

FUNDAMENTAL ATTRIBUTES OF SEDIMENTARY PARTICLES

by

W. C. Krumbein
University of Chicago
Chicago, Illinois

INTRODUCTION

Geologists and hydraulic engineers study sediments from different points of view. The geologist is concerned mainly with ancient sediments, from which the transporting agent has long since vanished. Hence he emphasizes particle properties in an effort to find clues to the nature and movement of the transporting agent. The hydraulic engineer deals specifically with fluids, and emphasizes the influence of fluid motion on the particles. The engineer has advanced beyond the geologist in his understanding of the dynamics of transportation, whereas the geologist is more advanced in his definitions and interpretations of particle attributes. As the two fields pool their knowledge, it becomes increasingly clear that the understanding of sedimentary phenomena depends upon a study of both the fluid and the particle.

The present paper considers particle properties which are fundamental from a sedimentary point of view, in a sense broad enough to interest both geologists and hydraulic engineers. The hydraulic engineer is interested in the laws of transportation and deposition as they affect the design, construction, and operation of hydraulic structures. The geologist is concerned with these laws as they affect the deposition of modern sediments and influence his reconstruction of the history of ancient deposits.

PROPERTIES OF INDIVIDUAL PARTICLES

As a framework for discussion, a representative number of particle properties may be considered, and narrowed down to those fundamental from the present viewpoint. The following list is not exhaustive but it illustrates that numerous properties are associated with individual particles:

Geometrical properties

- Size
- Shape
- Surface texture (roughness)
- Orientation ¹

Crystallographic properties

- Symmetry (system and class)
- Axial ratio and interfacial angles
- Lattice structure

Optical properties

- Indices of refraction
- Optical orientation
- Color and pleochroism

Chemical properties

- Chemical (mineralogical) composition
- Chemical reactivity
- Solubility

Mechanical properties

- Density
- Specific weight
- Hardness
- Elasticity
- Tensile and crushing strength
- Compressibility
- Seectility and malleability

Thermal properties

- Melting and boiling points
- Coefficient of thermal conductivity
- Specific heat
- Coefficient of thermal expansion

Electrical properties

- Electrical conductivity
- Dielectric constant
- Piezo- and pyro-electrical properties

Magnetic properties

- Diamagnetic constant
- Magnetic suseptibility

¹ This property of a particle refers to the directions of its principal axes with respect to coordinate axes fixed in space. The orientation of particles in an aggregate represents the structure or "fabric" of the aggregate.

A number of these attributes may be eliminated as of secondary importance from a sedimentary point of view. In transportation and deposition the geometrical, chemical, and mechanical properties are of greatest importance, whereas the others have little direct application. The sedimentary behavior of a particle is controlled by its settling velocity, which in turn is a function of particle size, shape, and density for any given fluid. However, the mechanics of particle movement is only one aspect of the sedimentary story. Despite the differences in their approach to particle transportation, both geologists and engineers recognize the operation of two important processes in natural streams. These are the selective effects of transportation itself, and the accompanying wear or abrasion of the particles as they move along. Selective transportation ("sorting action") is the preferential movement or deposition of certain sizes, shapes, or particle densities in response to velocity and turbulence conditions. Particle wear, on the other hand, involves particle changes en route due to rubbing, impact, or crushing.

Differences of opinion exist regarding the relative importance of selective transportation and abrasion in natural streams. Some geologists and engineers consider abrasion to be more important; others emphasize the role of selective transportation. Recent papers which bear on this problem include those by Shulits [1]¹ and Mason [2].

Inasmuch as particle wear involves changes in particle characteristics, attributes most sensitive to such changes must be considered. These include hardness (resistance to wear) and surface texture. It has been found that the shape concept itself contains at least two attributes, one important in hydrodynamic behavior, and the other important during abrasion. These two shape factors are sphericity and roundness, respectively [3]. Their implications will be brought out in a later section of this paper; for the present it is sufficient that the distinction be made. Particles differ in their orientation within sediments, depending upon the dynamical conditions of deposition, so that this attribute is also needed for complete sedimentary investigation.

If the mineralogical composition of a particle is stated, it is equivalent to the inclusion of a number of individual properties.

¹ References appear at the end of the article.

Thus if a particle is known to be quartz, reference tables give its density, hardness, chemical composition, color, and other attributes. In the following list of fundamental sedimentary properties, then, mineralogical composition is used to indicate any of several attributes which may be of importance in specific problems, as hardness, density, etc.

1. Size
2. Shape (sphericity)
3. Roundness
4. Mineral composition (density, etc.)
5. Surface texture
6. Orientation

In discussing these particle attributes, emphasis is placed on those which are perhaps least familiar to engineers in their study of transportation and deposition. References for the measurement of the several properties are given where needed.

GEOMETRICAL AND DYNAMICAL SIGNIFICANCE OF PARTICLE PROPERTIES

1. *Size.* Particle size may be defined as its volume, weight, settling velocity, sieve mesh, or by intercepts through the particle [4]. With the exception of volume, the definitions are influenced by the shape or density of the particle except in restricted instances. These considerations led Wadell [3] to define size in terms of the nominal diameter, which is the diameter of a sphere having the same volume as the particle.

The effect of particle size on transportation and deposition has been the subject of extensive study by both geologists and engineers. The literature is perhaps sufficiently well known to engineers to render unnecessary the citation of a bibliography here.

2, 3. *Shape (Sphericity) and Roundness.* Much confusion centers about the concept of particle shape. Generally speaking, shape refers to the overall geometrical form of a particle, regardless of size or composition. Two particles have the same geometrical shape if the ratios of their intercepts and the angles between the intercepts are the same for both particles. Particles of very different geometrical shape (but of the same volume and density) may behave the same in fluids, so that shape may also be defined in terms of dynamic behavior.

Wadell [3] was the first to derive more than a single variable

from the general shape concept. He proposed the term "sphericity" for the sedimentological shape of a particle, referring to the essentially similar sedimentary behavior of particles having the same sphericity, regardless of their geometrical form. The concept is based on the principle that a sphere has the smallest surface area per unit volume of any particle shape; sphericity is defined as the ratio of the surface area of a sphere of the same volume as the particle to the actual surface area of the particle.

In contrast to the sphericity of a particle is its roundness [3], which is defined as the ratio of the average radius of the corners and edges of a particle to the radius of a circle inscribed in the maximum projected area of the particle. Roundness is thus geometrically independent of sphericity. Field and laboratory studies show that roundness is essentially negligible in the hydrodynamic behavior of particles, but it is of first-order importance in abrasion. The wearing away of sharp edges changes roundness markedly, but affects sphericity hardly at all.

Both sphericity and roundness are non-dimensional. Methods of measurement, including various rapid methods for approximate values, are given by Wadell [5], Krumbein and Pettijohn [4], Krumbein [6], and Riley [7].

Sphericity may be related to other shape concepts by a non-dimensional approach based on particle intercepts. These intercepts are three mutually perpendicular axes through the particle:

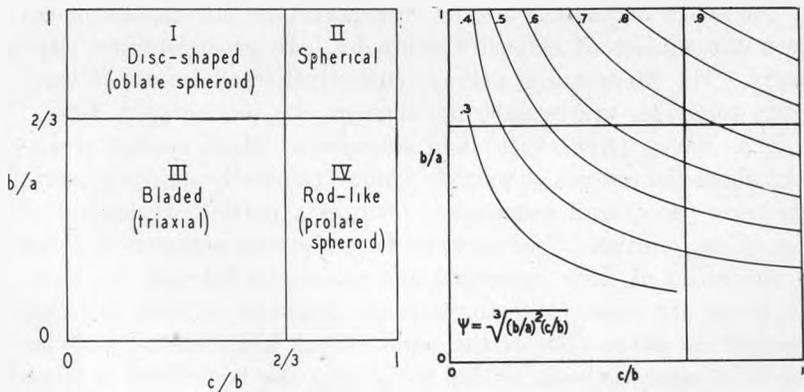


FIG. 1.—LEFT, ZINGG'S SHAPE CLASSIFICATION; RIGHT, LINES OF EQUAL SPHERICITY SUPERIMPOSED ON ZINGG'S CHART.

the longest, or a-axis; the intermediate, or b-axis; and the shortest, or c-axis. Zingg [8] has shown that if the ratio of the intermediate to the longest intercept (b/a) is plotted against the ratio of the shortest to the intermediate intercept (c/b), particles are classified according to their shapes. Fig. 1, *left*, shows the shape classification developed by Zingg. The writer recently showed [6] that it is possible to draw lines of equal sphericity on Zingg's chart (see Fig. 1, *right*), and thus unify the two points of view. Moreover, from two principles introduced by Wadell [9, 10], it has been shown by the writer [11] that an overall form coefficient may be developed from settling velocity, which permits direct correlation between shape concepts and hydrodynamic behavior.

Wadell broadened the definition of the coefficient of resistance by substituting the nominal diameters of particles of any shape for the true diameter of a sphere, on which the original definition was based. This modification extends the usefulness of the concept without changing established values for true spheres. By applying his definition to conventional graphs of the coefficient of resistance as a function of the Reynolds number, Wadell derived two generalizations of basic importance in shape studies. These generalizations are: (1) all particles of given density settling in a given fluid, regardless of particle shape, plot along a straight line of slope + 1 on the conventional chart, providing they have the same settling velocity; and (2) all particles of a given density settling in a given fluid, regardless of settling velocity or shape, plot along a straight line of slope - 2 if they have the same nominal diameter. These two principles are illustrated in Fig. 2. Point A represents a given non-spherical particle of nominal diameter d and settling velocity v . The heavy line on the graph is the conventional curve for spheres [12]. The dashed line of slope + 1 drawn through A is a line of constant settling velocity v , and the line of slope - 2 is a line of constant nominal diameter d . The two lines intersect the curve for spheres at B and C, respectively. Point B is the true sphere corresponding to particle A in terms of its settling velocity, and point C is the true sphere corresponding to A in terms of its nominal diameter. Points A, B, and C have individual values of the Reynolds number R_A , R_B , and R_C . Thus three ratios of values less than 1 are possible. Of these, $R_A/R_C = v_A/v_C$ represents the ratio of the actual settling velocity of the particle to the

settling velocity of a true sphere obtained by Wadell's second principle. This non-dimensional ratio is called by the writer the "form coefficient" [11], since it may be used as an overall shape factor.

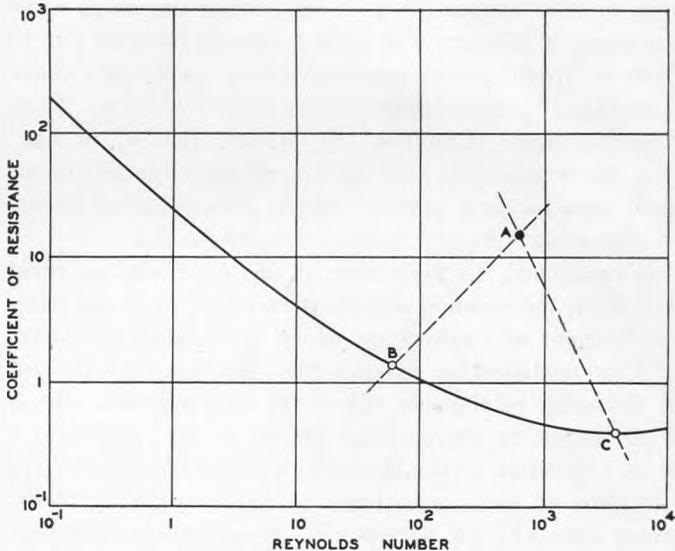


FIG. 2.—LOCATION OF THEORETICAL SPHERES CORRESPONDING TO GIVEN NON-SPHERICAL PARTICLE A.

The form coefficient is a dynamic shape factor which may itself be a function of the Reynolds number. At very low Reynolds numbers non-spherical particles tend to settle in fixed position, so that there may be maximum, average, and minimum settling velocities. As the Reynolds number increases, the settling particle tends to shift its orientation, and the average resistance of its cross-sections seems to control the process. Hence the ratio v_A/v_C may vary depending upon the regime involved. The writer tested this effect on given particles in fluids of markedly different viscosities, and found that the ratio appears to remain constant for the average settling velocity. Further work will be done on this problem.

If the ratio is itself a function of the Reynolds number, particles of given shape may not have the same dynamic behavior under varying conditions. Thus an interesting paradox arises, in which

particles of different geometrical form may have the same dynamic behavior, whereas particles of the same geometrical form may have different behavior under different conditions. This would have a strong bearing, for example, on differences in particle behavior in wind and water.

4. *Mineral Composition.* Mineral composition is important in the study of sediments. Natural sand is largely composed of quartz, but small amounts of other minerals of greater density (as garnet, magnetite, hornblende, etc.) are usually present. These "heavy minerals" furnish important information regarding the kind of parent rock from which the sediment was derived, as well as the distance the material was transported.

In addition to their importance in the geology of sediments, heavy minerals have a direct application to engineering, although apparently only limited use of the technique has been made. In problems associated with reservoir silting, for example, heavy minerals may permit an evaluation of the relative contributions of silt from various parts of the drainage basin. This is accomplished by taking cognizance of the kinds of bedrock in the area and their mineralogical composition. From the known composition of the parent rocks the mixture in the reservoir may be evaluated. Dr. Rittenhouse of the U. S. Soil Conservation Service has already undertaken basic studies of this type.

Rubey [13] investigated the dynamics of heavy-mineral occurrence in sandstone. He showed that the frequency distribution of the heavy minerals has a smaller mean size than the associated quartz, owing to the added effect of increased density on the settling velocity. Rubey's work provided a dynamic basis for setting up techniques of heavy-mineral study by showing that geological interpretation was influenced by the choice of size classes used in heavy-mineral work.

5. *Surface Texture.* The surface texture (surface roughness) of sedimentary particles is important in evaluating the abrasional history of the particles. Surface textures range from highly-polished and smooth surfaces to dull and rough surfaces, the latter caused by frosting, pitting, striations, etc. Fig. 3 illustrates the interrelations among surface textures, adapted from Williams [14]. Surfaces may be either smooth or rough and either polished or dull,

but combinations are possible; that is, a surface may be smooth and dull or smooth and polished.

Relatively little is known about the dynamical significance of surface textures, because of the unsatisfactory status of measuring

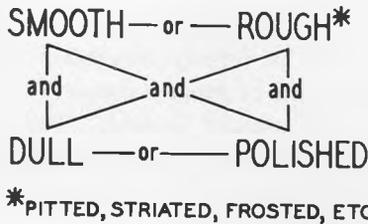


FIG. 3.—DIAGRAM ILLUSTRATING RELATIONS AMONG SURFACE TEXTURES.

techniques and because of the lack of experimental studies on the development of surfaces. It is known that some textures form in several ways. Polish may be produced by gentle attrition, by solution, or by the deposition of a vitreous film on the particle. Frosting may be caused by rigorous wind scour, by solution, or by incipient secondary growth.

Little more than qualitative interpretations can be made until the limiting conditions of these processes are understood.

The surface texture of individual particles is not the same as "surface roughness" of pipes or channel beds. Surface textures are the very small surface irregularities on individual particles, whereas surface roughness on the bed of a stream is on a larger scale, and is a function of particle size, roundness, and perhaps orientation.

6. *Orientation.* Particle orientation, both during transportation and after deposition, is one of the newer fields in the study of sediments. It has long been known that stream pebbles are imbricated, and recent studies show that most natural deposits display some degree of preferred orientation of their particles. Data are available on glacial deposits, beach deposits, esker deposits, and stream deposits (see references in [15]). Present methods of analysis are most satisfactory for particles larger than 1 centimeter, but they are also available for smaller particles.

Particle orientation involves both the instantaneous (changing) orientation of particles during movement, and the fixed orientation after deposition. Preferred orientation during movement may not be the same as that after deposition. Thus a cylindrical particle may roll with its long axis normal to stream flow, but on coming to

rest it may swing into parallel position. Such phenomena complicate the interpretation of ancient sediments.

Particle orientation is related to particle shape. Comparatively little is known about the dynamics of orientation, although Jeffery [16] developed a theory for particle orientation during laminar flow. Few experimental data are available for either laminar or turbulent flow, however. A review of the subject was made by the writer [17] in 1939. Unpublished data from more recent experiments suggest that the orientation of non-spherical particles during movement is a function of the Reynolds number of the flow. A disk, for example, may slide intermittently along the bottom at low flume velocities. At higher velocities it moves by a series of "flips" with the axis of rotation normal to the flow; at still higher velocities the disk rises on edge and rolls with the current. Finally, it may be swept free from the bottom into suspension. Thus a complete dynamical study of non-spherical particles may require the investigation of several regimes of behavior.

SUMMARY OF PARTICLE PROPERTIES

Much remains to be learned about the dynamics of particle behavior, but it is possible qualitatively to evaluate selective transportation and abrasion as they affect the fundamental properties of particles in transit along natural streams. The following tabulation summarizes these effects. The importance of each process is indicated by symbols: x is small and xxx is a large effect, whereas a dash indicates a negligible effect.

Property	Effect of	
	Abrasion ¹ (including solution)	Selective Transport
Size	x	xxx
Shape (sphericity)	xx	xxx
Roundness	xxx	—
Density	—	xx
Surface texture	xxx	—
Orientation	—	xxx

In general, abrasion affects roundness and surface texture most markedly; on the other hand, these attributes are essentially negli-

¹ The tabulation refers specifically to abrasion, a relatively mild type of wear caused by particles rubbing together during transit. More vigorous types of breakage are known, but their relative effects have not been studied.

ble factors in transport. What the table suggests in the main is that roundness and surface texture may be indices to the abrasive history of the particle, whereas the other properties reflect the dynamics of the transporting process.

PROPERTIES OF SEDIMENTARY AGGREGATES

A discussion of particle properties is not complete without some consideration of new variables introduced when particles occur in aggregates. The individual particles which comprise a sample are not all of the same size, shape or composition. Instead, each particle attribute is present as a frequency distribution, and must be summarized by statistical methods.

Fig. 4 illustrates several frequency distributions which occur in stream gravel. The graphs are histograms of size, shape (spher-

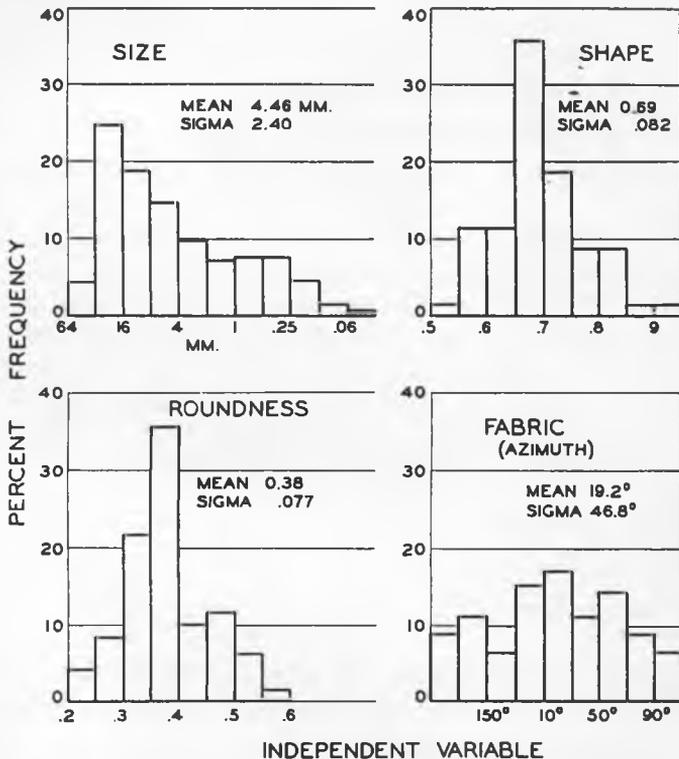


FIG. 4.—FREQUENCY DISTRIBUTIONS OF A SAMPLE OF FLOOD GRAVEL FROM SAN GABRIEL CANYON, CALIFORNIA.

ricity), roundness, and fabric (axis orientation in space) of the same sample of flood gravel from San Gabriel Canyon, California [18]. The size distribution indicates a poorly-sorted sandy gravel, with a marked skewness toward smaller sizes. The shape distribution shows a prominent maximum between 0.65 and 0.70, whereas the roundness is relatively low, with a maximum under 0.40. These two diagrams indicate the confusion which may arise unless shape and roundness are distinguished. The orientation of the pebble axes is not marked, although there is a preferred orientation toward the northeast-southwest. The proper interpretation of such a set of diagrams depends upon their relation to adjacent samples from the same environment. Details are given in the reference cited.

The statistical treatment of sedimentary data is in a much-confused state. Most workers develop their own devices, without regard to statistical theory. As a result, considerable space is devoted to the relative merits of methods which are questionable in the first place. The logical approach is to adapt conventional statistical techniques to the problem. These have already been scrutinized for their reliability by mathematical statisticians. Standard moment methods of analysis, for example, have stood the test of time, and they are directly applicable to all sedimentary characteristics. Logarithmic transformations are needed to convert size data into a form for convenient treatment, but shape and roundness data may be treated as they are. A discussion of standard statistical devices and their sedimentary application is given by Krumbein and Pettijohn [4]. Otto [19] has since developed graphical methods for the convenient moment analysis of size data.

In addition to new problems introduced by the occurrence of frequency distributions within sediments, several new properties are developed by the aggregate itself. Thus the grouping of particles results in the development of porosity, which is a function largely of the state of packing. Likewise, the aggregate is permeable; the permeability is a function not only of the degree of packing, but also of the size, shape, and orientation distributions. The aggregate may resist compressional and tangential stresses, thereby exhibiting crushing and shearing strengths. Strength is a function of a combination of particle properties, and of such extra factors as

water content. All of these properties of the aggregate may be referred to as "mass properties."

In general it is simpler to measure the mass properties directly, rather than to attempt to predict them from the individual particle properties. This is true of porosity, permeability, shearing strength, plasticity, and so on. Nevertheless, to a large degree the mass properties are controlled by the individual particle properties, and a study of the relation between the two would shed considerable light on the laws of mass-sediment behavior.

Mass properties of sediments are important in many engineering fields. The extensive applications of soil mechanics to construction engineering is a case in point. Many additional applications can be made in other fields. For example, the bulk volume of sediments in a reservoir is a function in part of particle orientation. In a haphazard arrangement the bulk volume is greater than with preferred orientation. The writer is not aware that the problem of controlling this factor in reservoirs has been studied. The relation of orientation to compactibility also affords some interesting problems.

CONCLUDING REMARKS

Perhaps the most important point in this paper is its insistence that the same fundamental principles of sediment transportation and deposition are common to geology and to hydraulic engineering. Although the two fields approach the subject from different angles and use their data for different purposes, the foundation is the same. For this reason future developments can be accelerated by the mutual exchange of ideas and techniques, and by the development of a common language for the description and analysis of sedimentary phenomena.

REFERENCES

- [1] Shulits, S., "Rational Equation of River-Bed Profile," *Trans. Am. Geophys. Union*, 1941, pp. 622-631.
- [2] Mason, M. A., "Abrasion of Beach Sand," *Beach Erosion Board, Techn. Mem.* 2, 1942.
- [3] Wadell, H., "Volume, Shape, and Roundness of Rock Particles," *Jour. Geol.* Vol. 40, 1932, pp. 443-451.
- [4] Krumbein, W. C., and Pettijohn, F. J., *Manual of Sedimentary Petrography*, New York, 1938.

- [5] Wadell, H., "Shape Determinations of Large Sedimental Rock Fragments," *Pan-Am. Geologist*, Vol. 61, 1934, pp. 187-220.
- [6] Krumbein, W. C., "Measurement and Geological Significance of Shape and Roundness of Sedimentary Particles," *Jour. Sed. Petrology*, Vol. 11, 1941, pp. 64-72.
- [7] Biley, N. A., "Projection sphericity," *Jour. Sed. Petrology*, Vol. 11, 1941, pp. 94-97.
- [8] Zingg, Th., "Beitrage zur Schotteranalyse," *Schweiz, Min. u. Pet. Mitt.*, Vol. 15, 1935, pp. 39-140.
- [9] Wadell, H., "The Coefficient of Resistance as a Function of Reynolds Number for Solids of Various Shapes," *Jour. Franklin Inst.*, Vol. 217, 1934, pp. 459-490.
- [10] Wadell, H., "Some Practical Sedimentation Formulas," *Geol. Fören. Förhandl.*, Vol. 58, 1936, pp. 397-408.
- [11] Krumbein, W. C., "Settling Velocity and Flume Behavior of Non-spherical Particles," *Trans. Am. Geophys. Union*, 1942, pp. 621-633.
- [12] Rouse, H., "Nomogram for Settling Velocity of Spheres," *Ann. Rep. Comm. Sedimentation, Nat. Research Council*, 1937, pp. 57-64.
- [13] Rubey, W. W., "The Size-Distribution of Heavy Minerals Within a Water-Laid Sandstone," *Jour. Sed. Petrology*, Vol. 3, 1933, pp. 3-29.
- [14] Williams, Lou, "Classification and Bibliography of Surface Textures of Sedimentary Fragments," *Rep. Comm. Sedimentation, Nat. Research Council*, 1937, pp. 114-128.
- [15] Krumbein, W. C., "Preferred Orientation of Pebbles in Sedimentary Deposits," *Jour. Geol.* Vol. 47, 1939, pp. 673-706.
- [16] Jeffery, G. B., "The Motion of Ellipsoidal Particles Immersed in a Viscous Fluid," *Proc. Roy. Soc. London*, Vol. 102A, 1922, pp. 161-179.
- [17] Krumbein, W. C., "Settling Velocity and Orientation of Sedimentary Particles," *Int. Union Geodesy and Geophysics*, Washington, 1939.
- [18] Krumbein, W. C., "Flood Gravel of San Gabriel Canyon, California," *Bull. Geol. Soc. America*, Vol. 51, 1940, pp. 639-676.
- [19] Otto, G. H., "A Modified Logarithmic Probability Graph for the Interpretation of Mechanical Analyses of Sediments," *Jour. Sed. Petrology*, Vol. 9, 1939, pp. 62-76.