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TRC9005

# Acceptance Tests for
# Coarse and Fine Aggregates

Stephen R. Addison

Final Report

1991

# Acceptance Tests for Coarse and Fine Aggregates

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| 1. Report No.<br><br>FHWA/AR-93/002 | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 4. Title and Subtitle<br><br>Acceptance tests for coarse and fine aggregates | | 5. Report Date<br><br>August 1991 |
| | | 6. Performing Organization Code |
| 7. Author's)<br><br>Stephen R. Addison | | 8. Performing Organization Report No.<br><br>SRA91-01 |
| 9. Performing Organization Name and Address<br><br>Physics Department<br>University of Central Arkansas<br>Conway, AR 72035 | | 10. Work Unit No. (TRAIS) |
| | | 11. Contract or Grant No.<br><br>TRC-9005 |
| 12. Sponsoring Agency Name and Address<br><br>Arkansas Highway and Transportation Department<br>P. O. Box 2261<br>Little Rock, AR 72203 | | 13. Type of Report and Period Covered<br><br>Final Report<br>March 1, 1990 –<br>March 1. 1991 |
| | | 14. Sponsoring Agency Code |

15. Supplementary Notes

16. Abstract

This report describes a method of determining the average shape of particles used in the aggregates used in highway engineering. The method has been used extensively in oil and gas well logging. The method involves the simultaneous measurement of porosity and formation resistivity factor. A measuring device is described and data in support of the method are reported. General recommendations and conclusions are included.

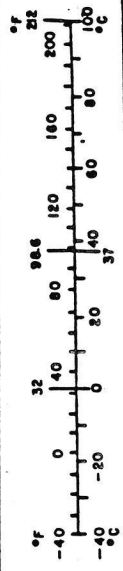| 17. Key Words<br><br>Aggregate, particle shape, porosity, formation resistivity factor | | 18. Distribution Statement<br><br>Unlimited | |
|---|---|---|---|
| 19. Security Classif. (of this report)<br><br>Unclassified | 20. Security Classif. (of this page)<br><br>Unclassified | 21. No. of Pages<br><br>40 | 22. Price |

Form DOT F 1700.7 (8-72)     Reproduction of completed page authorized

# METRIC CONVERSION FACTORS

## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| cm² | square centimeters | 0.16 | square inches | in² |
| m² | square meters | 1.2 | square yards | yd² |
| km² | square kilometers | 0.4 | square miles | mi² |
| ha | hectares (10,000 m²) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| m³ | cubic meters | 35 | cubic feet | ft³ |
| m³ | cubic meters | 1.3 | cubic yards | yd³ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |

## Approximate Conversions to Metric Measures
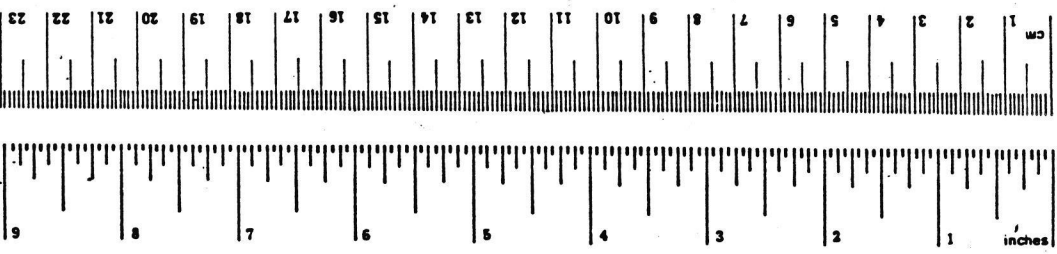
| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| in² | square inches | 6.5 | square centimeters | cm² |
| ft² | square feet | 0.09 | square meters | m² |
| yd² | square yards | 0.8 | square meters | m² |
| mi² | square miles | 2.6 | square kilometers | km² |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| ft³ | cubic feet | 0.03 | cubic meters | m³ |
| yd³ | cubic yards | 0.76 | cubic meters | m³ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286. Units of Weights and Measures. Price $2.25, SD Catalog No. C13.10:286.

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# I. INTRODUCTION

The purpose of the research described in this report is to contribute to the ability of highway engineers to control the shape of the particles used in asphalt aggregates used in highway construction and repair. The Arkansas Highway and Transportation Department does not currently have a standard method to determine the shape of particles used in highway aggregate mixes. It is known that the presence of rounded particles in the aggregate can produce a pavement of poor performance. Techniques that could be used to measure the shape of the particles have been developed, but they have not been used in highway engineering. This report describes how one of these methods could be used to measure the shape of particles in highway materials. The method has been found to produce reproducible results on particles over a wide range of particle sizes.

There are physical parameters that can be measured in a porous medium that are related to the shape of particles in that medium. This report will begin with an overview of these properties and a rationale for concentrating on the measurement of two of them - porosity and formation resistivity factor. Chapter II is mainly devoted to a description of the theoretical relationship between these parameters and the shape of particles in a porous medium. Chapter III provides a description of the methods of measuring

porosity and formation resistivity factor. Chapter IV describes the apparatus constructed to measure these quantities for materials used in highway aggregates, this chapter also includes a description of the way in which this apparatus was used to achieve the reported results. Chapter V presents the results of measurements performed using the apparatus described in chapter IV, and an analysis of these results. Chapter VI presents the conclusions arrived at on the basis of these measurements, as well as suggestions for the implementation of such measurements, recommendations for further tests, and a description of a method for translating the methods used in this project to the laboratories and field test sites of the Arkansas Highway and Transportation Department.

In this report all equations will be numbered sequentially beginning from 1 in each chapter. If an equation is referred to by a number (such as equation (10) for example) then that reference is to an equation in the same chapter. If an equation is referred to by a roman numeral followed by an ordinary number, such as equation (II-7) for example, that equation can be found in the chapter designated by the roman numeral. Figures will similarly be numbered sequentially within each chapter, with the first figure in each chapter always being Figure 1.

## II.  FORMATION RESISTIVITY FACTOR AND PARTICLE SHAPE

In this chapter the formation resistivity factor will be defined and its application to a variety of problems will be reviewed.

The formation resistivity factor was introduced by G.E. Archie (Archie, 1942).  It had long been the practice to measure the electrical conductivity, or resistivity, of geologic formations in the vicinity of wells in oil and gas reservoirs.  Prior to the work of Archie these logs were of limited use;  this was principally because there was no information relating the resistivity or conductivity of a formation to its fluid content, its degree of consolidation, its packing or to the shape of the constituents. Indeed before Archie's work the factors which can affect the measurement of these quantities were  not well understood.

Archie's studies revealed that it was not the resistivity of a formation itself that was important, rather, it was a ratio of resistivities that was of physical significance.  This ratio is the formation resistivity factor.  If we consider a sample of material of length, l, and of uniform cross-sectional area, A, and we apply an electric current across the parallel faces of the sample, then the electrical resistance, R, of the sample is given by

$$R = \rho l/A, \tag{1}$$

where $\rho$ is the resistivity of the material.   The formation

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resistivity factor of a porous medium is then defined as

$$F = \rho_o/\rho_w, \qquad (2)$$

where F is the formation resistivity factor, $\rho_w$ is the resistivity of the saturating fluid, and $\rho_o$ is the resistivity of the sample that is saturated with this fluid. When measurements are performed in the laboratory in a cell in which the sample length and cross-sectional area are fixed, the formation resistivity factor can be calculated from the corresponding ratio of resistances. In other words, an alternate definition of the formation resistivity factor is

$$F = R_o/R_w. \qquad (3)$$

The usual choice of saturating fluid is brine.

It is evident from the definition of the formation resistivity factor that if the particles from which the porous medium is constructed are electrical insulators then the formation resistivity factor depends on the porous medium alone, that is for a non-conducting porous medium the formation resistivity factor is independent of the saturating fluid. If the porous medium is an electrical conductor the formation resistivity factor can be affected by the choice of saturating fluid; depending on the ratio of the conductivity of the porous matrix to the saturating fluid, electrical conduction can take place preferentially in the fluid, or preferentially in the matrix, or, in the case where the conductivities of the matrix and the saturating fluid are comparable there is no preferred medium for electrical conduction. In the case of materials used in asphalt aggregates the possibility

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of conducting matrix will usually occur only if there is clay present within the aggregate.

Measured alone, the formation resistivity factor is of limited usefulness, it becomes a useful quantity when some of the other physical parameters of a porous formation are measured. If average particle shape is the quantity of interest, then the appropriate quantities to measure simultaneously are porosity and permeability. Archie measured both of these quantities simultaneously with his measurements of formation resistivity factor. While Archie found that both permeability and porosity were related to the formation resistivity factor of a porous matrix, he concentrated on the relationship with porosity because the amount of scatter in the permeability data was much greater than in the porosity data. In this study Archie's example is followed, the reasons are however different. While porosity may be measured easily, permeability is difficult to measure reliably - in fact it is likely that the scatter in Archie's permeability data is associated with problems in its measurement.

Archie found that a simple relationship existed between the formation resistivity factor and the porosity of a porous matrix. All the data available to Archie could be fitted by the equation

$$F = \phi^{-m}, \tag{4}$$

where $\phi$ is the porosity of the matrix and m is a constant. The constant m is sometime called the "cementation factor" (Hutt and Berg, 1968). The significance of m is revealed by taking the logarithm of this equation, this yields

$$\ln(F) = -m \ln(\phi).\qquad\qquad(5)$$

That is, -m is slope of a graph in which the logarithm of the formation resistivity factor is plotted as the ordinate axis and the logarithm of the porosity is the abscissa. Archie found that in his samples the cementation factor varied between 1.3 and 2.0. Equation (4) is usually called Archie's law. Archie did not investigate the relationship between the formation resistivity factor and the shape of the particles in his samples, he used the formation resistivity factor as a measure of the porosity of his samples, he also used it to estimate the water content and the degree of salinity of saturating water in his samples. Subsequent investigators have investigated the relationship of formation resistivity factor to particle shape, the chief results of these studies are reviewed below.

Winsauer, Shearin, Mason, and Williams (1952) investigated the relationship between resistivity and pore geometry. In fact the purpose of their study was to investigate the relationship between resistivity and any properties related to the texture of the particles of a porous matrix. In their study the term texture is taken to mean the shape of the constituent particles. One of the quantities investigated by these authors was the relationship between texture and formation resistivity factor. This work also noted that the frame parameters tortuosity and packing index were correlated with the porosity of the medium. In fact the correlations of the above quantities with porosity detailed in this study led to the decision to concentrate on the relationship

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between porosity, resistivity formation factor and particle shape in the measurements described in this report. Winsauer and his co-workers suggested a modification of Archie's law. The modified Archie equation is

$$F = C\phi^{-m}, \tag{6}$$

where C is a constant.

This modification has been used frequently by other investigators. It is obvious that if we choose the value of C to be equal to 1 then equation (6) reduces to the ordinary form of Archie's law.

It was decided that this study would use the original form of Archie's law, equation (4), rather than this modification. This decision was made on the basis of physical considerations. A fundamental relationship between quantities should hold over the range in which the assumptions underlying it can be taken to be accurate. The reason for preferring the original form of Archie's law emerges when the extreme values of porosity are considered. As the sample porosity tends to zero (i.e. the amount of conducting fluid decreases) the resistance of the sample should become large, and the formation resistivity factor should grow with it. Both equations (4) and (6) satisfy this limit. At the other extreme, as the porosity of the matrix tends to 1 (i.e as the amount of conducting fluid increases) the resistivity of the sample should approach the resistivity of the saturating fluid. In other words, the formation resistivity factor should approach 1 at this limit. Setting $\phi$ equal to 1 in equation (4) yields a formation resistivity factor of 1, setting $\phi$ equal to 1 in equation (6) yields a

formation factor of C. Thus the modified version of Archie's law was rejected in favor of the original form, equation (4), in the present study.

Wyllie and Gregory (1953) undertook a study of the relationship between formation resistivity factors and particle shape in porous media. These authors provide a review of several theories of the electrical conductivity of composite media and use these theories to calculate formation resistivity factors, their paper also presents some experimental results based on measurements performed on particles of known shape. More detailed theories have been developed since this paper was published, but this paper is recommended as a starting point in the study of theoretical developments related to formation resistivity factors. It should be noted in passing that a commonly used formula for the formation resistivity factor

$$F = (3-\phi)/2\phi, \tag{7}$$

the so-called Maxwell expression (Maxwell, 1891), will yield values for the formation resistivity factor that are consistently low at low porosities. In fact, this expression can be shown to be a lower bound on the formation resistivity factor (Addison and Bass, 1984). More recent theoretical developments are discussed by Woodside and Messmer (1961), Schopper (1966), Hutt and Berg (1968), Brown (1980), Sen, Scala, and Cohen (1981), and Sen (1991).

The experimental data presented by Wyllie and Gregory represent a series of measurements performed on controlled samples of spheres, discs, cubes, cylinders, and triangular prisms, as well

as measurements performed on more random media such as Ottawa sand, beach sand, and creek sand. This study concluded that at any porosity the minimum measured formation resistivity factor would be for a packing of spheres and that the formation resistivity factor of an unconsolidated aggregate was a function of the average shape of the particles in the sample under test.

Before considering other experimental data, the theoretical results of Sen, Scala, and Cohen (1981) should be summarized. This paper presents the results of self-similar calculations of the dielectric constants of porous media that are used to calculate the exponent m in Archie's law, equation (2). The calculations were performed by considering each grain of a porous medium to be coated with water. The dielectric constants of arrays of these particles were then calculated using a self-consistent, iterative, computational scheme. The resulting dielectric constants were used to calculate conductivities (electric conductivity is the reciprocal of electric resistivity) and so enabled the computation of formation resistivity factors.

The conclusion of Sen, Scala and Cohen was that the exponent, m, in equation (4) was dependent on the shape of the particles in any porous medium. More precisely, these authors calculated that for any array of spherical particles that the value of the Archie exponent m would be 3/2, that m would be greater than 3/2 for plate-like grains and cylinders with their axes perpendicular to the applied electric field, and that m would be less than 3/2 for plates and cylinders with their axes parallel to the applied

electric field. The apparent discrepancy between this result and the earlier result of Wyllie and Gregory (1953) can be resolved by observing that the study performed by Wyllie and Gregory did not use any of the needle shaped inclusions which yield formation factors lower than those of aggregates of spherical particles.

Sen, Scala, and Cohen also presented some experimental data and tested their calculations with their own data and with data from other researchers. Sen, Scala, and Cohen performed conductivity measurements on samples of glass beads with diameters between 88 $\mu$m and 297 $\mu$m (3.46 X $10^{-3}$ to 11.70 X $10^{-3}$ inches), for these measurements the measured value of m was 3/2. The results of other researchers are in general agreement with the theory of Sen, Scala, and Cohen, however, it should be noted that though all experiments have shown that the Archie exponent m is shape dependent, depending on the experimental arrangements other m values have been found for spheres, the m value for spheres, however, always lies close to the theoretical value of 3/2. As an example Wyllie and Gregory (1953) found that m was 1.3 for spherical particle aggregates in the low porosity range 0.1 to 0.25. Extensive measurements in agreement with the calculations of Sen, Scala, and Cohen are presented in the paper of Jackson, Taylor-Smith, and Stanford (1978). Other studies confirming their calculations were analyzed by Sen, Scala, and Cohen.

A survey of the literature reveals that, while there are other methods which could be used as a basis for particle shape determination, the method based on a simultaneous measurement of

porosity and formation resistivity is the most promising. In order for the measurements to be physically meaningful it is necessary to measure more than one physical property of porous media simultaneously. To measure porosity, permeability, tortuosity, or formation resistivity factor alone is not enough - similar results can be produced by a variety of particle shapes - shape measurements are only physically meaningful, and reproducible if two appropriately chosen physical quantities are measured simultaneously. Formation resistivity factor and porosity are an appropriate choice because they can be measured simply and accurately. In fact many of the other quantities associated with porous media are simply related to porosity and formation resistivity factor - and these quantities are often more difficult to measure and more abstractly defined. In the next chapter methods that can be used to measure porosity and formation resistivity factor will be described.

III. MEASUREMENT OF POROSITY AND FORMATION RESISTIVITY FACTOR

In this chapter the methods by which porosity and formation resistivity factor can be measured are described.

## A. Porosity

Before a description of the measurement of porosity is presented it will be useful to review the definition of porosity. The porosity of a medium, $\phi$, may be defined as the ratio of the volume of voids (or pores) in the medium to the total volume of the material, that is

$$\phi = V_{voids}/V_{total}, \tag{1}$$

where V is used to represent volume. This may be re-written as

$$\phi = (V_{total}-V_{particles})/V_{total} \tag{2}$$

in terms of the total volume and the volume occupied by the particles in the matrix, $V_{particles}$. Porosity and the rôle it plays in the dynamics of porous media are discussed in detail in Bear (1972). A variety of methods for measuring porosity are available in the literature, these have been described by Beranek (1949), Leonard (1948) and Head (1980). A simple determination of porosity can be performed if the bulk density of the particulate material is known (or if it can be measured), the porosity of the porous medium can then be determined from a knowledge of the mass and the total

volume of the porous sample. This was the method used in the data reported in this report, the details of the method will be provided in chapter IV.

## B. Formation Resistivity Factor

The formation resistivity factor of a porous medium has been defined in chapter II in terms of the ratio of resistivity of a saturating fluid to the resistivity of a porous sample saturated with this fluid, it was also noted that the formation resistivity factor could be calculated from the equivalent resistances if the measurements were made in a test cell of fixed dimension. Thus, in order to measure the formation resistivity factor it is necessary to measure the potential difference across, and the current passing through an electrolyte and through a porous sample saturated with that electrolyte. The formation resistivity factor can then be calculated.

In practice, measurements of the formation resistivity factor cannot be performed as easily as the previous paragraph suggests, a variety of problems are encountered. The first problem that should be noted is that any attempt to measure the resistivity or conductivity of an electrolyte, or of a sample containing an electrolyte, using a direct current source will not be successful. The application of a direct current to an electrolyte will immediately cause electrolysis. In practice the measurements are performed using alternating currents. The use of alternating

currents introduces new problems. If large, plate-electrodes are used to supply electric current to the sample then their capacitance must be taken into account when the formation resistivity factor is calculated; an alternative method of dealing with capacitance is to compensate for the plate capacitance and use an alternating current potentiometer. This latter method was used in some of the preliminary studies for the research reported in this report, however the method was abandoned because it did not yield reproducible results. A subsequent study of the literature has revealed that the problem occurred because of contact potentials and because of a polarization of the electrolyte. If an alternating current is connected to a two-electrode conductivity cell, the electrolyte in the vicinity of the electrodes becomes polarized and, as a result, the measured formation factors vary. The reason for the lack of reproducibility of results is that the effect is time dependent. These problems have been discussed in detail by Rust (1952), Jackson (1975) and by Jackson et al. (1978), as well as by many of the other articles cited in the references at the end of this report.

The problems associated with the use of plate electrodes in conductivity test cells have led to the use of point electrodes similar to the point electrodes used in field determinations of formation resistivities. These in-situ apparatuses have been described by Hutt and Berg (1968), and Jackson (1975). When point electrodes are used an alternative method of determining the resistivity has developed. This technique is called the four-

electrode method. A variant of the four-electrode method was used in the results presented in this report.

Rust (1952) performed a comparative study of electrical resistivity measurements on reservoir rocks using both two-electrode and the four-electrode resistivity cells. In a two electrode system, a current passes through a sample placed between these electrodes, and the potential difference across the cell is measured across this pair of electrodes. In a four electrode system, a current passes through the sample between one set of electrodes and the other pair of electrodes is placed along the sample to measure the potential difference arising from the current flow. This method means that contact potentials appearing at the current electrodes and polarization of the electrolyte in the vicinity of the current electrodes do not affect the measured formation factors. Rust also presents a method that allows the detection of contact potentials at the potential electrodes. This method was tested in the present study but it was not used as a matter of course since test results indicated that contact potentials at the potential electrodes were not ordinarily present in the measurements being performed. Rust (1952) provides complete details of this method, the interested reader should consult his work. Rust also compared measurements of resistivity formation factors made with two-electrode and four-electrode test cells and his general conclusions were that the results obtained using both systems were comparable. Rust recommended the use of both methods, and he points out that any discrepancies resulting would then cause

the researcher to find the source of the problem. In the present study the four electrode method was used almost exclusively due to variations observed in results from two-electrode measurements.

An ingenious variation of the four-electrode method has been described by Jackson (1975) and by Jackson, Taylor-Smith, and Stanford (1978). This variation involves an array of point electrodes being placed on either end of a test sample. This array has the advantage of providing multiple current paths through the porous medium, in other words, it behaves in the same manner as a plate electrode. However, an array of point electrodes has two advantages over a pair of plate electrodes. The first advantage is that the capacitance of the system is negligible. The capacitance, C, between a pair of parallel plates is given by

$$C = \epsilon_0 A/d, \tag{1}$$

where $\epsilon_0$ is the permittivity constant, A is the area of one of the parallel plates, and d is the separation between the plates. (Halliday and Resnick, 1986) By considering the array of electrodes to act effectively as a plate capacitor, its capacitance can immediately be seen to be much less because of the small effective area of the point electrodes. Attempts to measure the capacitance of the test cells constructed for the present research were unsuccessful since the capacitances of the cells were smaller than could be measured by the available test equipment. The capacitances were much less than a picofarad, and therefore were considered to be negligible. The second advantage is that the array can form either a two-electrode or a four-electrode

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resistivity measuring system.  Each array can be wired with alternating electrodes connected as current and voltage electrodes. This arrangement can produce a uniform current density and is effectively equivalent to supplying the current between one pair of plate electrodes and measuring the potential difference between a second pair of plate electrodes.  This arrangement has a distinct advantage over earlier implementations of the four-electrode method, that is, the distance between current and potential electrodes is the same.

A modification of Jackson's four-electrode system was used to acquire the data presented in chapter V of this report.  A description of the actual experimental arrangements used to acquire this data is provided in the next chapter.

IV.  THE CONSTRUCTION AND USE OF THE RESISTIVITY CELL

This chapter describes the construction of test cells that
were used to measure the formation resistivity factors and the
porosities of aggregate samples so that it could be determined
whether or not the methods described in earlier chapters of this
report were applicable to materials used in highway engineering.
It was noted in the previous chapter that some measurements had
been performed using plate electrodes.  Since the results of these
measurements were prone to error (for reasons described in chapter
III), no description of the test cell in which they were used will
be provided herein.  Section A of this chapter will describe the
construction of the test cells, section B will describe the methods
by which these cells were used to measure porosity and formation
resistivity factor.

A. The Construction of the Test Cells

The test cells used in this research were made from sheets of
plexiglas.  All test cells used in this project were rectangular.
The cells were constructed by first cutting the plexiglas to the
required size, the edges were then smoothed, and holes were drilled
in two of the sides for electrodes.  The electrodes were formed by
zinc-coated bolts with diameters of 0.3175 centimeters, the heads

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of the bolts functioned as the electrodes. The threads of the bolts were wrapped with Teflon® tape to prevent leakage of the electrolyte. Plexiglas can be welded by the application of a thin bead of methylene chloride. The cells were assembled using such welds, the shape of the cells was maintained by carpenter's clamps. Figure 1 is a photograph of a typical test cell.

The first test cell constructed using this method was 8 centimeters high and the inside dimension of each side was 4 centimeters. This cell had several advantages, contact potentials and electrolyte polarization did not affect the results, the capacitance between the electrodes was negligible, and the sample was completely undisturbed by the measurements. However, a new problem emerged - the results varied erratically if the electrolyte level changed drastically during the measurements. This new problem was traced to electric field lines emerging from the surface of the electrolyte. This problem was solved by building a larger test cell, which is pictured in Figure 1.

The large test cell was 20 centimeters high, with inside dimensions of 5 centimeters by 5 centimeters. The spacing between the centers of the electrodes was 1.5 centimeters and the top of the cell was 15 centimeters above the highest electrode. This larger cell removed the problem of field lines emerging from the electrolyte and the results achieved with this cell were reproducible. The cell was marked at intervals of 0.5 centimeters to facilitate the measurement of sample volumes.

Figure 1. A Formation Resistivity Factor Test Cell
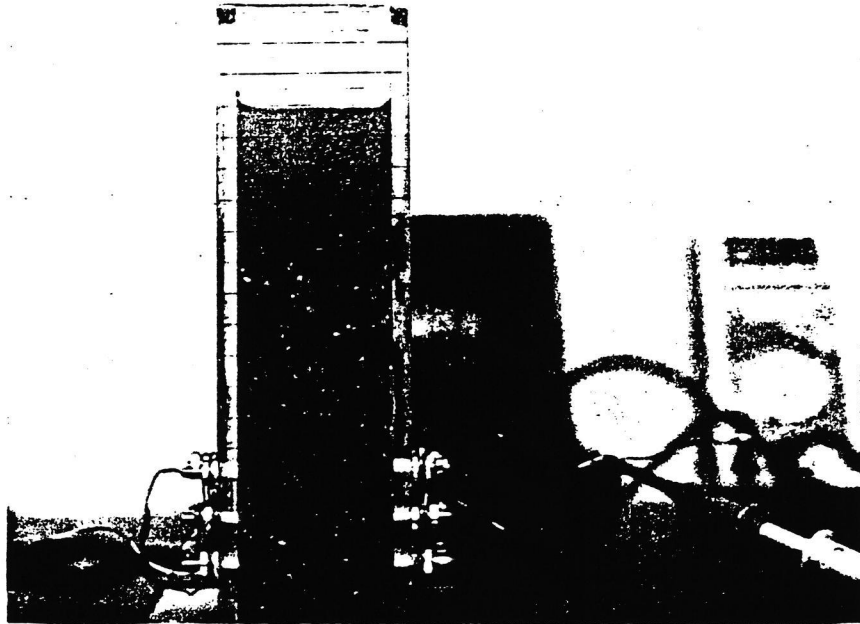
## B. Measurements of Porosity and Formation Resistivity Factor

After some experimentation a solution of sodium chloride (NaCl) was selected as the electrolyte to be used in the determination of formation resistivity factor. Water directly from the faucet was tried, and it worked reliably, but it was decided that it would be preferable to use a known electrolyte. Hydrochloric acid was also tested but it removed the zinc coating from the electrodes.

The first step in determining the formation resistivity factor was to prepare the electrolyte. The formation factor is independent of the electrolyte used but this study used a standard electrolyte. The standard electrolyte consisted of 2 grams of NaCl per liter of distilled water. The electrolyte was added to the test cell, an alternating current was applied to one set of electrodes, and the potential difference was measured across the other set of electrodes. In the initial stages, measurements were made with currents that alternated at frequencies between 10 and 10,000 Hz. The lower frequencies were found to cause some electrolysis, and since frequencies between 100 and 10,000 Hz produced comparable results, it was decided to perform the majority of measurements at a frequency 1,000 Hz. The alternating currents were produced by a Hewlett-Packard® model 200CD wide range

oscillator.  It was noted in these measurements that once the electrolyte was more than 7 centimeters above the highest electrode, no further changes in current and potential difference occurred.  To ensure that resistances rather than resistivities could be used to measure the formation resistivity factor, any experimental runs in which the level of particulate material approached a level 7 cm above the highest electrode were discarded.

After the resistance of the electrolyte in the cell was determined, some of the electrolyte was removed and the aggregate samples were added to the test cell.  The resistance was measured immediately and then the sample was compacted.  The method of compaction varied.  Sometimes the sample was allowed to compact under its own weight and the resistance was measured as a function of aggregate sediment height over time.  In other runs the sample was compacted by striking the base of the test cell on the workbench.  Both methods yielded similar results provided that the measurements were not made immediately following the strikes.  All the data presented in this report were the result of the natural compaction of the sample under its own weight.

The formation factors were then determined from the measured resistances using equation (II-3).  A block diagram of the electronics is provided in Figure 2.

The porosity was determined using the measured height of the aggregate in the sample cell.  A knowledge of the height of the sample enabled its volume to be calculated since the cross-sectional area of the test cell was a known quantity.  In fact, the

volumes had been checked at half-centimeter intervals using a standard burette. The samples used in these experiments were always sorted by size, and the bulk density of the material was determined using some of the larger samples. If the samples were not homogeneous (most were not), then enough of the aggregate material was used to ensure that the bulk density so obtained was representative of the sample as a whole. These larger particles were massed and their volume was determined using a graduated cylinder. This allowed the density of the material making up the aggregate to be computed. Once the density was known, the volume occupied by the particles could be calculated from their mass and density. This allowed the porosity of the sample to be determined using equation (III-2). An illustration of the method follows. If, for example, 450 grams of a material with a bulk density of 2.90 grams per cubic centimeter, occupied a volume of 300 cubic centimeters, its apparent density would be 1.5 grams per cubic centimeter. Solving equation (III-2) for density yields

$$\Phi = (\rho_{particles} - \rho_{total}) / \rho_{particles},$$

where $\rho$ is the density in this case. In this example, this yields a porosity of 0.48 given by:

$$\Phi = (2.9 - 1.5)/2.9 = 0.48.$$

Figure 2. The Circuit for Resistivity Measurements
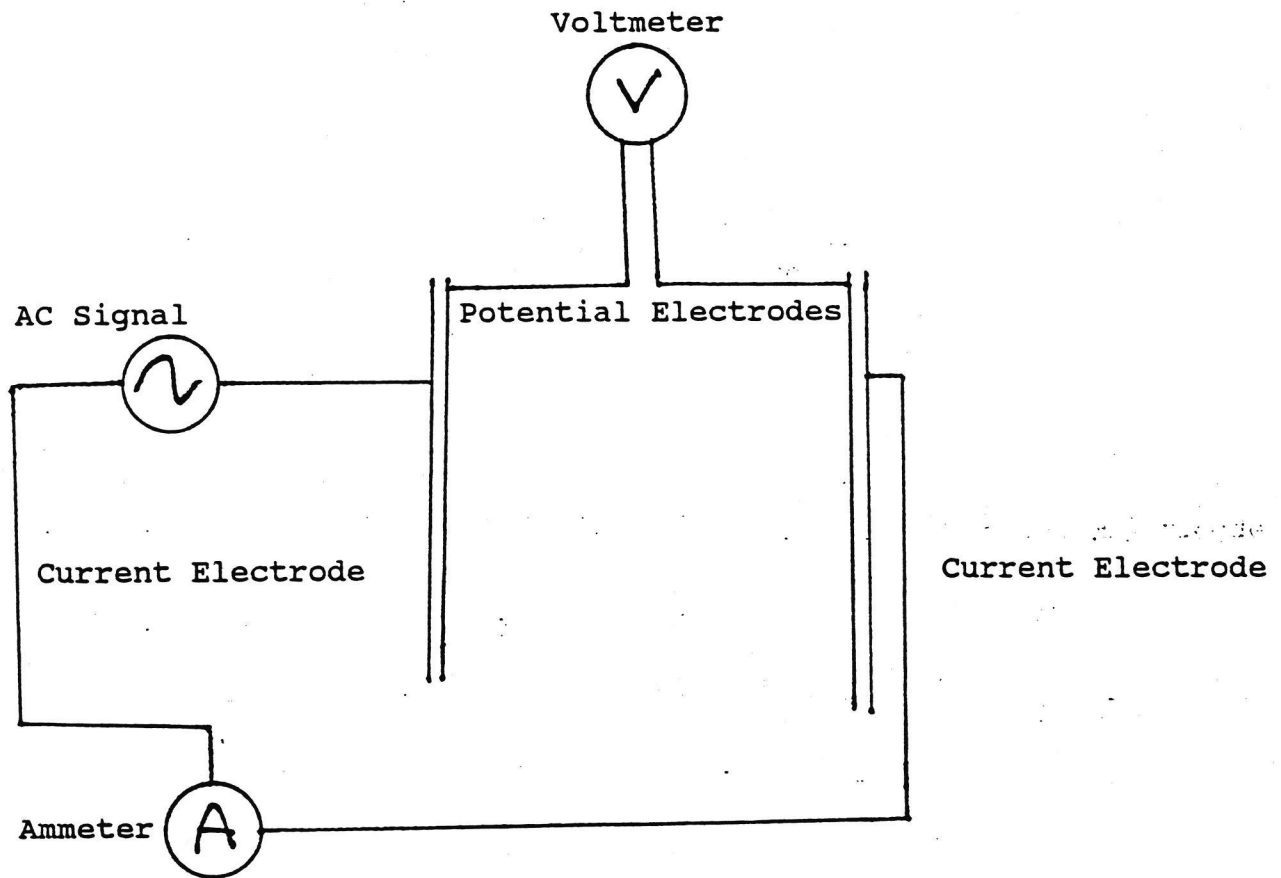
# V. RESULTS AND ANALYSIS

This chapter presents the results of the measurements performed in this study and presents an analysis of their usefulness.

In proposing a method that could be used to determine the average shape of particles contained in an aggregate, it is necessary to provide some confirmation of the accuracy of the results. When this study was undertaken it was originally planned that measurements on particles of controlled shape would be made. A literature survey proved that these experiments would be redundant - Wyllie and Gregory (1953) have already performed these measurements and many subsequent authors have verified their results. For example the results were verified by Sen, Scala, and Cohen (1981). Several methods in common use do not seem to provide appropriate measurements of particle shape. An example of this is the ASTM standard D 3398-81, the measurement basically depends on the deformation of a sample. Such deformations are highly sensitive to surface texture. Particles with surface ridges are more difficult to deform in bulk aggregates than particles with smooth surfaces. In fact, the precision of the standard is unknown. Most other methods suffer from similar problems. It is the present author's contention that the only reliable methods are those which involve the simultaneous measurement of two physical

parameters and direct visual inspection. The results of this study were therefore validated by direct visual inspection of the samples. Other valid measurement methods exist, but these are variants of the method proposed in this report. For example, tortuosity and permeability could be measured simultaneously (see Schopper, 1966 or Winsauer et al., 1952 for details of these measurements).

The roundness of the particles in each size class in an aggregate were determined using a visual chart from Pettijohn, Potter, and Seiver (1972). This chart has been redrawn as Figure 1 in this chapter. The roundness estimates were made prior to the reduction of formation resistivity factor/porosity data to remove personal bias.

The results of the measurements follow, section A contains some representative results from the small cell, and section B contains the results achieved using larger cells (there were actually two identical larger cells). Prior to the presentation of the results the method of data reduction will be described. The methods used in the determination of the formation resistivity factor and porosity were described in chapter V. This yields values for the porosity and for the formation resistivity factor. In order to determine the Archie exponent, m, it is necessary to plot a graph or to determine the slope mathematically using the method of least squares. This latter method was chosen, a least squares procedure was applied to equation (II-5). The method of performing a least squares fit when the basic quantities are

logarithmic is detailed in many sources. Examples are Arya (1966) and Krumbein and Graybill (1965). It should be noted that many Hewlett-Packard® calculators have built-in algorithms for this purpose and that one of these was used in the present study. An outline of the method used to determine the Archie exponent in this study is presented in Appendix 1.

## A. Representative small cell results

The results presented here are for a fine sand and a coarse sand. No size determinations were made beyond the classification into coarse and fine. In some of the early experiments when the final test-cell configuration was being developed, data that would allow the determination of the porosity and the formation resistivity factor was collected at thirty minute intervals. However, the results of all these measurements were consistent with the results of experiments conducted using three data points. The data presented in this report was produced by performing measurements immediately after sample preparation, after allowing the sample to settle for thirty minutes, and after allowing the sample to settle overnight.

1. Fine Sand

| | |
|---|---|
| Porosity range | 0.50 - 0.44 |
| Formation Resistivity Factor Range | 3.46 - 4.45 |
| Archie exponent, m | 1.8 |
| Visual Roundness categorization | sub-rounded |

2. Coarse Sand

| | |
|---|---|
| Porosity range | 0.45 - 0.41 |
| Formation Resistivity Factor Range | 4.27 - 5.54 |
| Archie exponent, m | 2.0 |
| Visual Roundness categorization | angular |

## B. Large Cell results

When the large cell was used, the samples were sorted using a variety of standard U.S. sieves. When the samples were not sorted the Archie exponent tended to be closer to that for spheres than for any of the sorted samples derived from it. These exponents for unsorted samples are not judged to be a useful measure of the particle shape. It is recommended that any subsequent experiments should perform a limited number of measurements on unsorted samples to assess whether or not there is any correlation with pavement characteristics. Before providing some of the actual results, it should be noted that some experimental runs produced formation resistivity factors that were unexpectedly low. Formation resistivity factors much below 3.2 would not be expected over the range of porosities used in the experiments reported here. On some occasions, lower formation resistivity factors were observed. On these occasions a suspension of fine particulate material was observed above the aggregate. It is thought that clays were present in these samples and that their polarization, and subsequent participation in the conduction process lowered the observed formation resistivity factors. These clays could be eliminated by washing the sample over a No. 200 sieve, or their effect could be mitigated by using a stronger, and hence, better conducting electrolyte. After the measurements of this report were made, Sen (1991) published an article that is germane to the

determination of the formation factor of shales and clays. The sphericity was also computed for some of these samples. Following Pettijohn, Potter, and Seiver (1972), the sphericity, $\Psi$, of a particle can be determined from the following prescription in terms of a particles short, S, long, L, and intermediate, I, axes:

$$\Psi = \{S^2/LI\}^{(1/3)}.$$ (1)

The sphericities reported below are average values over 50 particles.

## 1. Material A

Material Description                               concrete sand
Material Source                                     Courson, Harrel, AR
Visual roundness categorization        sub-rounded
Sphericity                                     0.66

| size: | pass 4 | trap 10 | Archie exponent, m | 1.68 |
|-------|--------|---------|--------------------|------|
|       | pass 10 | trap 20 | Archie exponent, m | 1.54 |
|       | pass 20 | trap 35 | Archie exponent, m | 1.65 |
|       | pass 35 | trap 60 | Archie exponent, m | 1.34 |
|       | gross sample | | Archie exponent, m | 1.45 |

## 2. Material B

Material Description                               fine abrasive
Material Source                                       Horner SA&GR, Haskell, AR
Visual roundness categorization        sub-angular
Sphericity                                     0.58

| size: | pass 4 | trap 10 | Archie exponent, m | 1.43 |
|-------|--------|---------|--------------------|------|
|       | pass 20 | trap 35 | Archie exponent, m | 1.40 |
|       | pass 35 | trap 60 | Archie exponent, m | 1.35 |
|       | gross sample | | Archie exponent, m | 1.44 |

## 3. Material C

Material Description                               Donna Fill
Material Source                                         AHTD
Visual roundness categorization        angular

Archie exponent, m  1.9

This sample was sorted by size, the same results were achieved for the sub-samples and the gross sample.

These results show that the method of shape determination adapted from petroleum engineers and marine geologists is applicable to highway materials, and that its results can be correlated with those of visual inspection and computed sphericity.

# VI. CONCLUSIONS

The ability to measure particle shape by simultaneously measuring formation resistivity factor and porosity for aggregates using highway materials has been demonstrated by the research reported herein. While this method can be used to determine the average shape of the particles in an aggregate, in order to develop acceptance tests for aggregate materials, it would first seem necessary to construct test roads in which all the aggregate used in the construction was subjected to tests similar to those described in this report. Such test sites would allow a determination of precisely which characteristics would result in a poorly performing pavement. Since it has proved necessary to separate the samples into particles of roughly the same size, such tests would be also be likely to determine the size range of particles where particle angularity is essential to good pavement performance.

Other methods have been proposed for measuring the shape of particles in aggregates. The method described in this report has the advantage that it is a three-dimensional measurement; another method which seems promising is the computer analysis of images of two-dimensional sections of aggregate. It would seem worthwhile to compare the two methods to provide cross-validation.

In order to implement the results of this study, the next

stage would be the development of prefabricated test cells in a variety of sizes. These test cells should then be used to measure the aggregates currently being used in road mixes in order to assess the results against subsequent pavement performance. The method has the advantage of being simple and of low cost, and its use in the laboratories of the Arkansas Highway and Transportation Department should not involve larger additional labor costs.

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## Appendix 1: Least squares and the Archie exponent

The method of determining the Archie exponent will be illustrated using equation II-6 for the modified Archie equation. Starting from $F = C\phi^{-m}$, in order to determine m by the method of least squares it is first necessary to take loagarithms of both sides of this equation. This yields

$$\log F = \log C - m \log\phi, \tag{A1.1}$$

this can be written in the standard form

$$\log F = a + M \log\phi. \tag{A1.2}$$

The normal equations from which a and M are then determined are

$$\Sigma \log F_i = Na + M \Sigma \log\phi_i, \tag{A1.3}$$

and

$$\Sigma (\log F_i)(\log\phi_i) = a \Sigma \log\phi_i + M \Sigma (\log\phi_i)^2. \tag{A1.4}$$

In these equations N represents the number of measurements. The normal equations can then be solved for a and M, and so the desired quantity m can be determined.