FINAL REPORT

MICROWAVE REFLECTION MEASUREMENTS OF THE DIELECTRIC PROPERTIES OF CONCRETE

by

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Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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ABSTRACT

The use of microwave reflection measurements to continuously and nondestructively monitor the hydration of concrete is described. The method relies upon the influence of the free-water content on the dielectric properties of the concrete. Use of the method on concrete blocks showed linear relations between the compressive strength, water-cement ratio, and block thickness with the dielectric properties. Some possible applications of the method are discussed.

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INTRODUCTION

The durability of a concrete is greatly influenced by the degree of curing, or hydration, attained by the cement used. At present, there is no satisfactory nondestructive method for determining the degree of hydration attained, especially for in-place concrete at an early age. Such a test method would be a convenient tool for studying concrete mixes incorporating new admixtures and industrial waste products prior to their use in construction projects, and in the inspection of in-place concrete at the earliest possible time, since large volumes of concrete are now being placed at one time.

The much studied technique of ultrasonic pulse velocity has the potential of filling the gap, especially with the recent development of portable instruments for making measurements. However, the technique is still hindered by (1) the need for perfect "acoustical" contact between the transducers and the concrete, (2) the need for the tranducers to be arranged directly opposite each other on opposite sides of the member being tested for most satisfactory results, and (3) interference from embedded reinforcing steels -- all of which render the technique impractical for on-site testing of newly placed concrete pavements and bridge decks.

Another potential method involves the measurement of microwave transmission through concrete, which was the subject of the investigation reported here.

BACKGROUND

Compared to ultrasonic pulse velocity, the use of microwave reflections in the testing of concrete has yet to be thoroughly studied, as evidenced by the scarcity and recentness of literature on the technique. The study reported by Bhargava and Lundberg was perhaps the earliest study and involved determining the moisture content of concrete and other building materials by measuring shifts in the microwave resonance frequency.(1) In the same year, Rzepecka et al. reported that it was feasible to nondestructively test concrete for strength during the curing process by observing variations in the dielectric permittivity.(2) This was followed in 1977 by a preliminary study by Morey and Kovacs.(3) The latest study was reported in 1982 by Gorur et al., and involved monitoring the curing of several cement pastes at very early ages.(4)

With the exception of the work by Morey and Kovacs, these studies were conducted with laboratory instrumentation and/or experimental setups utilizing waveguides for transmission measurements, neither of which is suitable for on-site testing of highway structures. In view of the potential of microwave measurements, it was decided to (1) verify that the curing of concrete can be continuously and nondestructively monitored through microwave measurements, using portable instrumentation and a setup suitable for on-site testing, (2) determine if there is any measured parameter that can be suitably correlated to compressive strength, which is often used to characterize the quality of a concrete, (3) determine if such relationship is affected by factors such as cement type, water-cement ratio, aggregate, and admixture, (4) determine how well the measured transit time of microwave radiations through concrete can be correlated to the thickness of a concrete member, and (5) determine the extent of interference that reinforcement in concrete pavements may present to microwave radiation.

PRINCIPLE

All materials can be classified as being either a metal or a dielectric; i.e., they are either good or poor electrical conductors. Also, they differ in their interactions with electromagnetic waves, such as microwaves. Microwaves tend to be almost completely reflected from metallic materials, while they penetrate and propagate through dielectric materials in varying degrees, depending on the conductivity and dielectric constant of the materials.

Concrete is a dielectric material. At early ages, its dielectric constant is very much influenced by the degree of hydration attained, or the amount of unreacted water left, since "free" water has a relatively high dielectric constant (about 80) in contrast to approximately 5 for physically or chemically bound water.(5) Therefore, continuous monitoring of the change in the dielectric constant of a concrete during its early age should provide a measure of hydration or, if desired, of strength development.

The dielectric constant can be indirectly determined by observing how the concrete interacts with microwave pulses. When these pulses from a transducer are radiated through a concrete, as shown in Figure 1, some of the pulse energy is reflected from the surface of the block. The amplitude of the reflected energy, A_s, is related to the dielectric constant, ε, of the concrete by the relationship

$$A_s = \rho_1 A_a = \left(\frac{1 - \sqrt{\varepsilon}}{1 + \sqrt{\varepsilon}}\right) A_a \quad , \tag{1}$$

since

$$\rho_1 = \frac{1 - \sqrt{\varepsilon}}{1 + \sqrt{\varepsilon}} \quad , \tag{2}$$

where

A_a = the amplitude of the incident pulse energy, and

ρ_1 = the reflection coefficient at the air/concrete interface.

The remaining pulse energy, $(1-\rho_1)A_a$, penetrates into the concrete until it strikes the bottom of the block, which is another interface (i.e., concrete/air) at which another reflection occurs. The energy reflected back up through the concrete, A_c, is given by

$$A_c = \rho_2 \{(1 - \rho_1) A_a\} = - \rho_1 (1 - \rho_1) A_a \quad , \tag{3}$$

where ρ_2 is the reflection coefficient at the concrete/air interface and is equal in magnitude but opposite in polarity to ρ_1, assuming that the concrete is completely homogeneous, since

$$\rho_2 = \frac{\sqrt{\varepsilon} - 1}{\sqrt{\varepsilon} + 1} = - \rho_1 \quad . \tag{4}$$

Finally, the fraction of A_c that manages to escape out of the concrete, A_b, can be similarly derived to yield

$$A_b = (1 - \rho_2) A_c = - \rho_1 (1 - \rho_1^2) A_a \, . \tag{5}$$

Equations 1 and 5 show how amplitudes of pulse reflections A_s and A_b, which can be continuously and nondestructively measured, can be indirectly correlated to the dielectric constant and, therefore, to the extent of hydration.

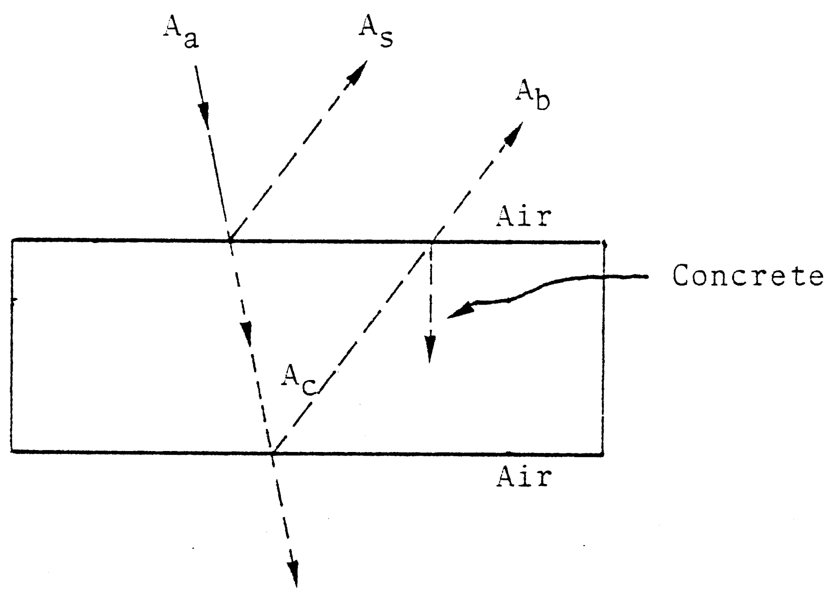


Figure 1. Propagation of microwave pulses in an air/concrete/air system.

Instrumentation

A portable impulse radar system consisting of a model 4000 control unit and a small 101c transducer, both manufactured by the Geophysical Survey Systems, Inc. was used. The small transducer, which measures 7 in. (17.8 cm) wide x 12 in. (30.5 cm) long x 3 in. (7.6 cm) high, contains a transducer and a receiving antenna. It operates at a center frequency of 900 MH_z, indicating a pulse width of approximately 1.1 ns. A Gulton TR711 waveform graphic recorder was used with the system to record the pulse signals received by the transducer.

Concrete Blocks and Cylinders

All concrete blocks were cast in plywood forms. Two blocks tested for the effect of reinforcement on the pulse amplitude measurement were 20.0 in. (50.8 cm) wide x 24.0 in. (61.0 cm) long x 8.0 in. (20.3 cm) high. Most of the other blocks measured 8.0 in. (20.3 cm) wide x 13.0 in. (33.0 cm) long x 8.0 in. (20.3 cm) high. The 8.0-in. (20.3-cm) thickness was chosen because the standard thickness of concrete bridge decks and highway pavements, which will be the objects the microwave technique ultimately will be applied on, are at least that thick. Except for two series of blocks used to measure separately the effects of types of cement and aggregates, a type II cement and a siliceous aggregate were used in all concrete mixes. Each block was covered with plastic film to prevent excessive evaporation of the mix water and was air cured in the laboratory.

A set of cylinders, each measuring 4.0 in. (10.2 cm) in diameter x 8.0 in. (20.3 c m) high, was made for each concrete block and similarly air cured. These cylinders were tested for compressive strength concurrently with the taking of microwave reflection measurements on the corresponding blocks by breaking a pair of cylinders on each test day.

Reflection Measurement Setups

The distance between the transducer and the surface of the concrete being testing affects the proper separation, in arrival time at the receiving antenna, of A_s and A_b from other concomitant pulses and the apparent amplitudes of these pulses. Attempts to arrive at a single setup that would be suitable for observing, or measuring, both reflection pulses without adapting measures that would not be practical or implementable in testing highway structures were not successful.

With the transducer 15 in. (38.1 cm) away from a block, A_s appeared to be sufficiently separated from the pulse that travelled through air directly from the transmitting to the receiving antenna, A_o, for good, continuous monitoring, as shown in Figure 2. However, the reflection from the bottom of the block, A_b, was relatively very weak and could hardly be discerned. (This reflection can be artificially strengthened by placing an aluminum foil on the bottom of the form, as was done elsewhere;(3) however, such a measure would be unrealistic in potential highway applications and wasn't used in this study.)

With this setup, the reflection coefficient of the surface of a block, ρ_1, can be established by placing a metal plate on the block and measuring the peak-to-peak amplitude of the reflected pulse, which is equivalent to A_o. (This was used as a baseline for all remaining calibrations, which were necessary to adjust for slight instrumentation drifts over observation periods, each often lasting for at least 28 days). Then, with the plate removed, the amplitude of A_s is measured. And, by definition in equation 1, ρ_1 is the ratio of A_s divided by A_o. The relative dielectric constant of the block can, in turn, be calculated.

A strong A_b was observed when the transducer was placed directly on the block as shown in Figure 2. Since this reflection arose from pulses that traversed through the whole thickness of the concrete, not only once but twice, it provides a more representative "sampling" of the bulk of the concrete as compared to the setup with the transducer 15 in. (38.1 cm) away. Consequently, this setup, shown in Figure 3, was used in most of the investigations described in this report. (The advantages and disadvantages of the measurement of A_s or A_b, with regard to potential applications in testing highway pavements and bridge decks, will be discussed further in a later section.)

The A_a observed in this setup didn't appear to have resulted purely from the pulse that travelled through air directly from the transmitting to the receiving antenna. However, it turned out to be a similarly useful wavelet, as A_o was in the former setup, in correcting the amplitude of A_b for instrument drift. The corrected amplitude, $A^*_{b,i}$, was calculated as

$$A^*_{b,i} = \left(\frac{A_{b,i}}{A_{o,i}}\right) A_{o,1} \quad , \qquad (6)$$

where

$i = 1, 2, \ldots\ldots$ nth measurement.

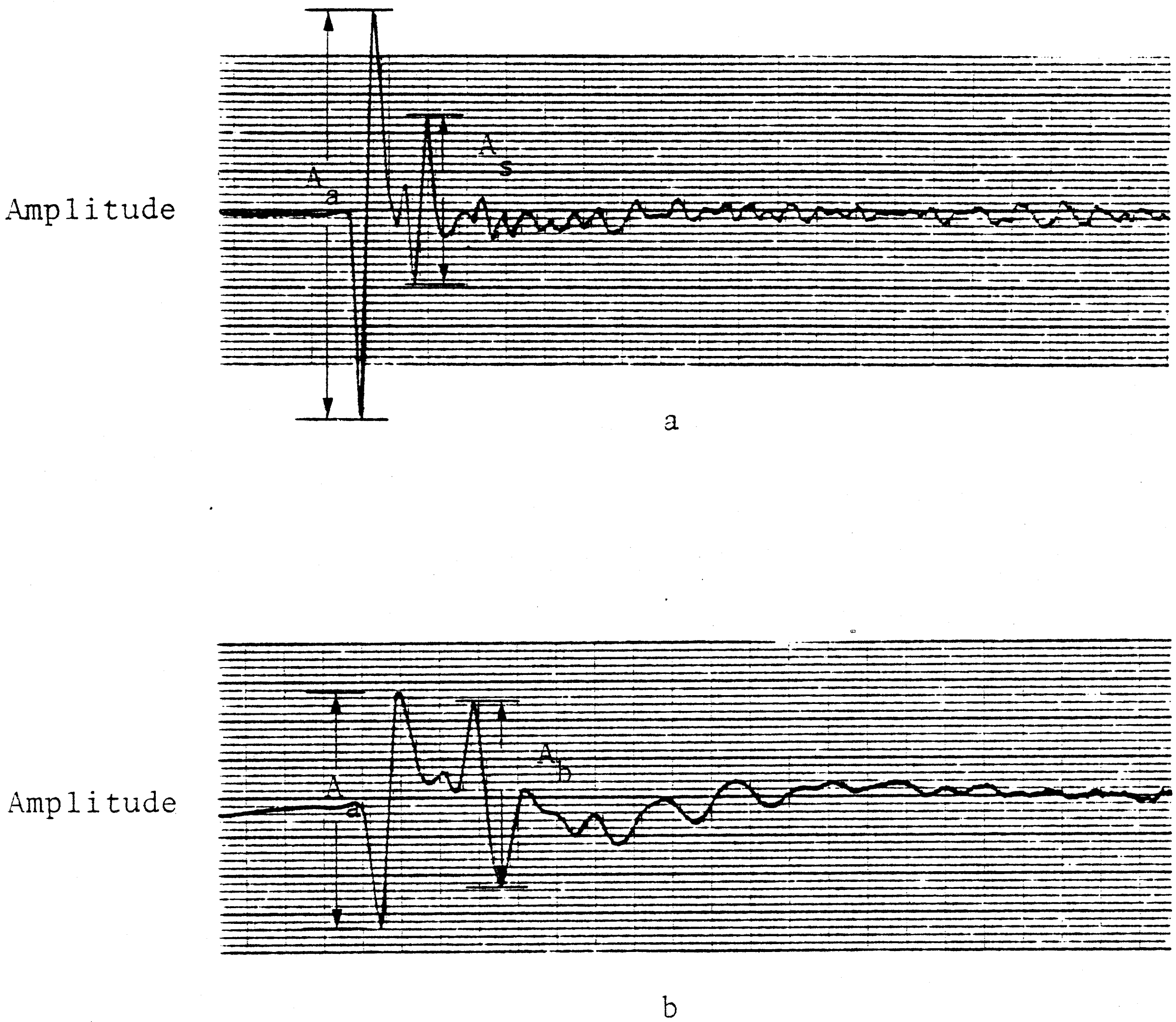


Figure 2. Examples of pulse radar signals received during sounding of concrete block. Top, transducer 15 in. (38.1 cm) away from the block; bottom, transducer directly on the block.

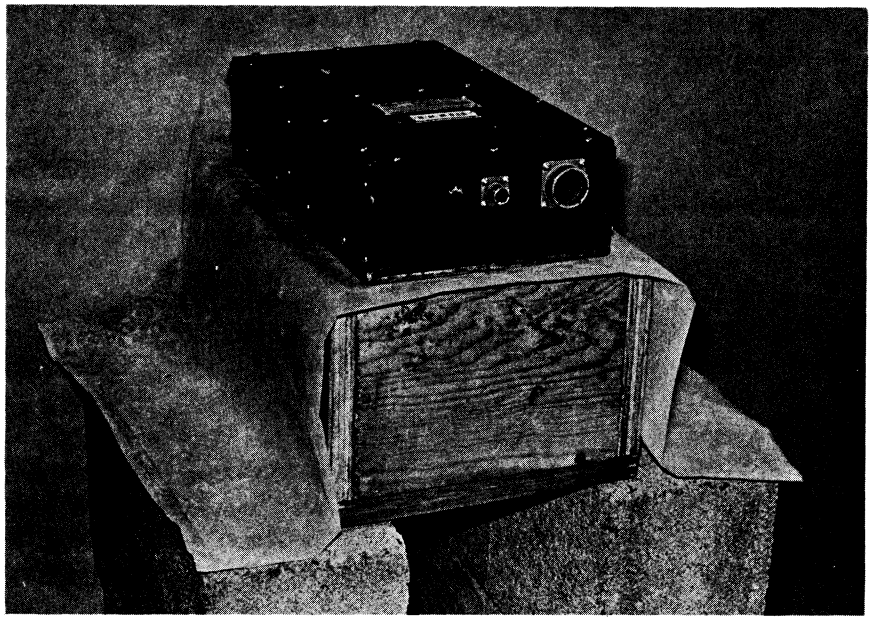


Figure 3. The measurement with the transducer directly above block.

RESULTS AND DISCUSSION

Pursuant to some of the objectives of this study, several series of concrete mixes were prepared. In each series, a component was varied, either in the amount or type used, so that the extent of the effect of the component on the dielectric property of concrete, whether as a result of its direct participation in the hydration process or otherwise, could be observed.

In one series, three mixes of different water-cement ratios (0.42, 0.50, and 0.60) were prepared with a type I cement at 17% by weight. Figure 4 shows that, at the same age, there was an inverse relationship between the w/c and the amplitude of the radar reflection from the bottom of the concrete slab, A_b, especially at an early age. As equations 2 and 4 indicate, A_b is inversely related to the relative dielectric constant, ε, of a concrete mix, which in turn is directly influenced by the amount of mix water left unreacted. This inverse relationship between w/c and A_b, which is similar to that between the w/c and strength, was also observed in measurements on series of specimens made with types II and III cements. Although for the type III, which is a high-early-strength type, the differences in the waveforms, such as those in Figure 4, for different w/c's were even more pronounced.

As hydration progressed and less unreacted mix water remained in each concrete mix, there was an observable, systematic change in the reflections, especially in the amplitude of A_b. This change is vividly illustrated in Figure 5, which shows the reflection waveforms recorded for the mix with a w/c of 0.42 at early ages of 1 to 7 days. A plot of the corrected amplitude of reflection from the bottom of a concrete block, A_b^*, versus age for each of the three mixes made with the type I cement is shown in Figure 6. For each mix, the A_b^*-age relation assumed a hyperbolic function, with A_b^* increasing in magnitude most rapidly during the first 14 days of hydration and eventually reaching a maximum value at a much later age. This relation was very similar to the hyperbolic strength-age relation observed for the corresponding test cylinders shown in Figure 6. This parallelism between the A_b^*-age and strength-age relations suggests that strength can be correlated to A_b^*, which will be discussed in a later section dealing with the potential applications of microwave reflection measurements.

Results obtained for the two series of concrete mixes made with types II and III cements showed similar hyperbolic A_b^*-age relations (Figure 7). The relative degrees of influences exerted by the different types of cement on the gain in A_b^* with age were generally in the order of type III > type I > type II (Figure 8). These are in agreement with the reported relative

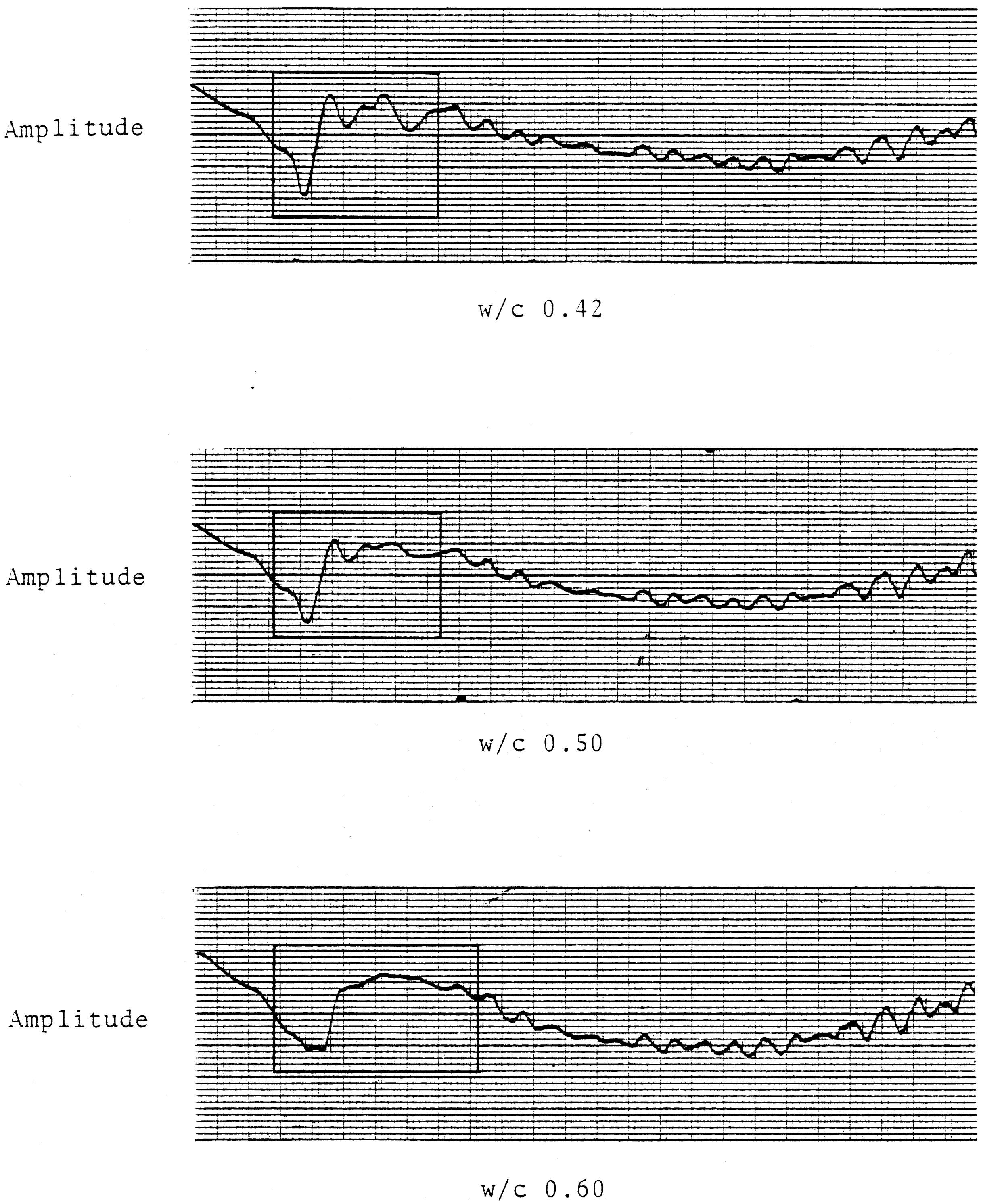


Figure 4. Reflection characteristics of concrete with type I cement and different water-cement ratios at 1 day old.

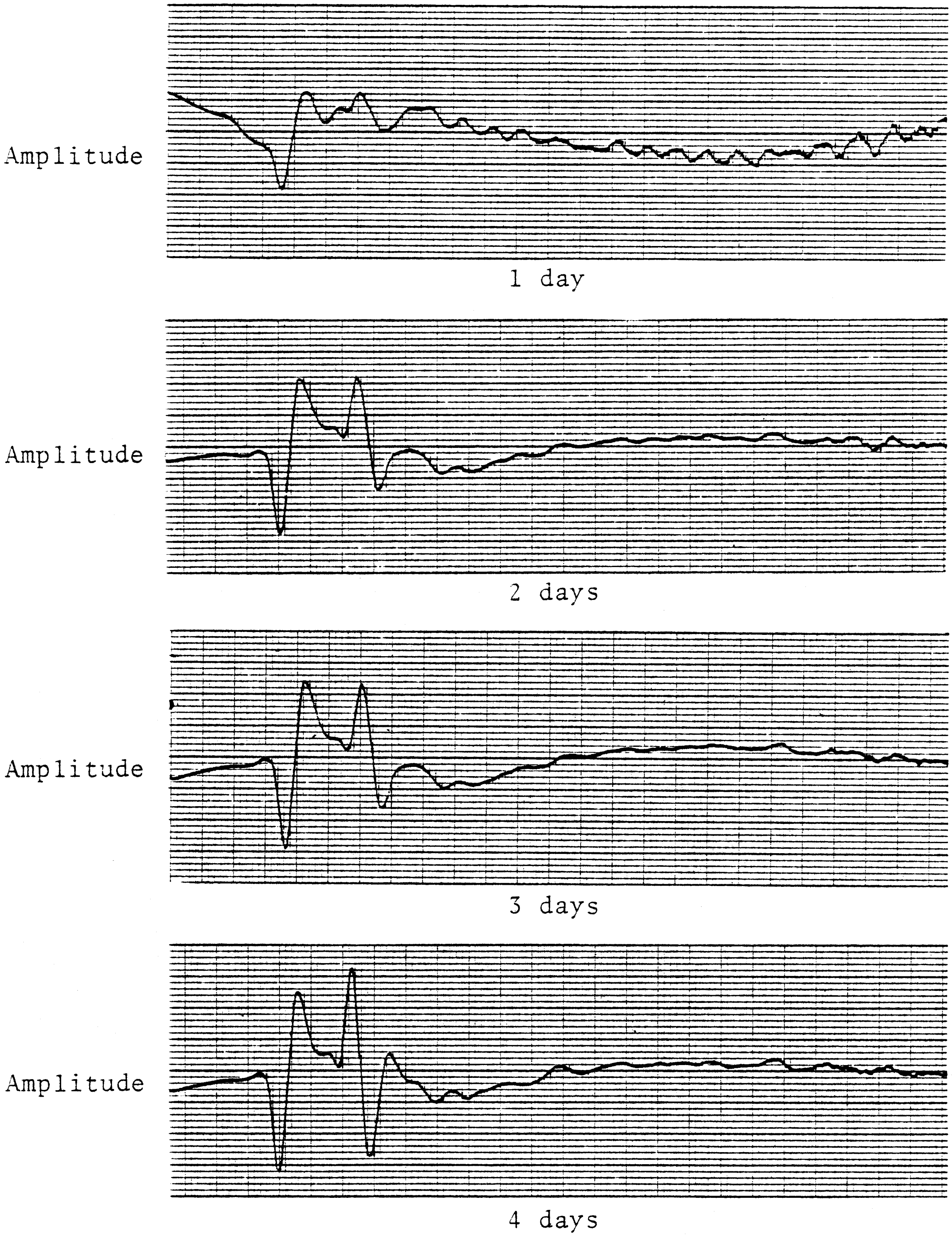


Figure 5. Microwave reflection characteristics of a concrete block containing type I cement and a water-cement ratio of 0.42, as a function of age.

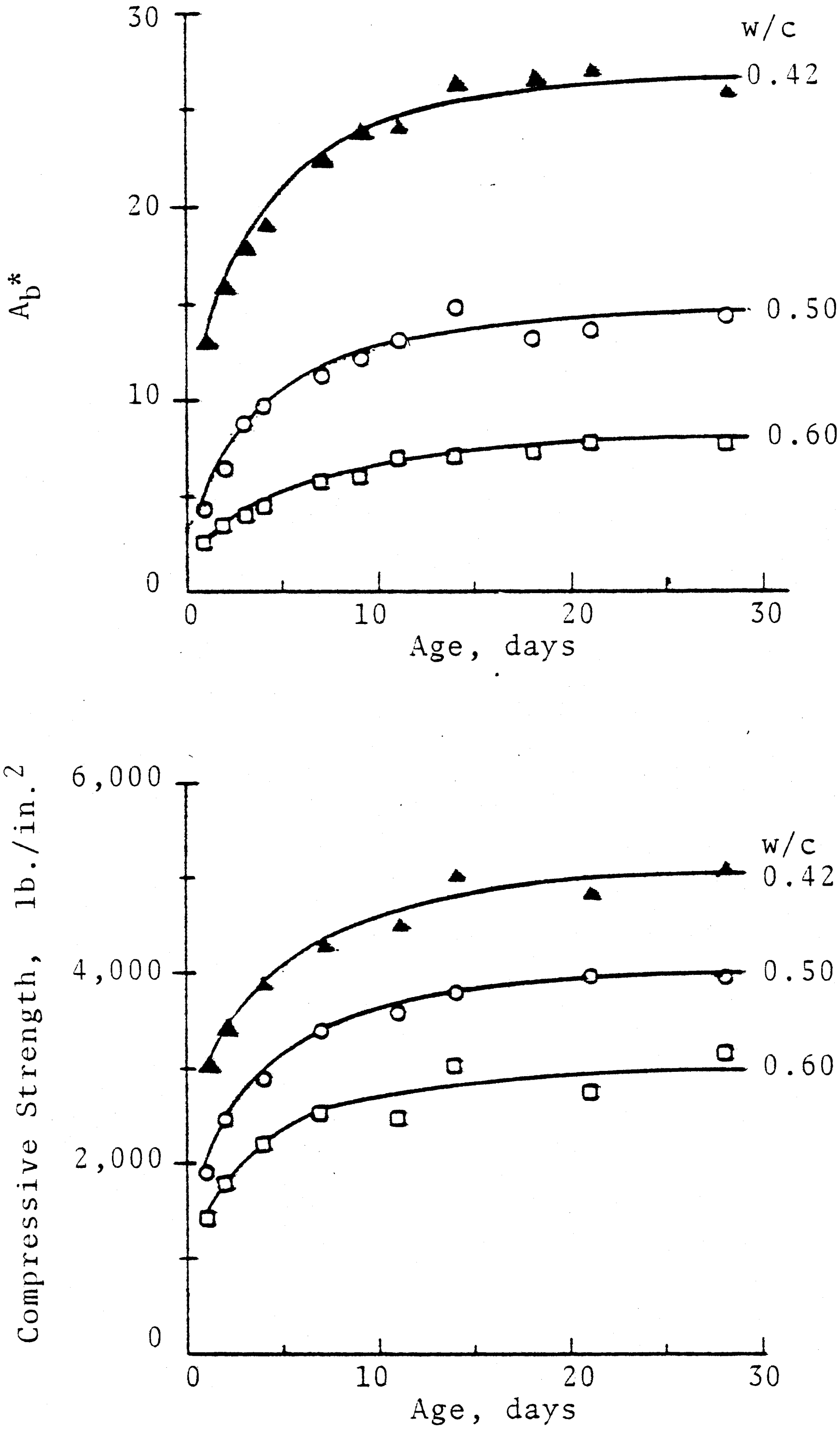
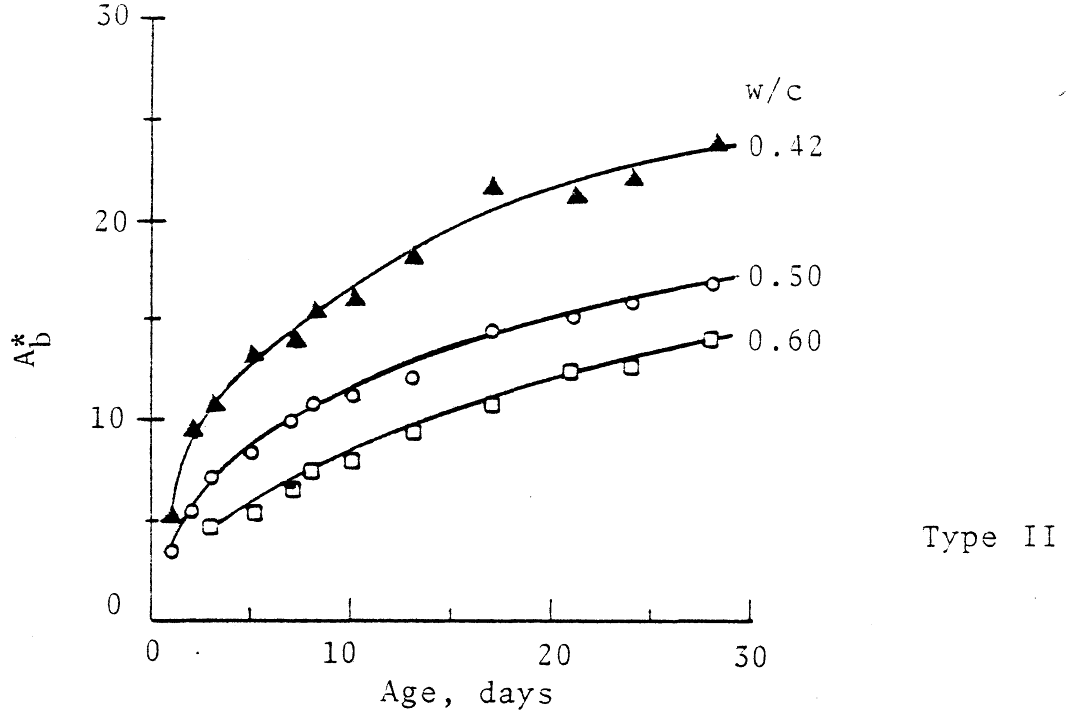


Figure 6. Relationship of microwave reflection (top) and compressive strength (bottom) with age, for concrete containing type I cement and different water-cement ratios. (1 lb./in.^{2} = 6.8948 x 10^{-3} MPa)



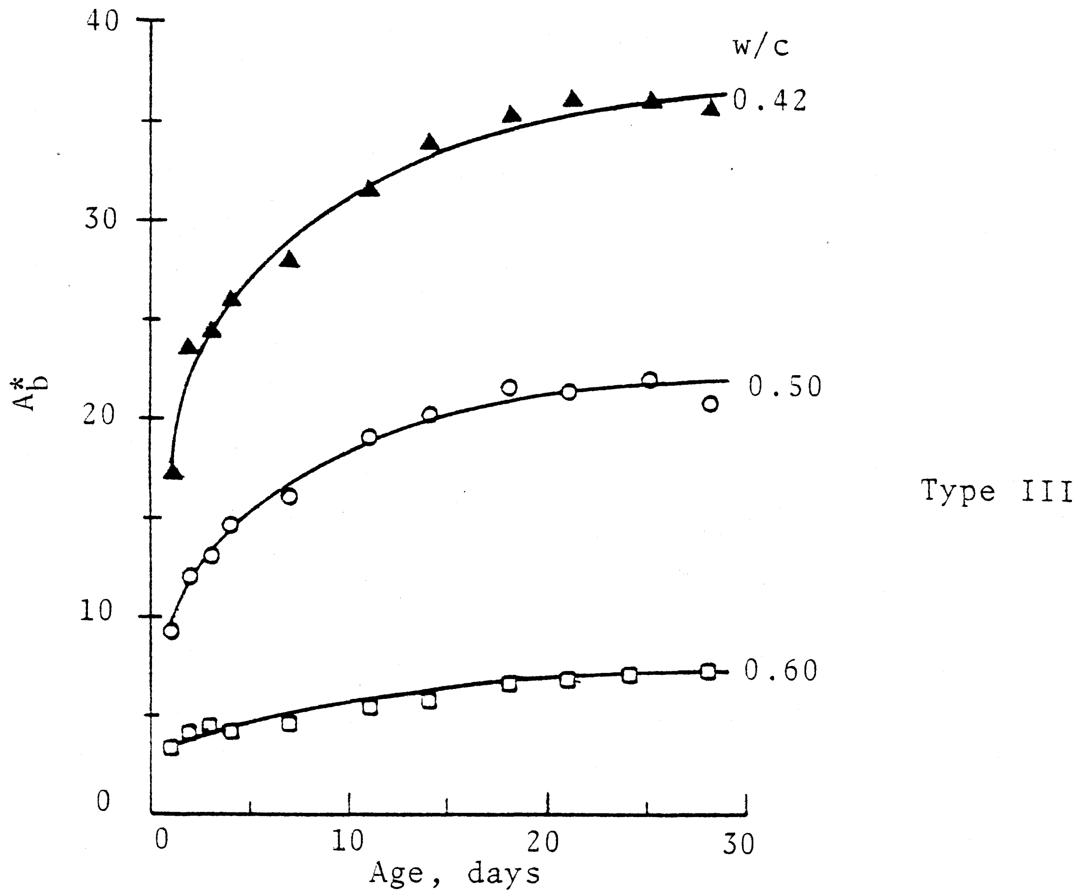
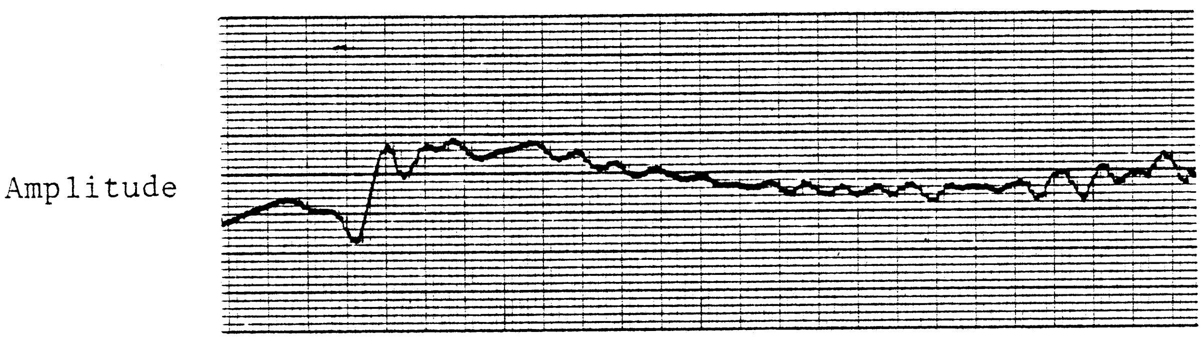
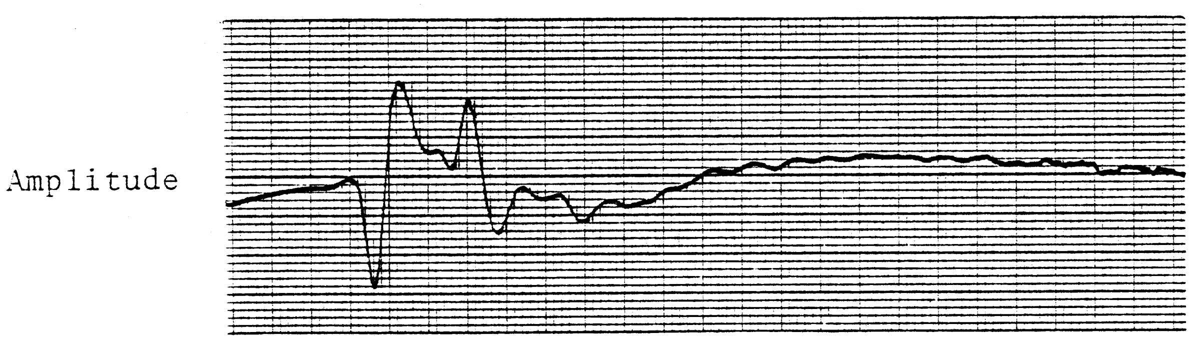


Figure 7. Relationship of microwave reflection with age for concrete containing type II (top) and type III (bottom) cements at different water-cement ratios.

Type I



Type II



Type III

Figure 8. Reflection characteristics of concrete with a water-cement ratio of 0.42 at 1 day old as a function of cement type.

degrees of influence exerted by these three types of cement on the strength gain of concrete[6] and those observed on the corresponding test cylinders.

It should be noted that the amplitude of A_b was very low during the first day of curing and that measurements were not made during that period, especially on concrete mixes made of cements other than type III. This situation resulted from the high moisture content at the surface of the mixes, which gave rise to large reflection coefficients at this surface, ρ_1, and prevented microwave pulses from penetrating into and escaping out of the concrete mixes.

Three concrete mixes were prepared in which only the type of aggregate was varied. The three aggregates, in the increasing order of dielectric constants as reported elsewhere,[7] were granite, limestone, and moist gravel. Figure 9 shows how the differences in the dielectric properties of these aggregates affected the characteristics of the microwave reflection from the mixes. The relative order of A_b^* for the three mixes at any age reflects the relative differences in the dielectric properties of the aggregates, since A_b^* is inversely related to the dielectric constants.

Being major components of the mixtures, the aggregates influenced to varying extents the dielectric properties of the mixtures. This influence may be evaluated theoretically. In contrast to the dielectric properties, the compressive strength attained by these concrete mixes in which the aggregate was the only variable appeared to be influenced by the surface texture of the aggregates. The rough surface of the crushed granite and limestone provided better bonding with the cement paste than did the smooth surface gravel, as indicated in Figure 9.

Microwave reflections also appeared to be influenced by the use of admixtures and additives in the mixes. An example is presented in Figure 10, which illustrates the A_b^*-age and strength-age relations for two mixes that were practically identical in composition except for the difference in the types of admixtures, which were used at the manufacturers' recommended dosages. The accelerator improved the early strength gain; however, the retarder showed the greater influence after approximately two weeks of hydration, as indicated by the reflection measurements shown in Figure 10.

Another example is shown in Figure 11, which gives the results of tests on mixes incorporating a fly ash as a partial replacement for cement in various percentages by weight of the latter. The strength-age relations reflected the known tendency of fly ash to decrease the early strength of concrete. The same tendency, perhaps in more appropriate proportionalities, is exhibited by the A_b^*-age relations.

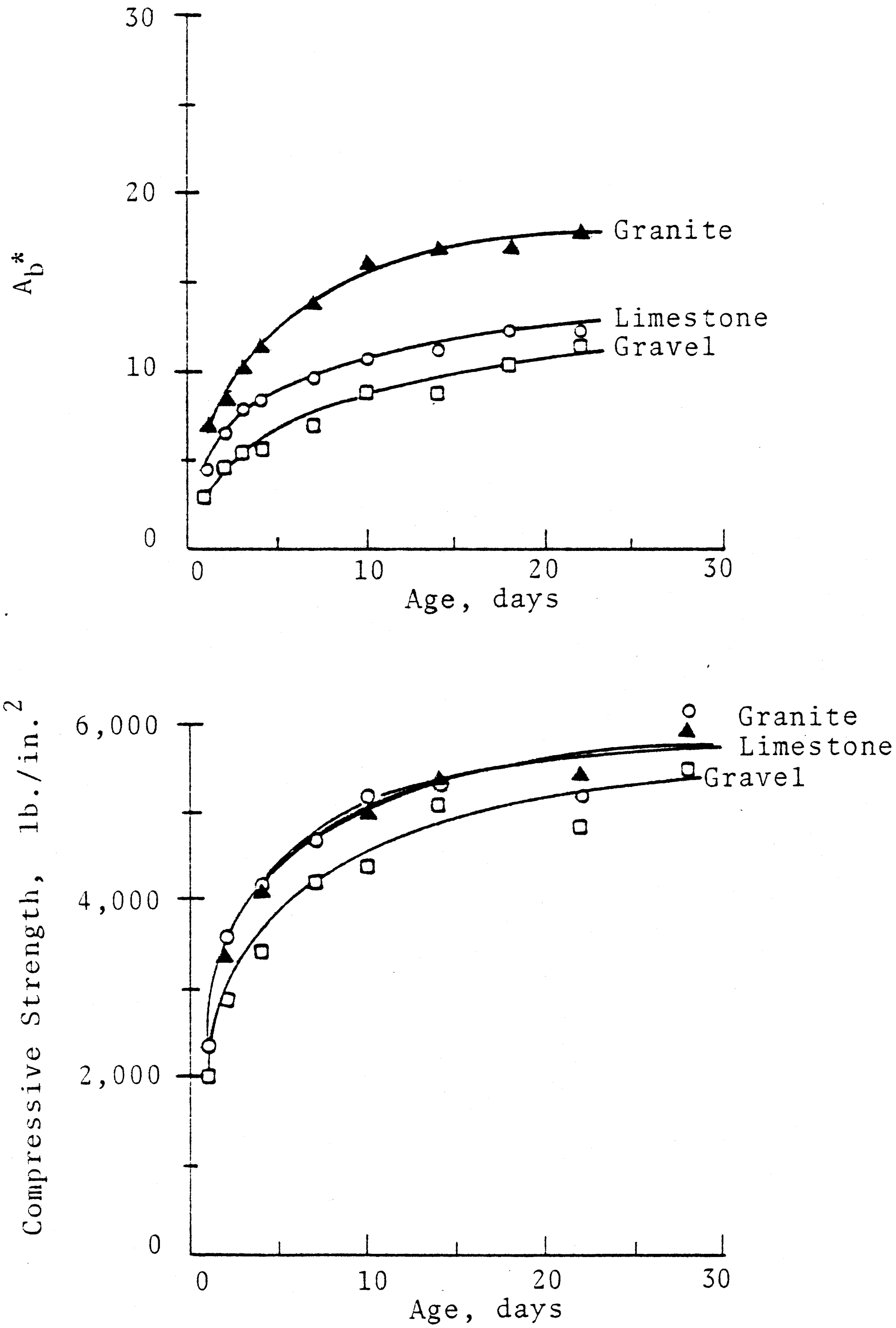


Figure 9. Microwave reflection (top) and compressive strength (bottom) characteristics of concrete mixes made from different aggregates. (1 lb./in.^{2} = 6.8948 x 10^{-3} MPa)

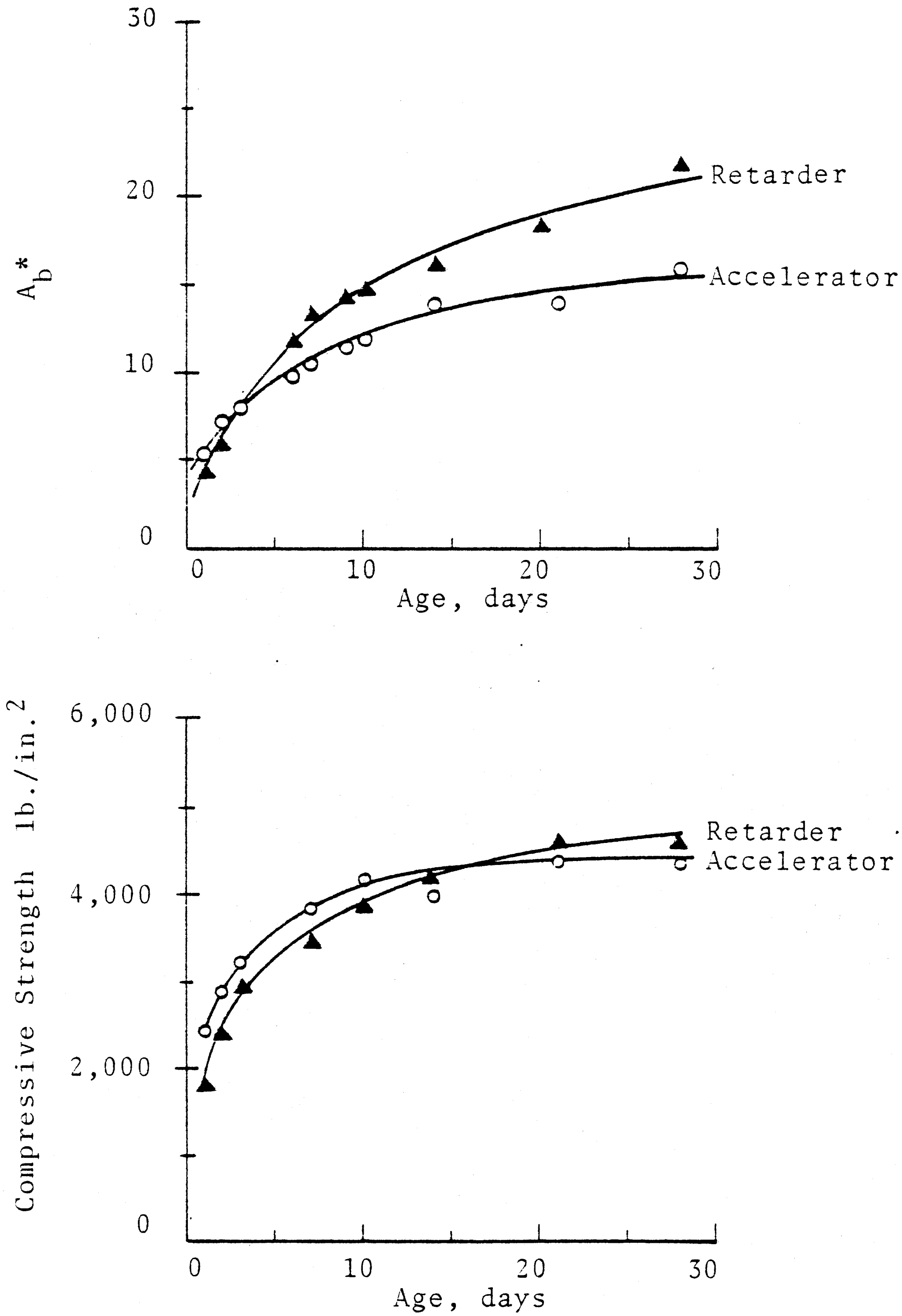
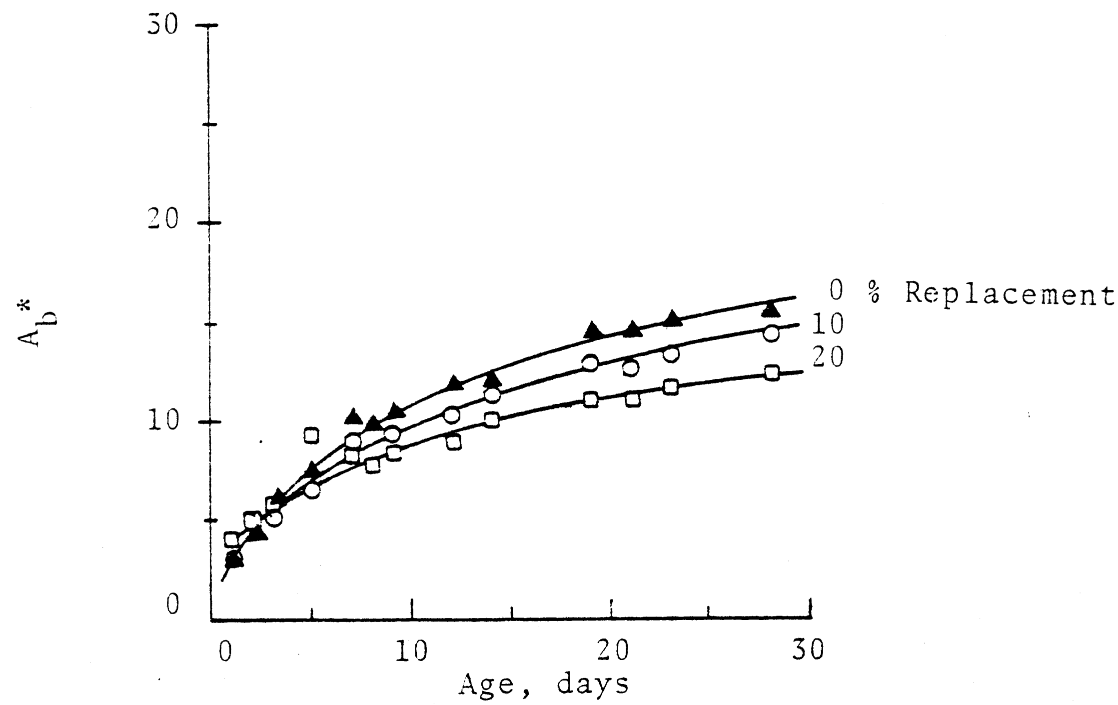


Figure 10. Microwave reflection (top) and compressive strength (bottom) characteristics of mixes incorporating different admixtures. (1 lb./in.^{2} = 6.8948 x 10^{-3} MPa)



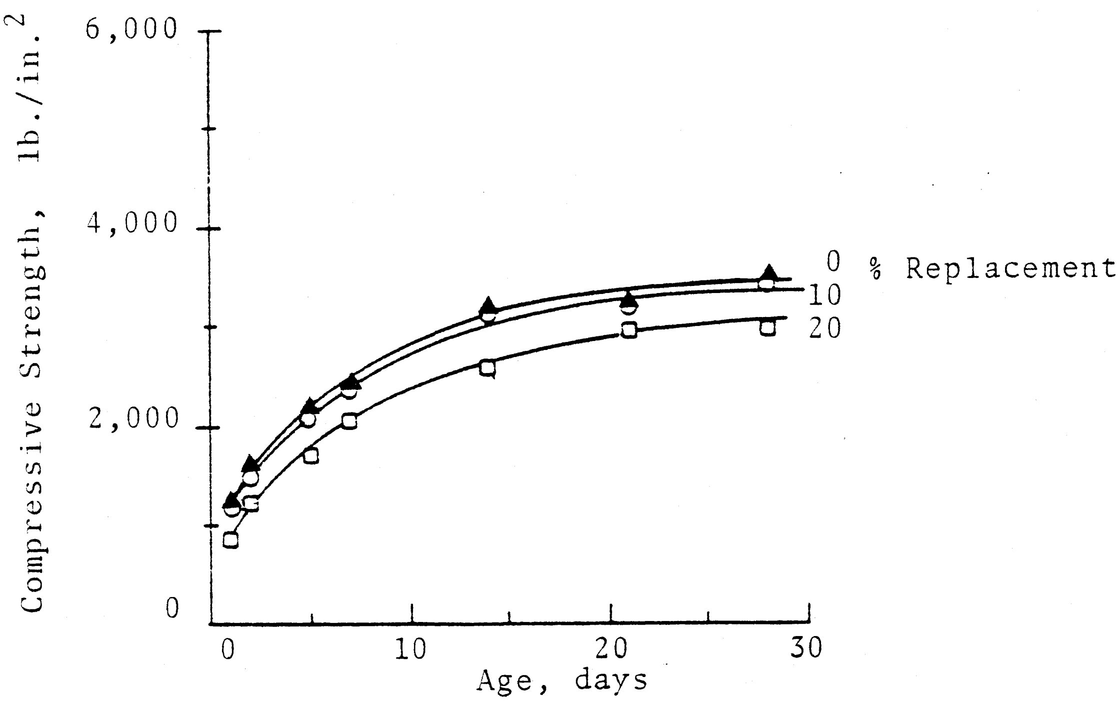


Figure 11. Microwave reflection and compressive strength characteristics of mixes with fly ash as partial replacement for cement. (1 lb./in.^{2} = 6.8948 x 10^{-3} MPa)

Applications

The results presented so far have indicated that simple measurements of microwave reflections can be used to conveniently study the progression of hydration in a concrete mix, beginning at approximately 1 day after mixing. And if the hydration has to be monitored at a still earlier age, say 1/2 hour after mixing, measurements of direct microwave transmissions, with a waveguide similar to that used by Gorur et al.,(4) can be used.

In an earlier discussion it was noted that the apparent parallelism between the A_b*-age and strength-age relations was an indication that the dielectric property and compressive strength of concrete are affected by essentially the same factors and that these two properties can be unambiguously related, if desired. This is borne out in Figure 12, which is a plot of A_b* versus compressive strength for each of the three mixes made with type I cement. It can be seen that there were very strong linear correlations between these properties, with correlation coefficients ranging from 0.95 to 0.99. When all these data points are considered, the resulting common regression line still has a high correlation coefficient of 0.96. Similar correlations were observed for the other series of concrete mixes, with correlation coefficients ranging between 0.94 and 0.98. There were, however, sufficient differences between the regression lines for the various series of concrete mixes to indicate that a new calibration line would likely be necessary for a concrete made with appreciably different materials. The strong relation between A_b* and compressive strength provides a second potential application of the method -- the nondestructive, indirect estimation of the strength of in-place concrete.

However, at least in the near future, this potential application will not be possible because of reflectional interference from the reinforcing steel. In an experiment involving large blocks with reinforcements similar to that in some concrete pavements, which probably represent the least reinforced concrete structures among those of most concern in highway construction, it was found that no meaningful measurements of the change of A_b with time could be obtained. It appeared that the steel bars not only reflected most of the pulses that struck them and thereby prevented these from penetrating deep into the block, but also prevented those pulses that managed to reach the bottom of the block and got reflected back from escaping out of the block and reaching the receiver. Consequently, placement of the transmitter/receiver antenna as much as possible in between adjacent bars didn't provide any more meaningful results than placement directly above or across a rebar. Perhaps a smaller antenna

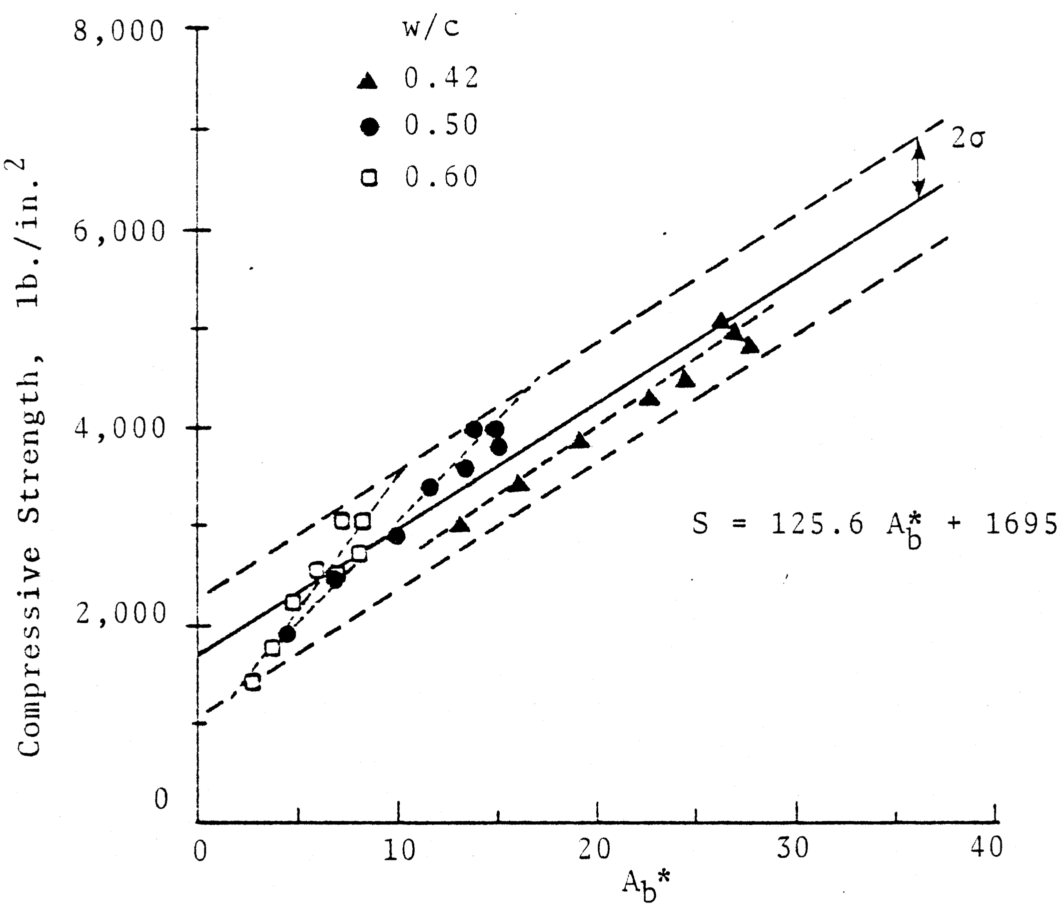


Figure 12. Correlations of dielectric parameter and compressive strength for concrete mixes with type I cement and various water-cement ratios. (1 lb./in.^{2} = 6.8948 x 10^{-3} (1 lb./in.^{2} = 6.8948 x 10^{-3} MPa)

with a more collimated microwave beam, which is yet to be manufactured, will eliminate this problem.

Nevertheless, by using direct measurements of microwave transmissions with a microwave transmitter on one side of a reinforced block and a receiver on the other side, as in ultrasonic testing, this potential application is still very much possible with currently available microwave antennas. However, as mentioned at the beginning of this report, this mode of measurement is not practical for highways.

Another potential application of microwave reflection measurements is in the nondestructive determination of the thickness of concrete pavements. Given the bulk dielectric constant, ε, of a concrete slab under inspection, its thickness, D, can be estimated by measuring the two-way transit time, t, of microwave pulses between the surface and bottom of the slab, since

$$D = \frac{1}{2} vt = \left(\frac{c}{2\sqrt{\varepsilon}}\right) t \quad , \qquad (7)$$

where

v = propagation velocity of microwave pulses through the concrete, and

c = propagation velocity of microwave pulses through air, which is 11.81 in./ns (30 cm/ns).

This is supported by results obtained from a series of blocks that were of various thicknesses but of the same composition. The results of measurements made at 14 days are shown in Figures 13 and 14, where it can be seen that the transit time was indeed linearly dependent upon the thickness of the block. The results for earlier ages showed similarly strong linear relationships between these two parameters. However, it must be noted that, as can be predicted from equation 7, the slope (or sensitivity) of the calibration line improves almost hyperbolically with age, showing no significant change at approximately 10 days and beyond.

Furthermore, the measured transit time at the later ages for the reinforced blocks showed reasonable agreement with those for the accompanying nonreinforced blocks of the same thickness and mix ingredients. This indicates that the measurement of transit times of microwave pulses through concrete is not adversely affected by the reinforcing bars.

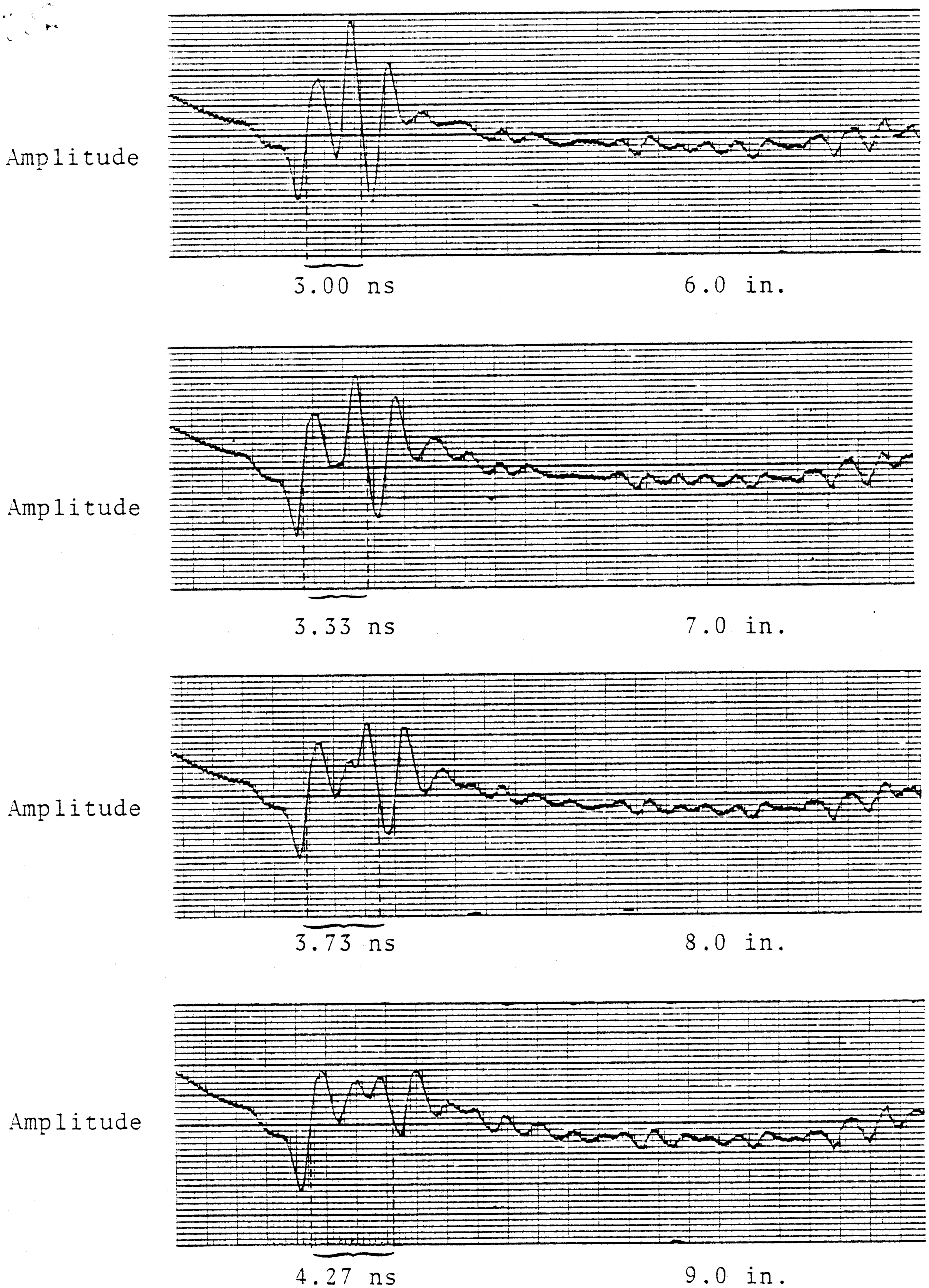


Figure 13. Two-way transit time of microwave pulses through blocks of various thicknessess at 14 days. (1.0 in. = 2.54 cm)

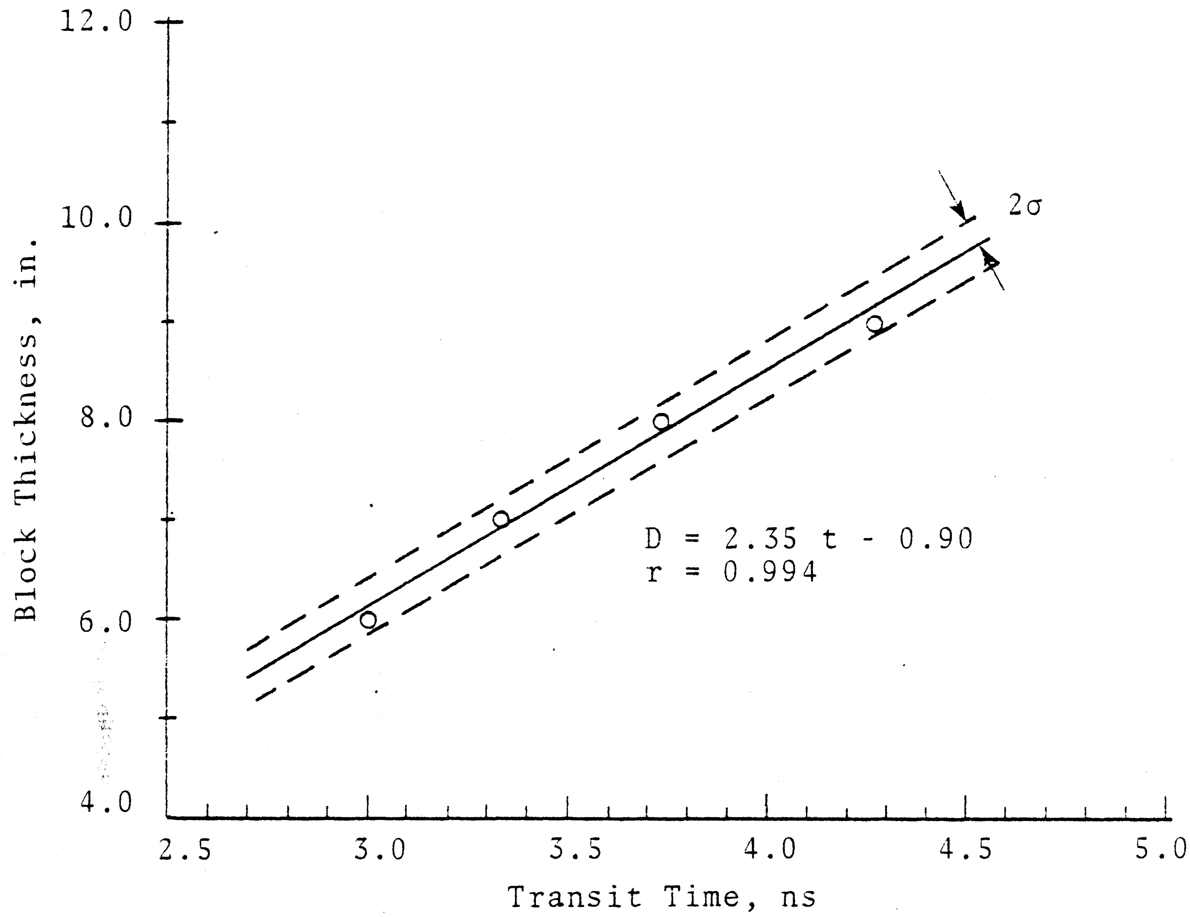


Figure 14. Correlations of transit time with block thickness at 14 days. (1.0 in. - 2.54 cm)

The strong correlation between transit time and slab thickness can be used to advantage in inspections for compliance to specifications on the thickness of newly constructed reinforced pavements. At present, this inspection requires coring the new pavement at certain lane-length intervals. However, this application must be preceded by a study of the effect of possible variations in the w/c and, therefore, the dielectric constant of in-place concrete on the accuracy of the technique.

The fourth possible application of this method is in the post-construction inspection for compliance with the specified concrete mix proportions, particularly the w/c, for possible pay adjustments. This application would be based on the observed influence of the w/c on A_b^*, which was previously shown in Figure 4. A more detailed analysis of data collected from the series of concrete mixes made with type III cement is presented in Figure 15, which shows a strong correlation between the w/c and A_b^* as soon as the latter could be measured, i.e., after 1 day of curing. The correlation coefficients ranged from 0.987 to 1.000. Similar analyses of data for the two series of concrete mixes which incorporated types I and II cements confirmed this strong correlation between the w/c and A_b^*.

Implementation of this application would entail sampling at some appropriate frequency portions of the fresh concrete before it is placed. Each sample could be cast in a wooden form similar to those used in this study, or maybe slightly thinner. Then all the samples could be cured under the same conditions as a series of standard specimens of known w/c's made concurrently with the same materials. After any desired, or convenient, length of curing, measurements of microwave reflections from the bottom of all the samples, including the standards, could be made. And, through the resulting calibration line, the w/c of each sample could be determined.

It must be pointed out that the alternative methods of determining the w/c of fresh concrete, the Kelly-Vail and the microwave-oven drying methods, can yield results as early as 1 hour after sampling. This rapidity provides an advantage, if the purpose of testing is also for spotting problems in process control, which should be the responsibility of the producer. However, if the testing is for pay adjustments under the construction contract, which appears to be the trend among state transportation agencies, then the three methods would be equally effective.

Another application of microwave reflection measurements may be to monitor curing in the outer layer instead of the bulk of a concrete member. It is believed that the deterioration noted in the exposed, outer layer of concrete frequently results

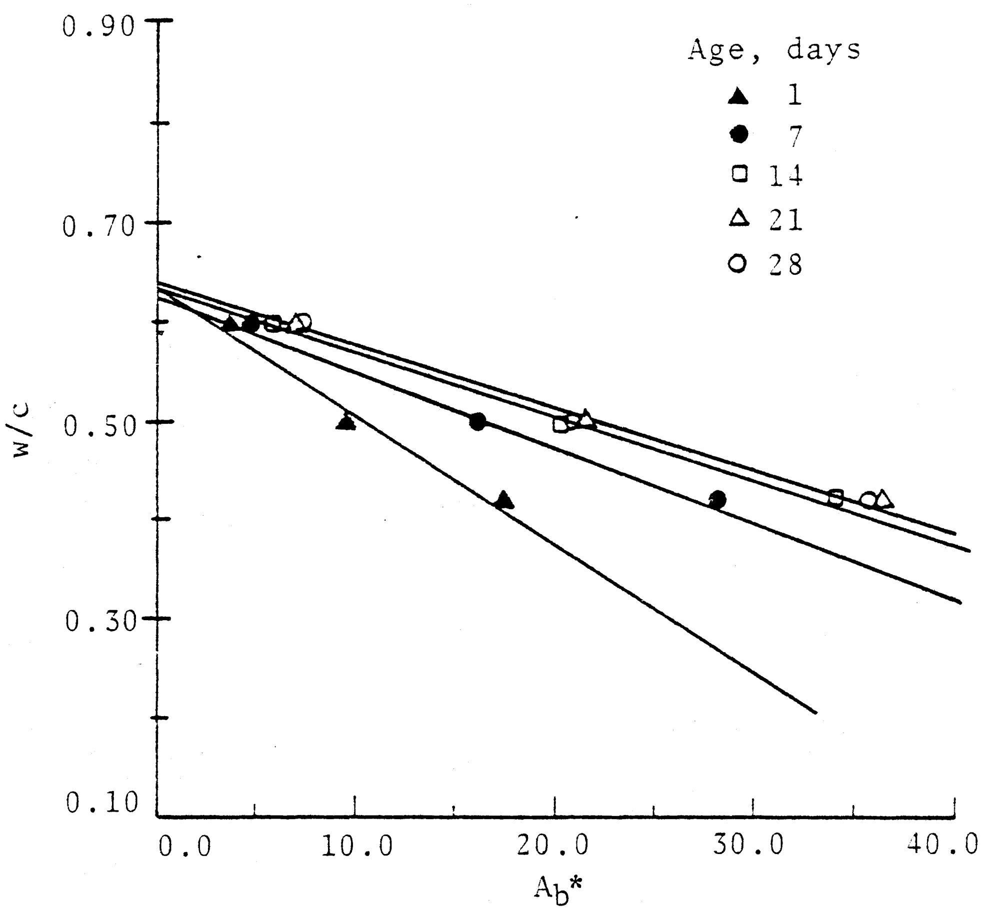


Figure 15. Correlation of A_b* with water-cement ratio for concrete with type III cement at various ages.

from improper curing brought about by the rapid loss of moisture. It has been recently suggested by Carrier[8] that new methods for monitoring the moisture content, or the curing, in this layer are needed. Data obtained from concurrent measurements of reflections from the surface and the bottom of a concrete block suggest that such measurements have the potential of satisfying this need.

Figure 16 shows the observed difference between the dielectric constants of the upper layer of the concrete block and of the bulk of the block. The former was estimated from measured amplitudes of the surface reflection, A_s, using equations 1 and 2, while the latter was determined from measured transit times and the known thickness using equation 7. It can be seen that the dielectric constant, or water content, of the uppermost layer was significantly higher than that for the bulk of the block during the relatively early stage of curing. Later, the two dielectric constants converged. This relatively higher water content at the top layer is caused by the natural upward migration of water molecules to form bleed water as they are displaced by the denser cement and aggregate particles that settle.

This measurement of the surface dielectric constant can be used to evaluate the effectiveness of different curing procedures and membrane curing compounds to determine their proper application rates for maximum effectiveness. Also, it may be possible to use this measurement to monitor curing of the surface layer of in-place concrete.

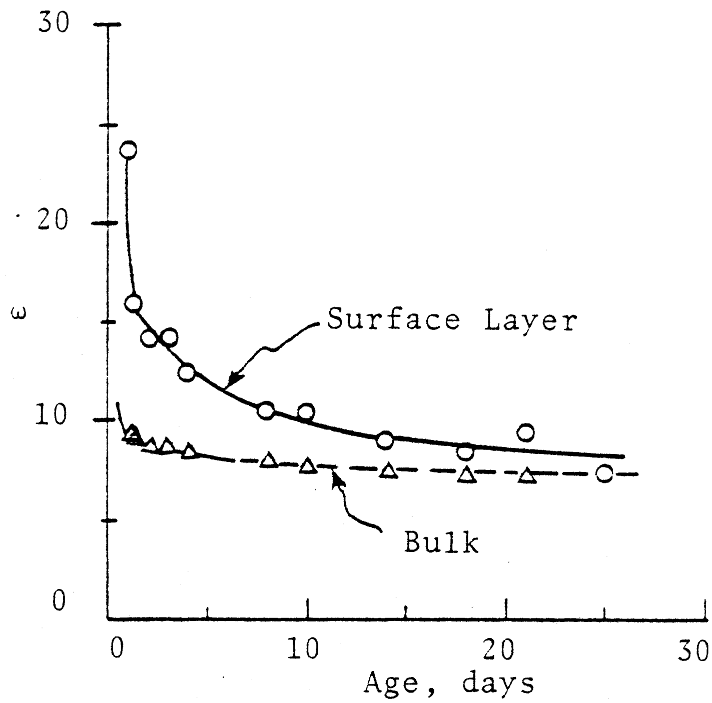


Figure 16. Dielectric constants of the upper layer and the bulk of a concrete block.

CONCLUSIONS

The following conclusions can be drawn.

1. The hydration of cement in a concrete can be continuously and nondestructively monitored by the simple measurement of microwave reflections, as described in this report.

2. Such measurements are probably sensitive enough for assessing the effect of any new admixture or material that may influence the early hydration process.

3. There is a good linear correlation between the corrected amplitude of pulse reflections from the bottom of a concrete block, A_b^*, and compressive strength. However, this correlation cannot yet be used to advantage in the non-destructive determination of the strength of in-place concrete in highway construction because the reinforcing bars interfere with the reflections.

4. The linear correlation between the transit time of microwave pulses through a block and the thickness of the block is even stronger. Indications from preliminary observations are that the transit time may be measured with some reliability even in the presence of reinforcement such as that used in concrete pavements. So it may be possible to use these relations in non-destructively inspecting the thickness of concrete pavements. However, further investigation is needed.

5. There is a strong linear dependence of A_b^* on the water-cement ratio. This relationship can be applied in a post-construction quality assurance program for pay adjustments under contracts.

6. Measurements of the microwave reflections from the upper layer of a concrete block have shown that during the relatively early stage of curing the dielectric constant, and, therefore, the water content, in the upper layer is higher than that for the bulk of the concrete, and that the curing of this upper layer can be continuously monitored. Such measurements can be applied in the study of the effectiveness of various curing compounds etc., and possibly in the monitoring of the curing of the upper layer of in-place concrete.

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