THE EFFECTS OF ANGULARITY ON THE COMPACTION AND SHEAR STRENGTH OF A COHESIONLESS MATERIAL

BY

RICHARD EDWARD SWIDERSKI

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APPROVAL OF THESIS

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BY

FACULTY COMMITTEE

APPROVED: ______________________________

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NEWARK, NEW JERSEY
MAY, 1976

Department of Civil and
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New Jersey Institute of Technology
323 High Street
Newark, New Jersey 07102

Dear Dr. Monahan: April 25, 1976

The following research report entitled "Effects of Angularity on the Compaction and Shear Strength of a Cohesionless Material" is submitted in partial fulfillment of the requirements for the Degree of Master of Science in the Civil Engineering Department of New Jersey Institute of Technology, Newark, New Jersey.

The thesis encompasses the development of experimental apparatus, collection and evaluation of data, extensive literature research, conclusions and recommendations on the subject of angularity and strength. The work was accomplished in accordance with your written and verbal directives. It is hoped that the thesis will satisfactorily fulfill your requirements and be of some value in future research.

Respectfully submitted,

Richard E. Swiderski

ABSTRACT

Several physical methods are described for the practical measurement and rating of angularity (shape) of cohesionless soil particles. Angularity is determined by utilizing the fundamental property of a sphere: a sphere has the smallest contact surface area of any shape for a given volume. Therefore, any other shape will exhibit a greater contact surface area and consequently will have a greater frictional resistance which is a function of its degree of angularity.

The effects of angularity on the physical behavior (e.g. strength) of cohesionless soils was investigated at various relative compaction densities. For this purpose a combined compaction and direct shear test device constructed from a modified standard Proctor compaction mold was devised.

The samples used to determine the effect of particle shape on the physical behavior of cohesionless materials were produced in the lab from pure quartz. This was done in order to avoid the problem of variations due to mineral composition and grain size distributions. It was hoped that this would insure a greater uniformity of test results. In addition, the shear test results derived from lab-produced quartz samples were compared to those of natural field samples in order to determine whether the behavior observed during lab tests was representative of natural field soils.

These experiments demonstrated that the strength of a cohesionless material increases with degree of angularity and relative density to an optimum point. Surpassing the optimum value implies substantial particle crushing which reduces the particle interlocking effect and can result in a reduction of soil strength. Crushing is greatest when cohesionless particles are poorly graded, highly angular, and large in size.

Generally, the degree of particle crushing influences strength, and particle shape determines the degree of crushing. Shape (angularity),therefore, significantly controls the overall strength of a cohesionless soil.

ACKNOWLEDGEMENTS

It is my pleasure to express my appreciation to Dr. Edward J. Monahan, P.E., Professor of Civil Engineering at New Jersey Institute of Technology who was my advisor. The original idea for this thesis came from Dr. Monahan and without his valuable assistance and supervision the thesis could not have been written.

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PREFACE

The original idea for this thesis came from Dr. Edward J. Monahan, P.E., who maintained the idea for some time that a practical method for predicting the physical behavior of an "acceptable" borrow material could serve as a solution to the problem of changing borrow. Probably the most common problem encountered in earth construction is this wide variability of borrow material. A natural soil used as borrow fill consists essentially of mineral particles of various shapes and sizes. Depending on varying particle arrangements, different soil characteristics will be produced. Natural soil deposits may contain a great number of similar size and shaped grains depending upon the mode of transportation prior to deposition. Effects of the environment tend to concentrate certain type soil constituents that are the most mobile in localized areas. On the other hand, the properties of an entire soil or borrow material may vary to a considerable degree in a small area.

Besides the wide variability of borrow materials an even greater problem exists - degree of compaction. What proportion of the maximum compaction density will achieve the most desirable physical qualities for the varying (i.e. shape, size, surface texture etc.) borrow materials?

Specifying a standard compaction density for almost all site preparation work, irrespective of the intended use of the fill, might not be the best engineering practice (Monahan, 1974). Instead, it may be more advisable and economical to specify a particular percentage compaction for different borrow materials and project types. A stringent standard compaction requirement when dealing with smaller projects such as parking areas, or subgrades and embankments for secondary roads may be unnecessary and could result in losses of time and money.

The present study is based on the hypothesis that an optimum compaction density resulting in a maximum of desirable physical properties exists for different types of borrow material containing particles of different shape. The British Standard Compaction Test, the Heavy Compaction Test, and the Modified AASHO specifications employ as common practice 90-95 percent relative compaction specifications. This figure may not necessarily represent an optimum compaction density for the material in question. Achieving the specified 90-95 percent compaction does not automatically guarantee the engineer a requisite strength, etc.. In fact in some cases, excessive compaction may substantially reduce the desired physical properties of a fill. This degree of compaction may be unnecessary unless it is associated with certain strength, rigidity, permeability or some combination of physical properties which are required by the specific engineering design.

Particle shape and optimum obtainable compaction density relationships may prove to be of major importance in judging the workability of borrow materials. Generally, the properties of a fill embankment are affected by the shape and arrangement of the individual components. Knowledge of these relationships might also predict conditions of density for different "shape" fills in excess of which would cause a decrease in strength.

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1 - INTRODUCTION

Several major fundamental properties of soil particles significantly influence the physical behavior of a cohesionless soil. Particle shape and surface texture are two properties of critical importance. Cohesionless materials, with little or no binder such as clay, depend almost exclusively upon particle shape and surface texture for their collective strength. Shape and surface texture determine the extent of particle and surface interlocking which in turn controls the overall strength and physical behavior of a soil material (with all other parameters remaining constant). Generally, surface texture is dependent on particle shape. Angular particles have rough surface textures and rounded particles have smooth surface textures. Therefore by describing shape, surface texture is simultaneously taken into consideration.

In the past inability to practically and accurately describe particle shape has made this property a secondary aspect in soils classification. The influence of particle shape on the physical behavior of cohesionless materials under engineering conditions has been established. Because of this property's marked effect on soil strength, it should be recognized as a fundamental rating index property.

Angularity rating methods will be proposed that are based on particle shape. The purpose of this investigation was to derive a rapid and reliable technique for field estimation of physical behavior of cohesionless materials under known loading conditions. A simple method for rating particle shape would provide a non-subjective and practical means of analyzing soil particles. Such a technique would avoid the use of such indefinite and for all intents and purposes meaningless, qualitative terms such as angular, subangular, subrounded, rounded, etc. An efficient angularity rating system would therefore be superior to any previously used shape terminology. Such a rating system would be a practical tool for soils classification in the field.

The relationship between angularity, density, and strength is as follows. An increase in angularity and density will result in an increase in strength. While this is generally true, completely opposite behavior occurs under certain conditions of high density in some cohesionless materials. The basis of this thesis is that there is an optimum compaction density determined by particle shape having a maximum degree of desirable physical properties. Overcompaction to high densities achieved through excessive particle crushing can surpass this optimum value and result in an overall reduction of strength. Since shape controls the amount of particle crushing during compaction, it must also directly determine the degree of strength loss at higher densities as a result of that crushing. It is assumed that a typical "shape" fill material at different relative compaction densities would exhibit specific physical behaviors.

Rating many types of different shaped borrow materials and testing their strength at different relative densities would provide an index value for that shape material and density with its corresponding engineering capabilities. Compiling data on the physical behavior of different shaped materials could result in standard tables, listing angularity indexes and corresponding optimum compaction densities. Standard angularity tables would categorize and predict conditions of compaction density most likely to induce favorable engineering properties. Such tabulated data could be used to evaluate the workability of the material. This would be a useful field index tool for soils that would significantly aid in the selection of an appropriate fill material. In conclusion a practical angularity rating method could ultimately save time and money, and eliminate the likelihood of detrimental overcompaction which could result in a reduction in strength.

2 -FUNDAMENTAL PROPERTIES OF COHESIONLESS MATERIALS

Five major physical characteristics of cohesionless particles affect the collective stability between the particles in a borrow-fill. These characteristics are: shape, size, mineralogical composition, surface texture and packing.

Shape (Sphericity vs Roundness)

Sedimentary petrology defines a particle shape by means of two basic properties: sphericity and roundness. The term roundness has often been misused in the literature, and in many cases, has even been incorrectly used interchangeably with sphericity. By definition, sphericity is the ratio of surface area of a particle to the surface area of a sphere of the same volume. It describes the degree in which the shape of a particle approaches the form of a sphere.

For a given volume a sphere has the least surface area of any shaped particle. As the shape departs from the ideal sphere, the ratio of surface area to volume increases. This relationship will affect particle resistance to movement along an inclined plane. Sphericity is largely controlled by the original particle shape, which in turn is controlled by mineral composition. The only relation between sphericity and roundness is that the maximum degree of roundness is defined as a sphere. On the other hand, a particle may be extremely well rounded and still be far from spherical. Conversely, a particle may approach a sphere in shape and yet not have any part of its surface rounded. The dodecahedral form of a garnet crystal is a case in point. In other words, a soil particle may approach a maximum surface to volume ratio and still be surficially angular. The engineering term equivalent to sphericity is "bulky". This term is applied when the three dimensions of a particle are of the same order of magnitude. However, in the description of the term "bulky" no attempt is made to describe the degree of roundness.

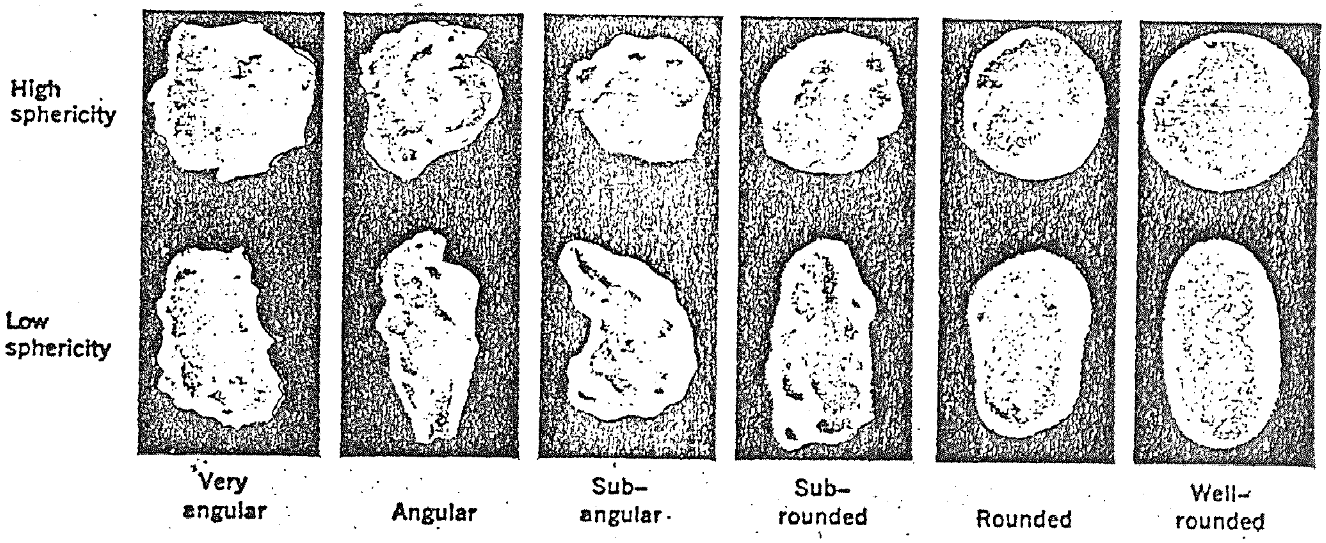
The term roundness describes the sharpness of the edges and corners of a grain. The description does not define the degree to which the particle approaches the shape of a sphere. For example, it is very possible to have a pebble which is rounded but fairly flat. It is apparent that as the roundness increases the flatness must decrease. Because the better rounded pebbles are also more spherical, it follows that prolonged abrasion tends to make pebbles more spherical and hence less flat.

The distinction between sphericity and roundness is clearer if one understands that particles may differ greatly in degree of sphericity but may have nearly the same degree of roundness. Powers (1953) made this distinction clear by means of a chart for the visual estimation of particle shape (Fig.1). Pettijohn (1957) proposed the existing roundness grades of angular, subangular, subrounded, rounded and well rounded (Fig. 2). These five broad classifications have served as the primary descriptions for roundness and angularity. They are inadequate as descriptions for this property due to the limited, small number and subjective nature of the categories. A physical means of classification is required in order to determine grain shape. Such a classification should result in a single number index description for grain shape.

Previous estimations of sphericity and roundness were extremely tedious and subjective in nature. Krumbein and Pettijohn (1938) used a direct measurement method which was based on a number of different measurements, i.e. the intermediate dimension and area of the section of the grain expressed as the diameter of a circle having the same area. Other examples of methods which proved to be too laborious and time consuming are: the "nominal section diameter" (Wadell,1935) and the "largest apparent diameter" (Friedman, 1958). Pettijohn (1957) supplemented his detailed roundness descriptions with visual classifications.

Fig. 1

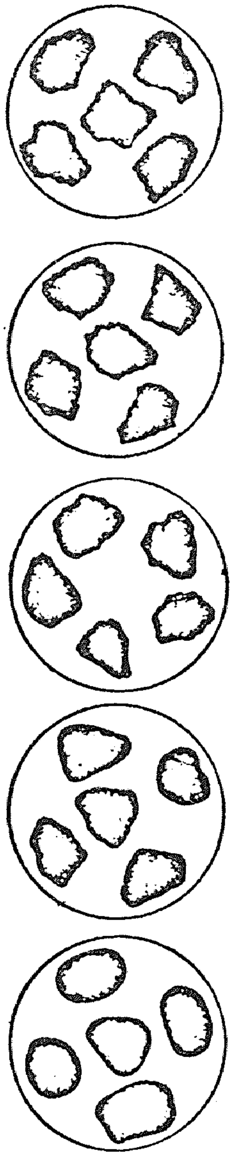
Chart For Visual Estimation Of Roundness



(After Powers, 1953)

Fig. 2

ROUNDNESS CLASSES SHOWING DIFFERENT DEGREES OF PARTICLE ROUNDNESS (After Pettijohn,1957)



Angular: Strongly developed faces with sharp edges and corners; secondary corners*are numerous.

Subangular: Strongly developed faces with somewhat rounded edges and corners; secondary corners are numerous.

Subrounded: The edges and corners are rounded and the area of flat faces is comparatively small; secondary corners are much rounded and reduced in number.

Rounded: Flat faces are practically absent; all edges and corners are rather broad curves, and there may be broad re-entrant angles; secondary corners have disappeared.

Well Rounded: There are no flat faces; the entire surface consists of broad curves.

*Secondary corners are the many minor convexities seen in the grain profile.

Krumbein and Sloss (1955) added a visual estimation for sphericity together with roundness, and Powers (1953) used actual photographs of grains for his visual estimation of roundness classes. Needless to say, visual classifications are highly subjective and therefore open to variance in opinion.

Angular particles are produced by the weathering of rocks. Transportation of these angular particles in a medium (e.g. water, air) rounds them. Well rounded quartz generally records a long geologic history passing through several cycles of erosion, transportation and deposition. According to Pettijohn (1957), resistant minerals like quartz require thousands of miles of stream transportation to become well rounded.

A natural deposit which was to be used as borrow material with predominantly rounded grains (i.e. alluvial deposits) would indicate a simplicity of detrital grains in which only the most stable or resistant minerals would remain (e.g. quartz). On the other hand, a naturally angular deposit (e.g. residual talus deposits) has not undergone as much weathering and will contain in addition to quartz, other minerals which comprise the parent rock.

A mineral of interest in the present study is quartz. Quartz grains vary in shape but predominantly they tend to be subspherical. However, detrital quartz even in the most mature sands tend to show a slight elongation. with a ratio of the long to short axis of 1.0:2.5. The elongation tendency is greatest in the direction of the c- axis.This is attributed to unequal abrasion due to slight differences in hardness of the three crystallographic directions (Pettijohn, 1975).

Angularity or roundness of soil particles is a function of hardness, degree of turbulence during transportation, and distance travelled. Resistance of a mineral to rounding is a function of its shape, specific gravity, hardness and cleavage. Some of the more common minerals, in order of decreasing resistance are: quartz, tourmaline, potash feldspar, titanite, magnetite, garnet, ilmenite, epidote, hornblende, and apatite (Friese, 1931) (Thiel, 1945). Resistance to rounding of some common rocks, in order of decreasing resistance are: chert, quartzite, granitic rocks, basaltic rocks, dolomite, limestone, sandstone, scoriaceous lavas, gneiss, and schist (Kuenen, 1956).

The importance of particle shape as it affects the behavior of a cohesionless material was clearly demonstrated by Morris (1959). He proved that a change in shape (with surface texture, size, and composition remaining constant) could produce a substantial (25 percent) change in strength. To further illustrate this point, the particles that were compared were both very rounded — one tending to be elongated and disk-shaped and the other nearly spherical. This proves that small disparities in grain shape influence soil behavior. This experiment also demonstrated the necessity for distinction between sphericity and roundness - neither type particles tested were angular.but still a sizable difference in strength resulted. This leads one to believe that the relationship between angularity and strength is not as simple and clear-cut as previously envisioned,i.e. a greater angularity always produces a greater strength. Particle shape, whether angular or rounded, exerts a marked influence on the strength of a cohesionless material.

Size

Particle size in itself affords clues as to the agent and duration of particle transportation. In a cohesionless material, the greater size particles have more influence on the strength properties of a soil. The size of a particle influences frictional resistance. For a given total normal load, the normal load per contact must increase as the particle size increases because the same total load must be distributed over a smaller number of contact points. This fact makes the larger size fraction more suceptible to crushing (especially angular grains) under a given load than smaller fractions.

It has been shown (Twenhofel and Tyler, 1941) that particles smaller in size than about 1/10 mm exhibit little or no rounding. Therefore measurements of angularity on small particles are probably meaningless. The reason that smaller size particles are usually more angular is that water acts as a protective film between such grains and tends to prevent abrasion. Generally, roundness is most rapidly attained by particles of larger size.

According to Kuenen (1956) the roundness of a large size pebble can be four or five times greater than that of a medium size pebble having undergone exactly the same amount of weathering. Size of particles also affects the shear resistance of a soil. This is easily understood since the larger the particle, the greater the probability of its having larger surface irregularities. And the greater degree of surface irregularities, the greater will be the frictional resistance between grains.

Also, a better distribution of particle sizes (greater interlocking effect) should produce a higher shear strength. Crushing of particles should be less for a well graded soil because the increased number of contacts can distribute load more evenly. In general, better gradation implies a higher strength.

Mineralogical Composition

The composition and arrangement of the atoms (structure) in the minerals composing a soil has a significant influence on the physical properties of the soil. The mineralogical composition of a soil will affect to some extent the soil particle size, shape, surface texture, color, and degree of roundness.

The mineral crystal structure will be reflected primarily through shape and surface texture. For example, the atomic structure of a mineral will determine to what degree a mineral will cleave or fracture. Cleavage faces give different contact (frictional) characteristics than do fracture surfaces with many irregularities. Atomic structure, therefore, controls the initial shape and surface texture of a particle.

Also, the shape of particles can be affected by the physical breakdown (under load) of minerals along cleavage planes or zones of weaknesses. It is believed that the particle shape and surface texture initially determined by mineral composition has a major influence on the overall strength of a soil mass. It is believed by some that the strength and stability of a cohesionless material depends solely upon the shape and surface texture of the individual particles and is independent of the crushing strength of the constituent grains.

Morris (1959) discussed the role of mineral composition on the strength of cohesionless aggregate in a study in which the particle size was kept constant but shaped varied. Of the materials tested: pumice, crushed bricks, basalt, and river gravel, all materials exhibited similar strength when particle shape and degree of surface roughness were similar, <u>regardless of mineral composition</u>. He demonstrated that "tough" or "hard" materials possess little if any strength advantage over relatively "soft" friable materials - unless they differ in shape and surface texture. His experiments showed that an increase in strength of a "weak" material could result by changing the physical roughness and particle shape. Similarly, a "hard" material could exhibit little resistance to stress by varying shape and surface texture. According to Morris, the chemical composition of a particle of itself has little to do with the strength of a cohesionless material, although the particle crystal chemistry does initially determine its shape and surface texture.

If one were to embellish Morris's idea further, it would be logical to assume that a soft material could produce as strong an embankment as a hard material if it exhibited favorable shape, surface texture, and degree of compaction. A distinct "weight credit" advantage could be achieved by utilizing light weight aggregates which met higher strength requirements due to particle shape and texture characteristics. A weight credit would allow a balanced transfer of loads, through the utilization of light weight fill materials from the foundation to the superstructure. This could mean additional available floor space otherwise impossible.

Surface Texture

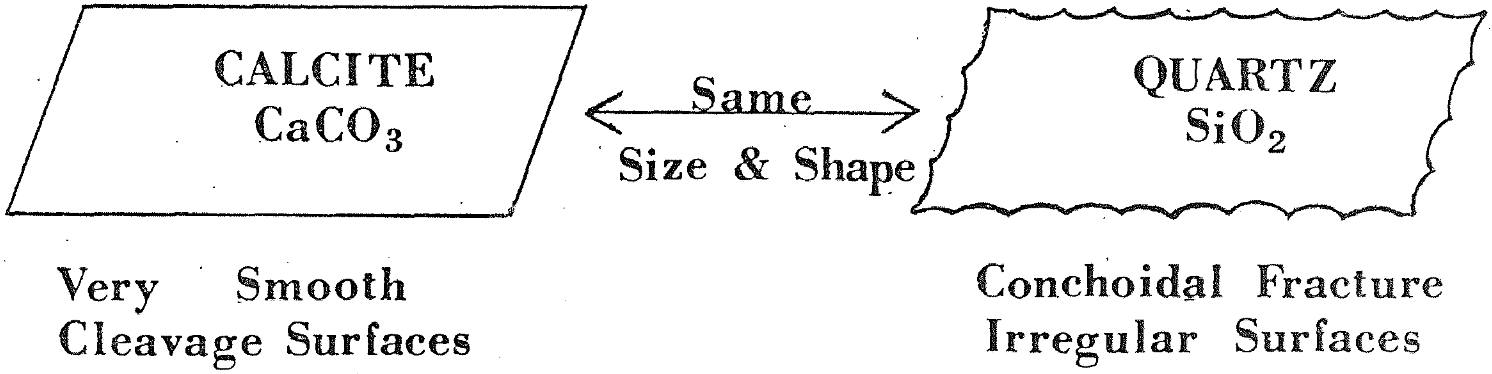
Surface texture is the combination of all minor surface features of a particle which are independent of particle size, shape, or degree of roundness. The abrasional history of the particle is reflected by these minute surface features. Some common examples of surface features are: smoothness, roughness, polish, dullness, pittedness, frost, striations, chips, faceted and grounded surfaces. Generally, surface texture is synonymous with surface roughness. Smooth (to the touch) surfaces have many irregularities and can be considered rough. Even mirror smooth surfaces are composed of many minute peaks and valleys. These surface irregularities contribute significantly to the frictional resistance beween individual grains. It is conceivable that two soil particles may have exactly the same size and shape although have different frictional characteristics as the result of varying surface texture (e.g. cleavage vs fracture) (Fig. 3). Frictional resistance is achieved by surface to surface interlocking which is not to be confused with particle interlocking. Both types of interlocking can work simultaneously to increase the strength of a soil. Fresh cleavage surfaces over large areas are extremely smooth and create high frictional resistance. This frictional resistance is a result of the tendency of cleavage faces to seize one another. A contaminating layer, such as water surrounding a soil particle, can lubricate the surfaces between grains and thereby reduce a soil's strength. This lubricating effect decreases as the surface roughness increases. Bowden and Tabor (1964) demonstrated this situation by showing that the frictional resistance of quartz is not greatly affected by the presence or absence of surface water due to the inherent roughness of its surfaces. From a practical standpoint, this fact is important since essentially all quartz particles in natural soils have rough surfaces. Smooth quartz is produced not by cleavage but instead by fracture followed by intense abrasion.

Generally speaking, the smoothness achieved by cleavage is far superior to that produced by any kind of abrasion. It is commonly believed that the rougher

Fig. 3

CLEAVAGE vs. FRACTURE

Different Mineralogical Composition



Variation In Surface Texture Creates Different Frictional Characteristics (Surface Interlocking)

the surface, the greater the shear strength due to greater surface interlocking of the greater number of irregularities which in turn increase the frictional resistance between adjacent grains. Although, Morris (1959) inferred that, other factors being held constant, surface roughness in excess of a critical value impedes the development of optimum structural arrangement (packing) of particles within a cohesionless mass. He also stated that the role of surface texture in determining strength is equal to that of shape.

Packing

When a normal load is applied to a soil mass in a rigid container, a decrease in volume occurs due to the rearrangement and interlocking of individual particles and results in tighter particle packing. Packing is a measure of the degree to which individual particles are in contact with or interlocking with their neighbors. If particles are packed systematically, void space for example is less than if arranged in a haphazard manner.

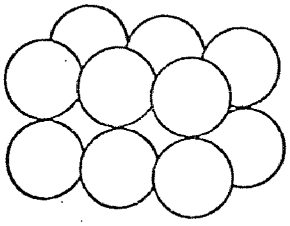
Change in density upon compaction is a function of packing which in turn is determined by particle shape. Ideally, the closest possible packing is achieved with uniform spheres. A sphere has the least surface area for a given volume. Of the possible packing arrangements of uniform spheres, hexagonal closest packing (stacking close-packed layers in the sequence ABAB etc.) creates a configuration with the maximum density (Hunt, 1972). In nature, hexagonal closest packing of homogeneous materials is responsible for such phenomena as polygonal cracks forming soil polygons (permafrost areas), mud cracks, and hexagonal columnar jointing in basalts. In this tightest possible packing arrangement of uniform spheres, the void space is equivalent to approximately 26 percent of the total volume and is independent of grain size (Fig 4A and Fig.4B).

In contrast, the loosest or most open type of systematic packing possible of uniform spheres is the simple cubic packing. In this type of packing the unit cell is a cube, the eight corners of which are the centers of the spheres involved. Void space in simple cubic packing is equivalent to approximately 47.6 percent of the total volume (Fig. 4A and Fig.16).

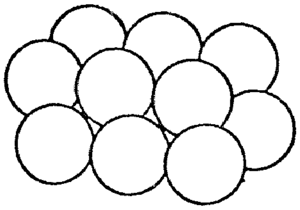
Additional compression of uniform spheres packed in the hexagonal closest packing configuration results in an increase in volume, hence void space. Over-compaction disturbs particle packing and rearranges the particles into a looser state which results in a reduction of strength. It is a known fact, that if a dense sand (usually rounded) is compressed in one direction it

Fig. 4A

PACKING OF UNIFORM SPHERES
(After Hunt,1972)



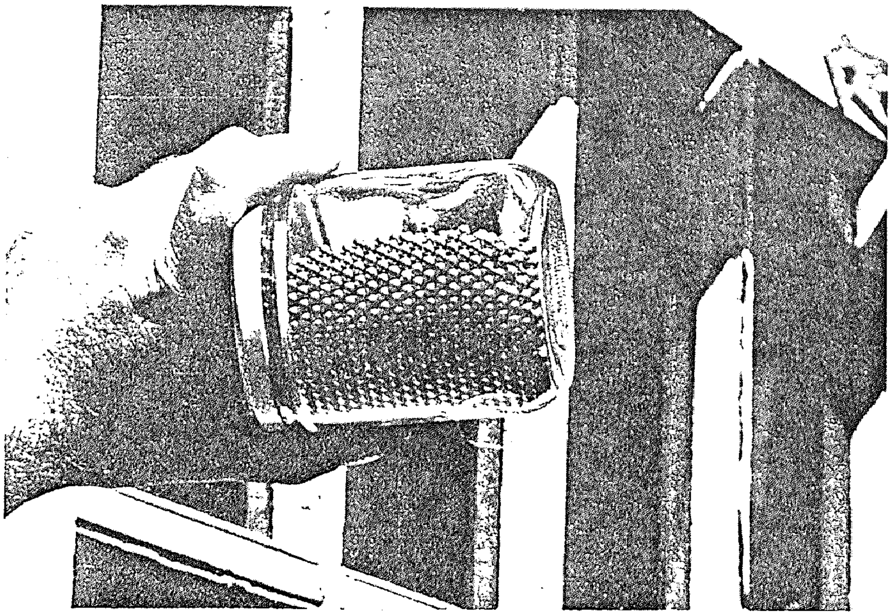
SIMPLE CUBIC PACKING
LOOSEST POSSIBLE PACKING
VOID SPACE EQUALS 47.6%



HEXAGONAL CLOSEST PACKING
TIGHTEST POSSIBLE PACKING
VOID SPACE EQUALS 26.0%

FIG. 4B

PRACTICAL EXAMPLE OF THE EASE OF FORMING THE HEXAGONAL-CLOSEST PACKING CONFIGURATION OF UNIFORM SPHERES WITH MAXIMUM DENSITY



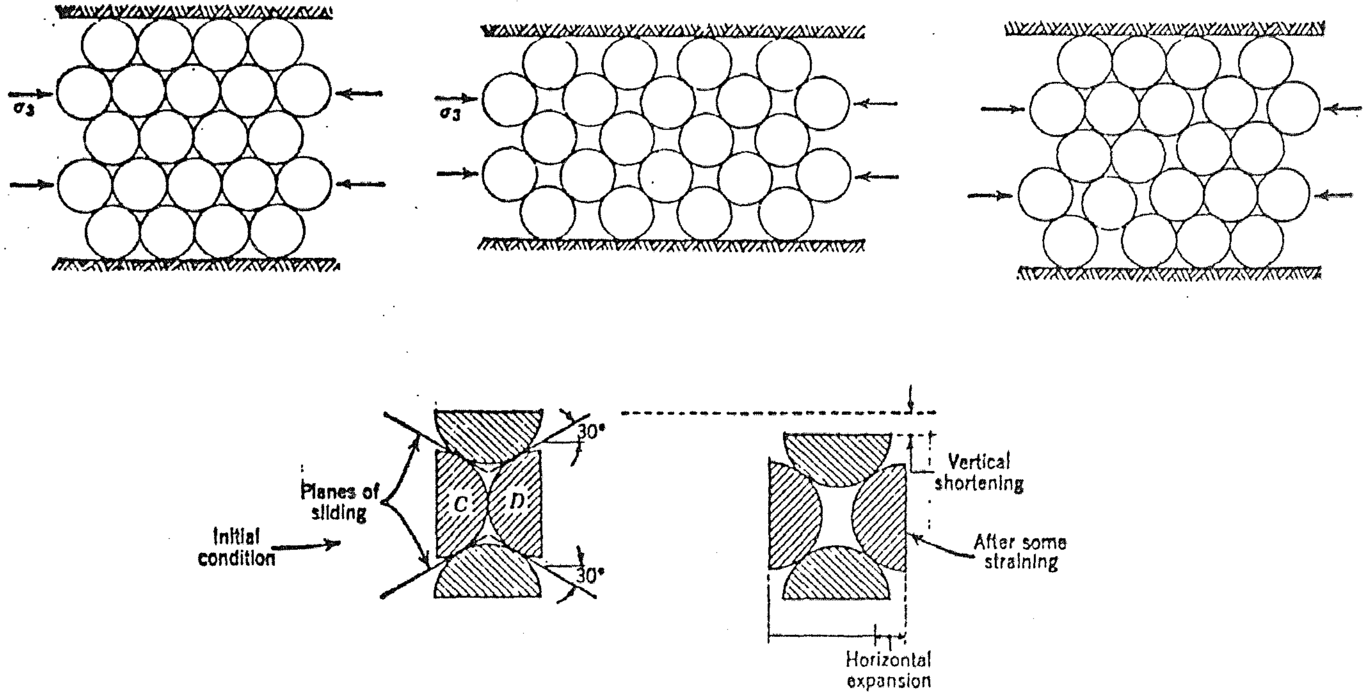
will increase in volume and decrease in strength, commonly known as dilatant behavior.(Fig. 5). That is, in a less dense state compaction produces volume reduction and in a more dense state compaction produces a volume increase and loss in strength. Over-compaction of an angular material can also result in strength loss. This phenomenon is caused by particle size reduction,due to excess crushing. This reduction of strength by over-compaction in both angular and rounded materials suggests the existence of a critical or optimum compaction density based on particle shape for different cohesionless fill material.

Particle shape factors more or less insure that certain preferred particle orientations will result during packing (compaction). The degree of grain alignment in a fill material after compaction is largely dependent on particle sphericity. This is because perfect spheres have no orientation and can pack easily. Whereas angular grains like a myriad of puzzle pieces, strongly oppose an orienting compactive force. Under certain conditions, particle shape and packing can influence the permeability or drainage characteristics of a fill. For example, this situation can be achieved by creating a preferential flow of fluids in one direction.

In general, greater densities can be achieved by

Fig. 5

Dilatant Behavior After Vertical Compression Of A Densely Packed Array Showing A Volume Increase



(After Lambe, 1969)

spheroidal particles, Observations of volume changes in the lab suggests that under conditions of maximum compaction, angular particles of uniform size have greater number of void spaces than rounded particles of the same size. It follows, therefore, that as a particle approaches a sphere in shape, the greater will be its ability to nestle closer to its neighbors. In other words, the more spherical a soil, the greater will be its maximum density. Also, the smaller the range of particle sizes present (uniform soil) and the more angular the particles, the greater the chance will be to form a loose structure within the soil. The combination of a small size distribution and degree of angularity are factors inhibiting densification. Whereas, a greater range of particle size (smaller grains can fill in voids produced by larger grains) and a degree of sphericity, effectively aid densification.

3 - SELECTION OF THE MINERAL QUARTZ FOR USE AS ARTIFICIAL SOIL

The physical characteristics (e.g. size, surface texture, composition) of a manufactured soil must be controlled in order to study the significance of particle shape on soil characteristics. Of the physical properties mentioned the one most easily controlled is mineralogical composition. The importance of controlling the mineralogical composition of the soil material is its influence on all initial physical properties e.g. cleavage, hardness, tenacity etc.. The selection of the mineral quartz for this study was based on the mineral's many advantageous physical properties which will be discussed below.

The earth's crust is composed chiefly of the elements oxygen (46.6 %) and silicon (27.7 %) by weight (Mason, 1958). The abundance of the mineral quartz (SiO_2) attests this fact. Silicon dioxide or quartz is found in nearly all igneous and metamorphic rocks and in most sedimentary rocks. The three most important sedimentary rocks encountered in engineering practice are: sandstone (mostly quartz), limestone (mostly calcite ($CaCO_3$)), and shale (mostly clay minerals). For this reason, the most logical mineral choice from the point of view of natural abundance would be the mineral quartz.

Another reason for its selection is that quartz is the most common mineral in a granular soil and therefore representative of a typical borrow material. Quartz also is the principal mineral in sands, silts, and rock flour and is abundantly found in granite and forms the light colored bands in metamorphic gneiss. Of all minerals, quartz is most nearly chemically "pure" possessing constant physical properties. Its high resistance to chemical weathering enables it to be broken into small particles by mechanical weathering without change in composition, thus contributing the greatest volume of detrital minerals in sediments.

Quartz is a very durable mineral with a hardness rating of 7 on Mohs hardness scale. For this reason its tenacity or ability to withstand crushing, tearing or bending is usually quite high. When quartz is crushed, it generally does not show preferred fracture directions and it is for this reason that quartz particles can be found in both the rounded and the angular state. Cleavage is poorly developed in quartz and therefore the mineral does not part along definite planes parallel to the crystallographic axes, but instead breaks along irregular surfaces that bear little or no relation to the crystal faces of the mineral. The fracture is typically conchoidal (shell-like), uneven or splintery. For example, if one crushes a quartz crystal with a hammer, it is broken generally into smaller pieces with conchoidal form, in much the same manner which glass is fractured.

In addition, the specific gravity of quartz is 2.65, this being very close to the average density of surficial deposits. Particle density of the majority of engineering soils varies within the narrow range of 2.60 to 2.75. This occurs because quartz, feldspar, and the major silicates have densities within this range and they make up the major portion of these soils, the largest portion of which is made up of quartz and other silicates. It is no coincidence therefore that for engineering computations, the specific gravity value is often assumed to be 2.65.

In conclusion, quartz was found to be a mineral representative of a large soil fraction and in this sense the best choice for the present study. Furthermore, its natural abundance, availability, fracture and lack of cleavage, hardness, lack of alteration, simple chemical composition and ease of identification makes it an excellent experimental material.

4 -ANGULARITY RATING METHOD I (FRICTION BOARD)

Description of Experimental Apparatus and Testing Procedure

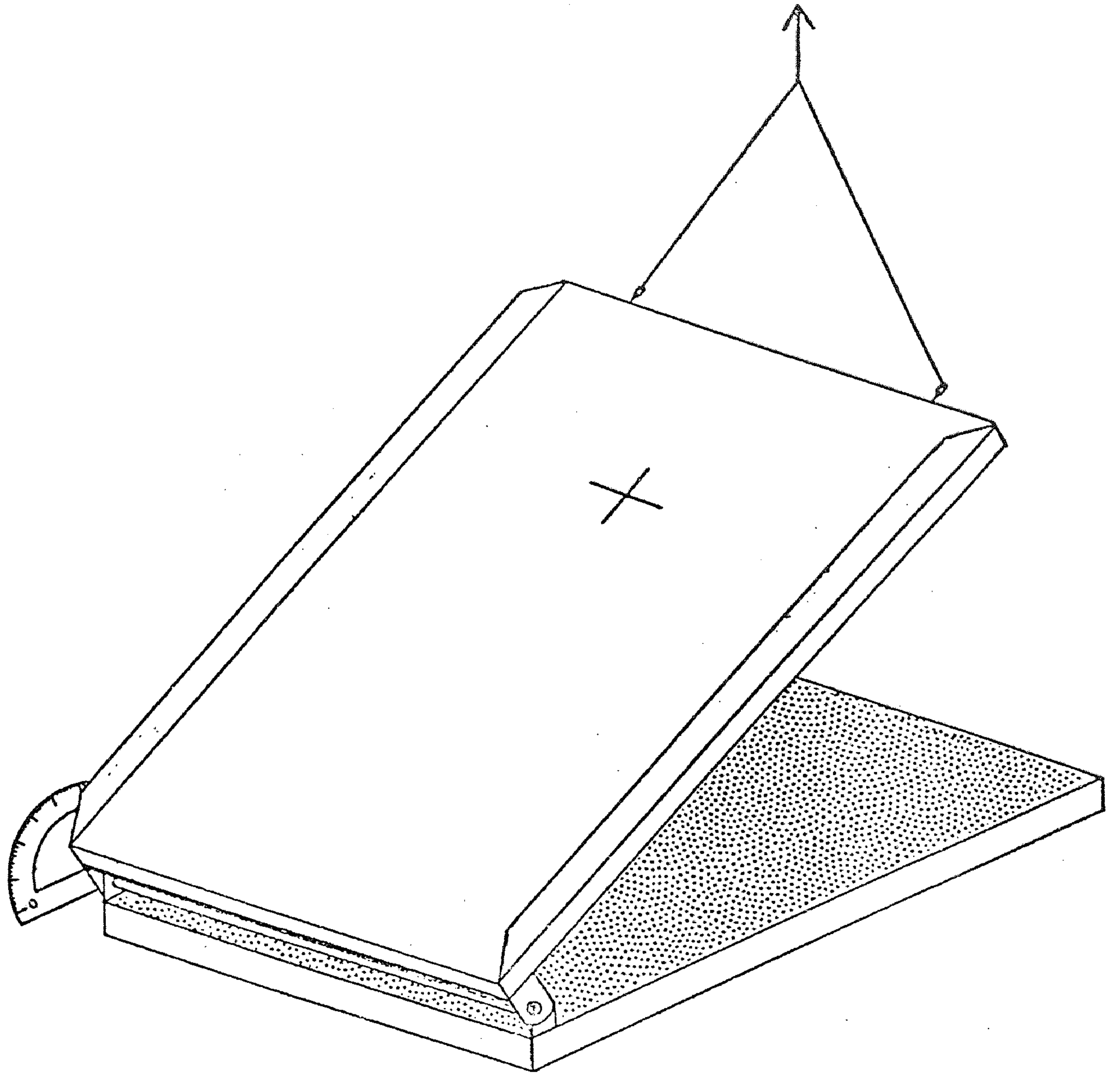
The apparatus used is a movable board hinged at one end to a similar base board. The upper movable board can be inclined from 0-90 degrees. This can be done mechanically with a ratchet motion or manually with a smooth, constant motion (Fig. 6). The sample material is placed on the upper board which is in the horizontal position. It then is raised at a slow uniform rate. The apparatus enables one to determine the angle of inclination at which particles of different shape begin to slide.

The movement of particles on the inclined surface, reflects some combination of sliding and rolling friction. It is believed that the angular material (with greater surface area) will have greater frictional resistance and remain on the board for greater angles of inclination. Thus, the degree of angularity can be represented by the angle of inclination of the board.

Several parameters were varied in order to determine whether a greater range in angularity rating could be induced. The board's surface texture was varied, e.g. stainless steel, wood, and sanded wood surfaces were used. Since the amount of friction depends upon the surface character of both the particles and the inclined board.

Fig. 6

ANGULARITY RATING METHOD -I
(FRICTION BOARD)



Also, the sample size distribution was varied,e.g. graded and uniform size fractions were used.

Particle shape and surface texture influence the amount of friction between the surface of the inclined board and the particles resting upon it. These particle properties were thought to be significant enough to be the basis for an angularity rating system.

Data Presentation Method - 1

ANGULARITY TEST # 1 - METHOD I

Surface of Friction Board - Wood Surface
Method of Raising Board - Ratchet Motion
Sample Material - Pure Quartz
Size Fraction - 50 gm each of (¼, 4, 10, 40, 70 200) sieves totalling 300 gm.
Comments - Mixed after each run to insure Uniform results

ROUNDED	ANGULAR
Test 1 22 - First Movement 32 - Bulk Movement 49 - Total Removal	Test 1 28 - First Movement 34 - Bulk Movement 55 - Total Removal
Test 2 25 - First Movement 32 - Bulk Movement 47 - Total Removal	Test 2 30 - First Movement 33 - Bulk Movement 56 - Total Removal
Test 3 20 - First Movement 33 - Bulk Movement 48 - Total Removal	Test 3 29 - First Movement 34 - Bulk Movement 54 - Total Removal
Test 4 19 - First Movement 33 - Bulk Movement 46 - Total Removal	Test 4 31 - First Movement 35 - Bulk Movement 56 - Total Removal
Test 5 24 - First Movement 34 - Bulk Movement 49 - Total Removal	Test 5 29 - First Movement 34 - Bulk Movement 54 - Total Removal
Test 6 25 - First Movement 32 - Bulk Movement 48 - Total Removal	Test 6 28 - First Movement 34 - Bulk Movement 56 - Total Removal
Test 7 20 - First Movement 32 - Bulk Movement 47 - Total Removal	Test 7 26 - First Movement 35 - Bulk Movement 58 - Total Removal
Test 8 21 - First Movement 34 - Bulk Movement 49 - Total Removal	Test 8 28 - First Movement 34 - Bulk Movement 55 - Total Removal
Test 9 24 - First Movement 33 - Bulk Movement 47 - Total Removal	Test 9 27 - First Movement 35 - Bulk Movement 58 - Total Removal
Test 10 25 - First Movement 34 - Bulk Movement 49 - Total Removal	Test 10 24 - First Movement 33 - Bulk Movement 54 - Total Removal
ROUNDED AVERAGE 22.5 - First Movement 32.9 - Bulk Movement 47.9 - Total Removal	ANGULAR AVERAGE 28.0 - First Movement 34.1 - Bulk Movement 55.6 - Total Removal

Table 1

Data Presentation Method - I

ANGULARITY TEST # 2 - METHOD I

Surface of Friction Board - Wood Surface
Method of Raising Board - Smooth, Constant Motion
Sample Material - Pure Quartz
Size Fractions - 50 gm each of (+ ¼, 4, 10, 40, 70, 200) totalling 300 gm
Comments - Mixed after each run to insure uniform results

ROUNDED	ANGULAR
Test 1 22 - First Movement 33 - Bulk Movement 47 - Total Removal	Test 1 24 - First Movement 35 - Bulk Movement 57 - Total Removal
Test 2 20 - First Movement 33 - Bulk Movement 49 - Total Removal	Test 2 26 - First Movement 33 - Bulk Movement 56 - Total Removal
Test 3 26 - First Movement 34 - Bulk Movement 49 - Total Removal	Test 3 30 - First Movement 34 - Bulk Movement 55 - Total Removal
Test 4 21 - First Movement 32 - Bulk Movement 48 - Total Removal	Test 4 27 - First Movement 36 - Bulk Movement 57 - Total Removal
Test 5 24 - First Movement 34 - Bulk Movement 49 - Total Removal	Test 5 29 - First Movement 34 - Bulk Movement 58 - Total Removal
Test 6 25 - First Movement 34 - Bulk Movement 50 - Total Removal	Test 6 28 - First Movement 36 - Bulk Movement 58 - Total Removal
Test 7 24 - First Movement 34 - Bulk Movement 48 - Total Removal	Test 7 31 - First Movement 35 - Bulk Movement 59 - Total Removal
Test 8 22 - First Movement 33 - Bulk Movement 49 - Total Removal	Test 8 30 - First Movement 34 - Bulk Movement 54 - Total Removal
Test 9 19 - First Movement 33 - Bulk Movement 49 - Total Removal	Test 9 30 - First Movement 34 - Bulk Movement 56 - Total Removal
Test 10 25 - First Movement 32 - Bulk Movement 48 - Total Removal	Test 10 28 - First Movement 35 - Bulk Movement 58 - Total Removal
ROUNDED AVERAGE 22.8 -First Movement 33.2 -Bulk Movement 48.6 -Total Removal	ANGULAR AVERAGE 28.3 - First Movement 34.6 - Bulk Movement 56.8 - Total Removal

Table 2

Data Presentation Method - I

ANGULARITY TEST # 3 - METHOD I

Surface of Friction Board - Wood Surface (Sanded)
Method of Raising Board - Rachet Motion
Sample Material - Pure Quartz
Size Fractions - ¼ sieve totalling 300 gm

ROUNDED	ANGULAR
Test 1 18 - First Movement 33 - Bulk Movement 38 - Total Removal	Test 1 26 - First Movement 34 - Bulk Movement 36 - Total Removal
Test 2 19 - First Movement 32 - Bulk Movement 37 - Total Removal	Test 2 20 - First Movement 34 - Bulk Movement 36 - Total Removal
Test 3 18 - First Movement 33 - Bulk Movement 37 - Total Removal	Test 3 27 - First Movement 34 - Bulk Movement 38 - Total Removal
Test 4 17 - First Movement 34 - Bulk Movement 38 - Total Removal	Test 4 24 - First Movement 35 - Bulk Movement 36 - Total Removal
Test 5 18 - First Movement 33 - Bulk Movement 38 - Total Removal	Test 5 26 - First Movement 34 - Bulk Movement 39 - Total Removal
Test 6 19 - First Movement 32 - Bulk Movement 36 - Total Removal	Test 6 22 - First Movement 33 - Bulk Movement 36 - Total Removal
Test 7 21 - First Movement 34 - Bulk Movement 39 - Total Removal	Test 7 24 - First Movement 34 - Bulk Movement 38 - Total Removal
Test 8 19 - First Movement 32 - Bulk Movement 37 - Total Removal	Test 8 22 - First Movement 33 - Bulk Movement 36 - Total Removal
Test 9 20 - First Movement 33 - Bulk Movement 36 - Total Removal	Test 9 24 - First Movement 34 - Bulk Movement 38 - Total Removal
Test 10 17 - First Movement 34 - Bulk Movement 37 - Total Removal	Test 10 19 - First Movement 36 - Bulk Movement 42 - Total Removal
ROUNDED AVERAGE 18.6 - First Movement 33.0 - Bulk Movement 37.3 - Total Removal	ANGULAR AVERAGE 23.4 - First Movement 34.1 - Bulk Movement 37.5 - Total Removal

Table 3

Data Presentation Method-1

ANGULARITY TEST # 4 - METHOD I

Surface of Friction Board - Wood Surface (sanded)
Method of Raising Board - Smooth, Constant Motion
Sample Material - Pure Quartz
Size Fractions - +¼ sieve totalling 300 gm

ROUNDED	ANGULAR
Test 1 18 - First Movement 34 - Bulk Movement 37 - Total Removal	Test 1 28 - First Movement 34 - Bulk Movement 37 - Total Removal
Test 2 19 - First Movement 33 - Bulk Movement 38 - Total Removal	Test 2 19 - First Movement 34 - Bulk Movement 36 - Total Removal
Test 3 19 - First Movement 32 - Bulk Movement 39 - Total Removal	Test 3 21 - First Movement 35 - Bulk Movement 39 - Total Removal
Test 4 21 - First Movement 34 - Bulk Movement 40 - Total Removal	Test 4 24 - First Movement 34 - Bulk Movement 39 - Total Removal
Test 5 19 - First Movement 36 - Bulk Movement 39 - Total Removal	Test 5 22 - First Movement 35 - Bulk Movement 38 - Total Removal
Test 6 18 - First Movement 33 - Bulk Movement 40 - Total Removal	Test 6 26 - First Movement 33 - Bulk Movement 36 - Total Removal
Test 7 19 - First Movement 34 - Bulk Movement 38 - Total Removal	Test 7 24 - First Movement 34 - Bulk Movement 38 - Total Removal
Test 8 20 - First Movement 33 - Bulk Movement 38 - Total Removal	Test 8 27 - First Movement 36 - Bulk Movement 38 - Total Removal
Test 9 19 - First Movement 33 - Bulk Movement 36 - Total Removal	Test 9 23 - First Movement 34 - Bulk Movement 38 - Total Removal
Test 10 19 - First Movement 32 - Bulk Movement 35 - Total Removal	Test 10 24 - First Movement 36 - Bulk Movement 42 - Total Removal
ROUNDED AVERAGE 19.1 - First Movement 33.4 - Bulk Movement 38.0 - Total Removal	ANGULAR AVERAGE 23.8 - First Movement 34.5 - Bulk Movement 38.1 - Total Removal

Table 4

Data Presentation Method-1

ANGULARITY TEST # 5 - METHOD I

Surface of Friction Board - Stainless Steel
Method of Raising Board - Rachet Motion
Sample Material - Pure Quartz
Size Fractions - 50 gm each of (+ ¼, 4, 10, 40, 70, 200) sieves totalling 300 gm
Comments - Mixed after each run to insure uniform results

ROUNDED	ANGULAR
Test 1 15 - First Movement 19 - Bulk Movement 22 - Total Removal	Test 1 20 - First Movement 22 - Bulk Movement 27 - Total Removal
Test 2 14 - First Movement 20 - Bulk Movement 24 - Total Removal	Test 2 19 - First Movement 21 - Bulk Movement 26 - Total Removal
Test 3 14 - First Movement 17 - Bulk Movement 20 - Total Removal	Test 3 17 - First Movement 20 - Bulk Movement 25 - Total Removal
Test 4 15 - First Movement 20 - Bulk Movement 24 - Total Removal	Test 4 19 - First Movement 22 - Bulk Movement 26 - Total Removal
Test 5 13 - First Movement 20 - Bulk Movement 24 - Total Removal	Test 5 15 - First Movement 21 - Bulk Movement 27 - Total Removal
Test 6 15 - First Movement 21 - Bulk Movement 24 - Total Removal	Test 6 18 - First Movement 20 - Bulk Movement 26 - Total Removal
Test 7 16 - First Movement 19 - Bulk Movement 22 - Total Removal	Test 7 17 - First Movement 20 - Bulk Movement 24 - Total Removal
Test 8 12 - First Movement 17 - Bulk Movement 21 - Total Removal	Test 8 19 - First Movement 21 - Bulk Movement 25 - Total Movement
Test 9 17 - First Movement 20 - Bulk Movement 23 - Total Removal	Test 9 20 - First Movement 24 - Bulk Movement 27 - Total Removal
Test 10 15 - First Movement 19 - Bulk Movement 23 - Total Removal	Test 10 19 - First Movement 22 - Bulk Movement 25 - Total Removal
ROUNDED AVERAGE 14.6 - First Movement 19.2 - Bulk Movement 22.7 - Total Removal	ANGULAR AVERAGE 19.0 - First Movement 22.0 - Bulk Movement 25.0 - Total Removal

Table 5

Data Presentation Method-1

ANGULARITY TEST # 6 - METHOD I

Surface of Friction Board - Stainless Steel
Method of Raising Board - Smooth, Constant Motion
Sample Material - Pure Quartz
Size Fractions - 50 gm each of (+¼, 4, 10, 40, 70, 200) totalling 300 gm
Comments - Mixed after each run to insure uniform results

ROUNDED	ANGULAR
Test 1 17 - First Movement 23 - Bulk Movement 26 - Total Removal	Test 1 20 - First Movement 26 - Bulk Movement 28 - Total Removal
Test 2 15 - First Movement 24 - Bulk Movement 24 - Total Removal	Test 2 23 - First Movement 26 - Bulk Movement 28 - Total Removal
Test 3 15 - First Movement 24 - Bulk Movement 27 - Total Removal	Test 3 18 - First Movement 22 - Bulk Movement 36 - Total Removal
Test 4 15 - First Movement 23 - Bulk Movement 24 - Total Removal	Test 4 20 - First Movement 24 - Bulk Movement 26 - Total Removal
Test 5 14 - First Movement 23 - Bulk Movement 26 - Total Removal	Test 5 19 - First Movement 24 - Bulk Movement 27 - Total Removal
Test 6 16 - First Movement 24 - Bulk Movement 25 - Total Removal	Test 6 21 - First Movement 25 - Bulk Movement 28 - Total Removal
Test 7 13 - First Movement 23 - Bulk Movement 25 - Total Removal	Test 7 19 - First Movement 26 - Bulk Movement 28 - Total Removal
Test 8 16 - First Movement 23 - Bulk Movement 25 - Total Removal	Test 8 22 - First Movement 27 - Bulk Movement 30 - Total Removal
Test 9 15 - First Movement 23 - Bulk Movement 25 - Total Removal	Test 9 18 - First Movement 22 - Bulk Movement 25 - Total Removal
Test 10 16 - First Movement 24 - Bulk Movement 26 - Total Removal	Test 10 23 - First Movement 26 - Bulk Movement 28 - Total Removal
ROUNDED AVERAGE 15.2 - First Movement 23.4 - Bulk Movement 25.3 - Total Removal	ANGULAR AVERAGE 20.3 - First Movement 24.8 - Bulk Movement 27.4 - Total Removal

Table 6

Data Summary Presentation Method-I

SUMMARY OF RESULTS OF ANGULARITY TESTS USING METHOD I

TEST # 1 - Using wood surface, ratchet motion, and 300 gm of graded sample.

Average of rounded sample for bulk movement - 32.9
Average of angular sample for bulk movement - 34.1

TEST # 2 - Using wood surface, smooth motion, and 300 gm of graded sample.

Average of rounded sample for bulk movement - 33.2
Average of angular sample for bulk movement - 34.6

TEST # 3 - Using sanded wood surface, ratchet motion, and 300 gm of uniform ¼ in. sieve.

Average of rounded sample for bulk movement - 33.0
Average of angular sample for bulk movement - 34.1

TEST # 4 - Using sanded wood surface, smooth motion, and 300 gm of uniform ¼ in. sieve.

Average of rounded sample for bulk movement - 33.4
Average of angular sample for bulk movement - 34.5

TEST # 5 - Using Stainless steel surface, ratchet motion, and 300 gm of graded sample.

Average of rounded sample for bulk movement - 19.2
Average of angular sample for bulk movement - 21.3

TEST # 6 - Using Stainless steel surface, smooth motion, and 300 gm of graded sample.

Average of rounded sample for bulk movement - 23.4
Average of angular sample for bulk movement - 24.8

Overall average of rounded sample for bulk movement - 29.2
Overall average of angular sample for bulk movement - 30.5

Overall average of rounded samples for bulk movement on wood surface - 33.1

Overall average of angular samples for bulk movement on wood surface - 34.3

Overall average of rounded samples for bulk movement on steel surface - 21.3

Overall average of angular samples for bulk movement on steel surface - 23.0

Table 7

Discussion of Results and Recommendations - Method I

Stainless steel was believed to be the best surface material for the friction board because of its hardness, and general durability, e.g. resistance to oxidation. It was hoped that this surface material would guarantee reproducibility or uniformity of test results. Unfortunately, the smoothness of the steel surface did not provide a sufficient frictional quality. Wood, slightly roughened by sandpaper, although much softer and more susceptible to abrasion provided the best overall frictional surface. But even with this most successful surface material, the range between the angular and rounded samples at best was only about 2 or 3 degrees (Tables 1-7).

The board length and the ratchet mechanism used to incline the board inhibited progress in establishing angularity variations. The ratchet device used to incline the board resulted in uneven or jerky motion which caused premature sliding. No significant relationships were observed between particle shape and frictional behavior. It is believed that this was in part due to the short length of the board. The magnitude of the variations in board angle between rounded and angular samples was minimal, and thought to be insufficient to develop and adequate rating system. The limitations which were observed during the experimental testing with Method I lead to the development of Method II and III.

Observations made on the mode of movement of rounded pebbles follow. Disc-shaped (two long and one short diameter) pebbles on steep grades were oriented such that the longer diameters were parallel to the surface of the board. These disc-shaped pebbles generally move by sliding. If they do roll, they roll around the longer of the two long diameters. When they come to rest, the shorter of the two long diameters are oriented in the direction of travel. In addition, disc-shaped pebbles with centers of gravity much to one end of the grain tend to come to rest with the larger half of the grain towards the bottom of the inclined board, thus attaining greater stability. Pebbles ellipsoidal (two short and one long diameter) in shape roll around the longest axis which is horizontal in position. When these ellipsoidal shaped pebbles come to rest, they are oriented with their longest axis horizontal and perpendicular to the direction of movement.

Both angular and rounded particles come to rest on surfaces of greatest area which are parallel to the surface of the board. The rounded particles roll down, and toward the sides of the board. Whereas, the angular samples slide predominantly straight down the length of the board.

Nearly all samples tested moved down the board in a series of three movements: the first being a slight initial instability; the second, a bulk or mass movement that accounted for the majority of the sample; and finally, the movement of the small remaining portion of the sample. Angular samples usually attained each of these three distinct movements at higher angles than rounded samples (Tables 1-7). The particles which moved during the initial instability were larger size fractions. Whereas, the last particles to remain on the inclined surface were those of smaller sizes.

It was noticed that the overall average for bulk movement of samples on the wooden surface was 34 degrees (Table 7). It is interesting to note that the leeward slope of a sand dune is also characteristically 34 degrees (Krynine and Judd, 1957). This angle being the angle of repose. The angle of repose for a clean, dry, cohesionless material is the steepest slope of stability, that is the angle of friction in the loose state. Dune sand consists predominantly of quartz fragments which is identical to the material being tested on the friction board. If the observation is not merely a coincidence that quartz both on the friction board and in nature have exactly the same angle, then it would be logical to assume that the friction board reflects to some extent the angle of repose of that material.

Results from Van Burkalow's (1945) experiments show that the angle of repose of soil fragments varies directly with angularity and surface roughness - all other factors remaining constant. And that specifically, the two elements of shape that affect the angle of repose are sphericity and roundness. Van Burkalow states that the more nearly spherical the fragments, the more gentle the slope of repose. And that among irregular shapes, the more rounded the fragments, the more gentle the slope of repose. As concerns the surface texture of fragments, the smoother the surface the more gentle the slope of repose. In addition she states that the angle of sliding friction (the critical angle of particle movement on an inclined board) varies directly with shape and surface roughness. This suggests that the angle of repose is an index of the angularity and surface texture of cohesionless material which is reflected on the friction board.

Assuming that shape and surface texture dominate the frictional characteristics created between cohesionless particles, then the natural angle of repose can be used as an angularity index. The angles forming the sides of a pile would give some indication of the particle's shape and perhaps surface texture. Unfortunately, it is not so simple. Careful measurements by Morris (1959) on a number of piles formed from an overhead opening at varying heights indicate that the natural angle of repose of cohesionless materials varies by as much as 8 degrees around the same pile.

Perhaps, the angle of repose could be measured more accurately by modifying the technique utilizing the friction board described in Method I. The modified friction board would have to produce surficial particle movement which would take place only when the frictional effect between the particles themselves is overcome. According to Tan (1947) the angle of repose of a cohesionless soil is an entirely superficial phenomenon. It should then magnify the influence of particle shape and texture. Surficial particle movement is controlled by the combined effect of shape and texture. Such conditions could be achieved by gluing a thin layer of the sample to be tested on a piece of cardboard, and attaching this cardboard to the horizontal surface of the friction board. The sample being tested would be placed on "itself", and slowly raised at a smooth, uniform rate until sliding occurs. In this manner, the frictional behavior will be restricted to the particles themselves. Thus eliminating the influence of the board surface - and additional variable. It is believed that such a proposed angularity rating system would clarify the frictional relationships associated with the different particle shapes and might serve as a future angularity index.

5 - ANGULARITY RATING METHOD II (INCLINED BOARD WITH CALIBRATED ROTATING DISC)

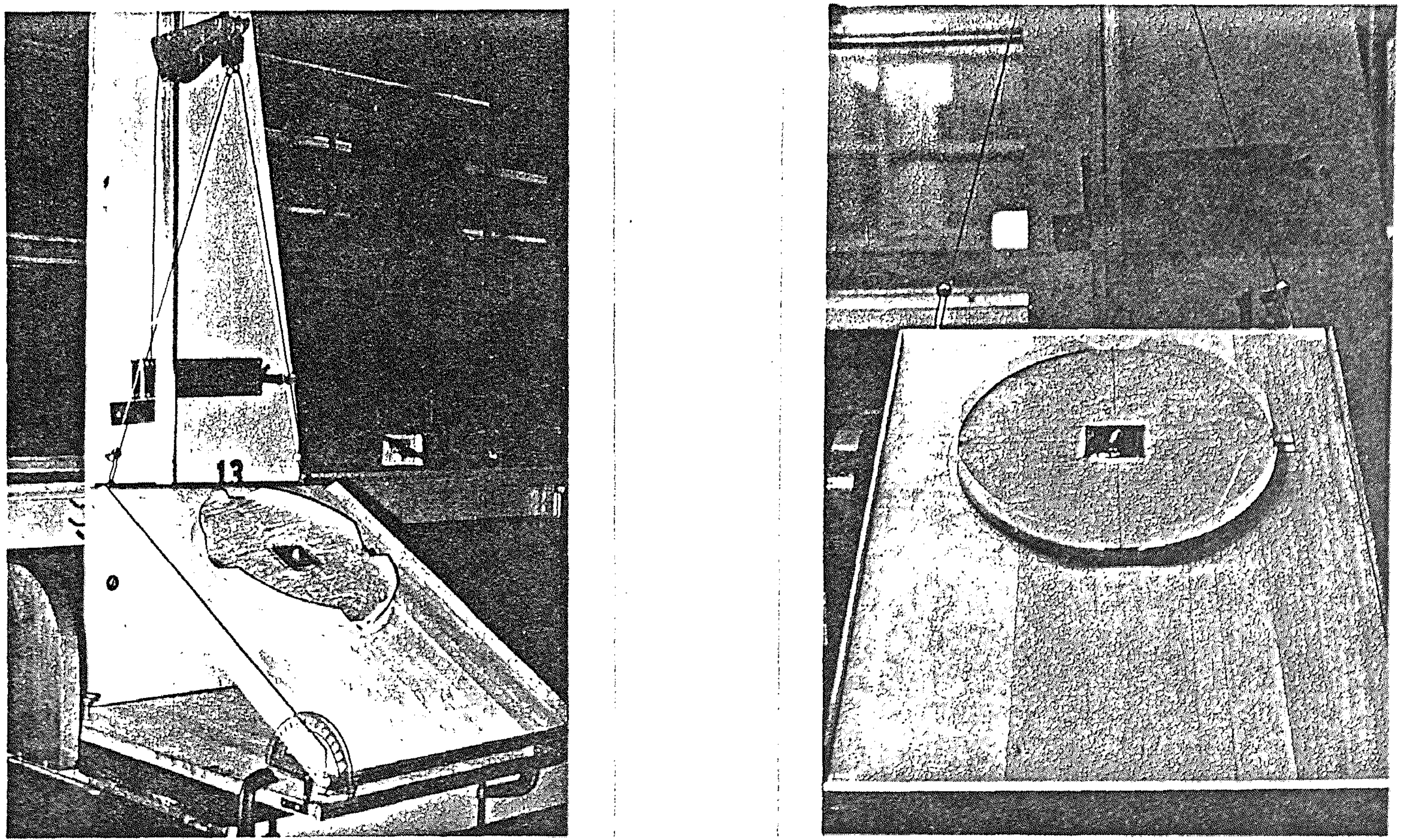
Description of Experimental Apparatus and Testing Procedure

The apparatus used is similar in principle to the friction board used in Method I, except for the addition of a rotating wooden disc (Fig. 7). The disc ten inches in diameter was attached flush to the surface of the upper movable board. By the addition of a felt cushion to the underside of the disc, resistance was added to the rotating motion in order to control the motion of the disc more easily. The central area of the disc where the particle is tested was covered with a thin foam rubber sheet. This surface material rendered favorable and consistent results and was employed to increase frictional resistance. Around the circumference of the disc calibrations were added on the surface of the friction board so that the amount of rotation could be measured in degrees. The circle was divided into four quadrants and calibrated with gradations every 5 degrees (Fig. 7).

Each side of every sample particle being tested for stability was rotated through the four quadrants at every desired angle of board inclination. The total number out of 360 degrees that a side was stable upon rotation was the stability value for that particular side. The total stability value for the particle at a given board

FIG. 7

ANGULARITY RATING METHOD II, BOARD WITH DISC



inclination is the sum of the total number of degrees of stability out of 360 for each side of the particle. Testing a particle on each one of its sides by rotating it through 360 degrees provides a complete description of the particle's behavior that is affected by the different centers of gravity for each side at any given inclination relative to the board.

A major procedural change incorporated in Method II is the individual testing of a particle instead of utilizing a mass of soil. It is believed that when a truly representative particle is chosen, it will justly depict the angularity of the entire soil mass being tested. A great number of trials on a large number of particles statistically improves the rating. Another change in procedure that proved to be more satisfactory was that of setting the board incline before placing the sample on the board. This was a distinct improvement over the previous reverse method which inevitably caused premature sliding and generally poorer results.

The underlying assumption of this rating system is that the greater the angularity of a particle the greater the stability. One hundred percent stability of a particle at any board inclination is defined as the ability to remain on one side without sliding, rolling, or tipping onto another side through a 360 degree rotation of the disc.

The stability of a particle at any board inclination is determined as follows. First, the number of sides is determined. This is necessary because each side must be tested individually for stability. A side is defined as a surface of a particle that is capable of supporting the particle on a horizontal plane. Therefore, the number of sides is determined by the number of faces on which a particle is stable on a flat surface. To repeat, the combined stability of each side represents the total stability of a particle at any given board inclination. Once the number of sides has been established, they are marked for later identification.together with an arrow on each side for orientation purposes.

Testing a particle's stability begins in the horizontal position in which a particle by definition must be 100 percent stable on all sides upon a 360 degree rotation. The next step is raising the inclination of the board 5 degrees. It was judged that 5 degree intervals were suitable angle increments until a more critical range of stability loss (steeper angles) was reached. At this time, the board was raised one degree at a time for a more precise definition of the stability of the particle. Next, the particle being rated was placed in the center of the disc with side number one up, arrow pointing north or to the top of the inclined board, and positioned on the

0 degree mark. The calibrations on the circle were such that rotation from N to E, or N to W, and S to E or S to W would be moving from 0 to 90 degrees in the respective quadrants. Then, the particle was rotated 90 degrees clockwise from the N to E position. If the particle slid, rolled or tipped before reaching the E position, the number of degrees before the instability ocurred was recorded. The arrow on the particle was then pointed to the E position and the same procedure was reversed, this time rotating counterclockwise from the E to N position. The total stability for that quadrant would be the sum of both the clockwise and counterclockwise stability readings.

On first consideration, it might seem unnecessary to test for stability in both the clockwise and counterclockwise directions for each quadrant. This was found to be necessary for several reasons. First, a particle may be stable or unstable for a number of degrees within a quadrant. A movement in only one direction would not necessarily detect the entire stability range within that quadrant. For example, if a particle is rotated clockwise from N to E and rolled at 30 degrees, it should not be immediately assumed that the particle would also be unstable in the remaining 60 degrees of that quadrant. The same particle rotated counterclockwise from E to N may initially exhibit stability and then roll after a 30 degree rotation toward the N. This example shows the necessity for both clockwise and counterclockwise movement. For if only one direction was used as an indication of stability for the quadrant, the stability rating for that quadrant would only be 30 degrees. When measured in both directions the true stability is shown to be 60 degrees with an intermediate 30 degree zone of instability.

The exact opposite situation would occur if an intermediate zone of stability existed within the quadrant, and instability at the extreme N and E positions. Similarly, this zone of intermediate stability must be identified and recorded for that quadrant. The above procedure should then be repeated for the remaining three quadrants. The sum of the stability readings of the four quadrants would only represent the total stability for one side of the particle at the 5 degree inclination. The entire procedure must be repeated for as many times as there are number of sides on each particle for every degree of inclination desired. Generally the accuracy or reproducibility of the stability determinations for any one side of a particle throughout a 360 degree rotation was found to be ± 5 degrees.

The maximum stability figure any particle can possess is 360 multiplied by the number of sides. Therefore, the reduction in stability with increasing inclination of the board can be calculated as a percent of this maximum vâlue. As an example, consider the stability determination of a four sided particle at a board inclination of 20 degrees. First of all, the particle's maximum stability would be (4 x 360) or 1140. Assume that side one has a total of 360 degree stability upon one full rotation. And sides two and three are identical; but, side four is only stable a total of 20 degrees out of 360. The total stability value for this particle at 20 degrees of board inclination would be (3 x 360 + 20) or 1100. The percent of maximum stability for this particle is 1100/1440 or 76.4 percent. That is, at a 20 degree board inclination the particle in question was stable 76.4 percent of the time.

Table 8

DATA PRESENTATION METHOD – II ANGULARITY RATING OF 7 ANGULAR QUARTZ PARTICLES RETAINED ON # $\frac{1}{4}$ SIEVE TOTALING 10 GRAMS

FRICTION BOARD ANGLE →	0°		5°		10°		15°		20°		25°		30°		31°		32°		33°		34°		35°		40°		45°		50°		55°		60°		65°		70°	
QUARTZ PARTICLE NUMBER ↓	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II
1	1800	100%	1515	84%	1480	82%	1465	81%	1315	73%	1015	56%	880	49%	880	49%	805	45%	800	44%	780	43%	770	43%	675	38%	470	26%	250	14%	55	3%	0	-	0	-	0	-
2	1800	100%	1585	88%	1510	84%	1335	74%	1180	66%	960	53%	860	48%	845	47%	835	46%	815	45%	790	43%	770	43%	710	39%	605	34%	435	24%	110	6%	0	-	0	-	0	-
3	1440	100%	1440	100%	1345	93%	1285	89%	1280	89%	1035	72%	910	63%	885	61%	860	60%	825	57%	790	55%	760	53%	600	42%	440	31%	165	13%	35	2%	0	-	0	-	0	-
4	1080	100%	1080	100%	1065	99%	985	91%	965	89%	875	81%	840	78%	830	77%	825	76%	825	76%	820	76%	815	75%	785	73%	695	64%	535	50%	410	38%	145	13%	80	7%	0	-
5	1080	100%	1080	100%	1080	100%	1025	95%	990	92%	990	92%	930	86%	905	84%	880	81%	855	79%	835	77%	815	75%	785	73%	735	68%	620	57%	370	34%	135	13%	20	2%	0	-
6	1440	100%	1440	100%	1440	100%	1320	92%	1295	90%	1200	83%	1140	79%	1135	79%	1125	78%	1105	77%	1075	75%	1055	73%	830	58%	620	43%	335	23%	115	8%	0	-	0	-	0	-
7	1800	100%	1700	94%	1630	91%	1485	83%	1380	77%	1100	61%	730	41%	730	41%	725	40%	715	40%	675	38%	660	37%	460	26%	280	16%	155	9%	50	3%	15	1%	0	-	0	-

I = SUM OF THE TOTAL STABILITY OF ALL SIDES IN DEGREES
II = TOTAL PARTICLE STABILITY IN PERCENT

$$\text{TOTAL PERCENT STABILITY OF A PARTICLE FOR A GIVEN ANGLE OF BOARD INCLINATION} = \frac{\text{SUM OF THE NUMBER OF DEGREES OF STABILITY WITH A 360 DEGREE ROTATION OF THE DISC FOR EACH SIDE OF THE PARTICLE}}{\text{IDEAL PERCENT STABILITY FOR THAT PARTICLE OR THE NUMBER OF SIDES x 360}} \times 100$$

Table 9

DATA PRESENTATION METHOD – II ANGULARITY RATING OF 7 ROUNDED QUARTZ PARTICLES RETAINED ON # $\frac{1}{4}$ SIEVE TOTALING 10 GRAMS

FRICTION BOARD ANGLE →	0°		5°		10°		15°		20°		25°		30°		31°		32°		33°		34°		35°		40°		45°		50°		55°		60°		65°		70°	
QUARTZ PARTICLE NUMBER ↓	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II
1	720	100%	720	100%	720	100%	475	66%	135	19%	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-
2	720	100%	720	100%	720	100%	650	90%	365	51%	185	26%	110	15%	105	15%	85	12%	80	11%	45	6%	25	3%	0	-	0	-	0	-	0	-	0	-	0	-	0	-
3	720	100%	720	100%	720	100%	720	100%	660	92%	620	86%	310	43%	175	24%	155	22%	120	17%	30	4%	25	3%	0	-	0	-	0	-	0	-	0	-	0	-	0	-
4	1080	100%	1080	100%	1040	96%	430	40%	115	11%	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-
5	1080	100%	1080	100%	785	73%	610	56%	435	40%	195	18%	10	1%	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-
6	720	100%	720	100%	720	100%	555	77%	270	38%	60	8%	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-
7	720	100%	720	100%	720	100%	720	100%	720	100%	470	65%	300	42%	215	30%	180	25%	165	23%	25	3%	20	3%	0	-	0	-	0	-	0	-	0	-	0	-	0	-

I = SUM OF THE TOTAL STABILITY OF ALL SIDES IN DEGREES
II = TOTAL PARTICLE STABILITY IN PERCENT

$$\text{TOTAL PERCENT STABILITY OF A PARTICLE FOR A GIVEN ANGLE OF BOARD INCLINATION} = \frac{\text{SUM OF THE NUMBER OF DEGREES OF STABILITY WITH A 360 DEGREE ROTATION OF THE DISC FOR EACH SIDE OF THE PARTICLE}}{\text{TOTAL PERCENT STABILITY FOR THAT PARTICLE OR THE NUMBER OF SIDES} \times 360} \times 100$$

Fig. 8

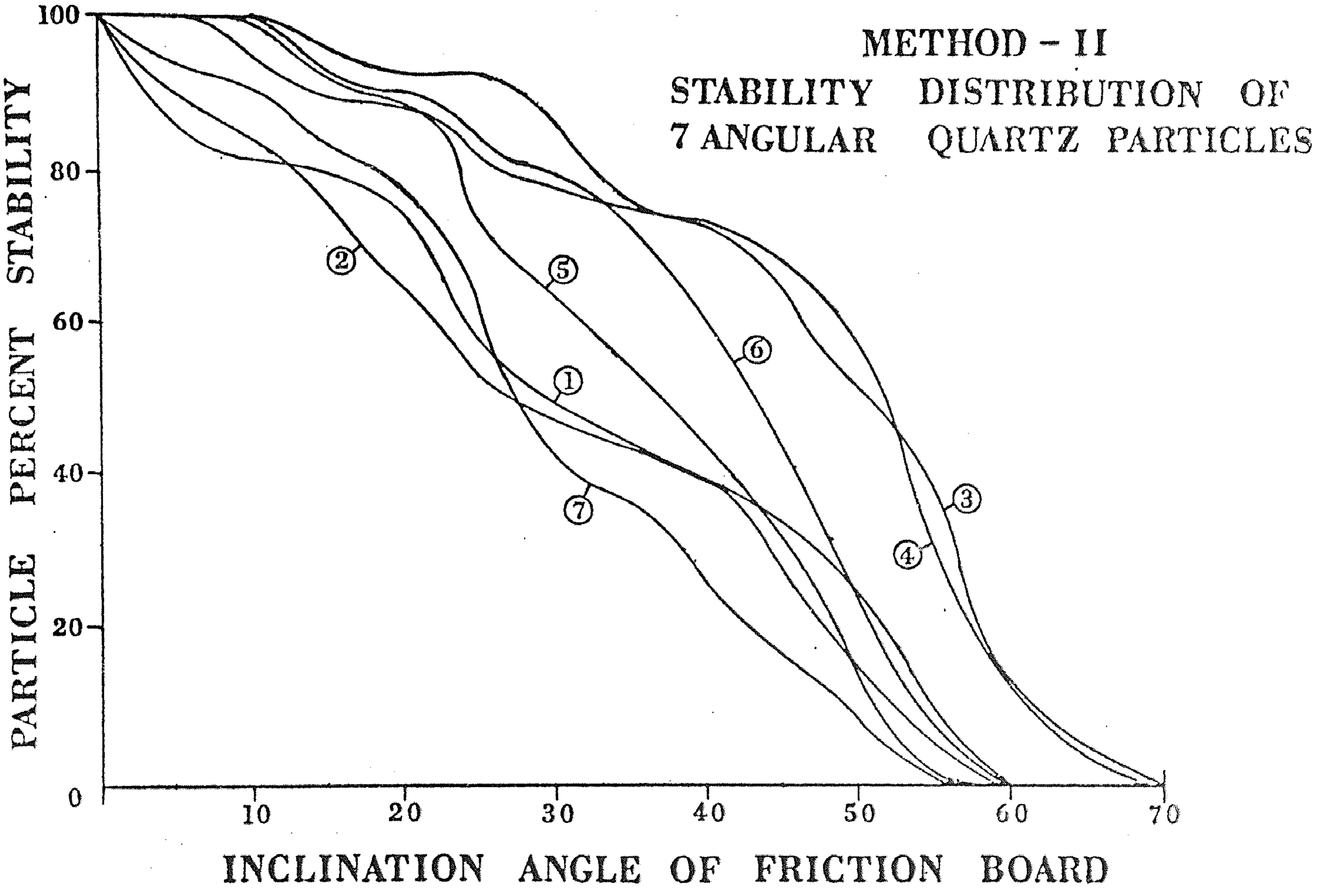
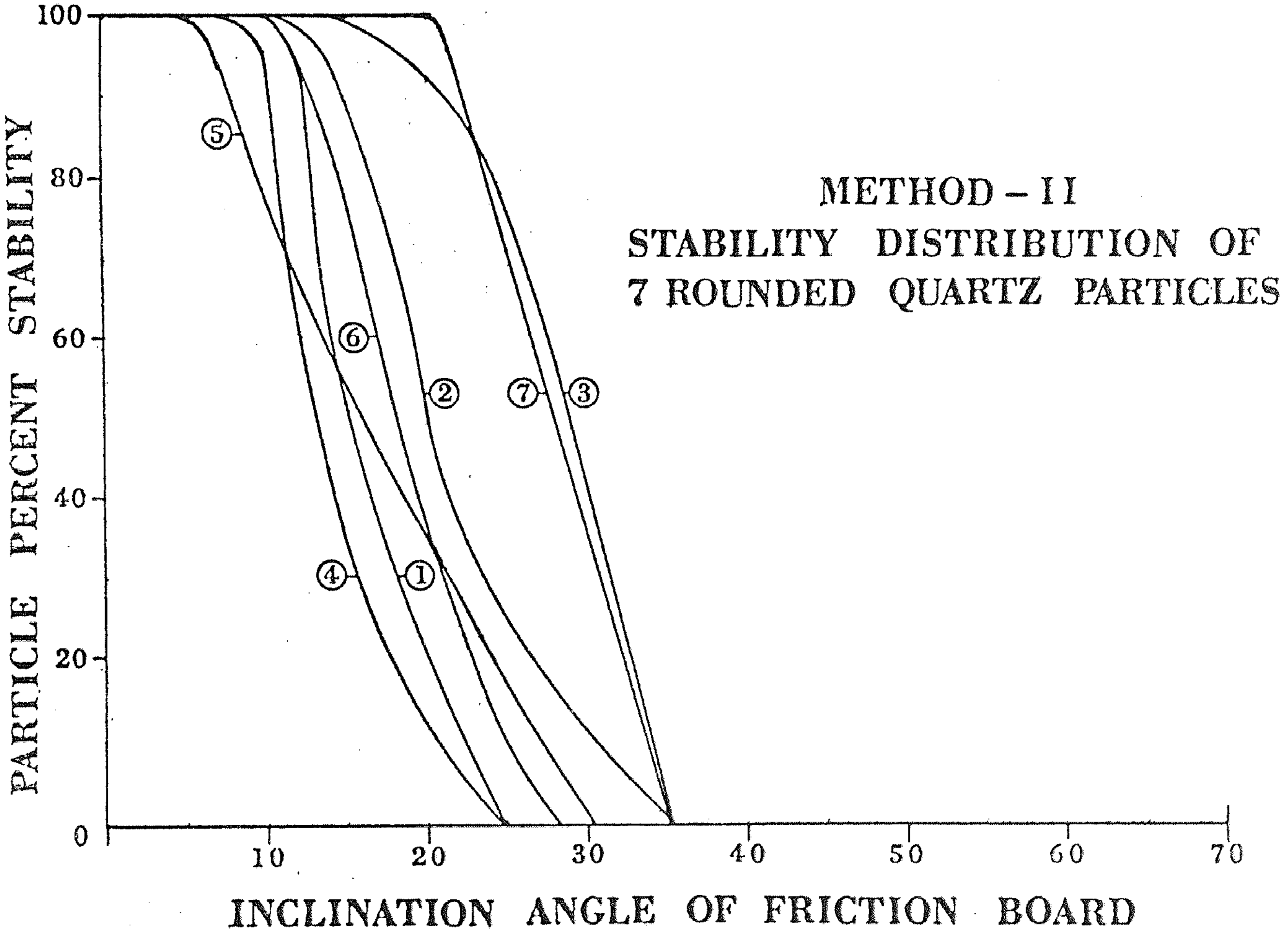

METHOD – II
STABILITY DISTRIBUTION OF
7 ANGULAR QUARTZ PARTICLES
PARTICLE PERCENT STABILITY
100
80
60
40
20
0
10
20
30
40
50
60
70
INCLINATION ANGLE OF FRICTION BOARD
①
②
③
④
⑤
⑥
⑦

Fig. 9



METHOD – II
STABILITY DISTRIBUTION OF
7 ROUNDED QUARTZ PARTICLES

Discussion of Results with Recommendations - Method II

The property being measured by this rating system is the total surface area of the particle. This will determine its stability regardless of the number of sides. The system is based on the assumption that the greater the angularity the greater the stability. The fact that surface area may be distributed over two predominant sides or six smaller ones is inconsequential. The maximum stability in both cases can still be measured and directly compared.

The sphere has an infinite number of sides and the smallest surface area to volume ratio. Hence the spherical shape is the least stable and has the lowest angularity rating. The other end member would be the particle having the smallest number of sides. Practically speaking a "two" sided platy particle respresents the other extreme. If a particle has only two predominant sides, it can be assumed that nearly its entire surface area is being justly represented by those two sides. The edges of this particle have little or no influence on the particle's overall stability. In principle, it is possible to make direct stability comparisons (angularity) between particles having various number of sides. In general, there is an inverse relationship between the number of sides and a particle's total stability; As the number of sides increase the stability decreases (Fig.10). And as the stability decreases so does the angularity rating.

The proposed rating index utilizing the data obtained from Method II is based on the general observation that angular particles lose their stability more gradually and at much higher angles of board inclination than do rounded particles. It is assumed that a perfectly sphericial particle will show instability at any angle of board inclination greater than zero. And conversely, a perfectly angular particle will show stability at any angle less than 90 degrees. These assumptions therefore establish the two extremes of angularity to be used in the index determinations (Tables 8 and 9).

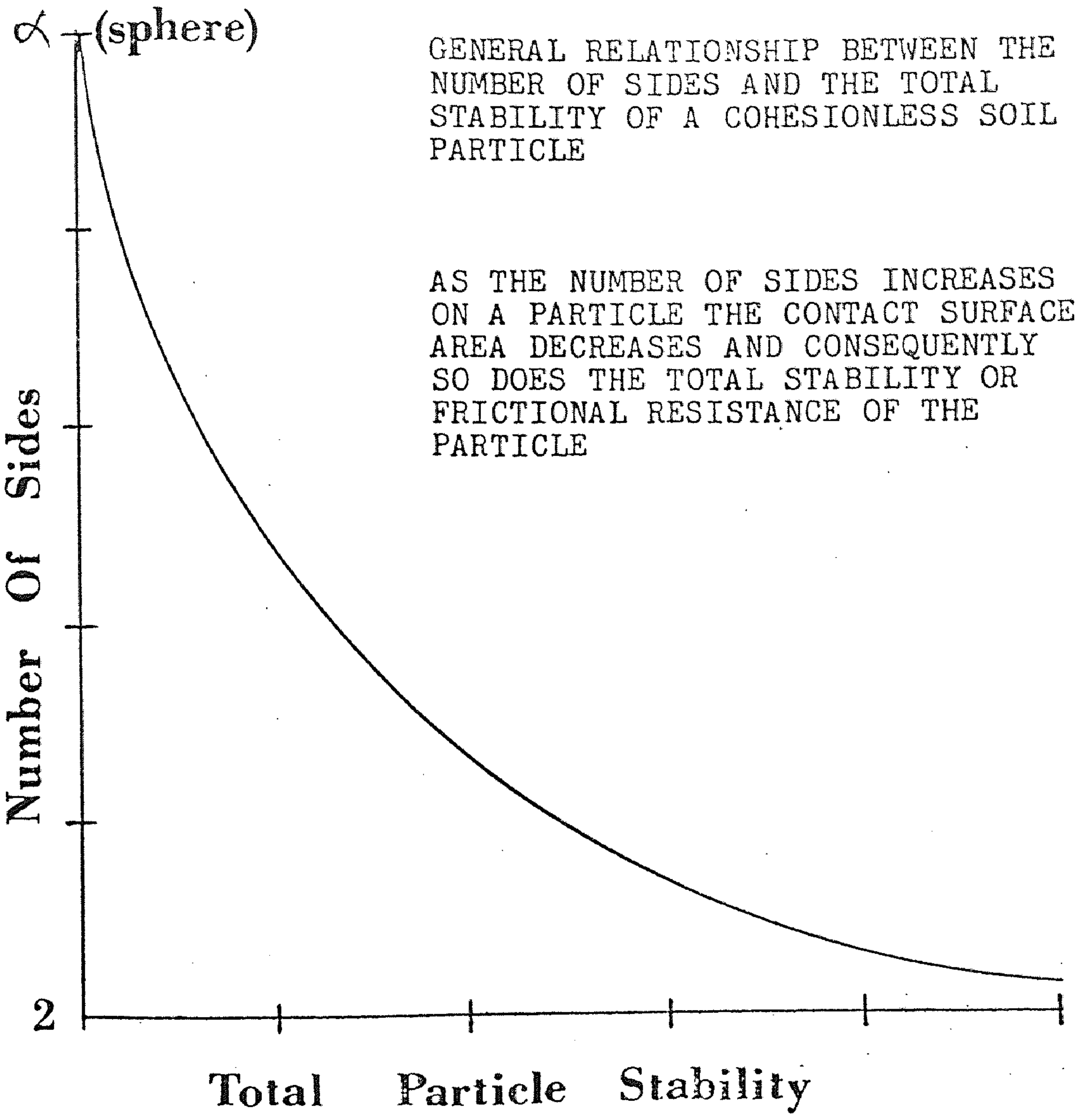
The first assumption that a sphere is able to roll at any angle greater than 0 degrees is easily understood. As previously mentioned, the ideally angular shape is a platy particle having only two predominant sides. The ideal platy particle with nearly 50 percent of its total surface area in direct contact (flush) with the board surface will remain stable on the board at high angles of inclination.

The stability distribution for a particle is easily visualized by plotting the angle of inclination for the board vs the total percent stability for the particle

Fig.10

Method-II

Number Of Sides vs. Stability



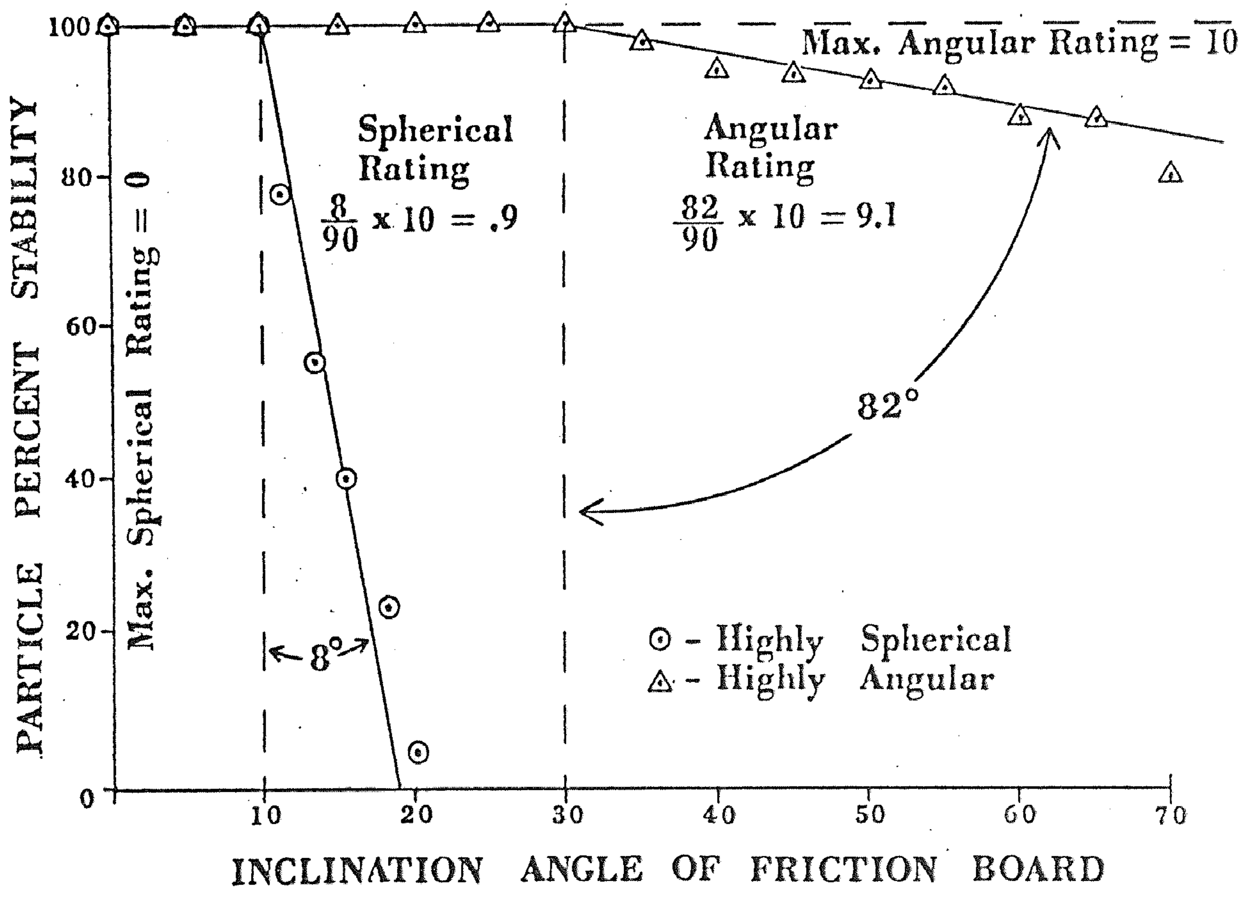
GENERAL RELATIONSHIP BETWEEN THE NUMBER OF SIDES AND THE TOTAL STABILITY OF A COHESIONLESS SOIL PARTICLE

AS THE NUMBER OF SIDES INCREASES ON A PARTICLE THE CONTACT SURFACE AREA DECREASES AND CONSEQUENTLY SO DOES THE TOTAL STABILITY OR FRICTIONAL RESISTANCE OF THE PARTICLE (percent stability placed on the y-axis and the board inclination on the x-axis). A spherical particle will approach a vertical representation on the graph and a very angular particle will converge on the horizontal (Fig. 8 and 9).

A rating index can be formulated with this information. The index range can be fixed on a scale from 1-10 assigning 10 to the state of maximum angularity. To establish an index rating the following procedure should be followed. First, plot the data for a particle on a graph as described above. Draw a straight line through the major concentration of points (fit the data to a straight line) approximating the stability distribution for that particle. Measure the angle it forms with the vertical. By allowing an angle of 90 degrees to represent the maximum angularity index of 10 any other variation in shape can be rated accordingly.(Fig. 11). The angle measured from the vertical divided by 90 and multiplied by 10 will result in the index rating value from 1-10 for any shaped particle. For example, if the measured angle for a spherical particle was 8 degrees from the vertical its angularity rating would be 8/90 x 10 or 0.9, reflecting a highly spherical shape. On the other hand, if the measured angle for an angular particle was 82 degrees from the vertical its rating index would be 82/90 x 10 or 9.1, indicating its angular shape (Fig. 11).

Fig. 11

METHOD - II
GRAPHICAL ANGULARITY RATING



This angularity index, therefore, really represents the rate at which instability is achieved which in turn describes the particle shape. That is, a gradual display of instability would indicate an angular particle where as a rapid instability would represent a nearly spherical particle. Perhaps, the greatest limitation of this rating technique is its time consuming nature. This may make it impractical as a field index tool for soils. Method III which follows evolved as a solution to this problem.

In conclusion, if this method was to be standardized for rating angularity two minor modifications should be made to eliminate human error and insure more consistent results. First it is suggested that a more reliable technique be developed to measure the angle of board inclination; and second that the wooden disc should be mechanically driven in order to provide a more uniform circular motion.

6 - ANGULARITY RATING METHOD III (DISTANCE ROLLED)

Description of Experimental Apparatus and Testing Procedure

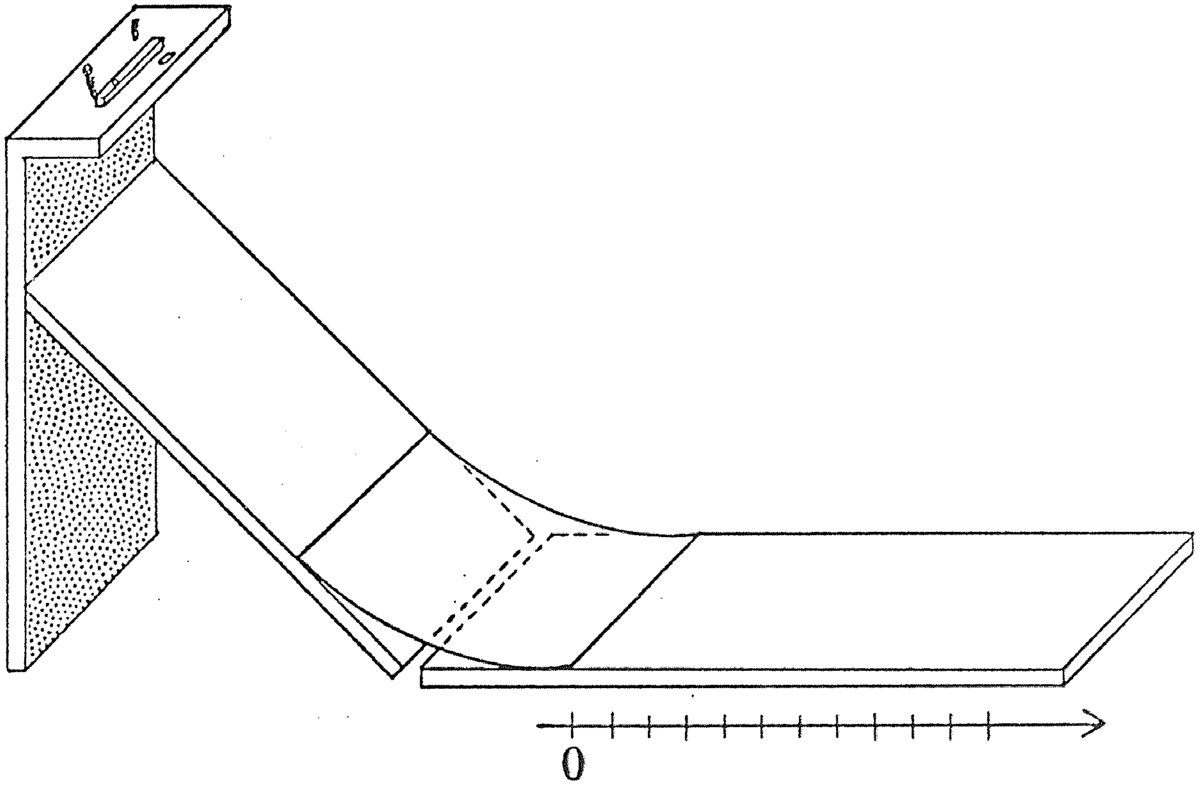
The friction board employed in Method I measured only one particle property. This property being the particle static friction. Different shaped particles exhibited similar relationships, probably due to the inappropriate length of the board. Such similarity in behavior of particles of different shape essentially masked any variations that might have been brought about by variations in the sliding and rolling friction of different shaped particles.

The apparatus used in rating Method III was designed to measure the relationships between sliding and/or rolling friction and particle shape. The rating measurements were made under conditions in which the effects of static friction were totally excluded. The procedure used to overcome the effect of particle static friction was to trigger each particle with an equal initial force. The force was initiated by mechanically triggering each particle off a platform of a set height onto an inclined board directly below. Ejecting the particle in this manner guaranteed uniformity of initial particle momentum and random particle orientation upon contact with the inclined board surface (Fig.12).

Rating method III is based on the fact that resistance to sliding is greater than resistance to rolling.

Fig. 12

ANGULARITY RATING METHOD - III
(DISTANCE-ROLLED)

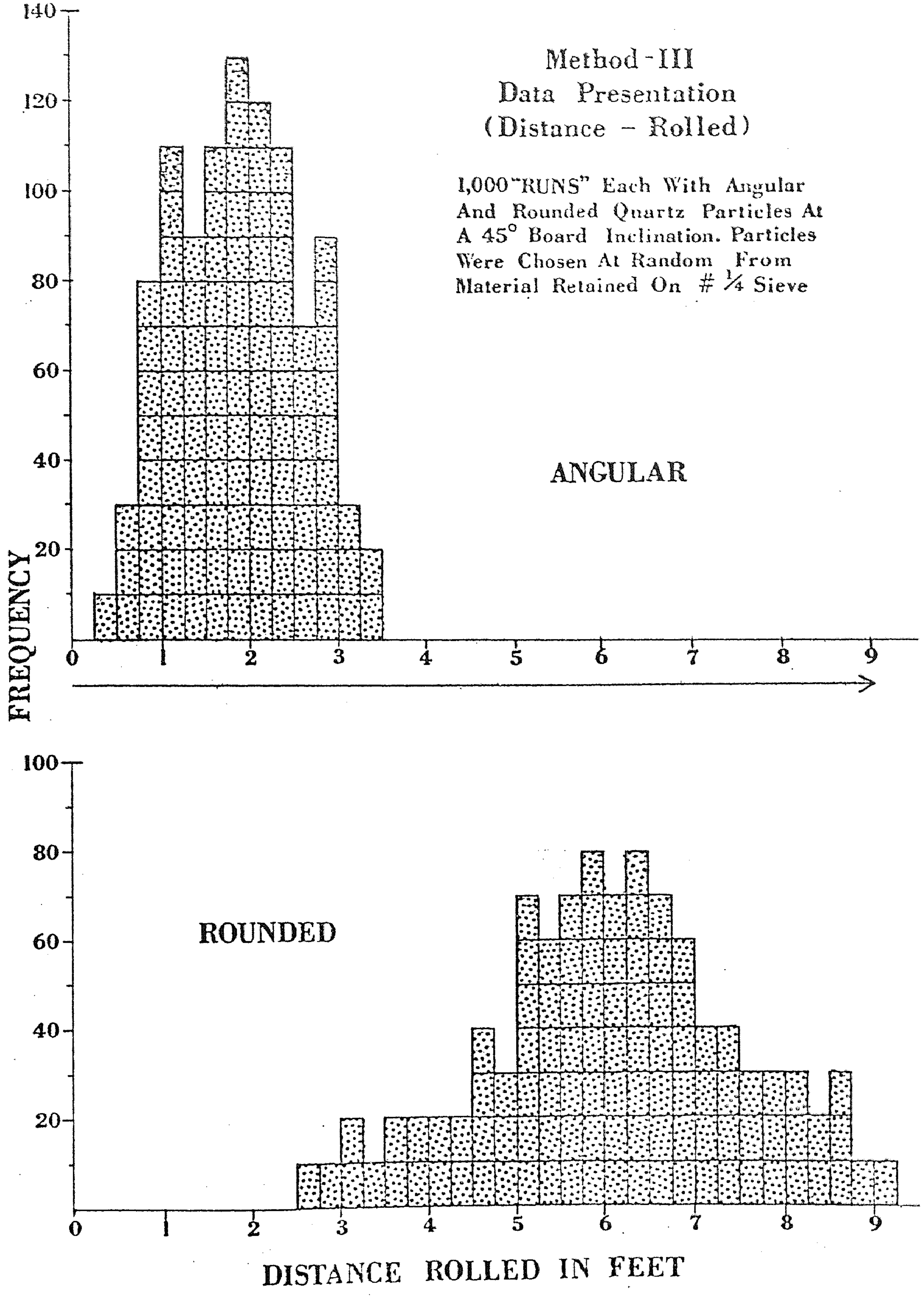


The more spherical a particle the further it will roll. On the other hand, angular particles seldom roll but instead generally slide. Frictional resistance of a rolling particle is low in comparison to static and sliding friction. A rolling particle will form weak bonds at contact points with the rolling surface. As the particle rolls these bonds are broken in tension, not in shear. The strength of the bonds in tension is usually almost zero. This is the case because adhesion between two surfaces occurs only under a compressive load. Rolling friction was found to be insignificant when compared to static and sliding friction (Lambe, 1969).

Individual particles to be tested were randomly selected from one size fraction of the sample. A particle was then placed on a marked position on the overhead platform directly above the inclined board. A spring loaded triggering arm, released using a latch, set the particle in motion. This setup insured a constant initial ejection force from test to test. A modification to method I employed in method III was one that insured that particle motion would cease somewhere along the board length where it could be measured. The original friction board because of its small length did not provide the distance required to stop particle motion. This problem was not overcome by merely extending the length of the board. Since theoretically, a perfectly spherical particle would never stop rolling on an infinitely long board. Instead a long horizontal board was added at the base of the inclined surface. This horizontal board would assuredly stop the motion of any particle at any board inclination somewhere along its length (Fig.12).

Overall frictional resistance is less for a spherical particle for several reasons. First, a sphere has the least surface area of any shaped particle for a given volume,which in turn determines its frictional resistance. Secondly, rolling which also reduces the total amount of friction is characteristic of spherical particles. Generally, it can be said that highly spherical particles given the same initial momentum roll more easily, faster and farther than their angular equivalents.

Fig. 13


Method - III
Data Presentation
(Distance - Rolled)
1,000 "RUNS" Each With Angular And Rounded Quartz Particles At A 45° Board Inclination. Particles Were Chosen At Random From Material Retained On # 1/4 Sieve
ANGULAR
ROUNDED
FREQUENCY
140
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
DISTANCE ROLLED IN FEET

Discussion of Results with Recommendations

The advantages of Method III for rating angularity are: its simplicity, speed, reproducibility and its direct correlation to particle shape. The distance rolled by a particle is inversely proportional to its degree of angularity. That is, the greater the angularity the smaller the distance rolled. In addition, the distance rolled method reflects nearly all the physical chracteristics of a particle in a non-subjective manner. Method III depicts important physical particle properties: shape, size, specific gravity, surface texture, and variations in centers of gravity. Some combination of the properties mentioned control the overall frictional resistance of a particle. Method III induces a greater degree of variation in angularity, thus, making the rating potential more discrete. This method might be used to rate entire soil samples containing various size fractions.

A qualitative indication of degree of angularity of a sample can be clearly deduced from the distance rolled method. For example, a particle which rolls 10 feet obviously must be more spherical than one which rolls 2 feet. Histograms (Figs. 13) presented in the previous section clearly demonstrate this observation. In addition, data on agularity (measured in terms of percent spherical) can be presented in graphical form as the degree of angularity (on the x-axis) vs frequency of each degree of angularity per number of particles (on the y-axis).

The larger size fractions are more convenient to handle during experimental studies utilizing this method. The use of larger size fractions for rating purposes should not be considered a disadvantage for various reasons. The larger size fractions have a greater influence on the physical behavior of a cohesionless soil. Also, the shape of the smaller size fractions of both angular and rounded soils are similar (generally angular). For this reason, the influence of the smaller particles on the overall physical behavior of a soil would be essentially the same.

If the method were to be used in the future, it is recommended that a modification be made which would result in an absolute rating method. This could be accomplished by fabricating several spheres of different densities for each size fraction of the sample to be rated. These spheres would be used to determine the absolute spherical value (in distance rolled) for a given board inclination and size fraction. The spheres of different density of the size fraction being tested would be varied according to the density of the material tested. Therefore, density is the only particle property that would have to be determined. Manufacturing different density spheres should not present a problem, for the range in specific gravity of the major soil forming minerals is quite small (2.60-2.80). Actually only about a dozen spheres need be produced.

The use of a sphere to establish the absolute spherical value for this rating system is valid for the following reasons. The ultimate state of roundness is defined as a sphere. An ideally angular shape was described previously as a two sided particle representing nearly all its surface area. In reality, a particle having only two sides is a physical impossibility. For this reason, the rating scale should be stated in terms of percent spherical, not in percent angular.

A composite rating for an entire fill could be obtained by combining any number of single particle ratings, perhaps giving slightly higher significance to the larger size fractions. The validity of the composite rating lies in the fact that it consists of many individual samples from various parts of the fill. Therefore, it is representative of the entire fill. The composite rating would provide general information on the physical behavior of the fill and would reduce the significance of any local variations that might be brought about during sampling. The number of single particle ratings performed would largely depend upon the size of the fill to be sampled, the time and money available, and the degree of accuracy required.

Generally, the distance rolled method for rating angularity is a simple solution to a complex problem. This method with the modifications suggested has a great advantage in that the ratings can be obtained in a short period of time. The testing of a particle can be repeated literally hundreds of times within several minutes; the average of which can be used for greater accuracy. Obviously, the greater number of particles per size fraction and the greater number of trials per particle - the better the rating for the sample. Even an inexperienced operator can use the suggested modified apparatus and obtain consistent results that could provide reliable, quick, and economical information on particle shape.

7 -COMPACTION AND SHEAR TESTING

Preparation and Description of Soil Samples

The purpose of this study is to determine the effect of particle shape (i.e. roundness and angularity) on the physical behavior of cohesionless materials. In order to accomplish this, representative populations of both extremes had to be obtained. Examples of rounded or well-worked deposits are abundant in nature and were used in this study. However, the angular or least worked extreme is less recognizable or identifiable. To circumvent the problem of identification of degree of angularity in geological environments, angularity in sample material was produced by crushing.

Well rounded stream and beach pebbles were obtained from several southern New Jersey shore areas. The pebbles of these well-worn deposits were optically examined for an estimate of percentage quartz. Twenty five randomly chosen pebbles were used to represent the sample and then individually crushed. The mineral composition of each pebble was determined by a Leitz polarizing microscope and accessory polarizing plates. Appropriate immersion oils were used to determine the indices of refraction of the fragments by means of the Becke line method (Correns, 1969). The form of the mineral fragments, color, lack of cleavage, relief, birefringence, extinction angle, lack of alteration, interference figures and other distinguishing optical properties were used to determine mineral composition using the polarizing microscope. Out of the twenty five randomly selected pebbles, twenty two were quartz, two were feldspar, and one was calcite. This means that the well rounded pebbles were predominantly quartz (90 percent). It is common for mature beach deposits to attain this degree of purity due to the stable nature of quartz. In general, well worked beach deposits of this type have smaller quantities of the alkalis(sodium and potassium) and the alkaline earths (calcium and magnesiun) because such elements are most easily leached.

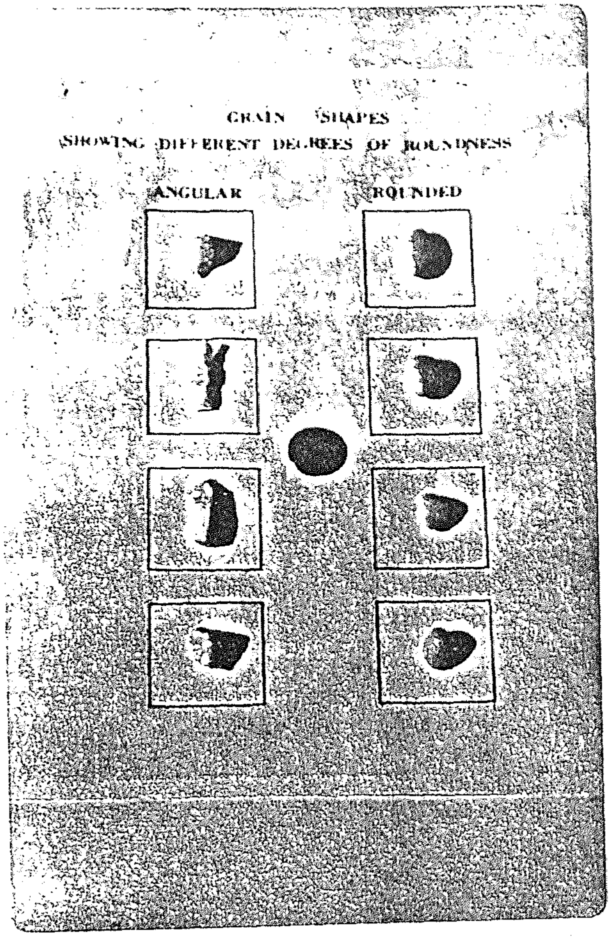
The quartz used to produce <u>angular</u> samples was obtained from a quartz vein deposit in the Ora Flame mine near Prescott, Arizona. The hard vein quartz was physically hand crushed, sieved, and recrushed until a sufficient quantity of each desired size fraction had been produced. The particles formed by crushing the massive vein material exhibited jagged and rough edges, corners and surfaces upon crushing. Rough surface textures are generally associated with angularity. Natural angular quartz deposits e.g. residual talus deposits, will always show some degree of roundness (wearing). Crushing simulates an unweathered, angular condition. Angular quartz was also optically examined for purity and found to be in excess of 95 percent quartz.

The rounded pebbles were thoroughly washed to remove impurities and then oven dried. Both the rounded and angular samples were then mechanically shaken through a nest of sieves to separate the different size fractions. Particles larger than 0.0029 inches in diameter, the size of the No. 200 sieve, yet no larger than 0.50 inches in diameter were separated into the size fractions of minus 0.25, 0.187, 0.0787, 0.0165, and 0.0083 inches in diameter. Typical examples of rounded and angular quartz used in this experiment are shown in Fig. 14.

The shear test results derived from lab-produced quartz samples were compared with natural field samples to determine whether the behavior observed during lab tests were representative of natural field samples. Natural field samples were collected in Livingston, N.J.. A stream bed deposit from Newman's Stream represented a rounded material; and a talus deposit from a road cut on Eisenhower Pkwy. represented the angular material. Before shear testing, these two field soils were prepared with identical grain size distributions, in a similar manner to that of the quartz samples. It was hoped that the results obtained from field soils would confirm relationships observed from lab-produced quartz samples.

FIG. 14

TYPICAL EXAMPLES OF ANGULAR AND ROUNDED QUARTZ PARTICLES USED DURING THE EXPERIMENT

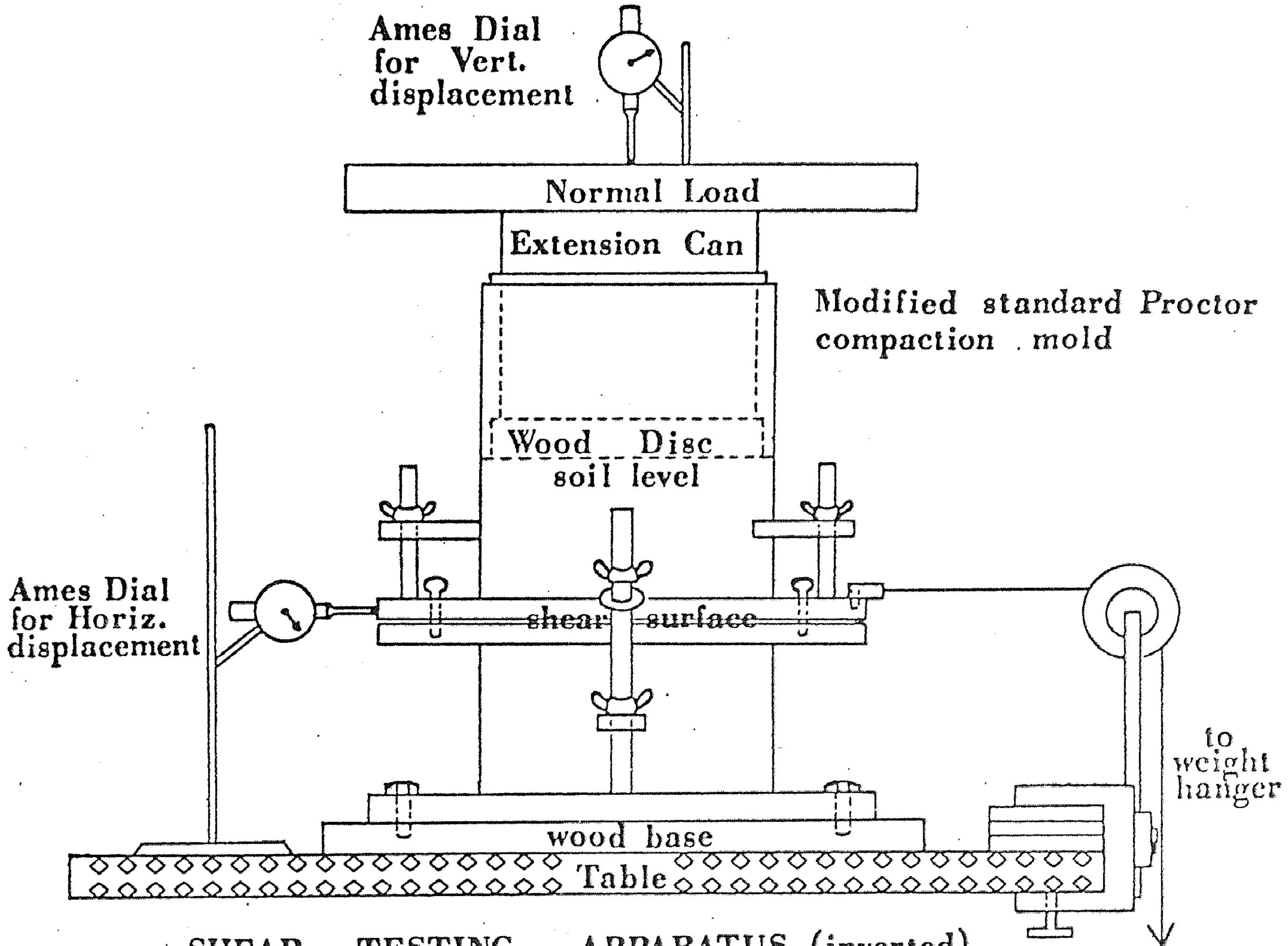


Description of Experimental Apparatus and Testing Procedure

On the recommendation of Professor Monahan, a direct shear test device was constructed from a modified standard Proctor compaction mold. The Proctor mold was inverted so that two steel plates could be added, thus separating both halves and accomodating a shearing displacement through the center of the compacted sample. A combined compaction and shearing device had to be employed since the samples were being tested in a dry state and could not be removed from the mold after compaction (Fig.15A and B). One hundred percent compaction was established for each sample material. This was done as a control so that other desired relative densities could be calculated for each shear test. The samples were compacted by means of vibration prior to the shear test. The source of vibration was a standard rammer weighing 5.5 lbs. dropped from a 12 inch height approximately one blow per second. The vibrational force was applied to the baseboard upon which the cylinder was afixed. During compaction frequent volume displacement readings were taken until the desired relative density had been reached.

The normal load (dead-weight) used to simulate field conditions during shear testing of the natural stream and talus deposits (at 80, 85, 90, 95, and 100 percent relative compaction) was 38.19 pounds (equivalent to a 16 kg weight,

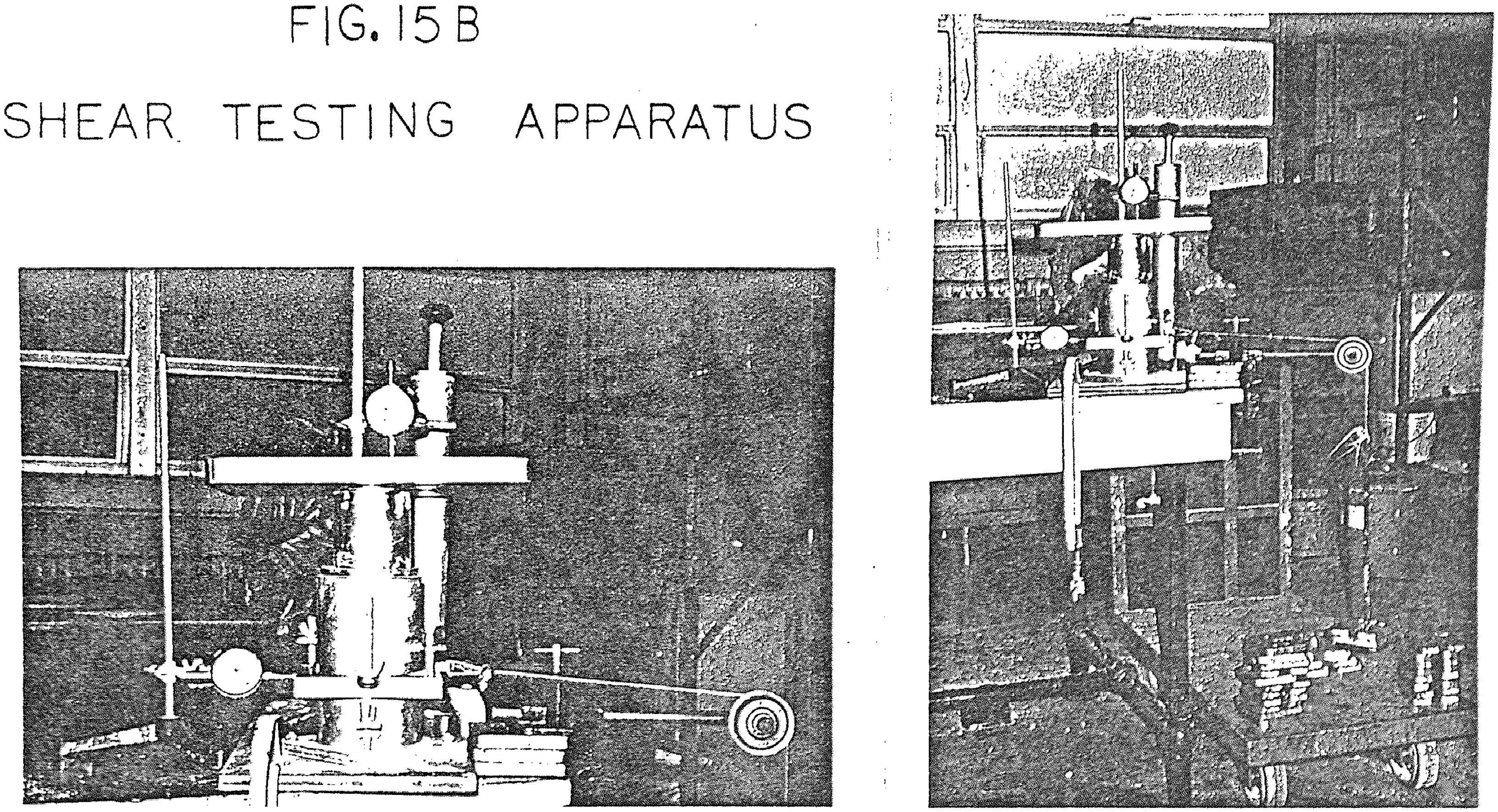
Fig. 15A



SHEAR TESTING APPARATUS (inverted)
PROCTOR MOLD

FIG. 15 B

SHEAR TESTING APPARATUS



a concrete filled extension can, and a wooden cover disc). It was belived that results more closely depicting field conditions could be achieved if the normal load was increased as the relative density increased. It is more realistic to assume that field conditions of 95 percent relative density would be associated with greater normal loads. Hence, when shear testing the quartz samples, the normal load used at 85 and 90 percent relative density was 46.98 pounds and at 90, 95 and 100 percent densities was 73.38 pounds.

The force used to shear the natural stream and talus deposits was applied by an incremental loading of 1 kg weights every thirty seconds after which time Ames dial readings were taken. This loading was continued until relative displacement between the two parts of the cylinder occurred. The Ames dials were used to monitor any pattern of horizontal or vertical displacement as the shear force was applied. One kg loading increments proved to be too large and this method of loading was abandoned. Shear tests conducted on the lab-manufactured pure quartz soils utilized a constant rate-of-stress loading method wherein the actual point of failure could be determined more accurately. This gradual and more uniform type of loading was achieved by allowing dry sand to run continuously through a funnel into a loading bucket until shear. Thus, the combined weight of the sand and bucket after shear was the force required to induce failure of the sample. The relative compaction density having the greatest strength for different shaped soils would therefore be the optimum compaction density for that "shape" material.

Particle Interlocking and Its Effect on Shear Strength

The shear strength of a cohesionless material is frictional in nature. Friction, in its simplest form, is the resistance to motion which exists when a solid object is moved tangentially with respect to the surface of another obeject. Friction depends on the physical properties of the contacting surfaces, and also on the surface contaminants which may be present. Physical reactions between particles largely take place at the particle surfaces, and surface contaminants i.e. water weaken the contacts in shear. Frictional resistance occurs when two solids are pressed together and bonding between their surface atoms results. These bonds have to be broken before sliding can start. The shape of a particle determines the degree of particle interlocking and thus the strength and number of bonds that form. In minerals that exhibit appreciable rough surface textures, bonding is confined to a few small areas where the high spots on both particles have made contact by fitting into one another (creating a surface interlocking effect).

In addition to the bonding or adhesion effect, which is the principal cause of friction, there are four other mechanisms which use up energy during shear. These mechanisms are:

1. A roughness effect caused by the interlocking

of high spots and the need to lift one surface over the high spots of the other. Greater surface roughness would indicate a greater surface interlocking.

2. A ploughing effect, whereby the high spots on a hard particle can dig grooves into a softer particle.

3. A hysteresis effect, whereby there is deformation of the particles at or near the contact points.

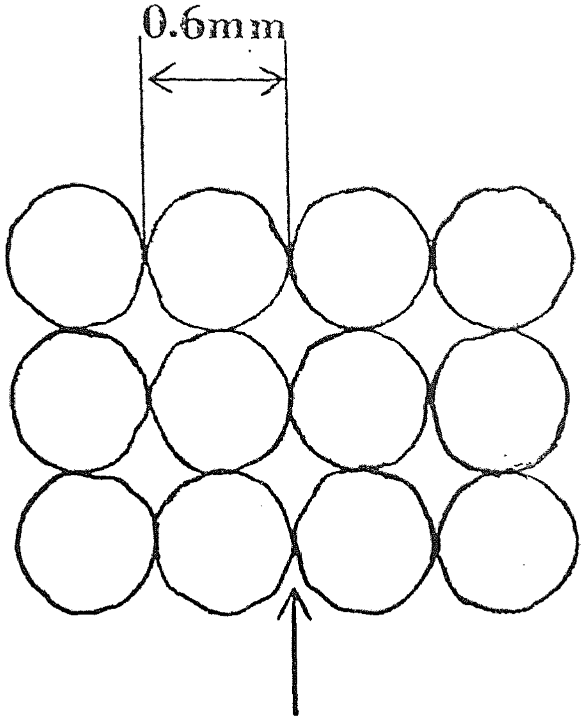
4. An electrostatic effect, where work must be done to separate electrically charged regions on the contact surfaces of the particles (Besancon, 1974).

In general, adhesive bonding at contact points together with the degree of surface and particle interlocking are the primary sources of shear resistance between cohesionless particles.

Cohesionless soil particles are relatively free to move with respect to one another however, as the soil density increases this movement becomes more restricted. Soil particles transmit an applied load between adjacent particles through their contact points. Apparent contact area between particles seems much greater than the actual contact area (Fig.16). In actuality when two particles touch, the area of contact is very small. For example, theoretically a well rounded fine sand (approx. size 0.6 mm) having simple cubic packing would only have a contact area of 0.03 percent of the total

Fig. 16

CONTACT AREA OF WELL ROUNDED SAND PARTICLES WITH SIMPLE CUBIC PACKING (POINT CONTACTS)



Contact Area Approx.
0.03% Of Total Area

Approx. 5 Million Point Contacts Within 1 cm^3

Apparent Contact Area Seems Much Greater Than Actual Contact Area

(After Lambe, 1969)

area. Although, there are on the order of 5 million point contacts within 1 cm^3 of fine sand (Lambe, 1969) (Fig. 16). The contact area between angular particles is impossible to ascertain because of the highly irregular shapes and arrangements inherent within such material.

The number of contact points between individual soil particles is determined by shape. Particle shape controls the degree of packing at a given compaction density and therefore controls the ultimate number of voids. That is, the number of contact points and therefore the degree of interlocking is determined by the particle shape (number of voids) of the material and the confining stress.

Shape controls the degree of <u>particle</u> interlocking and surface texture regulates the intensity of <u>surface</u> interlocking between individual particles. Morris (1959) supports the theory that shape and surface texture between individual particles of a cohesionless soil greatly affects strength properties. He claimed that particle shape and surface texture affect the frictional characteristics equally and that a change in either could produce more than a 30 percent variation in strength. A change of both simultaneously would increase the variation of frictional characteristics by as much as 40 percent. Generally stated, he claimed that the characteristics which determine the strength and stability of a cohesionless material are those which govern the frictional behavior (particle and surface interlocking) between its constituent parts - namely external particle shape and surface texture.

Particle shape which determines the number of contact points and the degree of interlocking must also determine the distribution of stress transmission through a cohesionless material. That is, the extent to which stresses are being transmitted through particles in direct contact is a function of particle shape. Particle shape directly controls a soil's shear strength. Changes in particle shape (changing the number of voids) perhaps even effected through crushing must have a marked effect on the degree of interlocking, thus changing the stability of the material.

Stress is transmitted through a cohesionless mass by means of particle to particle contact forces. Stress transmission through a perfectly isotropic material would be the same in all directions. Natural soil deposits are basically anisotropic, since a perfectly spherical material is rarely encountered in nature. The greater the angularity of a soil mass the greater the anisotropic behavior. Inherently, angular materials tend to increase number of voids. Although angular materials can easily be crushed and in such a manner reduce the void space under load. It is believed that the greater the sphericity of a soil mass the greater the packing potential (interlocking). And this results in greater uniformity of stress transmission and overall physical behavior.

When the total shear force at the contact points exceeds the shear resistance, relative displacement between the particles can occur. Sliding or shearing will decrease the amount of interlocking which in turn decreases the shearing resistance. A greater normal load produces a greater resistance to shear at each contact point hence a greater overall strength. This is the case until crushing begins. As the degree of compaction increases, the shearing force required to produce failure must also increase. This is true up to a critical value where overcompaction results in crushing and is detrimental to strength.

Particle interlocking during shear failure is overcome by either crushing, or movement of particles up and over, or around their neighbors. This occurs with an associated volume change in relation to the particle size. Rounded particles with their smooth shape exhibit less crushing and greater movement (rolling) around each other than angular particles. When trying to overcome interlocking, angular particles have less freedom of movement with respect to their neighbors and consequently greater crushing results from their irregular shapes. It follows then that rounded soils should experience greater volume changes than angular equivalents during shear. In addition, the largest size particles probably have the greatest degree of interlocking but are subjected to a greater degree of particle crushing and fracturing because of the greater forces per contact. That is, the load on a larger particle is distributed over a fewer number of contact points hence a greater load per contact point per particle. Crushing of larger particles might also be assumed to begin earlier and at smaller confining stresses.

The strength produced by the interlocking effect of angular particles is less at higher densities because of the greater degree of crushing. The rapid crushing of larger sizes minimizes the interlocking effect and decreases the overall strength. On the other hand, rounded particles which exhibit less crushing and a higher degree of packing can achieve slightly greater shear strengths under certain conditions of high density. That is, the interlocking effect is important for rounded materials at higher densities because of their resistance to particle crushing.

Particle Crushing and Its Effect on Shear Strength

Angularity of cohesionless soil material produces soil strength up to an optimum point, after which angularity impedes greater density resulting in particle crushing and associated strength loss. Crushing of individual soil particles which occur in the vicinity of the contact points creates an increase in surface or contact area between particles. Particle crushing increases surface area and greater surface area implies a higher degree of frictional resistance. Although frictional resistance must increase, it is believed that an optimum condition probably exists whereafter particle crushing is detrimental to strength. After crushing there are many more contact points, but collectively they provide less frictional resistance than before. This seemingly contradictory statement is found to be true because of two basic physical changes that occur as a result of particle crushing. First, the individual surface area of a grain becomes smaller as the size of the grain is reduced. And second, as the overall size of the particle is reduced its interlocking potential with other grains is reduced. As previously mentioned, the greater the particle size the greater will be its total influence on the physical behavior of the soil. To illustrate this point compare the shear strength of a coarse gravel to that of a fine sand of the same volume, compaction etc. Coarse gravel has a much greater strength although fine sand has many more contact points.

Under the same load, angular materials are much more susceptible to crushing than their rounded equivalents. Kuenen (1956) demonstrated that the greater the roundness of a particle, the smaller will be the percentage loss in weight per unit time during abrasion. In other words, increasing roundness of particle's edges and corners causes the rate of disintegration to decrease. Particle shape must therefore influence strength characteristics because it significantly determines the degree to which a particle is crushed. The present study suggests that an optimum compaction density exists for every fill material. This optimum condition can be predicted by particle shape, and degree of compaction. Exceeding the optimum would result in a general reduction of shear strength caused by particle crushing.

Observations that reduction in cohesionless soil strength exist with an increase in density is supported in the literature. For example, Feda (1971) stated that the peak angle of internal friction decreases with increasing pressure as a consequence of grain crushing. His measured values were both qualitatively and quantitatively comparable with results from rock -fill tests. Crushing of rock-fill particles is also described in detail by

Marsal (1967). He analyzed the effect of stress level on particle size, shape, porosity, saturation with water,etc. Supporting eveidence is given by Nichiporovitch and Rasskazov (1967) who claim that for many coarse fragmental soils the angle of internal friction decreases with an increase in stress. They attributed this strength loss to the destruction of particles both during compression and shearing of the soil. Morris (1959) conlcuded that compaction serves to give extra strength to a cohesionless material only to a point, and thereafter no advantage in strength results from further compaction. In addition, Bowden and Tabor (1964) demonstrated that when contact point deformation occurs the coefficient of friction will probably decrease with increased load reducing the overall strength of the soil mass. The physical behavior observed during the present study is substantiated by Foster (1953). He stated a similar argument that the strength of a soil increases with an increase in density up to a certain point, and further increases in density result in decreases in strength (at high densities).

The degree of crushing and reduction of strength during compaction can probably be determined through comparison of grain size distribution curves before and during (each lift) densification. For if the original grain size distribution curve changes substantially, crushing must have occurred and was possibly accompanied by a reduction in strength. It follows that an increase in density without measurable crushing would be approaching the optimum compaction density. Conversely, a further increase in density accompanied by strength reduction would imply surpassing the optimum value. The grain size distribution curves could also be used simultaneously as a qualitative measure of permeability and capillarity characteristics of the fill, since both are related to some effective particle diameter. As a first approximation, the relationship between crushing and strength was considered independent of other parameters, i.e. neglecting other factors such as moisture, etc..

Arguments can be presented which suggest that a relatively small degree of crushing may actually increase the ultimate strength of a cohesionless soil, but again up to an optimum value. Smaller particles formed during crushing in a poorly graded (uniform) soil would tend to fill the voids between the larger particles and consequently increase the soil's strength. Particle crushing should be more extensive in poorly graded soils due to the reduced number of contact points (greater unit load per contact). This increase in strength (if any) as a result of crushing would more greatly affect soils of greater angularity. This is due to the greater susceptibility of angular materials to crushing. Surface roughness is another factor that might contribute to increased strength as a result of particle crushing. According to Morris (1959), crushing during compaction intensifies surface roughness which contributes to strength. However, strength increases with surface roughness only to an optimum value beyond which an increase in roughness is accompanied by a decrease in strength. This decrease in strength is due to the overall reduction of particle size.

Particle crushing is not uniform with depth. It has been demonstrated (Capper and Cassie, 1969) that during compaction the distribution of stresses are highest near the surface of the material and decrease rapidly with depth. The degree of crushing should then be greatest near the surface. This condition is unfortunate since in the practical case considered, i.e. embankment construction, the greatest strength required is near the surface. From a practical standpoint, the upper surface of each lift of a compacted fill may therefore represent a zone of weakness which collectively form a cohesionless mass with stratified zones of weakness throughout its height.

In conclusion, crushing probably begins the moment a stress is applied but does not reach a significant degree until a critical force is reached. This critical stress being mainly determined by the angularity (shape) of the particles forming the soil and the angularity determines the degree of crushing which in turn determines the ultimate strength of a cohesionless soil. Finally, crushing is greatest when soil particles are poorly graded, highly angular, and large in size. The effect of particle crushing upon a uniform angular rock-fill with large particle sizes may therefore become a very important consideration even at relatively small stresses.

Table 10

SUMMARY OF SHEAR TEST RESULTS WITH LAB PRODUCED PURE QUARTZ SAMPLES

CONSTANT RATE OF STRESS LOADING
NORMAL LOAD 46.98 lbs.

	SHEARED	
ROUNDED	lbs.	p.s.i.
85% RELATIVE DENSITY	65.2	5.18
90% RELATIVE DENSITY	72.4	5.76
ANGULAR		
85% RELATIVE DENSITY	71.3	5.67
90% RELATIVE DENSITY	74.3	5.91

CONSTANT RATE OF STRESS LOADING
NORMAL LOAD 73.38 lbs.

	SHEARED	
ROUNDED	lbs.	p.s.i.
90% RELATIVE DENSITY	74.2	5.90
95% RELATIVE DENSITY	78.2	6.22
100% RELATIVE DENSITY	83.9	6.67
ANGULAR		
90% RELATIVE DENSITY	75.8	6.03
95% RELATIVE DENSITY	78.7	6.26
100% RELATIVE DENSITY	78.8	6.27

Table 11

SUMMARY OF SHEAR TEST RESULTS WITH NATURAL STREAM AND TALUS DEPOSITS

INCREMENTAL LOADING
NORMAL LOAD 38.18 lbs.

STREAM (ROUNDED)	SHEARED lbs.	SHEARED p.s.i.
80 % RELATIVE DENSITY	61.8	4.92
85 % RELATIVE DENSITY	55.3	4.40
90 % RELATIVE DENSITY	66.4	5.28
95 % RELATIVE DENSITY	74.0	5.89
100 % RELATIVE DENSITY	74.0	5.89

TALUS (ANGULAR)	SHEARED lbs.	SHEARED p.s.i.
80 % RELATIVE DENSITY	64.1	5.10
85 % RELATIVE DENSITY	70.8	5.63
90 % RELATIVE DENSITY	74.0	5.89
95 % RELATIVE DENSITY	74.0	5.89
100 % RELATIVE DENSITY	72.2	5.74

Discussion of Shear Test Results with Recommendations

Irregularity of shape under certain conditions,e.g. high confining stresses can cause particle crushing and reduction of strength. For this reason at high densities it is sometimes possible for a well rounded material to exhibit slightly higher strength than their angular equivalents. Generally crushing facilitates ease of shear failure. At high stresses crushing accelerates and permits greater relative movement, hence strength loss. The combination of relative motion (both sliding and rolling) between particles, and individual particle deformation at the contact points account for the overall strain of the soil mass during shear.

Angular samples seem to show a progressive failure where the critical stress was not reached simultaneously throughout the failure plane. Angular samples failed more gradually than the rounded upon the application of load. The rounded samples seemed to provide a greater initial strength or resistance to the load, but failure was rapid at the criticalstress. Also, just prior to failure the rounded samples showed a sudden vertical displacement. This fact can be explained by rounded material's resistance to crushing, and by particle movement over one another on the shearing plane before displacement could occur. The angular samples sheared with a "stick-slip" pattern. When sliding began, part of the shear force was released, accelerating the sample. This caused a decrease in the shear force needed to maintain motion. The sample then stopped shearing and the shear force had to be increased to induce sliding again. Sliding began again. This pattern of intermittent motion repeated itself two or three times until ultimate failure.

This jerky motion described above can be explained by realizing that the shear force required to initiate sliding is greater than the force required to maintain motion. The static friction (pressure exerted by the motionless mass) exceeds the kinetic (sliding) friction (Lambe, 1969). It is believed that what is occurring is a repeated sequence of contact point deformation, or crushing followed by sliding, then interlocking. For example, with increased shearing pressure there was a slight grinding sound followed by a quick but small jerk. The sample then would temporarily restablize itself. The sequence was repeated with additional shear pressure. Each successive set of movements weakened and brought the soil nearer to total failure. After each jerk, the soil would develop a new set of contact points. With freshly crushed material, the pattern continued again with crushing,sliding and interlocking. When the shearing stress became too great, the next sliding motion was greater than the remaining interlocking potential of the twice weakened mass. Movement did not cease and total failure consequently occurred.

Shear strengths of angular samples increased as the soil was compacted to higher relative densities. This occurred in smaller increments due to greater particle crushing as it neared the critical value. Overcompaction of cohesionless materials (especially angular shapes) can cause a decrease in measured strength. This fact has been observed in some construction projects and has been confirmed by behavior in traffic tests. Peck (1967) observed that a decrease in strength (mainly due to crushing and relative movement between particles) does actually occur with granular materials under heavy traffic conditions. Generally, greater relative densities, and higher normal loads during shearing must result in a greater degree of particle crushing (and strength loss). This is due to the fact that in order for shear to occur, displacement must also occur. If the normal load is great enough to restrict a volume displacement then the shearing displacement must be accomplished through prior particle crushing (greater for angular samples).

The fracturing and crushing of particles during compaction and shearing allow larger relative movements between particles. This reduces the overall strength of the sample. A considerable amount of particle degredation was actually demonstrated by comparing grain size analyses before and after compaction and shear testing (Figs.17,18). The grain size analyses clearly prove that not only are angular materials more easily crushed but also that crushing is greater among the larger size fractions(Table 12). Crushed material, consisted of small chips snapped off from the thinest (weakest) and most irregular tapered edges of the more angular particles. Crushing did not seem to affect the surface texture of the particles nearly as much as the shape. The angular particles were visibly rounded after compaction and shear. However, there were no noticeable changes of surface textures. This observation is by no means intended to undermine the already established importance of surface texture and its influence on strength. Morris (1959) noted that perfectly rounded (not spherical - material similar to that used in the present study) particles, merely with uniformly roughened (etched) surfaces gave a higher strength than an equivalent sample of crushed basalt having 100 percent freshly fractured surfaces both at maximum densities.

Generally, it was found that the shear strength of the samples tested increased with angularity, and density to an optimum value. It is usually the case that coarse grained soils with angular particles have a greater strength than those whose particles are rounded. But

Table 12

Grain crushing after 100% relative compaction and shear testing

Sieve	Angular sample weight before compaction & shear	Percent by weight	Angular sample weight after compaction & shear	Percent by weight	Rounded sample weight before compaction & shear	Percent by weight	Rounded sample weight after compaction & shear	Percent by weight
#¼	831.76g	37.0%	794.06g	35.4%	831.76g	37.0%	815.45g	36.3%
#4	717.36g	32.0%	700.77g	31.2%	717.36g	32.0%	732.72g	32.6%
#10	309.80g	13.8%	350.66g	15.6%	309.80g	13.8%	304.25g	13.6%
#40	310.64g	13.8%	316.30g	14.1%	310.64g	13.8%	299.86g	13.3%
#70	40.18g	1.8%	42.20g	1.8%	40.18g	1.8%	49.91g	2.2%
#200	31.81g	1.4%	33.06g	1.5%	31.81g	1.4%	39.30g	1.8%
Pan	4.93g	0.2%	8.86g	0.4%	4.93g	0.2%	4.05g	0.2%
Total Wt.& %	2246.48g	100%	2245.91g	100%	2246.48g	100%	2245.54g	100%
Wt. lost			0.57g				0.94g	

Slight weight loss due to dust and that some grains were retained in the meshes of the sieves.

Fig. 17

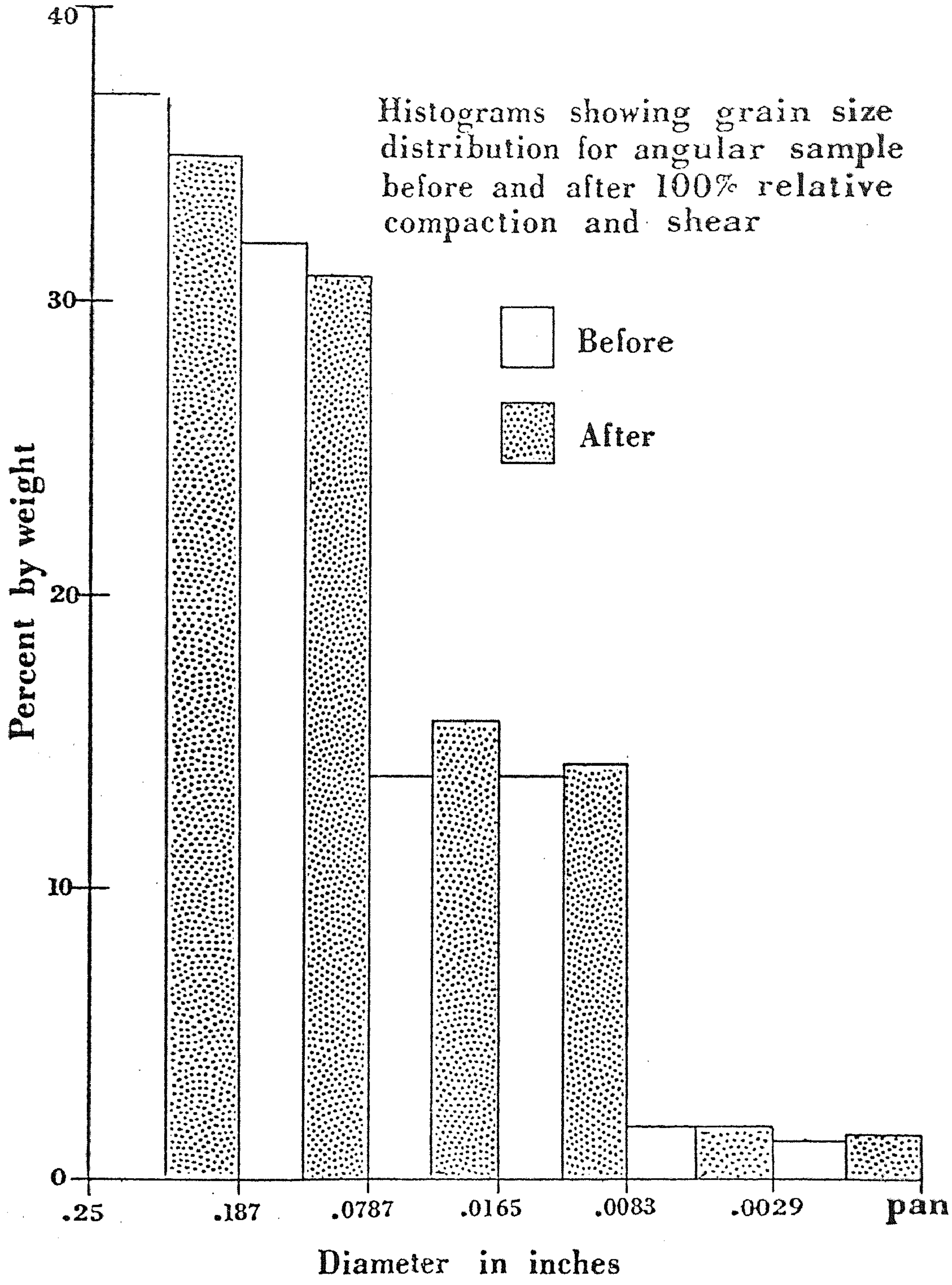
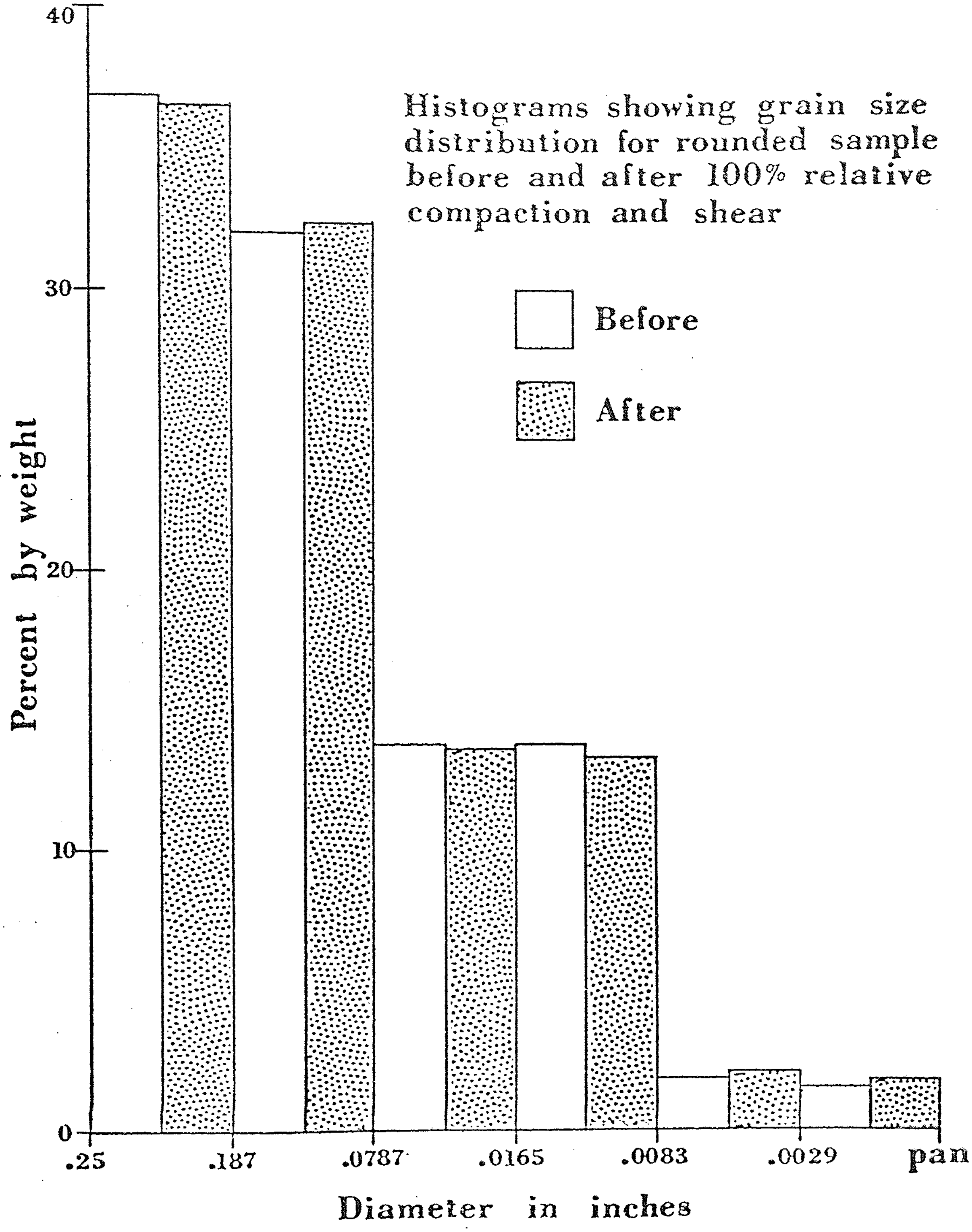

Histograms showing grain size distribution for angular sample before and after 100% relative compaction and shear
Before
After
Percent by weight
40
30
20
10
0
.25
.187
.0787
.0165
.0083
.0029
pan
Diameter in inches

Fig. 18

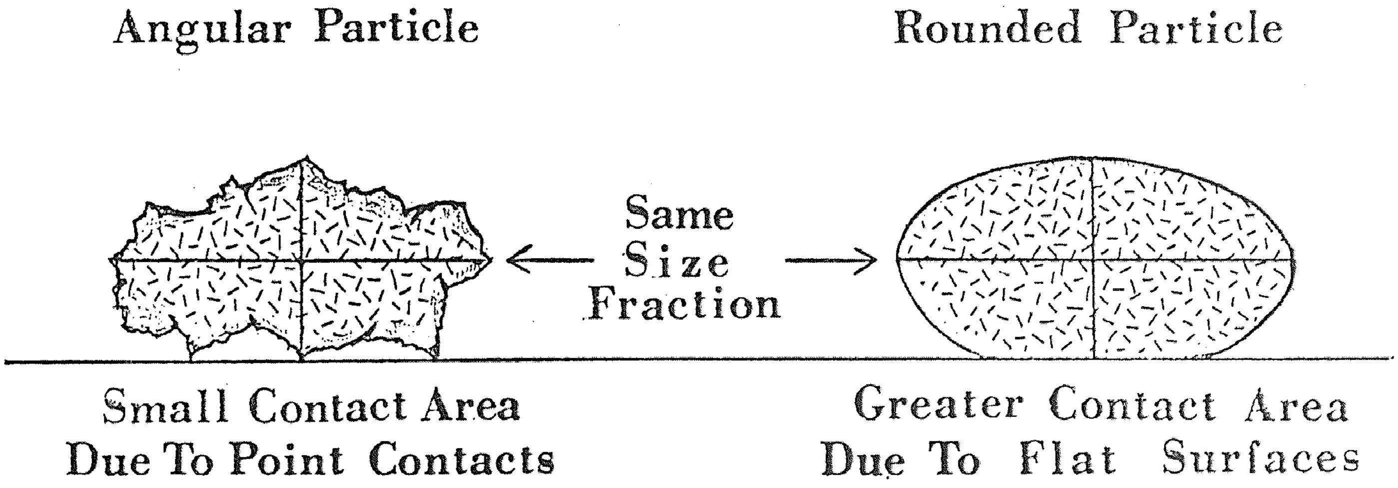


Histograms showing grain size distribution for rounded sample before and after 100% relative compaction and shear under certain conditions of excessive particle crushing, the rounded equivalent can be slightly stronger. Theoretically a perfectly spherical material would have the smallest number of contact points and be the weakest in shear. But since in nature one deals at best with well rounded particles this point contact relationship between adjacent spheres does not exist. In fact, quite the opposite might be true. For the same size fraction an angular particle may have a considerably smaller contact surface area than a well rounded particle, if both are resting on an equally flat surface under certain conditions (Fig.19).

It was demonstrated that some rounded samples achieved slightly greater strengths at higher densities (Tables 10 and 11). It is believed the strength exhibited by the rounded material is principally due to less crushing and greater particle packing. At maximum densities greater particle packing of the rounded samples was observed. As compared to the angular, rounded samples on the average occupied about a 10 percent smaller volume. In addition the rounded samples densified at a much quicker rate; rounded samples almost immediately nestled together to achieve a dense packing (Fig.4B). In contrast the angular samples gradually increased in density as a result of crushing.

Fig. 19

Greater Frictional Resistance Of Well Rounded Soil Particle On A Flat Surface



Shear test results are generally more reliable with more spherical shapes. Easy and greater packing potential of these particles would substantiate this belief. There are great variations in angular particle packing of the same sample due to their irregular shapes and orientations: Although statistically with a sufficient number of trials, results should be consistent.

Results obtained from natural field soils confirm the observations made with quartz samples. Naturally angular soil samples tested at 80, 85, and 90 percent relative densities had shear strengths that were higher than the rounded samples of the same densities. But at 95 percent relative density, angular and rounded shear strengths were found to be identical. And at 100 percent relative density the rounded sample was slightly higher in strength (Table 11).

In conclusion, gradual densification during compaction and the gradual shearing pattern characteristic of angular samples contribute to a higher degree of crushing, and strength loss at high densities. It is believed from the results of these tests that overcompaction reduces the strength of a cohesionless material (especially if angular) primarily through particle crushing. If the degree of particle crushing influences the shear strength, and particle shape controls the degree of crushing, then it follows that shape must significantly regulate strength. It is strongly believed that for every fill material, there is an optimum compaction density that can be determined by particle shape (other variables kept constant). Compaction beyond this optimum value would not only reduce strength but also be unnecessary and uneconomical.

The following modifications to the shear testing apparatus should be considered for future study. A device must be added, perhaps a track of some sort with stops, to prevent the separation of the shearing plates during testing. In so doing sample volume increase during shearing would be restricted insuring more reliable results. In addition ball bearings should be placed between the plates for a smoother and more "frictionless" movement. The source of vibration used during compaction should be improved, a mechanical procedure would be preferable and would render greater uniformity of test results.

8 - SUMMARY AND CONCLUSIONS

Relationships between angularity and strength are not as simplistic as previously envisioned: a greater angularity always produces a greater strength. For some "shaped" materials the overall strength of a cohesionless mass decreases with increasing density, as a consequence of particle crushing, both during compaction and shear. Particle shape characteristics determine the ultimate strength by determining the degree of particle crushing. Compaction renders extra strength to a cohesionless material only to an optimum point. Thus angularity induces soil strength to an optimum value, after which angularity impedes greater density resulting in particle crushing. Excessive crushing leads to a decrease in strength . Crushing changes the stability of a cohesionless material by reducing the overall particle size which reduces the degree of particle interlocking. Increases in density which exhibit no substantial degree of crushing indicate that the optimum compaction is being approached. A further increase in density accompanied by substantial crushing and strength loss indicate that the optimum density value has been surpassed. The degree of crushing and therefore strength loss during compaction can be analyzed through a comparison of grain size distribution curves before and during densification.

The greater the angularity of a soil mass, the greater the anisotropic behavior. In other words, the greater the sphericity, the tighter the packing potential (interlocking) which results in a greater uniformity of stress transmission and overall uniformity in physical behavior. Greater densities can be achieved by more spheroidal particles. Rounded materials achieve higher densities and at a more rapid rate than angular materials. Angular materials generally increase in density more gradually as a result of particle crushing. In addition, angular materials fail progressively in shear whereas failure of rounded equivalents is rapid at the critical stress. This gradual progressive pattern of shearing failure and the gradual densification during compaction is characteristic of angular materials. Both of these conditions contribute to the higher degree of crushing and potential strength loss at high densities of angular materials. Soils which are well graded and spherical effectively aid densification and exhibit a small degree of crushing. On the other hand, highly angular and poorly graded soils inhibit densification and are associated with higher degrees of crushing. Generally, rounded particles exhibit less crushing and a higher degree of particle packing during compaction and shear. Such particles can achieve slightly higher shear strengths under higher density conditions.

At high densities, the interlocking effect is more important for rounded materials than for angular. This is the case because rounded materials have a greater resistance to particle crushing. Under the same loading conditions, angular materials are much more susceptible to particle crushing than their rounded equivalents. That is, increased roundness of particles's edges and corners causes the rate of disintegration to decrease. Not only are angular materials more easily crushed but also crushing is greatest among larger size fractions. At high stresses, crushing is accelerated and permits greater relative movement which generally facilitates ease of shear failure. Rapid crushing of larger particles during compaction and shear minimizes the interlocking effect which ultimately decreases strength. Crushing of the larger angular particles begins at an earlier stage and at smaller confining stresses than their rounded equivalents. A small degree of particle crushing may be beneficial to strength. Initial crushing in a poorly graded soil will tend to increase the interlocking effect whereby the smaller particles formed during crushing would fill the voids between the larger particles. This beneficial aspect (if any) of crushing will only occur up to an optimum value. In addition, this effect would be more important when dealing with poorly graded soils of higher angularity due to their greater susceptibility to crushing.

In conclusion, the strength of a cohesionless material increases with the degree of angularity and relative density to an optimum point. Surpassing the optimum value implies substantial particle crushing which reduces the interlocking effect and can result in a strength reduction. Generally, the degree of particle crushing influences strength, and particle shape determines the degree of crushing. Thus, shape (angularity) must significantly control the overall soil strength. Crushing is greatest when cohesionless particles are poorly graded, highly angular, and large in size. From a practical point of view, the detrimental effect (strength loss) of particle crushing on a uniform, angular rock-fill having large particle sizes may become a very important soil strength factor, even at relatively small stresses.

9 - SUGGESTIONS FOR FURTHER RESEARCH

It is hoped that further experimentation and accumulation of data in this field will lead to a compilation of standard reference tables that could be used to predict the optimum compaction density of a borrow material based on particle shape. Further research could more accurately define the relationships between angularity, degree of compaction and resultant strength of cohesionless materials. For example, it might conclude that a standard compaction value should not be applied to all fill materials of varying shapes, as is presently standard practice. In light of results from the present particle angularity experiment, additional research should be conducted on the significance of particle size distribution. That is, investigations should be directed toward a better understanding of the effect on strength of the following factors : the degree of crushing at different compaction densities of different shaped particles having various size distributions. Perhaps more advantageous physical soil properties can be achieved by combining several of these variables in certain proportions. For example, a combination of angular and rounded soil materials, in varying proportions, could produce more desirable physical properties than either are capable of separately. Such a composite mixture (shape, size distribution, degree of compaction) if created could be the ideal borrow fill (strongest etc.) formed from the fill materials available.

The following proposed alternative rating methods for angularity are in some way related to the fundamental surface to volume ratio of a sphere. Shape of particles affects permeability. In general for larger size fractions, the more angular the grains, the greater the permeability. For example, in sand-size material shape affects permeability by as much as a factor of 2 (Hunt, 1972). Void ratio determines permeability and shape determines the number of voids. The amount of void space produced from the regular packing of uniform spheres is known. Increase of this void space results from divergence of particles from a spherical shape. Permeability of a cohesionless material may be used to describe bulk particle shape because the greater the angularity the greater the permeability (all other parameters being equal). Perfect spheres of a given size and compaction density could be used to determine the spherical (minimum) permeability value. All other shapes would have a greater permeability reflecting a more angular state. This method would rate the angularity of all the particles of one size fraction at a given density.

An alternative method is density comparison to perfect spheres. Perfect spheres of a given size fraction can achieve a known maximum density. Therefore, greater volumes (with equal weight) would imply greater angularity. Soils of greater angularity of one size would have a greater volume for a given weight. Soil sample volume could be compared to that of perfect spheres, thereby establishing a ratio that could be used to rate the angularity of the soil. Spheres exhibit maximum density. No natural soil can be composed of perfect spheres. The volume of any <u>natural</u> soil sample must be greater (in varying degrees) than an equal sample (same size fraction, weight, specific gravity) of perfectly spherical material. In addition, soils that are angular and contain many voids will have lower weight per unit volume than their rounded equivalents. Thus weight differences could also be used to rate particle shape.

The settling velocity that particles of one size fraction can achieve in a given medium is determined by the shape and specific gravity of the particles. If specific gravity is kept constant particle shape can be rated by comparing their settling velocities. The resistance to settlement is proportional to the drag resistance determined by the viscosity of the fluid. If a high viscosity fluid is employed the differences between the different shapes of one size could be magnified. Generally, the settling time of a sphere in any medium would be the smallest because a sphere has smallest surface to volume ratio.

The alternative methods suggested are based on the fact that a sphere has the smallest surface area for a given volume. These methods could help to further clarify the relationships between angularity and strength properties observed during the present study. Perhaps one of the proposed methods could even induce a wider range in particle shape variation, thus producing a more exact angularity rating index. In this way, the importance of particle shape as a practical field index tool for soils classification would become more applicable to engineering pratice.

10 - REFERENCES

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