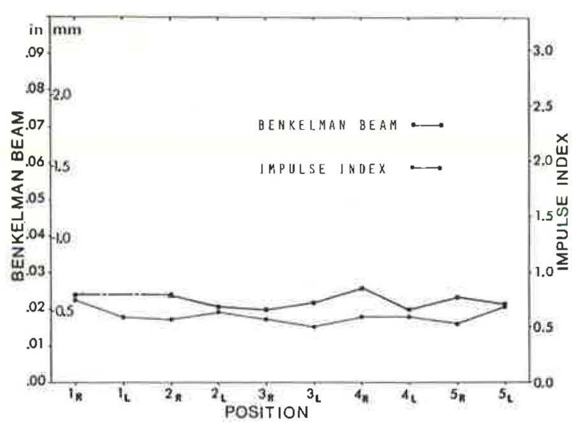

Figure 15. Benkelman beam and impulse index of Pullman area, test site B.

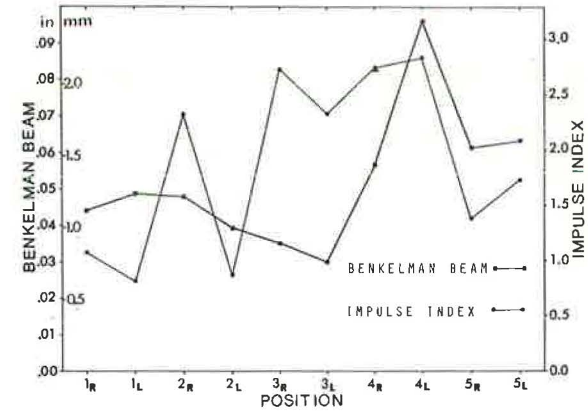

Figure 16. Benkelman beam and impulse index of Pullman area, test sites C and D.

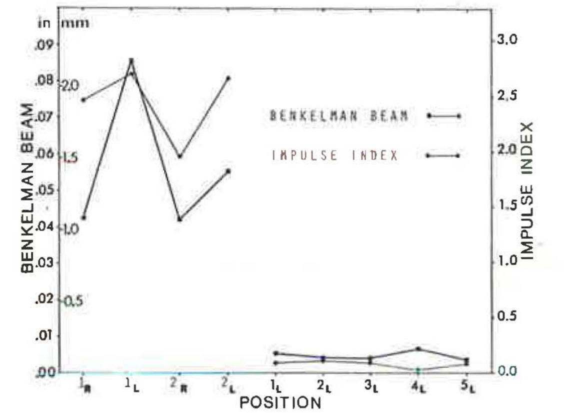

Figure 17. Benkelman beam and impulse index summary.

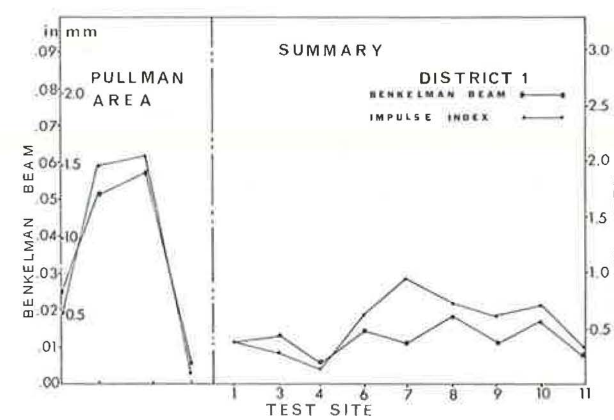

Table 2. Pullman area sites.

Site	Location	Surface
A	Westbound lane, southwest Crestview, 130 m west of Grand Avenue, Pullman	0.08-m AC, 0.08-m CSTC, 0.2-m GB
B	Intersection of parking lot entrance with approach road to new Pullman high school	0.08-m permanent vertical deformation, 0.05-m AC, 0.15-m GB
C	Larry Street extension, main access road to high school	0.05-m AC, 0.15-m GB
D	1000 block of North Grand, Pullman	0.15-m nonreinforced PCC, 0.3-m GB

Notes: 1 m = 3.28 ft.
AC = asphalt concrete; CSTC = crushed surfacing top course; GB = gravel base; PCC = portland cement concrete.

corded from the Benkelman beam.

The four impulse index readings obtained at each position were averaged and are shown in Figures 14, 15, and 16 along with Benkelman beam deflections at each point.

SUMMARY AND CONCLUSIONS

Because of anomalies in pavement structure, monitoring of a single point on a pavement does not give an adequate measure of pavement condition. Many points must be monitored to compensate for these variations. To compare the overall results of the Benkelman beam deflections with impulse index measurements, we averaged all of the Benkelman beam measurements made at each test site and all of the impulse index measurements obtained for each test site. The resulting data, shown in Figure 17, indicate the correlation between the impulse index and Benkelman beam deflections.

The advantage of the impulse index technique is the very small amount of time required for the tests and the light weight and portability of the equipment.

ACKNOWLEDGMENTS

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