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AMERICAN SOCIETY FOR TESTING AND MATERIALS
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Standard Test Method for Determining the Thickness of Bound Pavement Layers Using Short-Pulse Radar[1]

This standard is issued under the fixed designation D 4748; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the nondestructive determination of thickness of bound pavement layers using short-pulse radar. Bound pavement layers are defined as the upper layers of a pavement, consisting of materials such as bituminous, concrete, portland-cement concrete, roller-compacted concrete, and stabilized bases. Bound pavement layers does not include granular base and subbase materials.

1.1.1 As the electromagnetic wave generated by radar propagates through the bound pavement layers, the wave is attenuated, dispersed and reflected at layer interfaces. At some depth, due to the wave attenuation and dispersion, the reflections at the layer interfaces cannot be detected by the radar. This maximum penetration depth is a complex function of radar system parameters such as transmitted power, receiver sensitivity, center frequency and bandwidth of the radar system and signal processing, as well as the electromagnetic properties of the pavement materials and environmental factors such as moisture content.

1.1.2 Radar system resolution is determined mainly by the transmitted pulse length and bandwidth of the radar. A typical system for this application usually has a resolution sufficient to determine a minimum layer thickness of 40 mm (1.5 in.) to an accuracy of ±5 mm (±0.2 in.). Improvements in system resolution may be possible with additional signal processing.

1.2 This test method may not be suitable for application to pavements which exhibit increased conductivity due to the increased attenuation of the electromagnetic signal. Examples of senarios which may cause this are: extremely moist or wet (saturated) pavements if free electrolytes are present and slag aggregate with high iron content.

1.3 The values stated in mm-kilogram units are to be regarded as the standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* Specific hazard statements are given in Section 6.

NOTE 1—Bound pavement layers are defined as the upper layers of a pavement, consisting of materials such as bituminous, concrete, portland-cement concrete, roller-compacted concrete, and stabilized bases. Bound pavement layers do not include granular base and subbase materials.

2. Summary of Test Method

2.1 Since this test method is based upon measurements performed by a short-pulse radar system, a brief description of the operating principles of such a system are included herein.

2.2 The detection of an interface between two different materials by radar depends upon the partial reflection of incident energy at that interface. The amplitude of the reflected energy at that interface, with respect to the incident energy, is related to the relative dielectric constants of the two materials according to the formula:

$$\frac{A}{A_0} = \frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_1} + \sqrt{\epsilon_2}} \tag{1}$$

where:
A = the reflected energy, amplitude
A_0 = the incident energy, amplitude
ϵ_1 = the dielectric constant material 1, and
ϵ_2 = the dielectric constant material 2.

The ability to detect the thickness of a layer depends on the contrast between the dielectric constant of that layer and the layer beneath. A sufficient contrast for thickness determination usually exists between asphaltic layers and soil or aggregate base materials. Such a contrast may not always be sufficient between concrete and agggregate base materials, or between individual layers of asphalt.

2.3 Layer thickness can be determined using radar technology if the dielectric constant of that material and the two-way travel time for the radar wave to pass through the layer are known. The relationship is defined by the following equation:

$$T = \frac{\Delta t \times c}{2\sqrt{\epsilon_r}} \tag{2}$$

where:
T = layer thickness,
c = speed of light in air, 300 mm/nsec for T in mm (11.8 in/nsec for T in inches),
ϵ_r = relative dielectric constant of layer, and
Δ_t = two-way pulse travel time through layer (in nanoseconds).

2.4 The dielectric constant of a pavement material can vary

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somewhat depending on aggregate types, asphalt cement sources, density, cracking, and moisture content. Using an air-coupled horn antenna radar this variation may be calculated directly from the radar data by using the known dielectric constant of air and the equation in Section 2.2

2.5 Determining the dielectric constant when using ground coupled dipole antenna radar requires an independent means, such as coring or a radar based dielectric constant measurement using two or more antennas.

3. Significance and Use

3.1 This test method permits accurate and nondestructive thickness determination of bound pavement layers. As such, this test method is widely applicable as a pavement system-assessment technique.

3.2 Although this test method, under the right conditions, can be highly accurate as a layer-thickness indicator, consistently reliable interpretation of the received radar signal to determine layer thicknesses can be performed only by an experienced data analyst. Such experience can be gained through use of the system and through training courses supplied by various equipment manufacturers or consulting companies. Alternatively, the operator may wish to use computer software to automatically track the layer boundaries and layer thickness, where applicable..

4. Interferences

4.1 Determinations made with radar are adversely affected by surface and subsurface water. In the case of horn antenna, standing water on the surface of the pavement decreases the amount of energy that penetrates the pavement. This effect is difficult to measure and may vary dramatically over a short time interval due to variations in the thickness of the water layer caused by run-off or evaporation. However, in general, testing with horn antennas shall not be conducted in the presence of standing water.

4.2 The apparatus is subject to interference from other sources of electromagnetic radiation. Interference from nearby high-power transmitters manifests itself as large, high-frequency variations in the radar return across the entire measurement depth. Other sources of intermittent interference may include mobile phones and CB radios. Testing shall not be conducted in the presence of observed interference.

4.3 Large objects such as vehicles have the potential to interfere with the radar return. A conservative, equipment independent approach to minimize the effects of large objects is to maintain these objects at a distance outside the zone of influence as calculated by the following expression:

$$d = \frac{t}{2 \times k} \tag{3}$$

where:

d = the zone of influence,

k = multiplication constant, 3.28 for d in meters (1 for d in feet), and

t = time in nanoseconds of the measurement time window.

For horn antennas, this equation does not take into account the spacing between the horn and the pavement. The closer the spacing between the horn and the pavement, the less influence from large objects and therefore a more liberal approach to the distance calculation above is permissible.

5. Apparatus

5.1 The apparatus consists of an antenna, radar transducer, and suitable display devices. The radar transducer consists of a transmitter, receiver, and timing and control electronics. The display device may be an oscilloscope, grey-level chart recorder, or a CRT monitor, or a personal computer with a data acquisition board.

5.2 The schematic drawing in Fig. 1 illustrates the equipment and configuration. The antenna and transducer are typically in close proximity to one another, lightweight, and maneuverable, either by hand or a suitable support or mounting system. Mobility is desirable for positioning over the test area. Display devices are generally heavier and mounted on a movable platform such as a cart or a vehicle.

5.2.1 The transducer is connected to the antenna and display devices. The transducer generates, transmits, and receives low-power broad band radio frequency (rf) signals through the antenna. The rf signals are then converted into an audio-frequency signal suitable for display and resulting interpretation.

5.3 Two basic types of antenna systems are in use (1) air-coupled horn antennas; and (2) ground-coupled dipole antennas. The horn antennas are specifically designed to radiate into the air, and thus to be used at some distance above the pavement surface, usually 8 to 20 inches (20 to 50 cm). The ground-coupled antennas are specifically designed to operate in contact with the pavement surface.

5.3.1 The general specifications for the radar system apparatus components are:

5.3.1.1 *Antenna*—A bandwidth shall be appropriate to handle selected transmitted pulse frequency components.

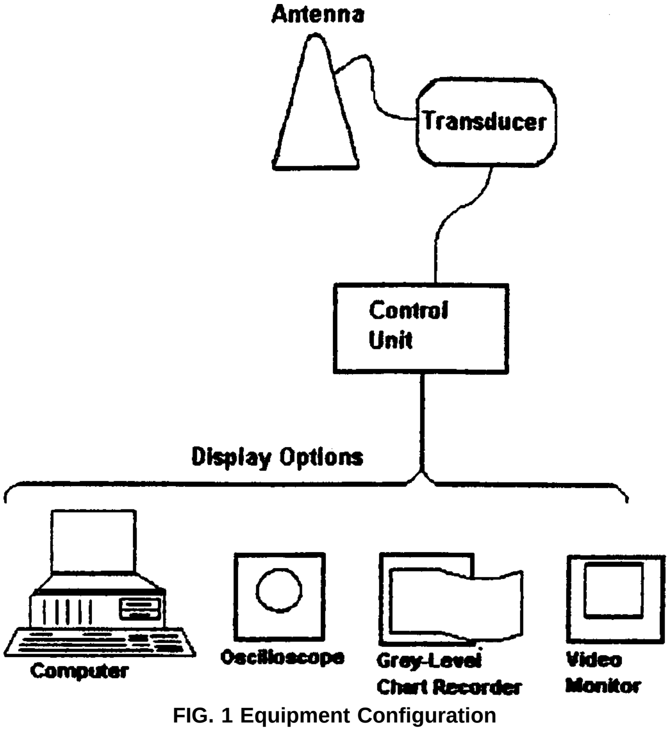

FIG. 1 Equipment Configuration

5.3.1.2 *Transmitter*, short-pulse (0.5 to 2.0 ns) low-power (1 to 20 W maximum).

5.3.1.3 *Receiver Processing*—A wide bandwidth capable of processing time signals corresponding to a depth of several feet.

5.3.2 The general specifications for the display devices are:

5.3.2.1 *Grey-Level Chart Recorder*, with analog signal input capability that has externally-synchronized expandable data display and 16 grey-levels.

5.3.2.2 *Oscilloscope*— A single-channel analog input oscilloscope that is externally synchronized.

5.3.2.3 *Video/Computer Monitor* that has analog input and is externally synchronized. It shall have 16 grey-levels and 16 colors and continuous real-time display capability.

5.3.3 A power source, typically 110 V ac or 12 V dc, shall be available for the apparatus.

6. Hazards

6.1 **Warning**—The radar apparatus used in this test method is potentially a microwave radiation hazard. All personnel shall stand clear of the region directly under the antenna when the system is energized.

6.2 Electromagnetic emissions from the radar apparatus, if the system is improperly operated, could potentially interfere with commercial communications, especially if the antenna is not properly oriented toward the ground. Take care to ensure that all such emissions from the system comply with Part 15 of the Federal Communications Commission (FCC) Regulations.

6.3 Take care to ensure that appropriate traffic control measures are employed when operating the radar apparatus on highways, roads, and airports. Such measures are essential for the safety of system operators as well as that of the general traveling public.

7. Calibration and Standardization

7.1 A calibration time constant, C_T, is established for the radar system by measuring the time interval between reflections from two precisely spaced metal plates as follows:

7.1.1 Separate two metal plates by a distance, d_c, of approximately 300 ±5 mm (12 ±0.2 in.) using four small non conductive spacers, one attached to each corner of the metal plates (see Fig. 2). The upper plate is approximately 125 by 125mm (5 by 5 in.) and the lower plate is approximately 300 by 300 mm (12 by 12 in.).

7.1.2 Place the calibration fixture below the antenna and energize the radar system.

7.1.3 Measure the time delay between the two reflections from the pair of plates by observing the received signal on the display device. This time delay is the calibration time constant, C_T, in nanoseconds. (See Fig. 3)

7.1.4 The calibration time constant does not have to be measured before each attempt to determine pavement layer thickness. The radar system itself should remain in calibration for long periods of time (>1 day). If adjustments or changes that affect the radar system timing are made, a calibration measurement shall be made or the system shall be capable of self calibration on a continuous basis.

7.2 The relative dielectric constant, ϵ_r, for the pavement layer of interest must be estimated or calculated. This dielectric constant is used to calculate thicknesses of pavement layers.

7.2.1 Position the antenna over an area of known layer thickness. Typically, a precise layer thickness for calibration purposes is determined by taking a core sample and measuring the appropriate layer thickness from the sample or alternatively refraction techniques can be used to measure in situ material velocities. If it is impossible to core or obtain in situ velocity measurements and obtain an accurate calibration of the dielectric constant, then "best-guess" estimates shall be made by the operator based on known dielectric constants for given materials.

7.2.2 Using the radar display device, measure the time interval in nanoseconds, Δt, between the surface reflection or top of the layer reflection and the corresponding reflection from the bottom of the layer of interest.

7.2.3 Calculate the relative dielectric constant, ϵ_r, for that layer using the equation:

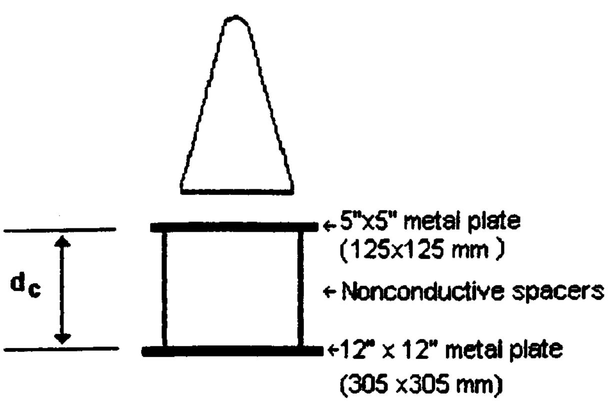

FIG. 2 Calibration Measurement

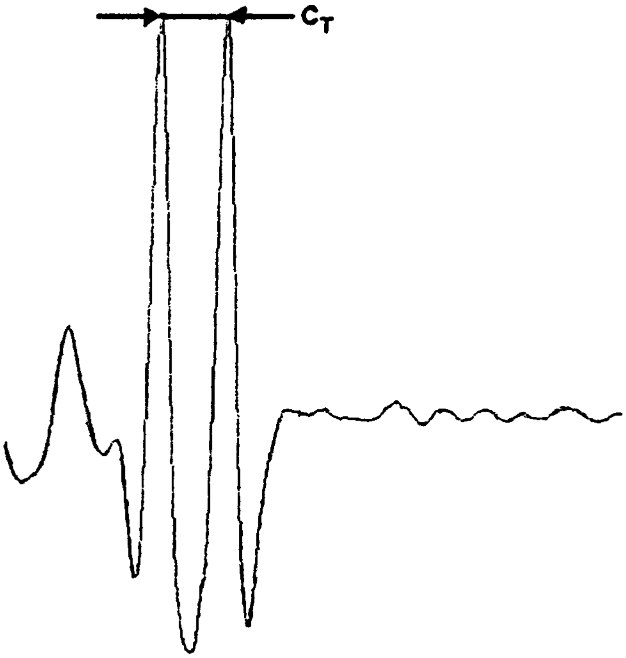

FIG. 3 C_T Measurement

$$\epsilon_r = \left[\frac{\Delta t \times d_c}{2 \times T \times C_T}\right]^2 \tag{4}$$

where:

ϵ_r = relative dielectric constant of layer,
Δt = two-way pulse travel time through layer (in nanoseconds),
d_c = distance between metal plates,
T = measured layer thickness, and
C_T = calibration time constant (in nanoseconds).

7.2.4 The relative dielectric constant thus calculated can be used for all measurements made where the pavement layer materials are identical to those in the locale of the calibration core. If the materials change, a new calibration core may be necessary.

7.2.5 Typical relative dielectric constants are given in Table 1.

8. Procedure

8.1 Continuously traverse the radar antenna across the pavement to be tested. The speed of the traverse will determine the number of data points per unit distance. For horn antennas, the traverse speed is constrained only by the desired spacing of radar scans. For ground coupled antennas, the traverse speed is limited to approximately 8 kph (5 mph) in order to maintain steady ground contact.

8.2 Identify the signal reflection associated with the surface of the pavement or upper interface of the layer of interest using the display devices.

8.3 Identify the coherent signal reflection associated with the lower surface interface of the layer of interest.

8.4 Determine the time interval, Δt, between these two reflections.

TABLE 1 Relative Dielectric Constants

Material	Range, ϵ_r	Average, ϵ_r
Concrete (PCC)^A	6–11	9
Roller-Compacted Concrete (RCC)^A	5–7	6
Bituminous Concrete	3–5	4
Gravel	5–9	7
Sand	2–6	4
Rock	6–12	9

[A] The relative dielectric constants for PCC and RCC apply only to concrete that has been in place at least 28 days.

9. Calculation

9.1 Calculate the thickness of the layer of interest using the constants C_T and ϵ_r obtained in Section 7 and the time interval Δt, (in nanoseconds) determined in 8.4, using the following equation:

$$T = \frac{\Delta t \times d_c}{2\sqrt{\epsilon_r \times C_T}} \tag{5}$$

where:

T = measured layer thickness,
Δt = two-way pulse travel time through layer (in nanoseconds),
d_c = distance between metal plates,
ϵ_r = relative dielectric constant of layer, and
C_T = calibration time constant (in nanoseconds).

9.2 The thickness of all layers may be determined using the time intervals and associated relative dielectric constants.

10. Precision and Bias

10.1 The standard deviation of precision of the determination of thickness is given by the following:

$$SD = \frac{P_L \times C}{2\sqrt{r \times SNR}} \tag{6}$$

where:

SD = standard deviation of precision, (mm), in.
SNR = signal to noise ratio,
C = speed of light in air, 300 mm/nsec (11.8 in/nsec), and
P_L = transmitted radar pulse length (in nanoseconds).

10.2 Inter-operator testing of similar bound pavements has shown predicted determinations to within ±0.2 in. (±5 mm) of measured thickness.

10.3 *Bias*—This test method does not lend itself to bias, therefore; no statement is being made as to the bias of this test method.

11. Keywords

11.1 layer thickness; pavement thickness; radar; short-pulse radar