Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/VA-88/16		

4. Title and Subtitle
Measurements of the Thickness of In-Place Concrete With Microwave Reflection

5. Report Date
April 1988

6. Performing Organization Code

8. Performing Organization Report No.
VTRC 88-R16

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10. Work Unit No. (TRAIS)

11. Contract or Grant No.
HPR 2391

12. Sponsoring Agency Name and Address
Virginia Department of Transportation
1221 E. Broad Street
Richmond, Virginia 23219

13. Type of Report and Period Covered
Final

14. Sponsoring Agency Code

15. Supplementary Notes
In cooperation with the U. S. Department of Transportation, Federal Highway Administration.

16. Abstract

Previous microwave reflection measurements made on simple, unreinforced concrete blocks have shown that the transit time of a microwave through concrete is linearly related to its thickness. In this study measurements were conducted on concrete slabs that were built to simulate pavements and on an actual continuously reinforced concrete pavement to determine whether this type of rapid nondestructive measurement could be used in lieu of coring in the inspection of newly built concrete pavements for compliance with slab thickness specifications.

It was found that reflections from the bottom of a concrete pavement slab may often be too weak and difficult to identify in a radar profile; therefore, the transit time of a microwave through reinforced concrete slab would often be difficult to measure with reasonable accuracy. The results obtained with radar measurements made on simulated pavement slabs showed that radar was only able to indicate whether a slab is too thin (i.e., less than 8 in); but those measurements made on an actual pavement yielded reasonably good agreement between the thickness determined by coring and those determined by reflection measurements in conjunction with a calibration procedure.

Based on these mixed results, it would be difficult to predict how reliable radar would be for precise quantitative measurement of slab thickness of a particular pavement until an actual radar scan of the pavement has been conducted. If the reflection from the bottom of the slab appeared to be identifiable, then the calibration procedure could be used to determine the slab thickness for the entire pavement. Otherwise, radar can be used at least as a screening tool to spot areas in the pavement that appear to be too thin. These areas would then be cored to verify the radar readings.

17. Key Words	18. Distribution Statement
Concrete pavement, thickness, nondestructive inspection, radar.	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Va. 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	36	

SI CONVERSION FACTORS

To Convert From	To	Multiply By
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ft	m	0.304 8
yd	m	0.914 4
mi	km	1 . 609 344
Area:		
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ft^2	m^2	9.290 304 E-02
yd^2	m^2	8.361 274 E-01
mi^2	Hectares	2.589 988 E+02
acre (s)	Hectares	4.046 856 E-01
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pt	m^3	4.731 765 E-04
qt	m^3	9.463 529 E-04
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ft^3/s	m^3/sec	2.831 685 E-02
in^3/min	m^3/sec	2.731 177 E-07
yd^3/min	m^3/sec	1.274 258 E-02
gal/min	m^3/sec	6.309 020 E-05
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lb	kg	4.535 924 E-01
ton (2000 lb)	kg	9.071 847 E+02
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lb/ft^3	kg/m^3	1.601 846 E+01
lb/yd^3	kg/m^3	5.932 764 E-01
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mi/h	m/s	4.470 400 E-01
knot	m/s	5.144 444 E-01
mi/h	km/h	1.609 344 E+00
Force Per Unit Area:		
lbf/in^2 or psi	Pa	6.894 757 E+03
lbf/ft^2	Pa	4.788 026 E+01
Viscosity:		
cS_t	m^2/s	1.000 000 E-06
P	Pa·s	1.000 000 E-01

Temperature: $(°F-32)^5/9 = °C$

MEASUREMENTS OF THE THICKNESS OF IN-PLACE CONCRETE WITH MICROWAVE REFLECTION

by

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and

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Materials Engineer

Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the
Virginia Department of Transportation and
the University of Virginia

In Cooperation with the U. S. Department of Transportation
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Charlottesville, Virginia

April 1988
VTRC 88-R16

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ABSTRACT

Previous microwave reflection measurements made on simple, unreinforced concrete blocks have shown that the transit time of a microwave through concrete is linearly related to its thickness. In this study measurements were conducted on concrete slabs that were built to simulate pavements and on an actual continuously reinforced concrete pavement to determine whether this type of rapid nondestructive measurement could be used in lieu of coring in the inspection of newly built concrete pavements for compliance with slab thickness specifications.

It was found that reflections from the bottom of a concrete pavement slab may often be too weak and difficult to identify in a radar profile; therefore, the transit time of a microwave through reinforced concrete slab would often be difficult to measure with reasonable accuracy. The results obtained with radar measurements made on simulated pavement slabs showed that radar was only able to indicate whether a slab is too thin (i.e., less than 8 in); but those measurements made on an actual pavement yielded reasonably good agreement between the thicknesses determined by coring and those determined by reflection measurements in conjunction with a calibration procedure.

Based on these mixed results, it would be difficult to predict how reliable radar would be for precise quantitative measurement of slab thickness of a particular pavement until an actual radar scan of the pavement has been conducted. If the reflection from the bottom of the slab appeared to be identifiable, then the calibration procedure could be used to determine the slab thickness for the entire pavement. Otherwise, radar can be used at least as a screening tool to spot areas in the pavement that appear to be too thin. These areas would then be cored to verify the radar readings.

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INTRODUCTION

The thickness of a portland cement concrete pavement has a strong influence on its service life. To ensure that thickness specifications are complied with in newly built concrete pavements, 4-in diameter cores are extracted at specified intervals in each construction lane and directly measured in accordance with AASHTO T148. In addition to creating undesirable discontinuities in the pavement, this destructive method of inspection is time-consuming and costly. It is feared that concern with these disadvantages in the present method has resulted in compromising close inspection of newly built pavements. Consequently, there is a need for a faster, less costly, and nondestructive method that would eliminate the problems of the current quality-assurance inspection.

In a 1976 NCHRP-sponsored study, several techniques that could be used in the nondestructive measurement of pavement thickness and in the location of reinforcement steel were examined. It was reported that a prototype microwave thickness gage, which utilized the radar principle, could detect the thickness of concrete to about 6 in with an accuracy of 0.25 in, and that with further development the device should be capable of detecting thicker concrete (10 to 12 in) with better accuracy (1). It appeared that microwave reflection (or radar) measurement had a reasonably good potential of fulfilling the need for a fast, inexpensive, and nondestructive method for determining the thickness of concrete pavement. Unfortunately, beyond this assessment no further information, particularly on the potential interference from reinforcing steel, was made available by the investigators. To appreciate this concern a brief discussion of the principle involved in the propagation of microwave as it applies to a concrete pavement is in order.

When a beam of microwave energy is transmitted at a concrete slab, some portion of the energy is reflected from the surface of the concrete (see Figure 1). The intensity of this reflection (A_s) is governed by the relationship

$$\rho_s = \frac{A_s}{A_i} = \frac{\sqrt{\Sigma_a} - \sqrt{\Sigma_c}}{\sqrt{\Sigma_a} + \sqrt{\Sigma_c}} = \frac{1 - \sqrt{\Sigma_c}}{1 + \sqrt{\Sigma_c}} \qquad (1)$$

where A_i = the intensity of the transmitted pulses
ρ_s = the reflectivity coefficient at the surface
Σ_a = 1 (the relative dielectric constant of air)
Σ_c = the relative dielectric constant of the concrete.

The remaining energy penetrates the surface and propagates through the concrete at a velocity (V_c) related to the relative dielectric constant of the concrete by

$$V_c = \frac{C}{\sqrt{\Sigma_c}} \qquad (2)$$

where C is the velocity of electromagnetic pulses through free space, which is 11.81 in/ns.

When this microwave strikes the bottom of the slab, another portion of this energy is reflected and eventually escapes back out through the surface of the concrete. By measuring the two-way transit time (t_c) required for the microwave energy to travel through the concrete, the thickness (D_c) of the slab can be calculated from

$$D_c = \frac{Ct_c}{2\sqrt{\Sigma_c}} \quad . \qquad (3)$$

It is obvious from equation 3 that the accurate determination of the thickness of the slab will depend on the accurate measurements of t_c and Σ_c. For reinforced concrete pavements, this raises some concerns that must be investigated before this technique can be used.

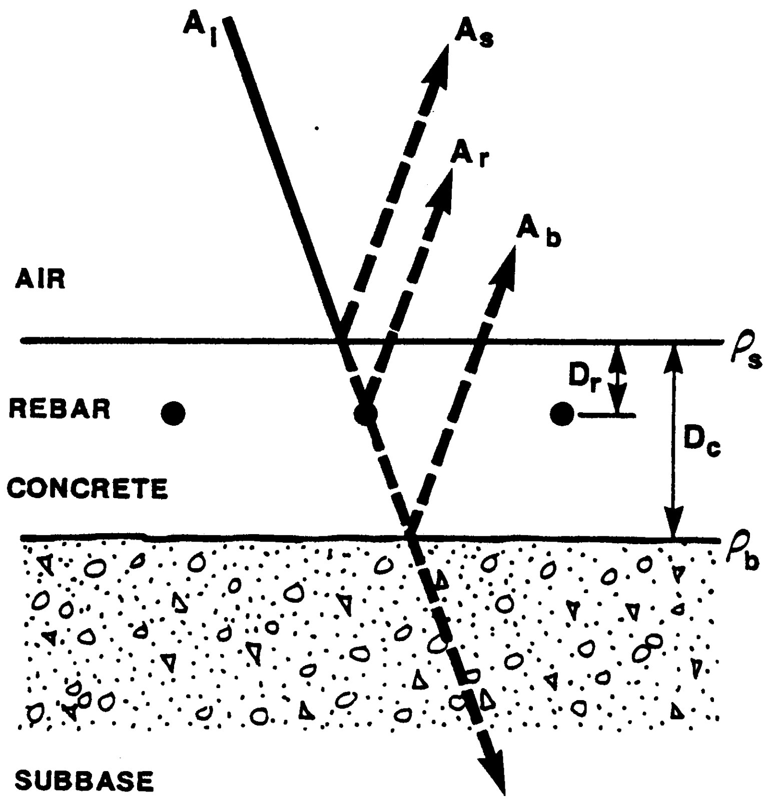


Figure 1. Propagation of microwave energy through a reinforced concrete pavement.

The reinforcing steel, which is almost a perfect reflector of microwave energy, significantly reduces not only the amount of microwave energy reaching the bottom of the slab but also the amount that manages to escape back out of the slab. In addition to this undesirable interference from the reinforcing steel, the relative dielectric constant of the subbase (Σ_s) is also a concern, since it influences the reflectivity (ρ_b) at the bottom of the slab, that is, the boundary between the concrete slab and the subbase, in accordance with

$$\rho_b = \frac{\sqrt{\Sigma_c} - \sqrt{\Sigma_s}}{\sqrt{\Sigma_c} + \sqrt{\Sigma_s}} \quad . \tag{4}$$

It is desirable for ρ_b to be as large as possible, which means that the difference between the relative dielectric constants of the concrete and the subbase should also be as large as possible. Otherwise, a small ρ_b and the interference from the steel can combine to cause the reflection from the bottom of the concrete slab to be too weak to detect. This in turn would make it difficult for t_c to be determined with sufficient accuracy. It is suspected that the detection of this reflection from the bottom of a pavement slab would be the most difficult task.

The second concern is the accurate determination of Σ_c. There are two alternative procedures for determining it. The first procedure involves measuring Ai and As, from which Σ_c can be calculated using equation 1. This procedure is the easiest but possibly the least reliable because the resulting Σ_c is susceptible to influence by the variable moisture content in the surface layer of the concrete pavement and may not be representative of the entire layer of the concrete slab. The second procedure involves first measuring the depth of the rebars (D_r) and the transit time for the reflection from these rebars (t_r), and then estimating Σ_c by substituting these values in equation 3, which in turn becomes

$$D_c = \frac{t_c D_r}{t_r} \quad . \tag{5}$$

This procedure is cumbersome because D_r has to be measured at each sampling location on a concrete pavement the thickness of which is being determined. In addition the accuracy of the Σ_c and therefore the calculated thickness of the concrete slab would be affected by the accuracy with which D_r were measured.

This investigation was, therefore, conducted in an attempt to examine these factors and to assess their overall effect on the use of microwave reflection measurement in the determination of the thickness of concrete pavements.

PROCEDURE

To simulate concrete pavements, three reinforced concrete slabs with different water-cement ratios (W/C) were cast over a carefully prepared base course made of dense-graded aggregate (see Figures 2 and 3). The thickness of each slab was varied from 6 to 10 in, in 1-in increments, from one end to the other. The three W/Cs used were 0.45, 0.48, and 0.54.

In addition to these three slabs, another similar slab was constructed with a sheet of heavy-duty aluminum foil sandwiched between the concrete and the dense-graded aggregate, to enhance the reflection of microwave energy from the bottom of the concrete slab. As illustrated in Figure 4, the 1.5-ft-wide aluminum foil covered approximately half the width of the slab from one end to the other. Microwave reflection profiles were recorded at several locations over each of these four slabs.

Additionally, measurements were made at 51 locations in a two-mile section of an actual continuously reinforced concrete pavement for comparison with cores taken from these locations. At each sampling location, the depth of the rebars was also determined with a pachometer.

All of the reflection measurements were made with a portable microwave radar system that consisted of a transducer, a control unit, and an oscillographic recorder (Figure 5). This transducer, which serves both as a transmitter and receiver of microwave energy, operates at a central frequency of 900 Mhz, with a characteristic received pulse width of 1.1 ns.

RESULTS AND DISCUSSION

Measurements Made on the Reinforced Concrete Slabs

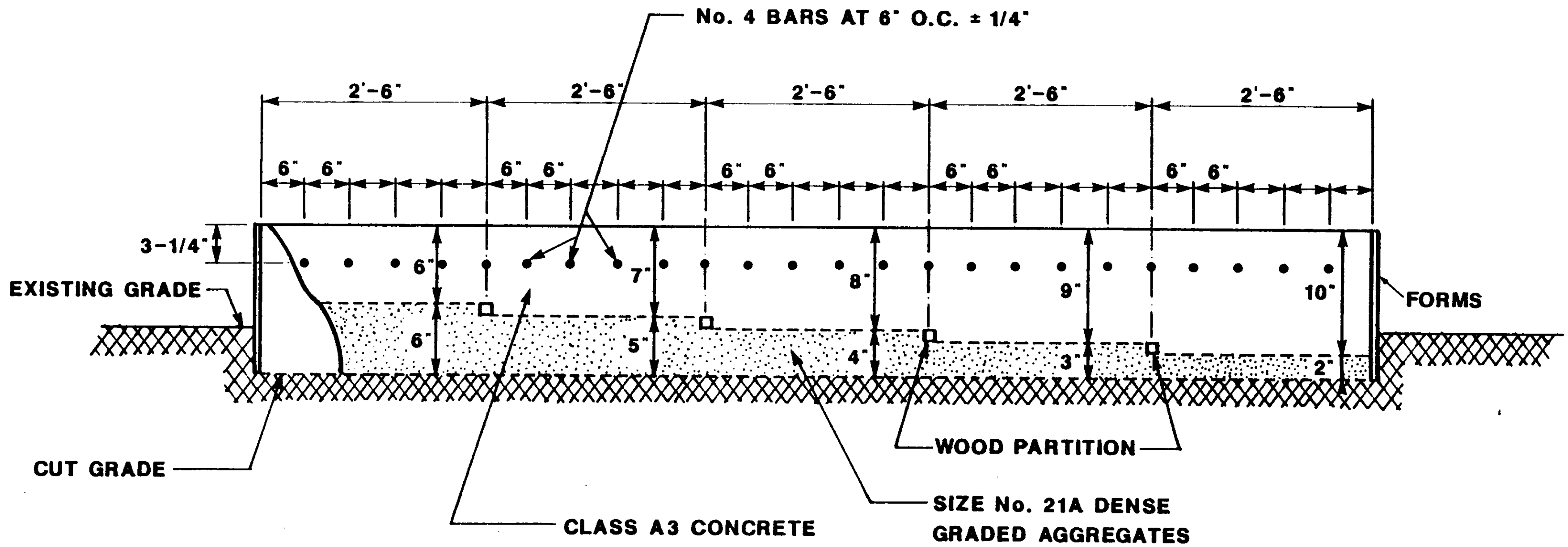
A set of the reflection profiles recorded for the first three reinforced slabs is shown in Figures 6 to 8. This set was recorded when the slabs were 52 days old. The five profiles, or waveforms, in Figure 6 were recorded over the slab with a W/C of 0.45 at five locations where the slab was 6, 7, 8, 9, or 10 in thick. Similarly, the sets of waveforms in Figures 7 and 8 correspond to the slabs with the W/Cs of 0.48 and 0.54, respectively.

Each waveform consists of reflections from the surface of the slab, the rebars, the bottom of the slab, and so on that arrived at the transducer at different transit times (along the X axis) and with different amplitudes (along the Y axis). In addition to these reflections, there is also reverberation of the reflection from the rebars. The actual shape of each reflected pulse resembles an asymmetric sinusoidal wave with a polarity and an amplitude that are dependent on the reflection coefficient of the reflecting interface. To simplify the analysis, these reflections may be identified as peaks. The first two peaks in each waveform are attributed to the reflections from the surface of a slab and the rebars in the slab, respectively. At some time after the reflection from the rebars, there is a reflection from the bottom of the slab hidden among the reverberations of the reflection from the rebars.

There are small but discernible differences between the waveforms at slab thicknesses of 6, 7, and 8 in in between the second peak and the prominent peak at approximately 7.0 ns (see Figure 6). This region is where the reflection from the bottom of the concrete slab is expected to be. In contrast there isn't any discernible difference between the waveforms for 8, 9, and 10 in thick slabs.

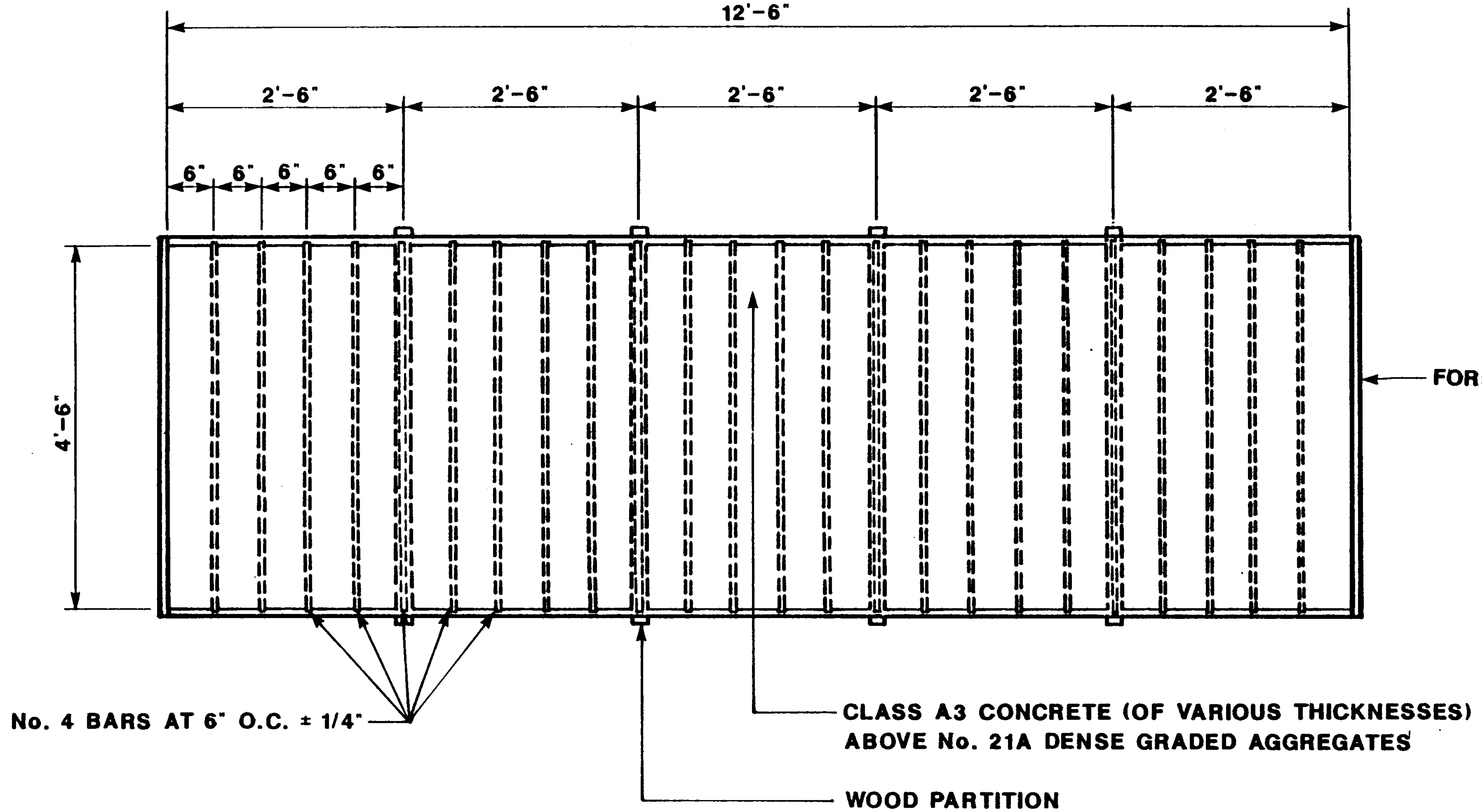
Using the known depth of the rebars in the slab, the dielectric constant of the concrete at each of the five locations where the waveforms were recorded was estimated using equation 3 from the observed transit times for the reflection from the rebars at these locations. Then, from each estimated dielectric constant, the expected transit time for the reflection from the bottom of the slab at the corresponding location was calculated from the known slab thickness (using equation 3 again). These expected transit times together with those for the other two slabs are presented in Table 1.

When each of the five waveforms in Figure 6 was carefully examined at the place where the reflection from the bottom of the slab was expected, it was apparent that this reflection was so weak that, even at locations where the slab was only 6 and 7 in thick, it was only slightly discernible. In addition it appeared that at these two locations the reflection from the bottom of the slab arrived at times too close to the first reverberation from the steel, which can be observed in the last two waveforms to arrive at approximately 4.3 ns (see Table 1).



(a) SIDE VIEW OF TEST SLABS (AS BUILT)

Figure 2. Reinforced concrete test slabs built over a layer of dense-graded aggregates



TOP VIEW OF TEST SLAB (AS BUILT)

Cont: Figure 2

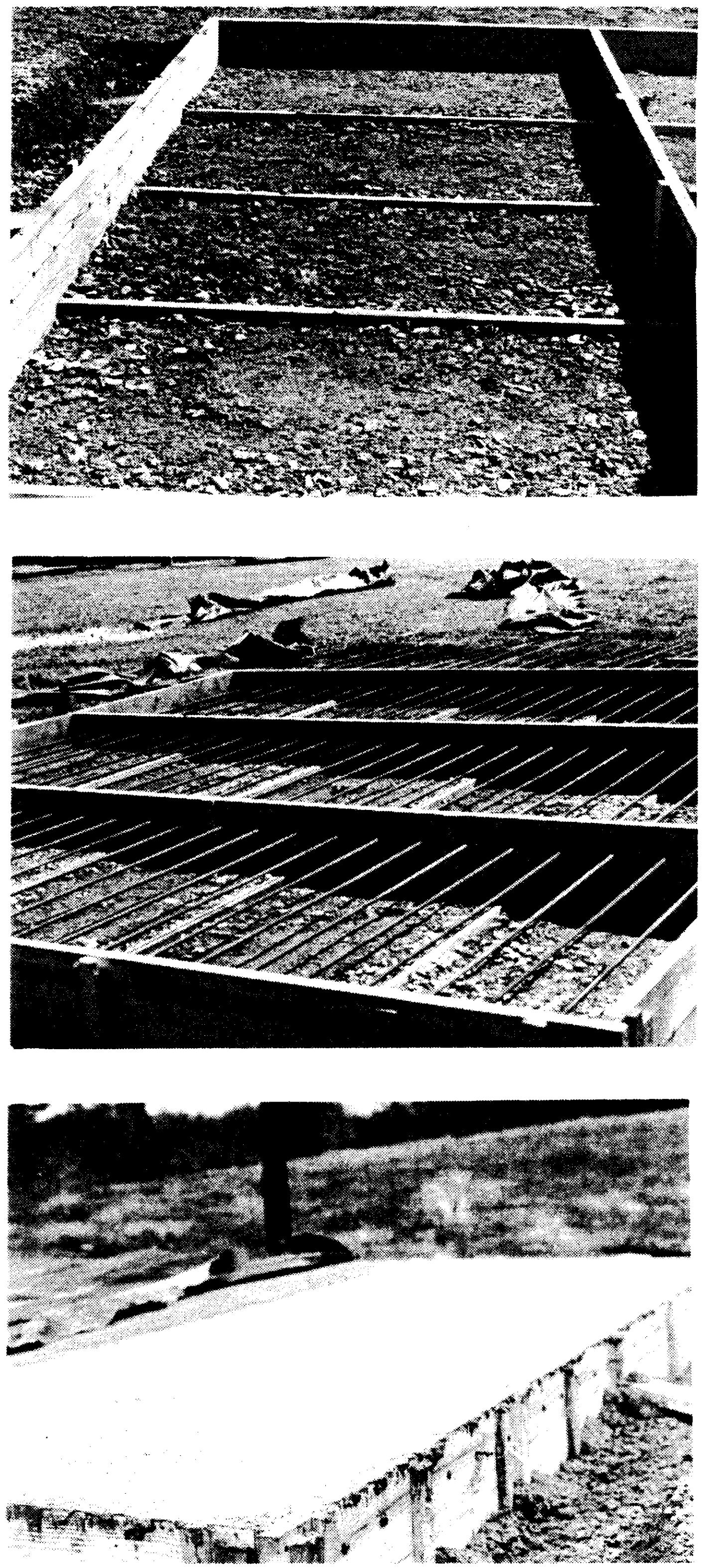
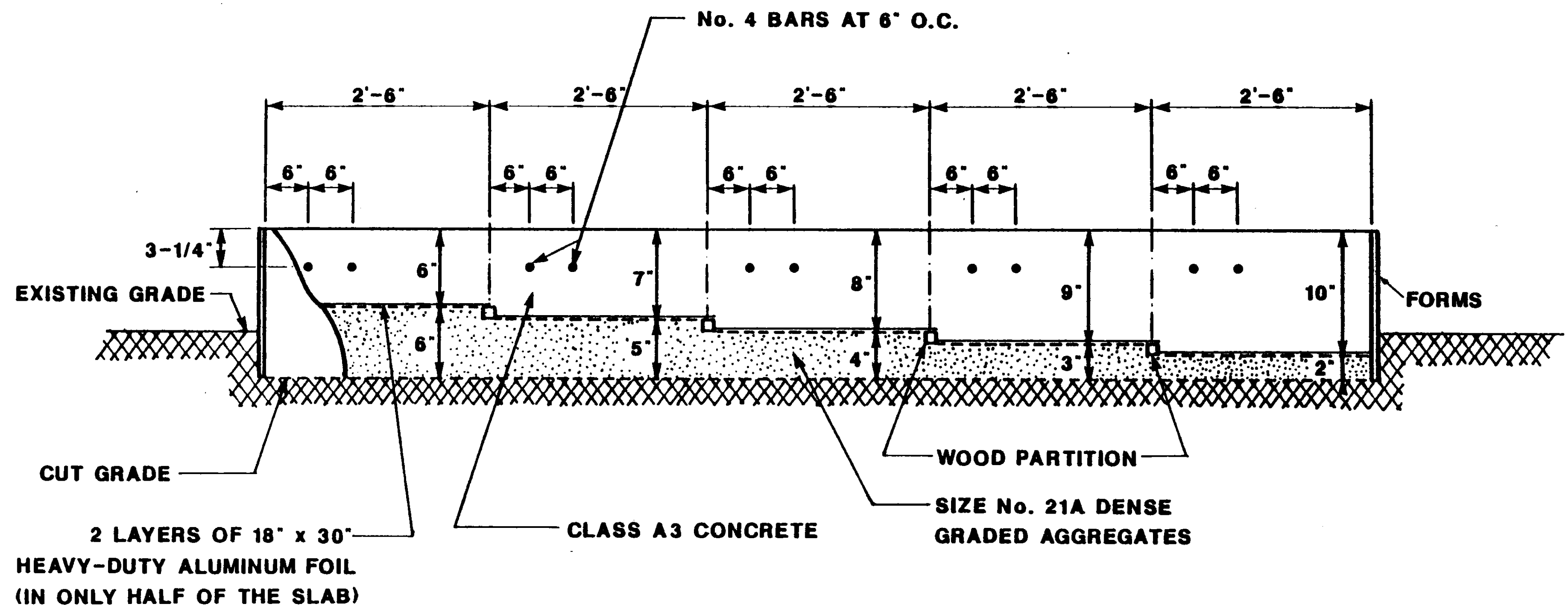
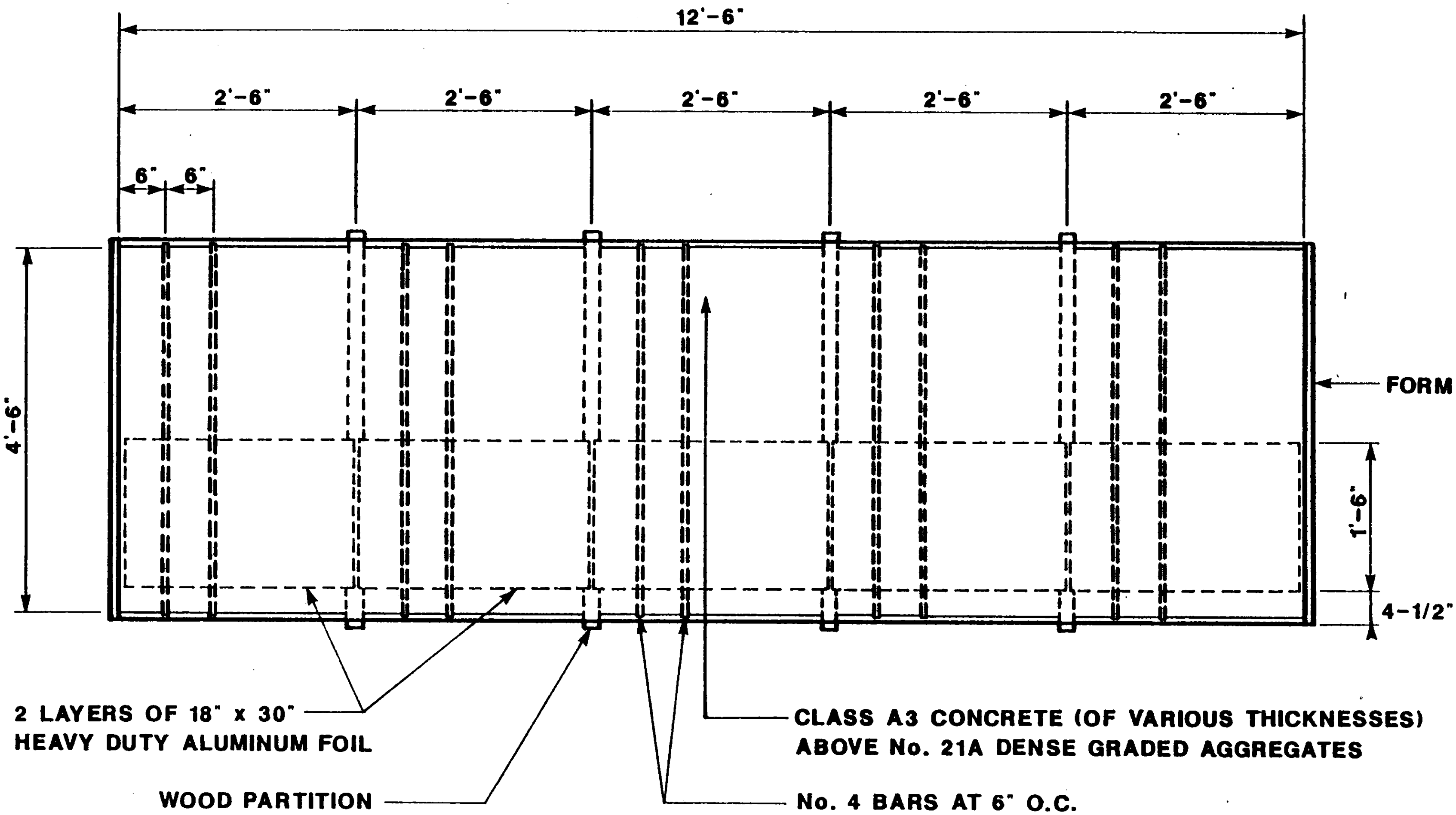


Figure 3. Building of the test slabs.



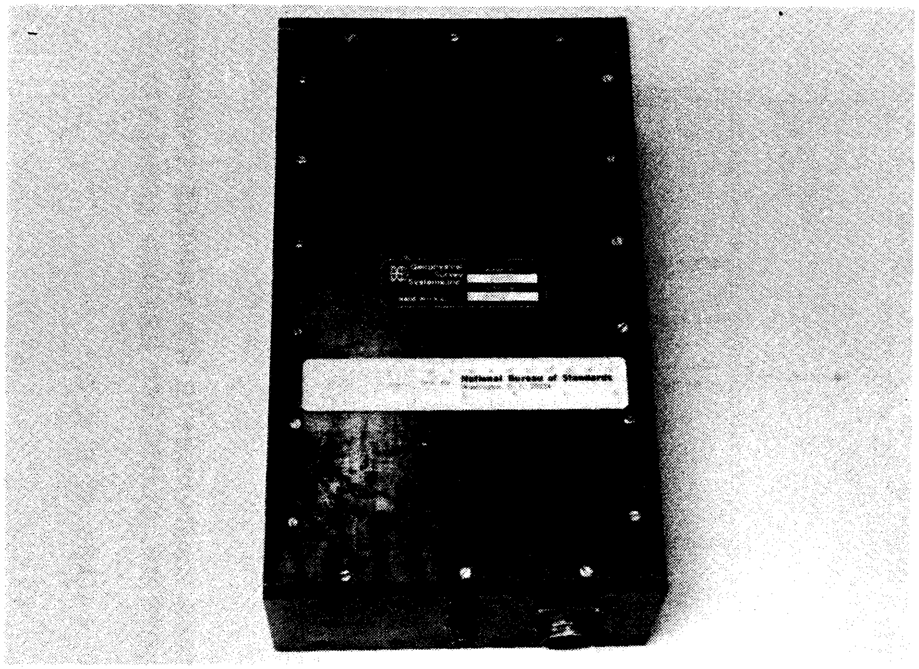
(a) SIDE VIEW OF TEST SLAB

Figure 4. Reinforced concrete slab with a reflector (aluminum foil) sandwiched between the slab and a layer of dense-graded aggregates

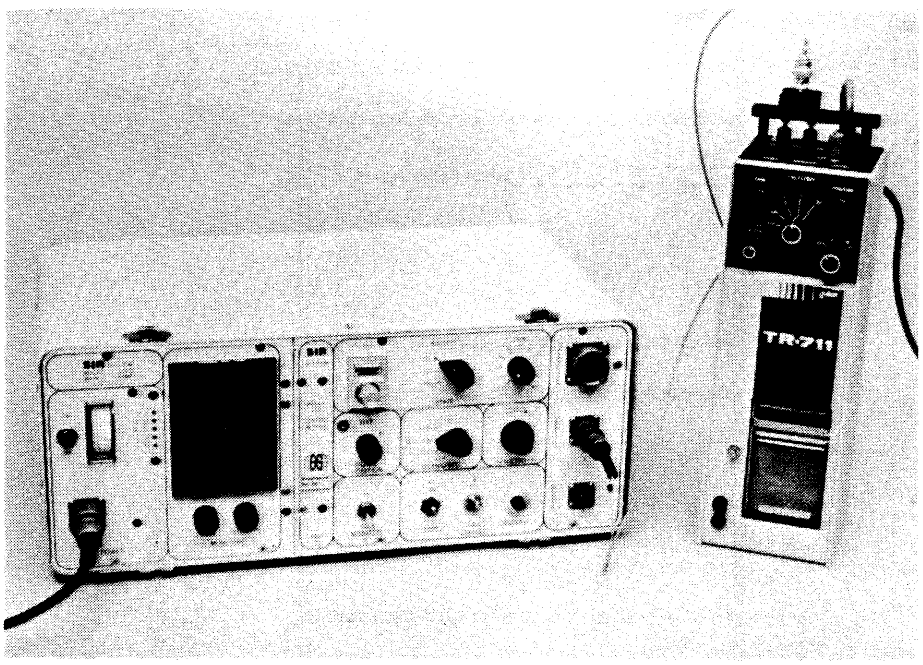


TOP VIEW OF TEST SLAB

Cont: Figure 4



(a)



(b)

Figure 5. Microwave radar components: (a) transducer, (b) control unit and oscillographic recorder.

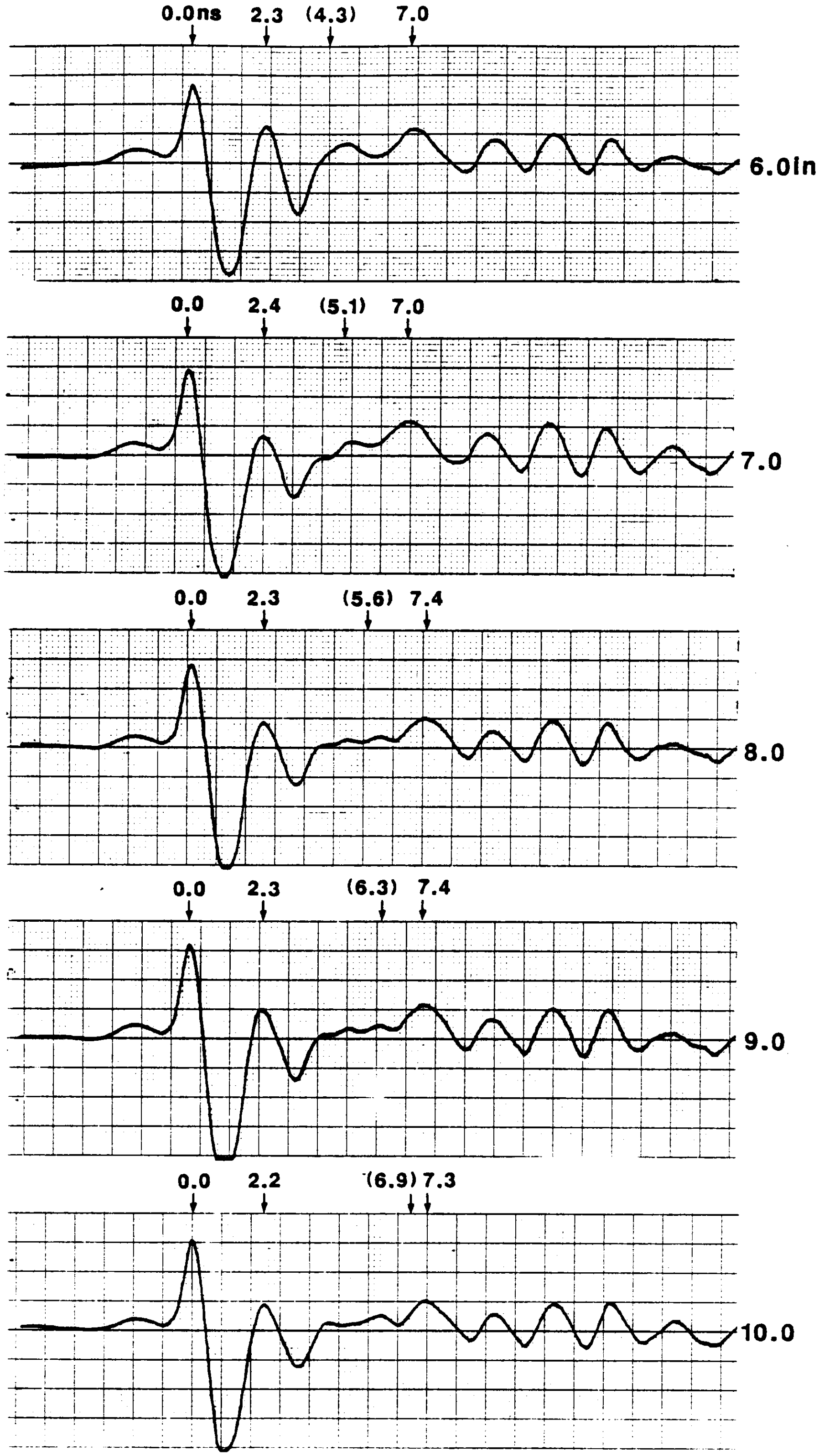


Figure 6. Reflection waveforms for the reinforced concrete slab with the w/c of 0.45 at slab thicknesses of 6 to 10 inches.

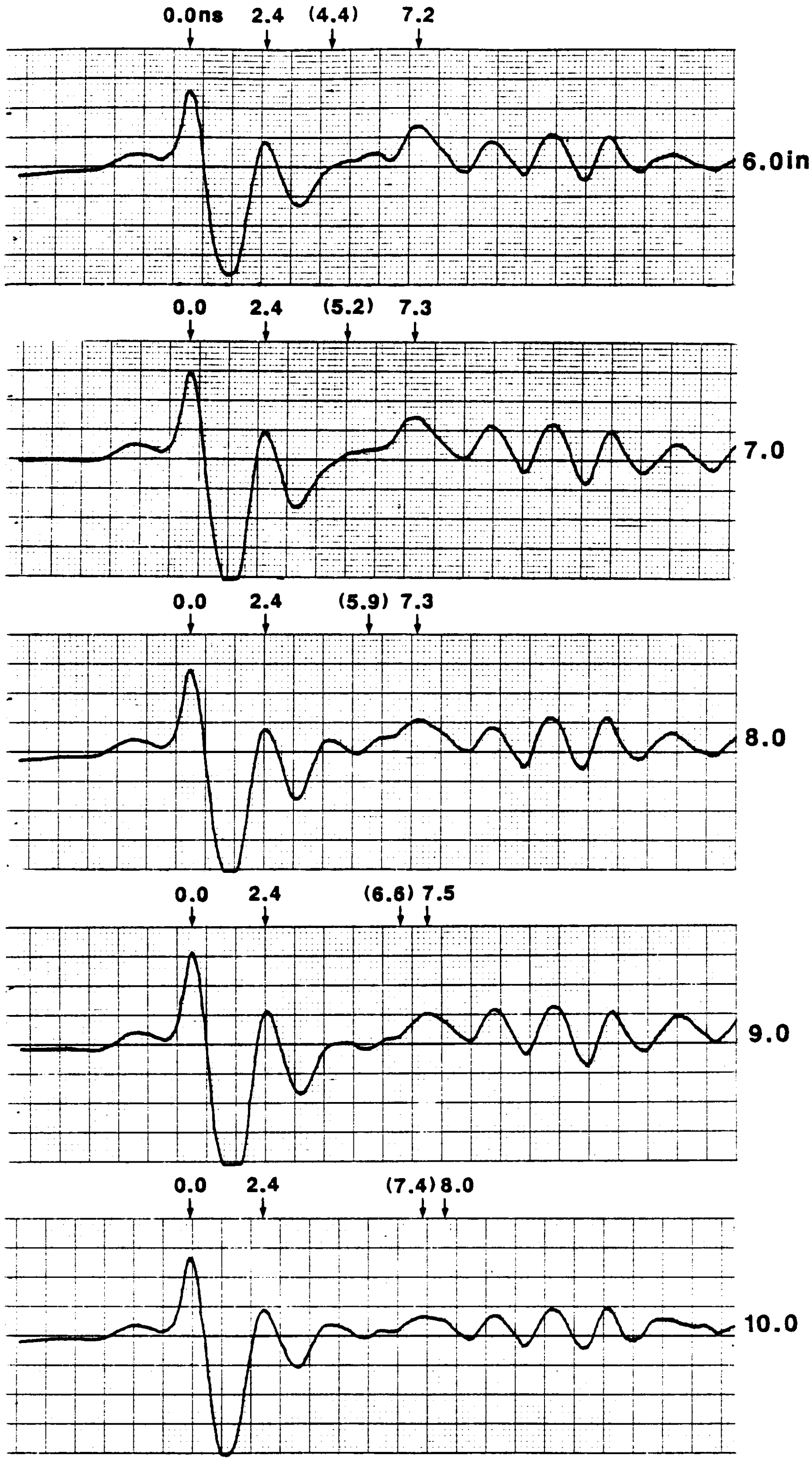


Figure 7. Reflection waveforms for the reinforced concrete slab with the w/c of 0.48 at slab thicknesses of 6 to 10 inches.

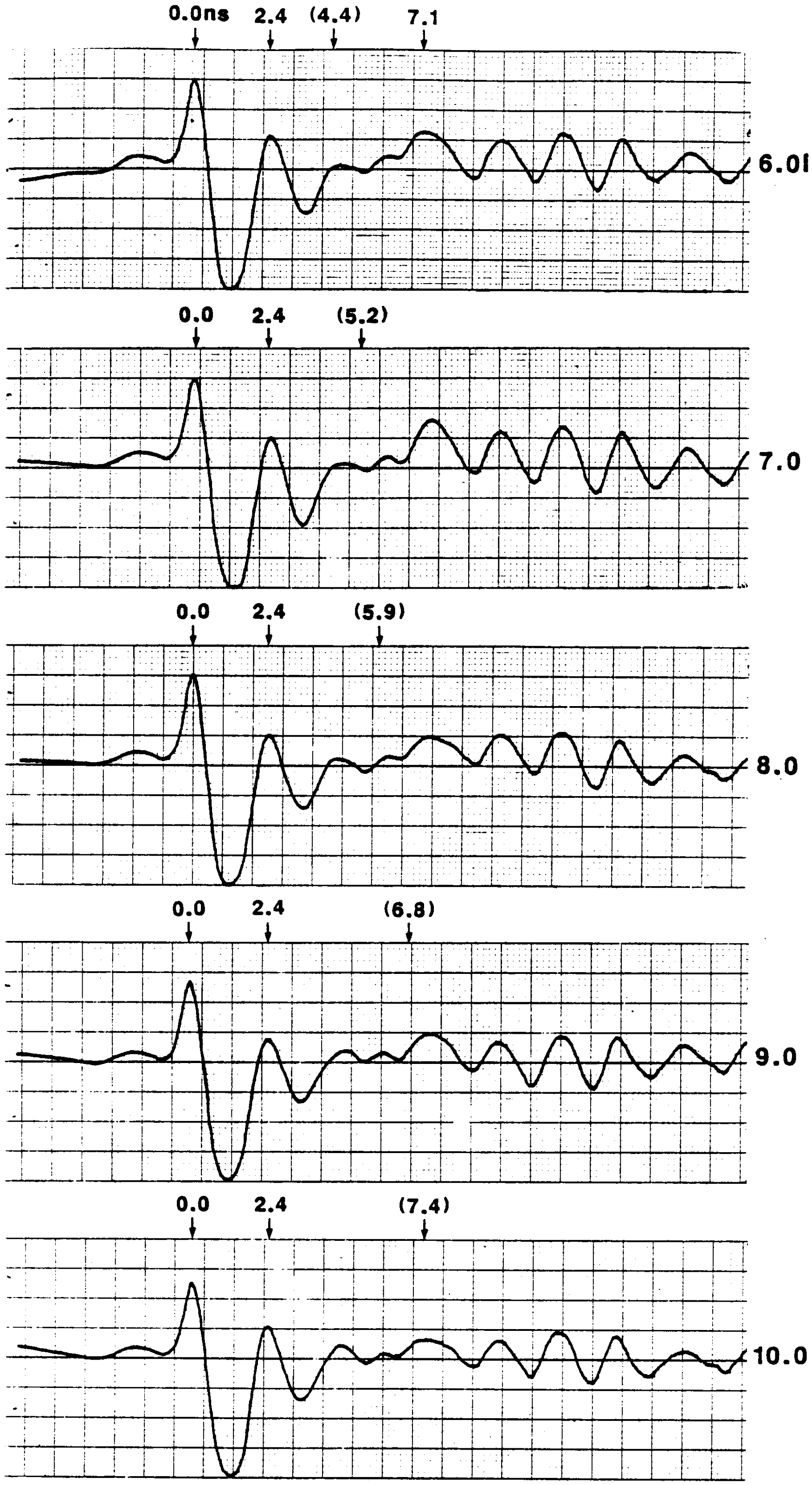


Figure 8. Reflection waveforms for the reinforced concrete slab with the w/c of 0.54 at slab thicknesses of 6 to 10 inches.

Table 1

Expected Transit Time for the Reflection
From the Bottom of the Slab

Slab W/C	Dr (in)	Tr (ns)	Dielectric Constant	Dc (in)	Tc (ns)
0.45	3.25	2.31	17.7	6.0	4.3
	3.25	2.37	18.5	7.0	5.1
	3.25	2.28	17.1	8.0	5.6
	3.25	2.28	17.1	9.0	6.3
0.48	3.25	2.39	18.8	6.0	4.4
	3.25	2.39	18.8	7.0	5.2
	3.25	2.39	18.8	8.0	5.9
	3.25	2.37	18.5	9.0	6.6
	3.25	2.39	18.8	10.0	7.4
0.54	3.25	2.41	19.1	6.0	4.4
	3.25	2.39	18.8	7.0	5.2
	3.25	2.41	19.1	8.0	5.9
	3.25	2.44	19.7	9.0	6.8
	3.25	2.39	18.8	10.0	7.4

Dr = concrete cover over the rebar
Tr = transit time of reflection from the rebar
Dc = concrete slab thickness
Tc = transit time of reflection from the slab bottom

The weak reflection from the bottom of the slab was likely due to the low reflection coefficient there, which according to equation 4 is dependent on the extent of the difference between the dielectric constants of the concrete and the subbase. As shown by measurements made at several points on an existing concrete pavement that has undergone complete slab replacement (Table 2), the dielectric constants of the concrete slab and the subbase can be relatively similar so that the resulting reflection coefficient at their interface would be extremely small. For this particular pavement, the average dielectric constants for the concrete and the subbase were 8.3 and 7.2, respectively; the resulting reflection coefficient was 0.034, which means that only 3.4% of the microwave reaching the bottom of those concrete slabs will be reflected back into the slabs.

Table 2

Fluctuation in the Dielectric Constants of the Materials
In a Section of Interstate Route 64, Virginia

Material	Measurement	Aoi	Ai	Aos	As	Rs	Es
Concrete	1	30.4	40.5	30.6	-19.0	-0.466	7.5
	2			30.9	-19.3	-0.469	7.6
	3			30.9	-20.4	-0.496	8.8
	4			30.9	-19.8	-0.481	8.1
	5			31.0	-20.4	-0.494	8.7
	6			30.9	-20.7	-0.503	9.1
	7			31.0	-19.8	-0.479	8.1
	8			31.0	-20.0	-0.484	8.3
	9			31.0	-19.6	-0.475	7.9
	10			31.0	-20.3	-0.492	8.6
					Average	-0.484	8.3
					Std.Dev.	0.011	0.5
Subbase	1	31.2	42.3	31.3	-19.0	-0.448	6.9
				31.5	-19.8	-0.464	7.4
				31.6	-19.5	-0.455	7.1
				31.5	-19.5	-0.457	7.2
				31.6	-20.0	-0.467	7.6
					Average	-0.458	7.2
					Std.Dev.	0.007	0.2

Reflectivity at the Bottom of the Concrete Slab = 0.034

Where the slab was more than 7 in thick, this reflection simply became even weaker and impossible to discern with any degree of certainty. This is because concrete attenuates microwave energy, and as the slab became thicker, the already weak reflection from its bottom became even weaker as it reached the transducer. This attenuation by a concrete slab also increases with increasing moisture content in the concrete.

Nevertheless, it appeared that the two waveforms recorded at the locations where the slab was only 6 and 7 in thick were markedly different (between 2.3 to 7.0 ns), from those recorded at locations where the slab was thicker.

It is interesting to note that, although the entire slab was supposed to have the same W/C ratio of 0.45, the dielectric constant of the slab varied from 16.9 to 18.5 (with an average of 17.5) at the five locations where reflection profiles were recorded. This fluctuation reflects the likely absence of homogeneity in the W/C of the entire batch of the concrete mixture from which the slab was made and/or in the moisture content in the slab at the time of the measurement.

The reflection profiles (Figure 7) for the slab with the W/C of 0.48, which had an average dielectric constant of 18.7, show slight resemblance to those shown in Figure 6. Similarly, the reflection from the bottom of the slab cannot be distinctly identified at the place where it was expected to arrive for the different slab thicknesses (see Table 1), especially where the slab was thicker than 8 in. However, there was again a distinct difference (between 2.4 to 7.2 ns for this slab) between the waveforms recorded where the slab was thinner than 8 in and those recorded where the slab was thicker.

Among the profiles shown in Figure 8 for the slab with the W/C of 0.54, which had an average dielectric constant of 19.1, such qualitative differences between the profiles for locations where the slab was thinner than 8 in and those for locations where the slab was thicker cannot be found.

Incidentally, it appeared that there was a direct correlation between the average dielectric constant and the intended W/C of each of the slabs (see Table 1). This is in agreement with the linear dependency of the dielectric constant (or reflectivity) of a concrete on its water content, which has been reported elsewhere (2).

The attenuation of microwave energy by a concrete decreases with decreased dielectric constant and electrical conductivity in the concrete. Since these latter properties have been reported to decrease with the age of a concrete in the manner illustrated in Figure 9 for a Virginia class A-4 concrete (3), attenuation is practically at the lowest possible degree when the concrete is at least several days old. Unfortunately, it wouldn't be possible to take advantage of this situation and schedule inspection of a newly built concrete pavement at that stage of curing to ensure maximum reflection from the bottom of the slab, because the final intensity of the reflection reaching the antenna is also controlled by the reflectivity at the bottom of the slab, which in turn is directly related to the degree of difference between the dielectric constants of the concrete and the subbase (see equation 4). Figure 10 shows a set of hypothetical relationships between the age of a class A-4 concrete slab and the estimated relative intensity of the reflection from the bottom of the slab for various assumed subbase dielectric constants. The increasing adverse influence of age on the reflectivity at the bottom of the concrete slab counteracts its diminishing influence on the attenuation of microwave pulses by the concrete. It is, therefore, doubtful that the use of microwave reflection measurements to determine the thickness of concrete pavements can be enhanced at all by consideration of the age of the concrete in scheduling such measurements.

Figure 11 shows a set of reflection profiles recorded over the portion of a reinforced slab that had a piece of aluminum foil sandwiched between the concrete and the subbase. Figure 12 shows another set recorded over the other half of the same slab that did not have the reflector over the subbase. Comparison of these two sets of reflection profiles shows that, when a good reflector such as an aluminum foil was placed over the subbase before the concrete was placed, the sought-after reflection from the bottom of the resulting reinforced concrete slab was considerably enhanced. This enhancement, which clearly diminished with increasing slab thickness, was manifested by the appearance of a relatively strong reflection in each of the profiles shown in Figure 11 between 2.22 to 7.30 ns (depending on the thickness). These reflections were at best difficult to discern in the profiles shown in Figure 12.

Again, the dielectric constant of this concrete slab at each of the five locations where the reflection profiles were recorded (Figure 11) can be calculated from the respective observed transit times of the reflection from the rebars, the depths of which are known. Using these estimated (or measured) dielectric constants, the thickness of the slab can be calculated from the respective measured transit time for the reflection from the bottom of the slab at each of those locations. By comparison with the known thicknesses of the slab at those five locations, it appeared that the procedure yielded an accuracy that ranged from -0.2 to -1.0 in and consistently led to the underestimation of the thickness (see Table 3).

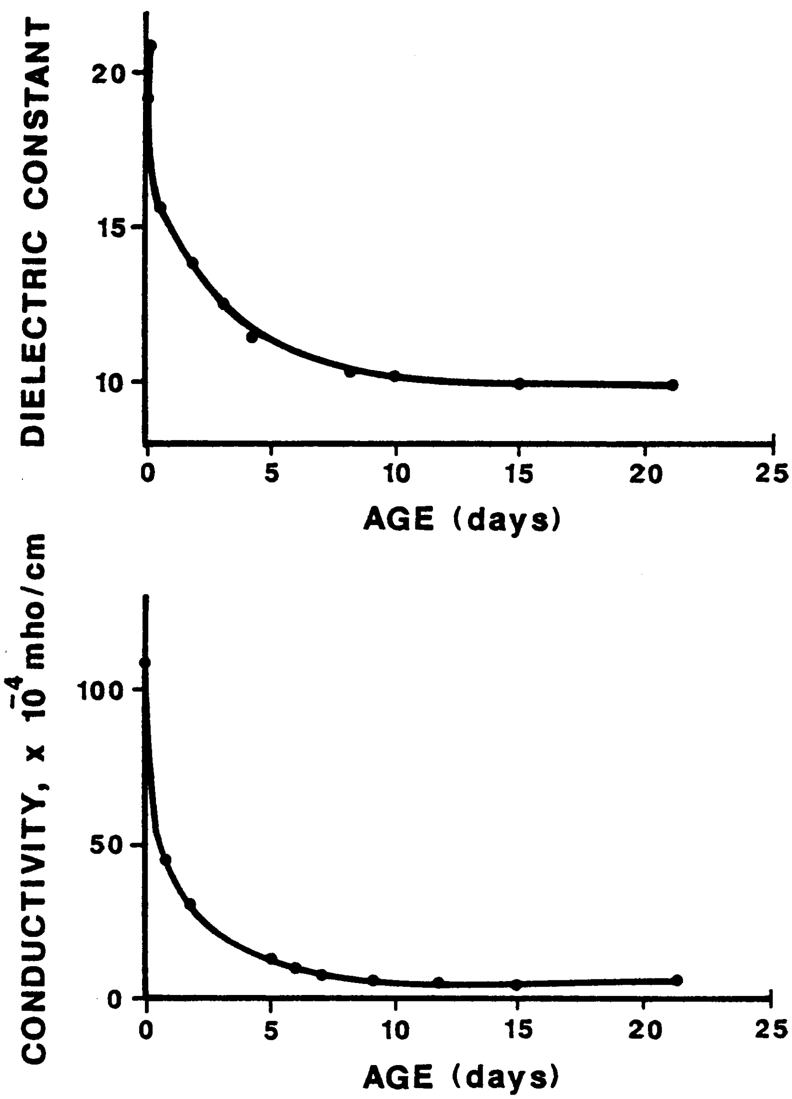


Figure 9. Change in the dielectric constant and the electrical conductivity of a concrete with its age.

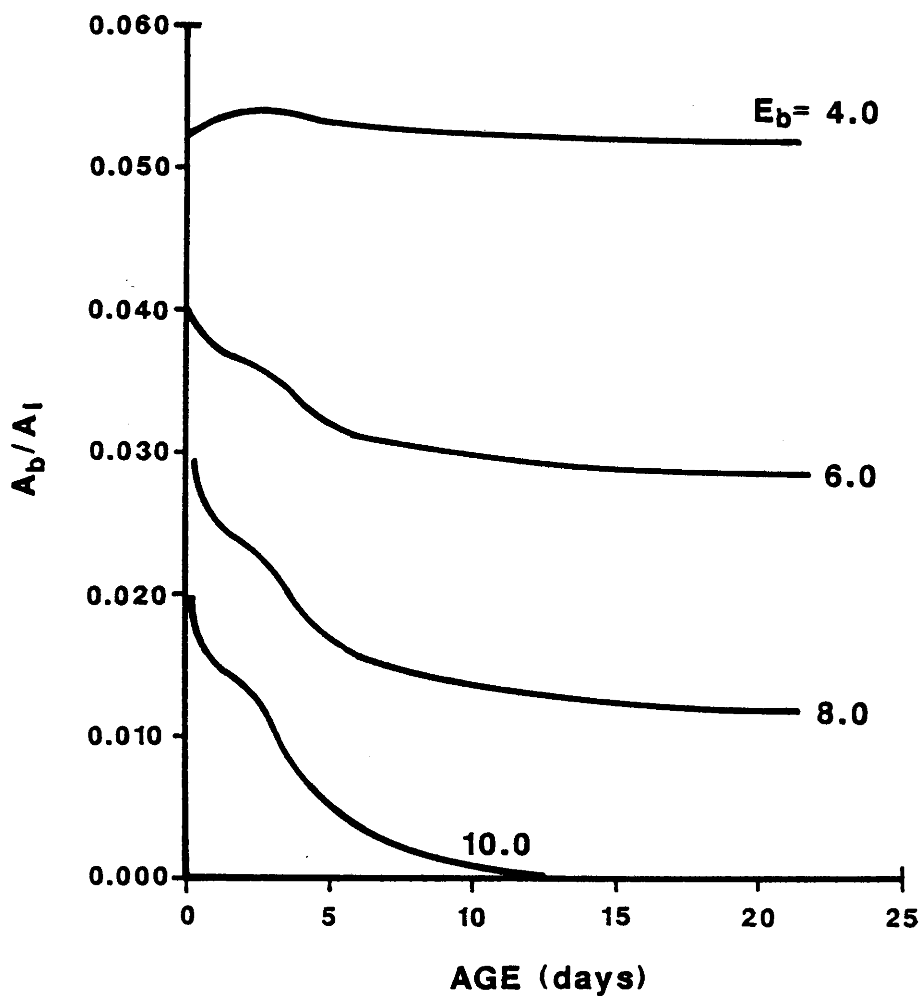


Figure 10. Influence of the age of a concrete slab on the relative intensity of the reflection from its bottom for various subbase's dielectric constants.

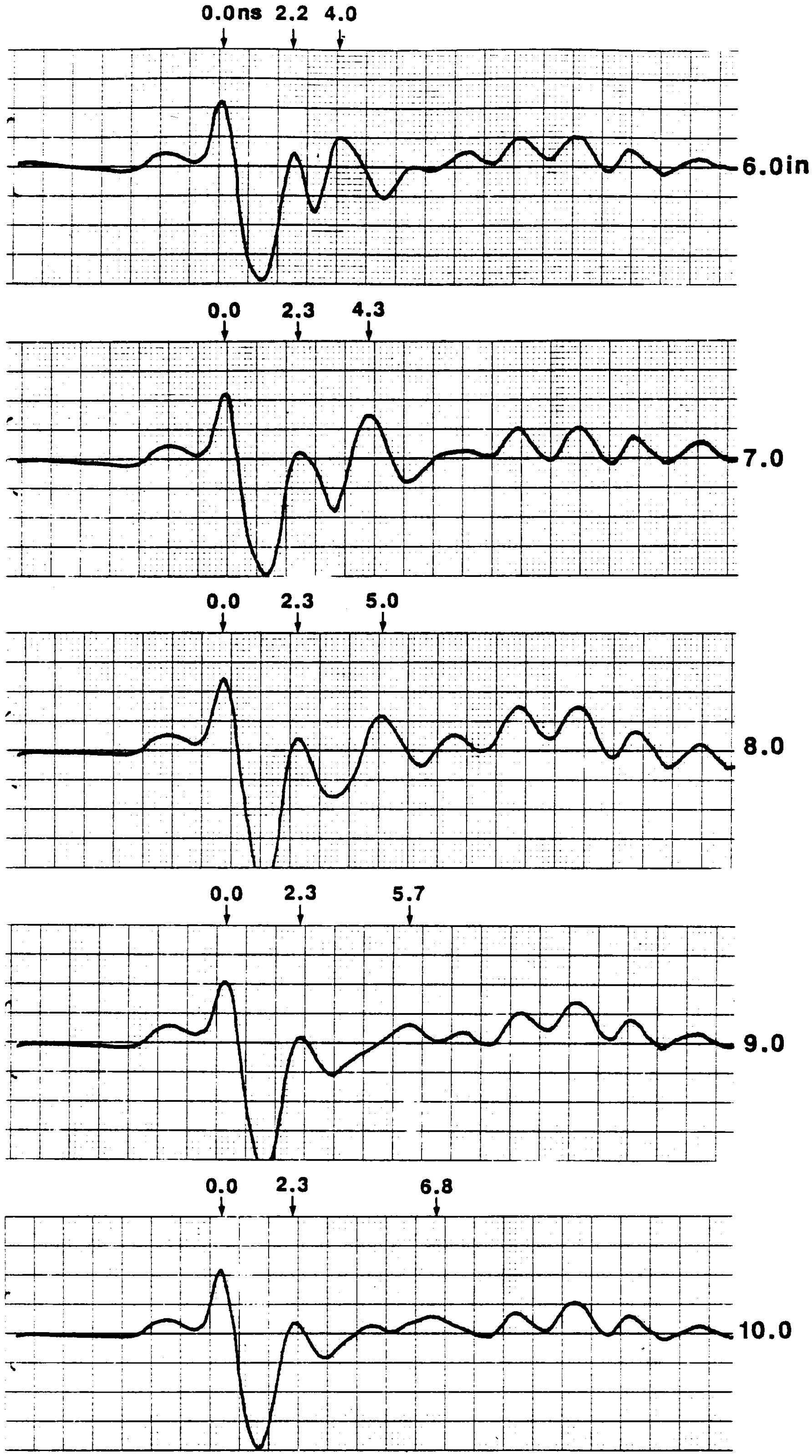


Figure 11. Reflection waveforms for the reinforced concrete slab with an aluminum reflector sandwiched between the slab and the subbase at various slab thicknesses.

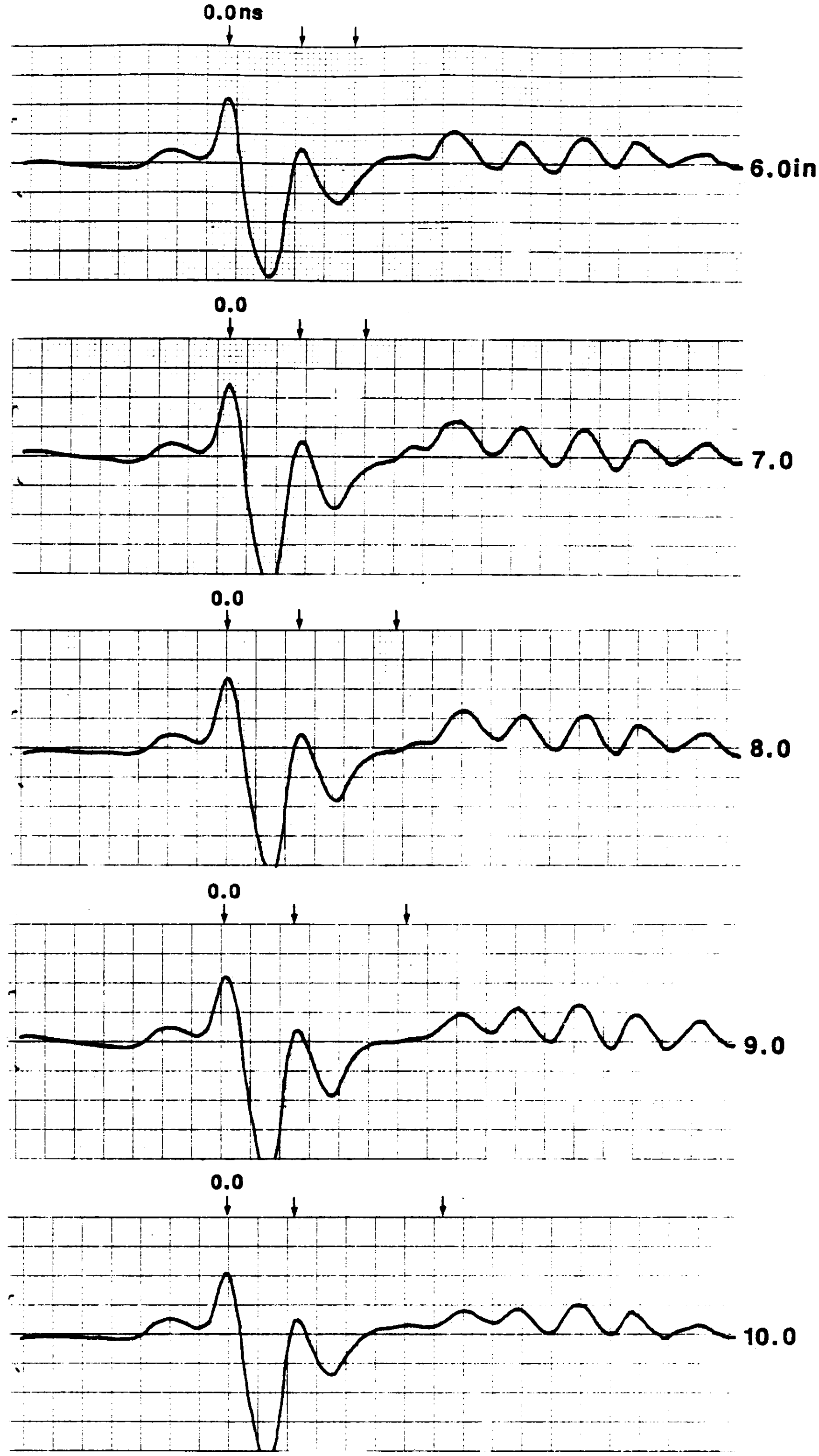


Figure 12. Reflection waveforms for the reinforced concrete slab without the aluminum reflector at various slab thicknesses.

Table 3

Accuracy of Measured Concrete Thickness for the Slab Underlaid with an Aluminum Reflector

Measured Drebar (in)	Measured Trebar (ns)	Measured Dielectric Constant	Measured Tconc. (ns)	Measured Dconc. (in)	Known Dconc. (in)	Error (in)
3.25	2.22	16.3	3.98	5.8	6.0	-0.2
3.25	2.31	17.7	4.35	6.1	7.0	-0.9
3.25	2.31	17.7	5.00	7.0	8.0	-1.0
3.25	2.28	17.1	5.74	8.2	9.0	-0.8
3.25	2.31	17.7	6.76	9.5	10.0	-0.5

Measurements taken on the same slab on other days did not yield better results. However, these measurements did confirm that the dielectric constant of a concrete slab would change with age in the manner illustrated in Figure 9. Although for this slab, which was exposed to outdoor environment, its dielectric constant at any moment appeared to be affected also by precipitation. This effect, of course, is likely to be most pronounced at the surface of the slab.

Measurements Made on a Continuously Reinforced Concrete Pavement

Radar measurements were also made at 51 sampling locations in an existing continuously reinforced concrete pavement where cores had been extracted for thickness-compliance measurements using the conventional method. The radar measurements at each of these locations consisted of three measurements at three different spots surrounding the corresponding core hole. For example, Figure 13 shows the three recorded reflection profiles for Location 1, each of which consists of the reflections from the surface of the concrete pavement, the rebars, and the bottom of the concrete slab. Sandwiched between the latter two reflections is the reverberation from the rebars. These profiles are slightly influenced by the orientation of the antenna with respect to the rebars.

The reflection from the bottom of the slab at this sampling location was relatively easy to identify. At some other locations, particularly where the slab was thicker, identification of this reflection could only be achieved with uncertainty.

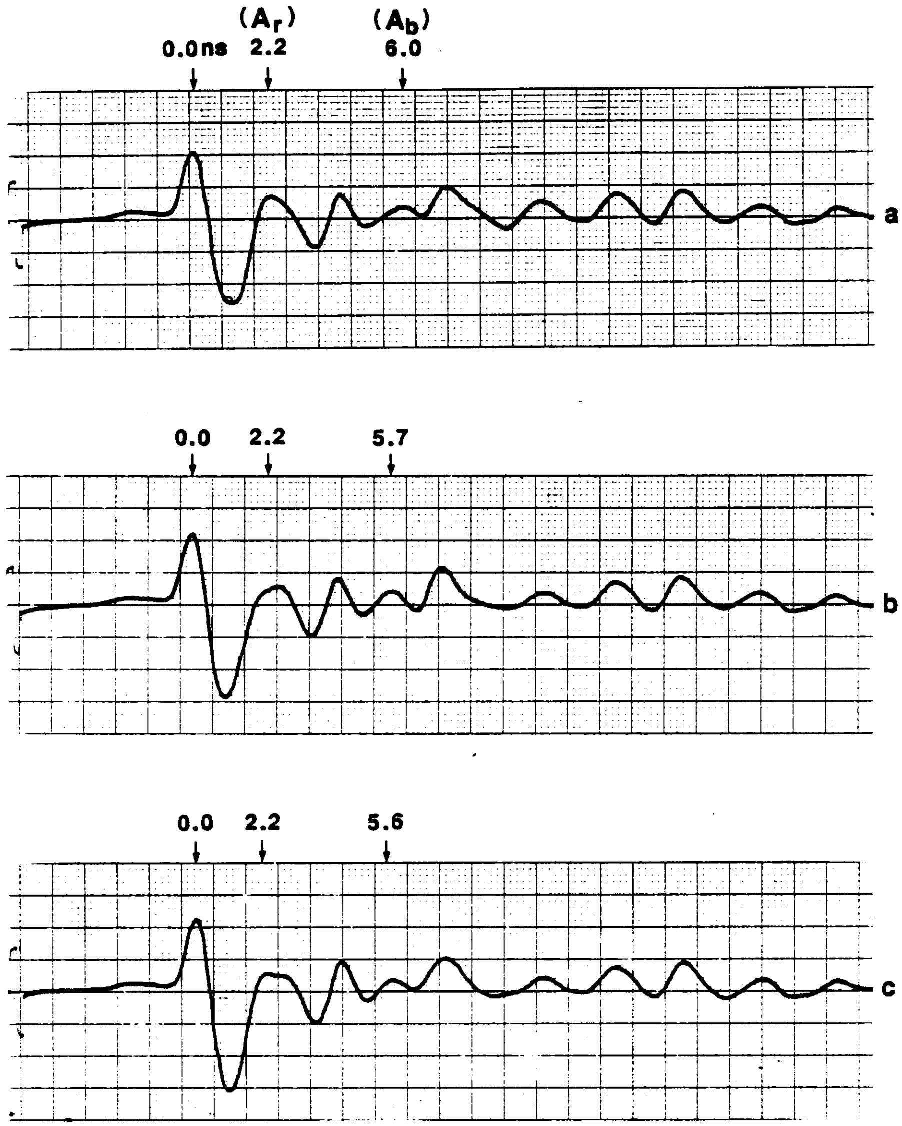


Figure 13. Three reflection waveforms recorded around core no. 1 on Interstate Route 295 in Richmond, Virginia.

The thickness of the concrete slab at each of the 51 sampling locations can be determined from the radar-measured t_r and T_b and the pachometer-measured (D_r) by using equation 5. It is clear that, for this series of samples, the thickness of the slab as determined by this procedure showed reasonable agreement with the results of coring, with the radar-measured thicknesses falling within 1.1 in of the coring results, at 95% confidence level (see Figure 14). Unfortunately, this level of accuracy is not quite acceptable.

The error associated with radar appeared to be higher and more varied as the thickness of the slab increased (Table 4). This trend is not unexpected, since as a reinforced concrete slab becomes thicker, the reflection from its bottom becomes weaker and more difficult to define. In addition, the adverse effect of the error associated with the measurement of rebar depth by pachometer (which may vary between ± 0.25 in) increases as the slab thickness increases.

Table 4

Characterization of the Difference Between the Coring and Radar Results

Concrete Slab Thickness (in)	Number of Samples	Absolute Difference (in) Lowest	Highest	Average	Std. Dev.
7.1 - 8.0	4	0.2	0.3	0.2	0.04
8.1 - 9.0	24	0.1	0.8	0.3	0.22
9.1 - 10.0	19	0.1	2.2	1.2	0.60
10.1 - 11.0	2	0.8	1.6	1.2	--
11.1 - 12.0	2	1.5	2.2	1.9	--

An easier procedure for the determination of concrete pavement thickness can be derived if it is assumed that the dielectric constant of the concrete is uniform throughout the pavement. Under this condition, equation 3 becomes

$$D_c = kt_c. \qquad (6)$$

This implies that, at any point on the pavement, the thickness of the concrete slab is simply directly proportional to the transit time of the microwave pulses through the concrete slab. To utilize this simple relationship, all that is necessary is to determine the proportionality constant through the establishment of a calibration line that relates the two variables.

The above data set of 51 sampling locations were used to demonstrate and assess this approach. To established the necessary calibration line, a linear regression analysis was conducted on the data for seven locations that were randomly selected from the five ranges of slab thickness previously mentioned (see Table 5). Based on the resulting calibration line, which is shown in Figure 15, the thickness of the concrete slab at each of the remaining 44 sampling locations was then estimated.

Table 5

Randomly Selected Data Points for Use in Calibration

Range of Concrete Slab Thickness (in)	Total Number of Samples	Number of Samples Selected	Core No.	Variable Tc (ns)	Variable Dc (in)
7.1 - 8.0	4	1	13	5.28	7.9
8.1 - 9.0	24	2	51	5.77	8.5
			47	5.93	8.8
9.1 - 10.0	19	2	18	6.76	9.4
			42	7.69	9.8
10.1 - 11.0	2	1	12	7.81	10.6
11.1 - 12.0	2	1	31	8.98	11.3

Figure 16 illustrates how these estimates compare with the figures derived from coring. The radar results were within 0.4 in of the coring results, at a 95% confidence level. When observed deviations are similarly categorized into different ranges of thickness (see Table 6), it is apparent that this particular radar procedure yielded better results than the first procedure (see Table 4). A noticeable improvement in the results of this last procedure is the absence of a tendency for the error in the radar results to increase with the true thickness of the concrete slab, which is a weakness that was observed in the first procedure. This weakness was avoided in the last procedure through the proper selection of core samples to be used in the establishment of the calibration line, which should be spread sufficiently (as was the case in the exercise) to encompass the range of thicknesses that would be encountered in an inspection.

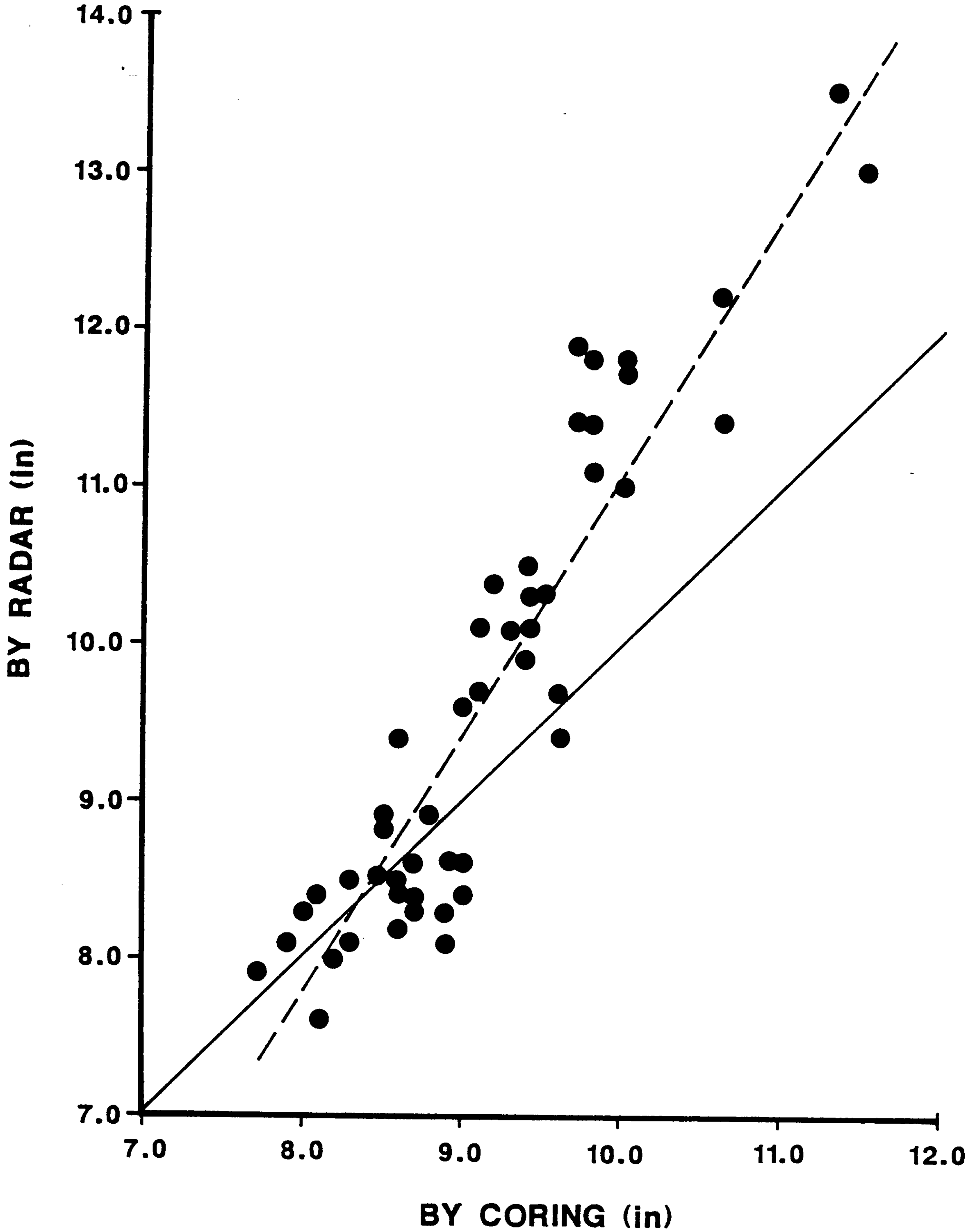


Figure 14. Comparison of concrete slab thickness in Interstate Route 295 as determined by coring and by radar.

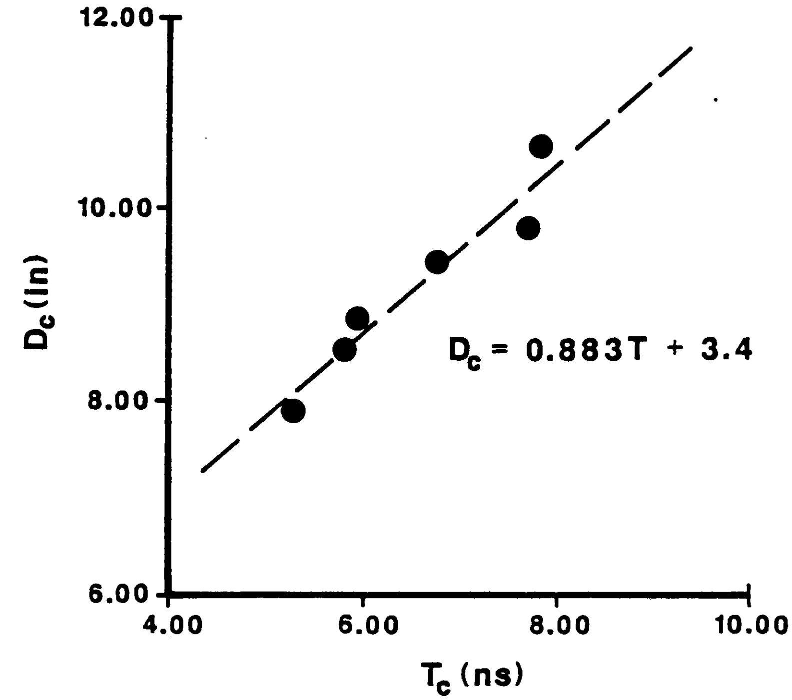


Figure 15. A calibration line for determining the thickness of concrete slab in Interstate Route 295 in Richmond, Virginia from microwave transit time through the slab.

In the inspection of a new concrete pavement, this last procedure could be implemented by continuously scanning each traffic lane with a radar antenna, just as the inspection of concrete pavements for voids underneath the slabs is presently being performed. Afterward, the recorded waveform can be examined for the selection of several coring locations that would yield cores which adequately represent the entire range of slab thicknesses that appeared to exist in the pavement. The cores would then be extracted and their lengths measured and correlated with the observed microwave transit times at those selected locations to obtain a calibration line from which the thickness of the concrete slab at any other portion of the pavement could be estimated.

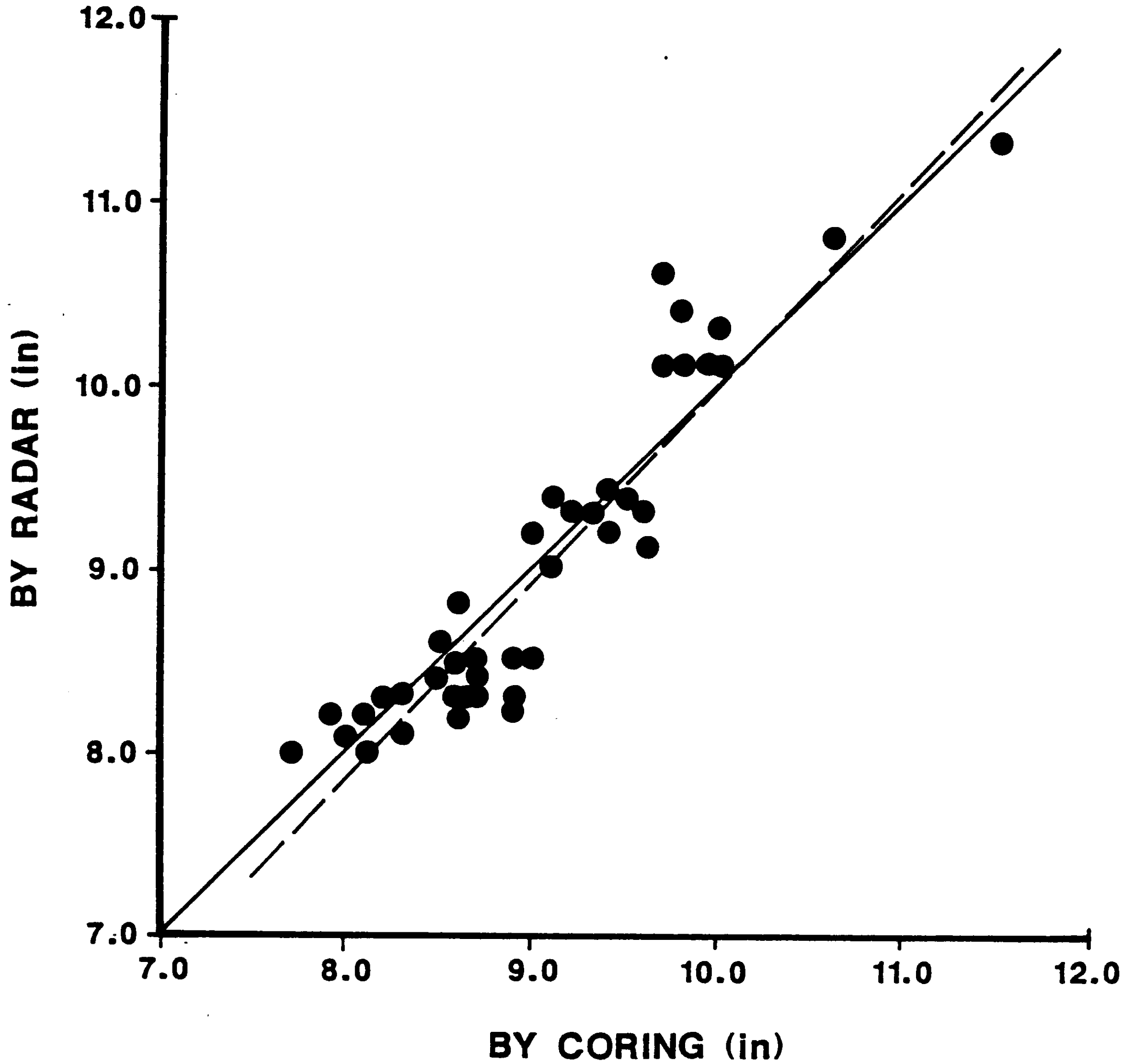


Figure 16. Comparison of concrete slab thickness in Interstate Route 295 as determined by coring and by radar (using a calibration line).

Table 6

Categorization of the Differences Between the Coring and Radar Results (Using Calibration Line)

Concrete Slab Thickness (in)	Number of Samples	Absolute Difference (in) Lowest	Highest	Average	Std.Dev.
7.1 - 8.0	3	0.1	0.3	0.2	0.09
8.1 - 9.0	22	0.0	0.7	0.3	0.18
9.1 - 10.0	17	0.0	0.9	0.3	0.24
10.1 - 11.0	1	0.2	0.2	N.A.	N.A.
11.1 - 12.0	1	0.2	0.2	N.A.	N.A.

It must be emphasized again that, regardless of which radar procedure is used, the identification in the recorded waveform of the reflection from the bottom of the reinforced concrete slab is critical to the success of the procedure. Since the intensity of this reflection depends on several factors, which may vary from one pavement to another, it appears that the reliability of radar in the inspection of concrete pavements for thickness may be variable. It is beyond any doubt that, with an antenna that is more directive and has a narrower pulse, it should be easier to rapidly determine the thickness of new pavements with relatively more reliability.

CONCLUSIONS

The following conclusions can be made:

1. The definitive identification in a recorded waveform of the reflection from the bottom of a reinforced concrete slab is critical to the successful use of radar to measure the thickness of concrete pavement slabs.

2. However, the presence of strongly reflecting reinforcement and very low reflectivity at the interface between the concrete slab and the subbase caused this reflection to be often very weak and difficult to identify precisely, especially when the slab is thicker than 8 in.

3. When this reflection in a particular pavement is difficult to pinpoint precisely, radar may be used as a screening tool to spot areas where the slab is too thin. The

thickness in these suspected areas would then be verified by coring.

4. In pavement in which the conditions favor the identification of this reflection even where the slab is relatively thick, the calibration procedure may be a reasonably reliable approach for determining the thickness of the slab throughout the pavement.

REFERENCES

1. Weber, W. G. Jr., R. L. Grey, and P. D. Cady, "NCHRP Report 168 -- Rapid Measurement of Concrete Pavement Thickness and Reinforcement Location -- Field Evaluation of Nondestructive Systems," Transportation Research Board, Washington, D.C. 1976.

2. Clemeña, G. G., "Determining Water Content of Fresh Concrete by Microwave Reflection or Transmission Measurement," VTRC 88-R3, Virginia Transportation Research Council, Charlottesville, Virginia, 1987.

3. _______, Microwave Reflection Measurements of the Dielectric Properties of Concrete," VHTRC 84-R10, Virginia Highway and Transportation Research Council, Charlottesville, Virginia, 1983.