Statistical Analysis of Pavement Structure Data in PMS Data Base

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The Tokyo Metropolitan Government Road Authority is currently performing pavement structure surveys using a system that integrates ground penetrating radar and a proprietary borehole camera. The road authority's intention is to increase the efficiency and usefulness of its pavement management system (PMS) data base related to pavement structure. A large amount of data was acquired during 1992 and 1993. By means of statistical methods, these structure data could be manipulated to illustrate the nature of several segments of pavement structure in the Tokyo metropolitan area. The results were successful, thus reassuring the road authority of the usefulness of this relatively new system of PMS data base input. Statistical methods determined that the segment lengths are relatively short (an average of 500 m per segment). The accuracy of the field data is good enough to use as structure thickness for the PMS data base, but it must be noted that normalized thickness is achieved as a result of averaging the actual thickness that includes some irregularity due to the irregularity of the layer. In most of the areas surveyed, designed structures corresponded to measured structures with a few exceptions. These exceptions were detected by the field survey system. Though there is no practical difference between normalized and actual segment thicknesses when they are used to perform falling weight deflectometer inverse analysis, further field data and a statistical data correlation study are needed to develop this method to a more practical level.

Knowledge of pavement structure plays an important role in failure curve determination by providing indispensable information to a pavement management system (PMS) data base. A pavement structure data base must include initially designed data and subsequent maintenance records. A large number of underground utilities (water, sewer, electrical, steam, etc.) in a city area repeatedly require road maintenance work that is likely to overwrite historical structure information. Often no information is available for roads constructed prior to the establishment of modern record keeping. As a result, it is inevitable that those areas of pavement structure with unknown thicknesses within a given road authority jurisdiction will constitute a significant portion of the total road miles represented in the data base.

The survey system integrated with ground penetrating radar (GPR) and the borehole camera (BHC) discussed here was developed specifically for acquiring real structure data to upgrade existing records, and to create records where none exist. Using this system, data have been collected for pavement structure data base input for the Tokyo metropolitan PMS from 1992 to 1993, and this effort is ongoing. Further, the focus here is to describe the use of statistical methods when large amounts of structure data are available.

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DESCRIPTION OF SURVEYS

The pavement structure survey under discussion consists of two individual surveys, the preliminary survey and the precise survey (*1*). The preliminary survey is carried out by vehicle-mounted GPR followed by a segmentation analysis. The central frequency of the radar pulse is 750 MHz. The precise survey is carried out using the BHC followed by a section profiling analysis. Figure 1 contains the working flow diagram.

Preliminary Survey

The preliminary survey is carried out by driving a GPR-mounted survey vehicle at a speed of 30 to 40 kmph. The electromagnetic wave that radiates from the GPR antenna enters the ground and reflects off of each boundary. The return wave forms a continuous wave that is charted in variable density. A study of the chart gives a rough idea of the pavement structure. The initial purpose here is to divide the road into segments by determining which lengths have uniform or homogeneous structure. The structure might change transversely so it is necessary to survey additional lanes to develop a more complete image of the structure, but the current study included single lane data only.

Pavement segments in Tokyo are specifically designed, section by section, with an eye to traffic load and bearing capacity of subgrade using indexes such as the California bearing ratio (CBR). Repeatedly performed maintenance works in an area, however, easily overwrite and alter "as-designed" information.

Segment boundaries cannot be observed from the surface of a lane segment. GPR enables the pavement engineer to determine boundary information rationally by analysis of the trace output.

The purpose of the preliminary survey is not to gain a precise determination of pavement section, but just a segmentation. The GPR survey supplies lists and maps of segmentation, including number of segments, segment length, and start and end coordinates measured with block ending-beginning linkage. The coordinates are input directly into the PMS data base, and the map is used to determine the boring points where simulated video core samples have been taken in the precise survey.

Precise Survey

The velocity of an electromagnetic wave depends upon the material of the medium through which it travels. Direct reading of layer thickness from GPR records does not give an actual thickness. Additionally, the material composition of each layer cannot be determined from a GPR record. Only layer continuity can be deter-

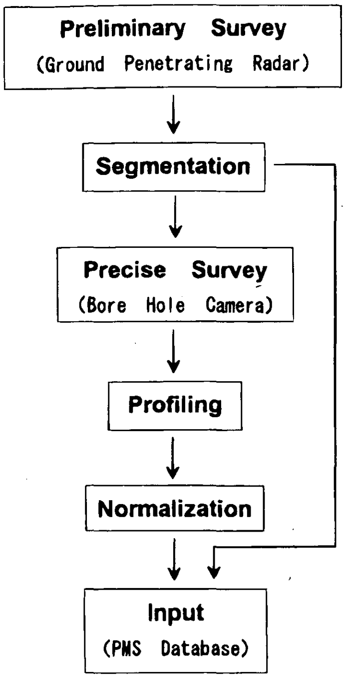

FIGURE 1 Work flow.

mined. Calibration of GPR data by BHC ground truth data is required to determine actual thickness.

For that purpose, a BHC survey, which is preceded by a small diameter boring, is performed. If CBR data are required, a visual observation survey, which must be preceded by a large diameter boring, is performed instead of the BHC survey.

Given a known material composition and actual thickness, a specific dielectric constant is determined by comparing the GPR and BHC data. The scaling accuracy of the BHC image is 0.5 percent. The dielectric constant is used for determining the calibration coefficient. Calibration must be performed not by an automatic comparison, but by a deliberate and rational consideration of dielectric constant values aimed at minimizing errors.

The profile is made by preparing a plot every 10 m. It is too precise to treat as PMS input data since the normal data base segment is 500 m. Consequently, normalized values per segment are prepared as input data by averaging profile values. As the PMS data base evolves over time, it will be possible to treat the precise data themselves as input data because the survey interval of the falling weight deflectometer (FWD) is currently 20 m, and FWD is becoming more popular in Japan, hence the justification for a smaller segment length.

ANALYSIS

Segmentation

Segmentation determination is not automatic; it is conducted with rational consideration. There are some key points for judgment. The five main points to consider are as follows:

- Break of segment should be indicated at the point where the overall appearance of the GPR record changes. But careful attention must be paid to avoid misinterpreting a break at railway crossings, bridges, and local repair locations where a false break could be read.
- Reflection at the bottom of the asphalt mixture layer is usually very strong because of a high contrast in the dielectric constant. The break should be indicated at the location where thicknesses on the GPR record obviously change despite the thicknesses being precalibrated because a calibration error originated from dielectric constants is usually very small and is nullified by the actual thickness.
- A noted difference in the number of layers is itself a decisive factor in the determination of a segmentation break.
- Even though the thicknesses of the asphalt mixture are the same, a break should be noted where the thicknesses of the crushed stone layer are different. Because crushed stone layers are likely to be more irregular than asphalt mixtures, global consideration is needed to avoid misjudgment at locally changed layer thickness points.
- There are some cases where reflection intensities are different while thicknesses are the same. Though it is caused by the difference of dielectric constant contrasts, it is ambiguous whether the anomaly is subgrade oriented or subbase oriented. Most of the cases in the Tokyo area showed that the difference comes from loam as subgrade, which has a very high dielectric constant with water content. Therefore, the break is basically not noted in that case as it is better under such circumstances to select the bottom of the asphalt mixture as the break criteria.

Profiling

Calibration is carried out before profiling. Figure 2 is a schematic explanation of the difference between actual thickness and thickness on the record. The data are calibrated by means of the following formula:

$$Tactual = M \cdot \frac{Vi}{Vo} \cdot Trecord = \frac{M}{\sqrt{\varepsilon i}} \cdot Trecord$$

where

εi = dielectric constant of ith layer,
Vo = electromagnetic wave velocity in a vacuum,
Vi = electromagnetic wave velocity in ith layer's material,
M = constant related to output machine,
$Tactual$ = actual thickness, and
$Trecord$ = thickness on the record.

Materials used for pavement have standard values of dielectric constants. If the value calculated with GPR and BHC data comparison deviates highly from the standard, it will not provide proper calibration and should be excluded.

The dielectric constant of mixed material is calculated from the component materials. In the case of crushed stone, it is calculated as follows:

$$\sqrt{\varepsilon} = \eta a \sqrt{\varepsilon a} + \eta w \sqrt{\varepsilon w} + \eta s \sqrt{\varepsilon s}$$

$$\eta w = \frac{2.5\,\gamma\,(1-\phi)}{1-\gamma}$$

$$\eta a = \phi - \eta w$$

$$\eta s = 1 - \phi$$

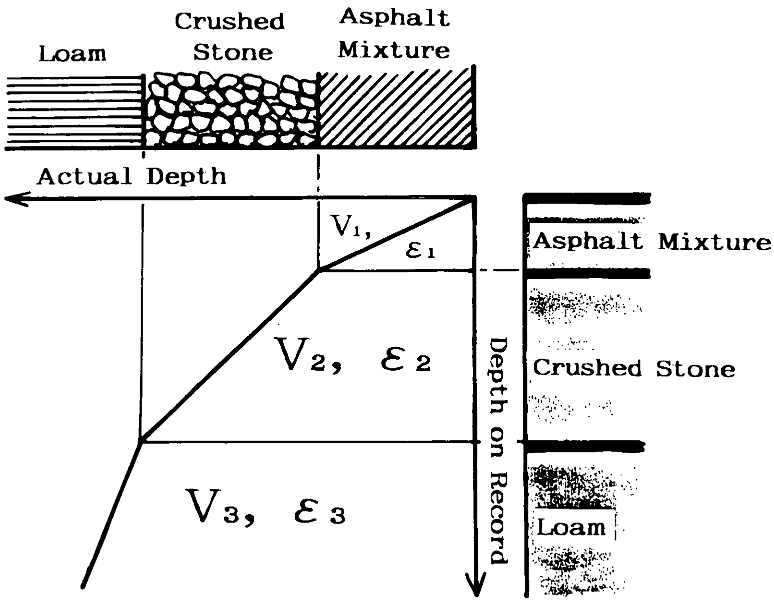

FIGURE 2 Schematic view of dielectric constant effect.

where

- ε = dielectric constant of crushed stone,
- εa = dielectric constant of air (1),
- εw = dielectric constant of water (81),
- εs = dielectric constant of soil particle,
- ηa = volume fraction of air,
- ηw = volume fraction of water,
- ηs = volume fraction of soil particle,
- γ = water content rate, and
- ϕ = porosity.

It has been demonstrated that the dielectric constant of soil particles is assumed to be approximately four (2). The calculated dielectric constant is shown in Figure 3. Besides the theoretical approach, statistical values collected through past calibration works in Figure 4 for crushed stone and in Figure 5 for asphalt mixture are indicated. The standard values are estimated at from four to six for asphalt mixtures and from six to nine for crushed stone.

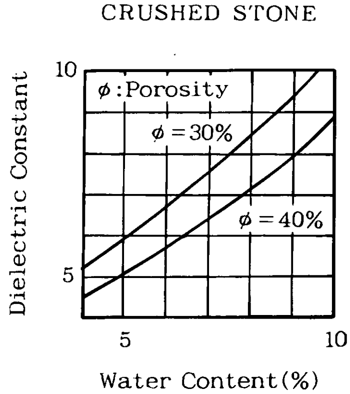

FIGURE 3 Calculated dielectric constant of crushed stone.

Though only one calibrating ratio is determined per segment, that value should not be considered representative of the segment. The tendency of all the values in the route should be looked over first. If the tendency is normal, the average can be taken. If some values are abnormal, the average can be taken after eliminating them. If it is a specific value in the segment, the specific value may be taken for the segment. By these deliberate considerations, the error cancellation will be realized despite each value containing some error-oriented variation.

FEATURE OF SEGMENT LENGTH

Using GPR data acquired in 1992 and 1993, the distribution of segment lengths has been quantified. Figure 6 indicates the distribution, including all the data. Figure 7 includes data for both light traffic and heavy traffic.

Segments with lengths distributed from 100 to 200 m occupy the largest portion of all the segments at over 20 percent. While the longest segment exceeds 2 km, the average segment length is 472 m.

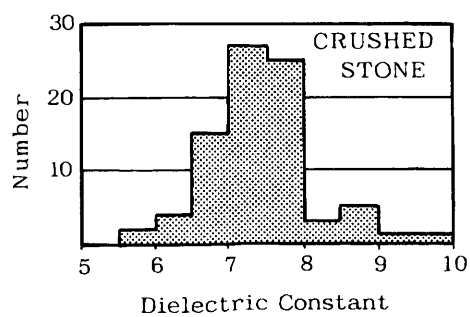

FIGURE 4 Observed dielectric constant of crushed stone.

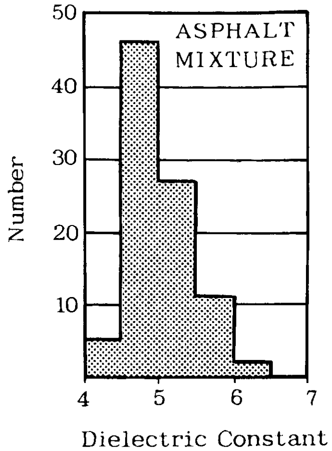

FIGURE 5 Observed dielectric constant of asphalt mixture.

No remarkable difference has been observed in the distribution of segment length correlated with traffic flow. As previously noted, almost all the pavement segments in the Tokyo metropolitan area are designed as an average 500-m-long segment.

The average restriction length for 2,586 cases of road maintenance operations that were performed from 1979 through 1988 is 395 m. In 1992, this figure was approximately 200 m. It is much shorter compared with the previous period because of increasingly severe restrictions in working time on the road (lane closure period) and in working space. The distribution of road working segments in 1992 is depicted in Figure 8.

ACCURACY

The accuracy of layer thicknesses measured by this system depends upon two criteria.

- *Nonuniformity of dielectric constant.* A pavement material has a specific value of dielectric constant but even though it is the same material, the dielectric constant is influenced by nonuniformity, which essentially exists in combined materials such as asphalt mixtures. For example, variation in the relative amounts of aggregate in asphalt mixtures, water content ratio, and porosity in the crushed stone as subbase all bring about a small deviation in dielectric constants. As a result, an error from the small deviation appears in plotted sections after calibration. The error is small in asphalt mixture layers, and larger (±2 cm) in subbase materials.
- *Vehicle speed and irregularity in layer thickness.* The speed of the survey vehicle is about 30 kmph. In the precise survey, a boring is carried out at a representative location within the segment. The boring point cannot be expected to be the exact same point as that on the GPR record. It has already been proven that probability of discrepancy in location increases in proportion to vehicle speed (*3*). This results in some thickness error in plotted sections. This error occurs in linkage with the original application irregularity of layer thicknesses. The layer irregularity is expected to be within an allowable standard by design. Irregularities may become considerably larger as a result of repeated maintenance work, such as cutting and filling and overlay.

In the actual survey, the error occurs as a result of the two aforementioned factors and diminishes thickness accuracy. A test survey (*5*) performed by the Tokyo metropolitan government showed that 84 percent of the asphalt mixture layer data and 78 percent of the crushed stone layer data were within allowable values, which were determined to be ±2.5 cm for asphalt mixture and ±5 cm for crushed stone, considering a vehicle speed of 30 to 40 kmph. Asphalt mixture thickness is designed with a 5-cm tolerance in Tokyo; therefore, an accuracy of ±2.5 cm is required. There is, however, no theoretical reason for crushed stone to use a tolerance of ±5 cm; this figure is determined as a rule of thumb based on the lesser need for accuracy with crushed stone than with asphalt mixtures.

A statistical approach has been performed using 1992 data, which include 300 locations of boring data. Correlations between GPR-oriented data and boring-oriented data are shown in Figure 9 (asphalt mixture) and in Figure 10 (crushed stone). It has been reconfirmed that layer thicknesses can be measured with the same degree of accuracy as with a test survey. Eighty percent of asphalt

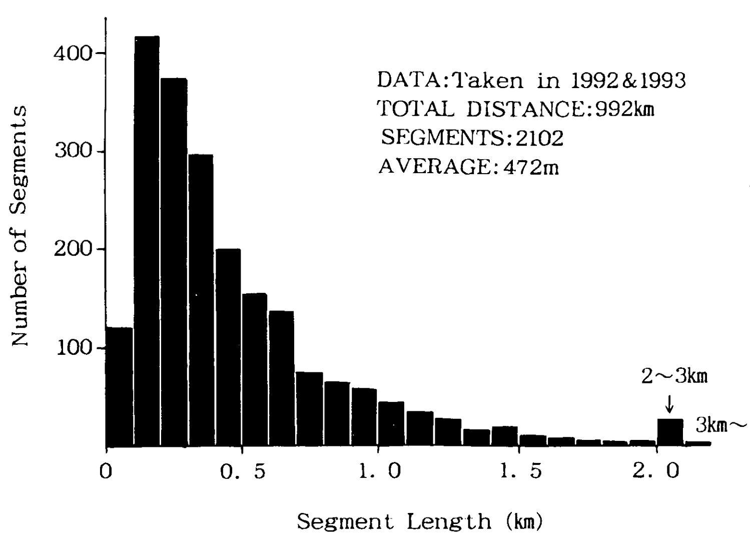

FIGURE 6 Distribution of segment lengths (all data).

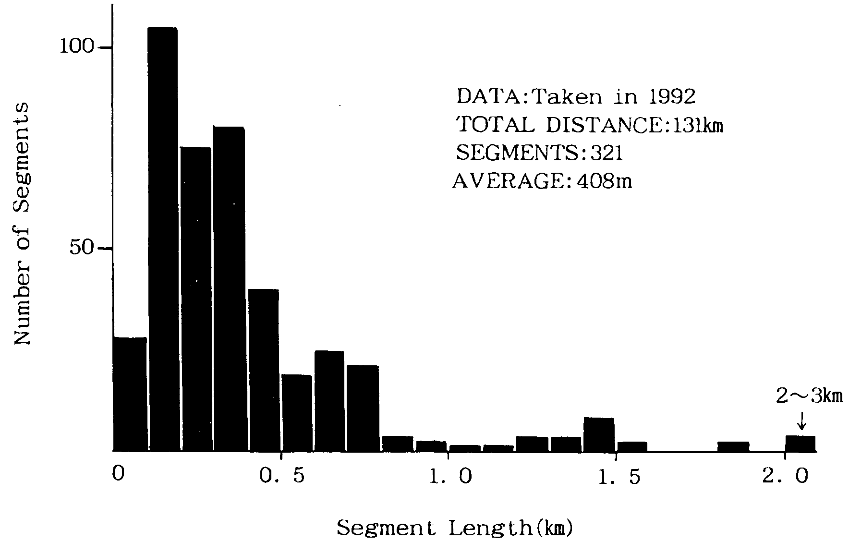

FIGURE 7 Distribution of segment lengths (based on traffic variation).

mixture and 70 percent of crushed stone have been measured within allowable values.

Comparison between GPR and boring data in a static condition (vehicle speed is 0 kmph) indicated that 80 percent of asphalt mixtures were measured within ±1 cm (*5*). This indicates that the main reason for the error originated in the linkage effect of vehicle speed and pavement layer irregularity.

Assuming the data shown in Figures 9 and 10 represent normal distribution, it was determined that a 95 percent reliable range of the data are ±5.1 cm for asphalt mixture and ±10.2 cm for crushed stone. This means the allowable values of ±2.5 cm and ±5 cm are both considered a severe condition. Despite the severity, the allowable values are considered to be reasonable in terms of accuracy needed for pavement structure information, which is stored in the referenced PMS data base.

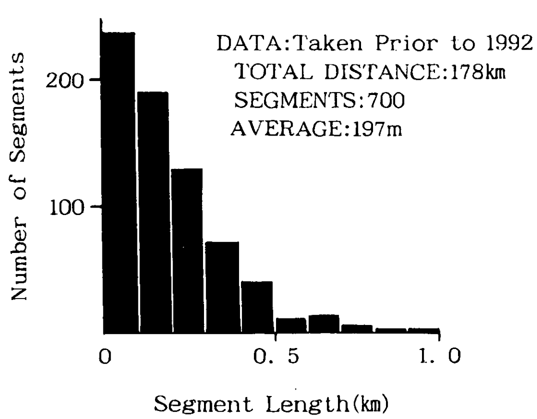

FIGURE 8 Distribution of road maintenance operation segments.

IRREGULARITY OF LAYER THICKNESS

Thickness data stored in the PMS data base are a normalized value. They represent the average and normalized thickness of segments. Basically, normalization is performed by averaging every 10 meters of plotted thickness values in a profile. The concern here is how large an irregularity of layer thickness might be concentrated to only one normalized value. For that purpose, the degree of irregularity was expressed as a distribution of standard deviations. The standard deviations are calculated from layer thicknesses to normalized

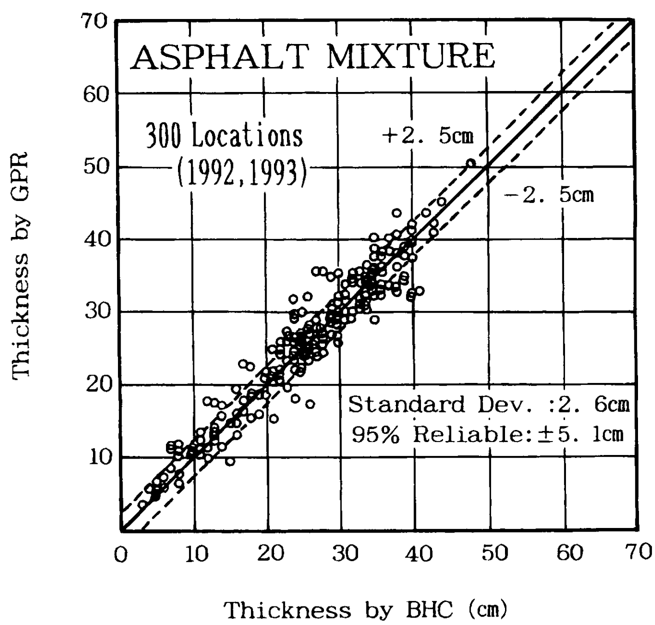

FIGURE 9 Accuracy in asphalt mixture.

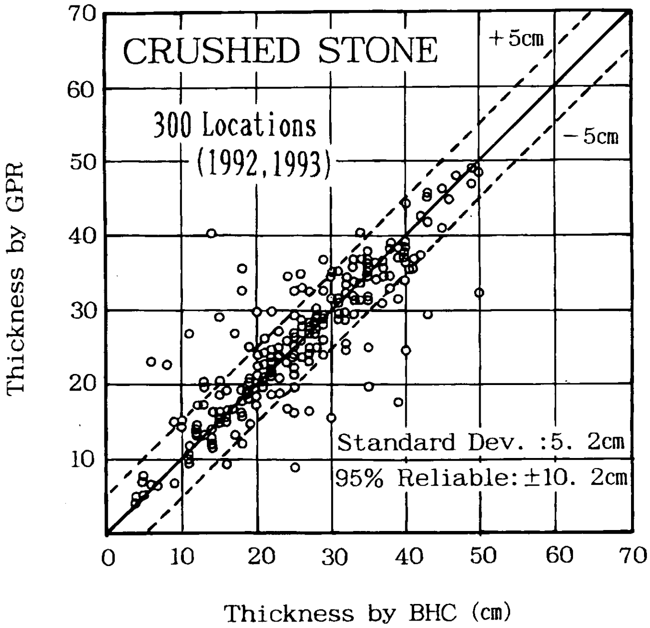

FIGURE 10 Accuracy in crushed stone.

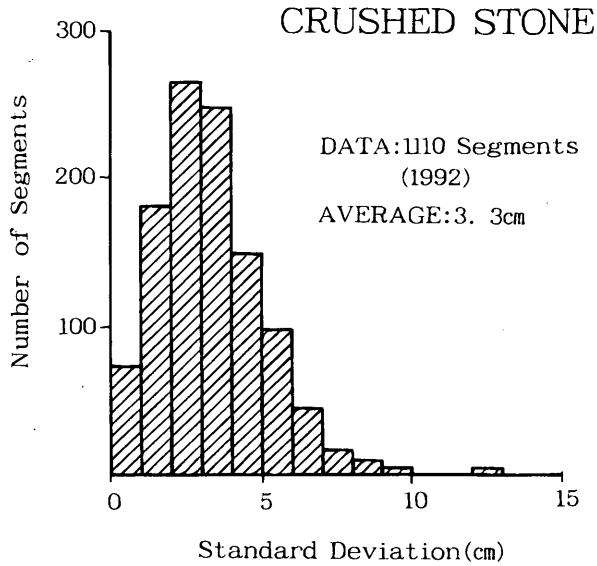

FIGURE 12 Distribution of standard deviation for crushed stone.

value. The results are shown in Figure 11 for asphalt mixtures and Figure 12 for crushed stone. The average standard deviation for asphalt mixture is 2.3 cm and 3.3 cm for crushed stone. The irregularity of asphalt mixture is smaller than that of crushed stone as might be expected.

An example of a GPR record is shown in Figure 13. Surface reflection is not smooth, because the antenna moves up and down on the *Y* axis while the survey vehicle runs on the *X* axis. When a profile is made, an absolute value is taken between the surface and the bottom of asphalt mixture layer. Therefore, surface irregularity does not affect that calculation of layer thickness. What should be kept in mind is that every layer still has an original irregularity even though the surface reflection is shifted to form a smooth line. Nonuniformity of the dielectric constant and vehicle speed influence do not explain the irregularity sufficiently. The irregularity in the record reflects an actual irregularity that originally existed in the pavement structure.

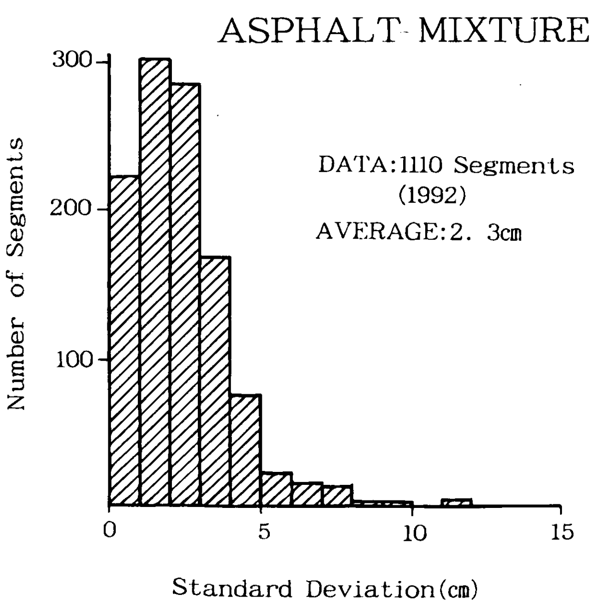

FIGURE 11 Distribution of standard deviation for asphalt mixture.

Ta COMPARISON BETWEEN NORMALIZED AND DESIGNED LAYER THICKNESS

To view the extent of difference between normalized and initially designed thicknesses, the difference was calculated with a Ta structure index comparison. The Ta index, widely used in Japan, can be converted to an AASHTO structure number by dividing the Ta number by 5.68. The result is shown in Figure 14. Data used in calculations are the values of 92 segments that were wholly reconstructed in 1992.

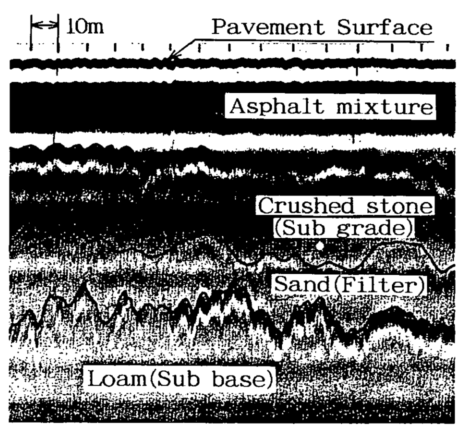

FIGURE 13 Example of GPR record.

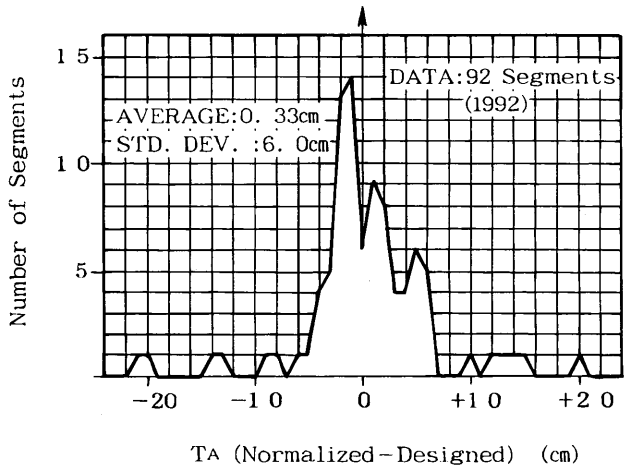

FIGURE 14 Ta comparison between normalized and designed thickness.

Coefficients of relative strength to calculate Ta are 1 for asphalt mixture and 0.55 for cement treatment. Because crushed stone (subbase) is difficult to recognize as a different grade of composition, 0.3 has been adopted as an average value coefficient. The magnitude of error due to adoption of the average value of the coefficient to subbase is estimated to be maximum ±2 cm, while the subbase thickness is assumed to be 40 cm.

All the data are classified into five types according to asphalt mixture thickness, 45 cm, 36 cm, 35 cm, 32 cm, and 27 cm. The average of subtracted Ta (normalized less designed) is 0.33 cm, which means the normalized value closely corresponds to the designed value. The shape of the distribution looks like a normal distribution with standard deviation and has been calculated to be 6 cm.

Most of the large differences are the result of the difference in asphalt mixture layer thickness. It is considered that repair work such as cutting and overlaying after whole reconstruction resulted in the large differences. Extremely large differences are probably caused by input mistakes of maintenance records or by incorrect determination of sample location. To avoid such a misjudgment, the data base of maintenance history should be updated as soon as possible. The GPR survey is useful to pick up the portions in existing pavement where the design information is uncertain.

CONCLUSION

The data base of pavement structure gives us valuable information that contributes to the more accurate evaluation of pavement design and repair strategy. Pavement structure cannot be observed from the surface of the road, and the accuracy of structure information is easily skewed by ongoing road maintenance work. These factors contribute to the difficulty in managing an accurate road structure data base.

The system integrated with GPR and BHC proved its practicability through actual surveys and statistical analysis using large amounts of data.

The nature of segment length distribution in the routes managed by the Tokyo metropolitan government, the accuracy of measurement, and the relationship between actual thicknesses and normalized thicknesses have been quantitatively clarified. This system can be used to find abnormal locations where designed and actual structures are significantly different.

Change of design conditions due to such changes as traffic load increases requires a change of pavement structure. Design change conditions occur as often as maintenance operations. It is important to make a single structure's segment a quantifiable unit, and to prepare a format that allows the value in the data base to be easily updated.

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