A Laboratory Measurement of The Hydraulic Conductivity of Fragmented Gravels

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ABSTRACT: Due to severe environmental conditions and the action of different type of loading forces, granular materials that form the base of a road pavement may be subjected to crushing and fragmentation. The effect of the small fragments that move into the voids as a result of crushing is that they may have increased the bearing capacity of the base material. However, when the volume of the voids is decreased due to the migration, the flow ability of the material is said to reduce. This change in the engineering property of the material may lead to an undesirable drainage pattern within the pavement. A number of laboratory tests were conducted and repeated whereby small gravels were gradually fragmented and the hydraulic conductivity of the materials were measured. In this study, the pattern of fragmentation of different gravels was analyzed using fractal theory and the hydraulic conductivity of the gravels before and after different stages of fragmentation were measured. From the measurement of fractal dimension number in the fragmented rock it was found that as the fractal dimension is increased the hydraulic conductivity of the material is decreased.

KEY WORDS: Fragmented gravels, Fractal dimension, Hydraulic conductivity.

1 INTRODUCTION

In a road construction of a flexible pavement, granular materials are commonly used as the base course to absorb the intensity of the load due to traffic. When subjected to static and dynamic load these materials often experience crushing and fragmentation and for the base layer of the pavement this particular phenomenon is found to be more frequent during the construction stage (Brown 1996). In tropical climate, the typical hot and humid condition often accompanied with spells of heavy rain provides a much more conducive environment for crushing and fragmentation of the granular medium. Other engineering structures such as rockfill dams display evidence of crushing and fragmentation in their granular materials components due to the effect of sustained gravitational force (Terzaghi 1960) and along with this phenomenon was settlement. Therefore, layers of the granular materials that form the core components of the engineering structures settled under sustained forces and thus in the process may represent a more resilient component than the ones that were previously employed.

As a result of the compressive stresses that sometimes accompanied by naturally harsh environment, the granular materials break into pieces of different sizes ranging from the very fine to the larger pieces. Thus, the original engineering properties with which the base of the pavement structure or the rockfill dam was designed with, such as the hydraulic conductivity, the shear strength and the elastic moduli, will inevitably change during its engineering life (Feda 2002). Such change in the original engineering properties could affect the designed stability of the structures and could render them unsafe. This paper looks into the general crushing phenomenon of two types of granular material and 5mm. diameter glass beads were used as a control in the compression test. However, the focus of the investigation was specifically on the small angular gravels of average diameter of 5mm. retained on sieve no.4.Therefore a large number of gravels was prepared to represent the angular-shaped gravels and round-shaped gravels. The size distribution of the broken granular materials was analyzed by fractal dimension using fractal theory. A particular laboratory procedure was performed to capture the effect of fragmentation on the hydraulic conductivity of the granular medium so as to understand the development of fractal fragmentation with regard to the hydraulic conductivity of the tested medium.

2 SERIES OF TESTS

Induced crushing load was performed using a Universal Testing Machine commonly used in most laboratories however, with an addition of a piston that could fit inside the test cylinder extending to the top of the test specimen. Together with an especially fitted base that plugs in perfectly from the bottom of the test cylinder as indicated in Figure 1. The steel test cylinder was especially designed with precision dimensioning in order to function efficiently in both the crushing compression test as well as the constant head hydraulic conductivity test in the permeameter apparatus. The compression tests were carried out in stages of increasing crushing loads and performed continuously so that an evolution of crushing and fragmentation may be observed.

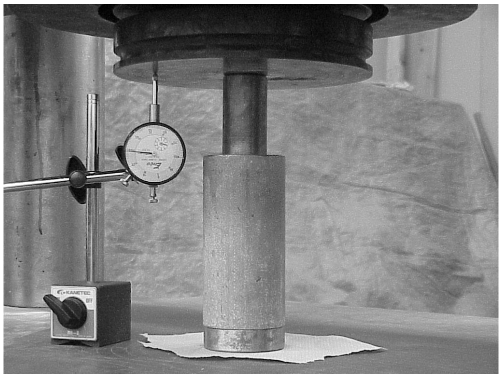


Figure 1: Crushing of a sample of small gravels due to compression in a test cylinder using The Universal Testing Machine.

As it is extremely important to retain in the best possible manner the entire quantity of the sample as well as the arrangement of granular particles after each and every tests, the use of a filter paper is introduced at the top and bottom of the test specimen especially during the test for the hydraulic conductivity of the sample.

Without the filters most of the fines product accumulated at the bottom of the granulate as a result of fragmentation of materials would be washed away during the tests for the hydraulic conductivity as water percolate through the fines filled voids of the granular medium transporting them out of the permeameter cell resulting in inaccurate data. The increased weight of the filters before and after the tests indicated the relevance of this particular procedure.

It is therefore the objective of the laboratory works to have a fragmented granular medium tested for its hydraulic conductivity while maintaining the position and the affected arrangement of the particles. While the sample still in the same cylinder is oven-dried and is returned to the compression machine for the second time to sustain increased compression and further fragmentation before again tested for the hydraulic conductivity. These series of tests were repeated for a number of 3 sets with increasing crushing loads being applied to the specimens of small gravels simulating the evolution of fragmentation and crushing accompanied by the simultaneous condition of wet and dry spells.

3 FRACTAL DIMENSION AND THE PARTICLE SIZE DISTRIBUTION

Suggested application of fractal dimension based on fractal theory in soil physical properties such as the grain size or the particle size distribution (Tyler and Wheatcraft 1992, Wu et.al. 1993), the pore-size distribution (Brakensiek et.al. 1992) and pore surface area (Friesen and Mikula 1987) provide a unique opportunity to the understanding of the scale invariance property of the natural soil. Fractal theory and fractal scaling concept (Mandelbrot 1982) suggests that across a wide range of scales, the solid phase of a soil as it applies to particle-size distribution, appears self-similar. The distributions at different scale could then be related to each other by a power law function with an exponent termed fractal dimension *D*. The relationship for the grain-size distribution based on fractal concept (Mandelbrot 1982, Turcotte 1986) is of the form

$$N(r > R) \propto R^{-D} \tag{1}$$

where $N(r > R)$= total number of particles of size $> R$; and D is the fractal dimension. However, as mass or weight is more easily measured as in the usage of mechanical sieves where an upper and lower bound of sieves define the range of sizes of the soil is obtained, a mass-based relationship was developed (Tyler and Wheatcraft 1992) in the form of

$$\frac{M(R < r)}{M_T} = \left(\frac{r}{r_L} \right)^{3-D} \tag{2}$$

where $M(R < r)$ is the cumulative mass of particles with size R smaller than a given comparative size r and that is, “percentage of mass less than”; M_T is the total mass of particles (introduced for normalization); r is the sieve size opening; r_L is the maximum or the upper limit of the particle size as defined by the largest sieve size opening. D, the fragmentation fractal dimension is obtained using the slope coefficient m (Hyslip and Vallejo 1997), for the linear regression line of a log-log plot, giving the equation,

$$D = 3 - m \tag{3}$$

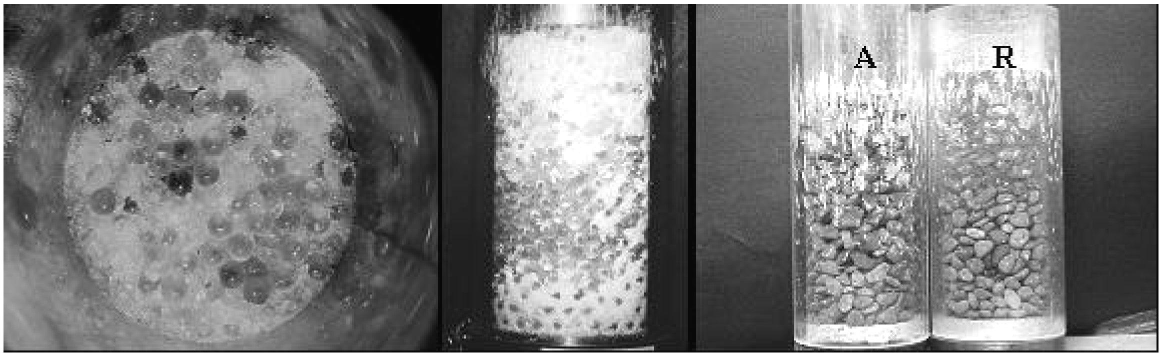
Recent research shows that hydraulic conductivity of soils is greatly influenced by the grain-size distribution. Consequently, attempts have been made to develop new models to predict hydraulic conductivity of soils based on the grain-size distribution using the fractal dimension as an alternative representation of the characteristics of the grain-size distribution (Boadu 2000). The purpose of this paper is to present the laboratory results of the hydraulic conductivity on continuously fragmented soil and incorporating fractal dimension in the experimental results as a quantitative measure of grain-size distribution of the soil.

4 EXPERIMENTAL OBSERVATION AND FRACTAL FRAGMENTATION

4.1 Crushing Compression Test

To observe crushing and fragmentation characteristics of granular material, an initial laboratory experiment was carried out with a Plexi-glass tube of 2.0 inches in diameter filled with 5.0 mm. diameter glass beads having specific gravity of 2.5 to a depth of twice the tube diameter. A ratio of sample diameter to the maximum particle size of approximately 6:1 was maintained. The tube was set upright with a steel plug at the bottom on which the beads are rested and a 2.0 kg. piston head pressing against the grains at the top of the beads. The objective of the exercise is to impound a crushing condition to the grains and to observe the crushing characteristics of the perfectly spherical beads as a control. At the maximum compression load applied, a high degree of material packing was observed at the top of the cylinder and a lesser degree of packing took place at the bottom plug. The glass beads at the top that came into contact with the piston load drew the highest concentration of stresses and crushed and fragmented more than anywhere else in the medium. Migration of small broken material into the voids took place and some of the very fine grains produced were seen accumulated at the base of the test specimen as can be seen in Figure 2 (a) and (b).

In general, crushed products in small gravels medium demonstrated similar crushing characteristics to that of the glass beads. In these cases, it was discovered that as the compression progressed and the specimen became more compacted it became increasingly difficult for further fragmentation and crushing to take place. However, due to mainly the difference in material elasticity, unlike the glass beads, the compression stress in gravels was mostly affecting the top most layer of the packing and not distributed more evenly downwards leaving the lower layers relatively not much affected. Thus, Figure 2(c) shows that voids in the top layer of the granular column were mostly filled with the broken pieces of the fragmented gravels with minimal quantity of fines migrated into voids located at the lower column and only traces of fines ended up at the base of the specimen unlike the observation made with the glass beads test specimen.

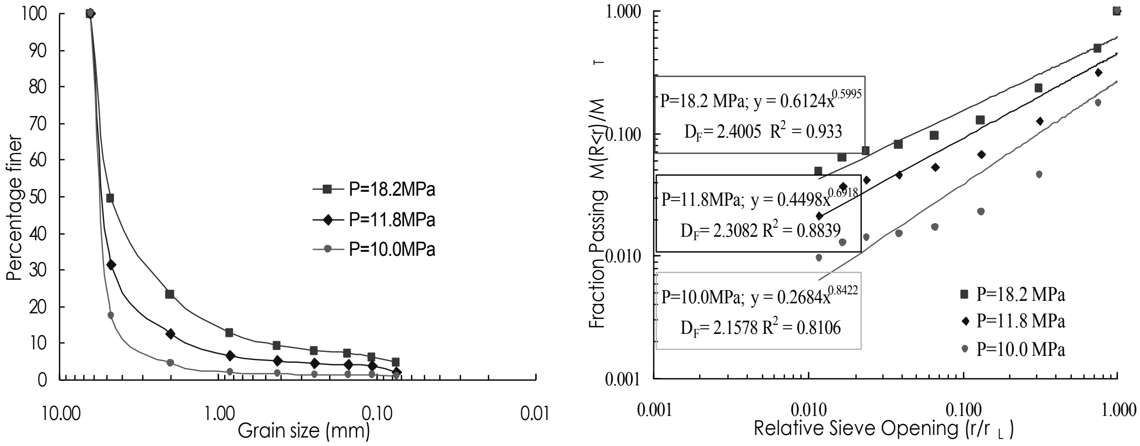


(a) (b) (c)

Figure 2: (a) View of fragmented top layer of glass beads column, (b) Migration of fines in glass beads, and (c) Crushed angular gravels [A] and round gravels [B] test specimens.

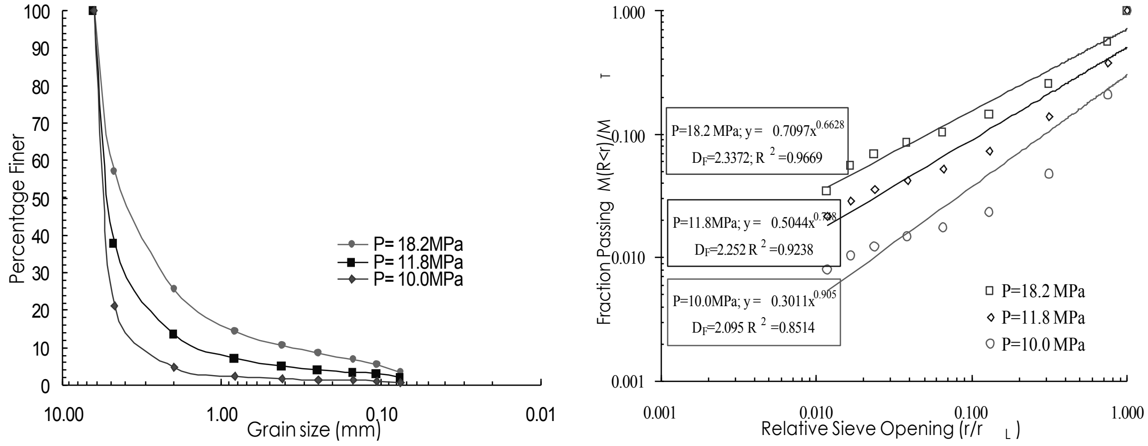
4.2 Fragmentation of the Gravels

The UTM used was a constant-stress testing machine. Applied load readings were set to exert only very low increments of 10 lbs. reading (22 kgf.) at a time. For example to achieve a maximum compressive load of 10,000 lbs., the sample was loaded for 150 minutes. As observed, gravels that were loaded to crush in the UTM were fragmented in the manner presented in the photos in Figure 2. By using mechanical sieves the fragmented product of the compacted samples can presented by the Particle-Size Distribution (PSD) and the corresponding power-law plots as shown in Figures 3(a) and 3(b) respectively for round gravels and Figures 4(a) and 4(b) respectively for angular gravels.



(a) (b)

Figure 3: Fragmentation in round gravels (a) PSD and Fractal analysis at 10.0MPa, 11.8MPa and 18.2MPa.



(a) (b)

Figure 4: Fragmentation in angular gravels (a) PSD and Fractal analysis at 10.0MPa, 11.8MPa and 18.2MPa.

The results due to static compression loading on the gravels with different structural shape revealed almost the same amount of fragments were produced in the round gravel as well as the angular shaped gravels for the given crushing compressions of 10 MPa., 11.8MPa. and 18.2MPa. The fractal dimensions of the crushed samples showed very identical values for both although the power-law plots seemed to indicate that the correlations are better in the fragmented angular specimens. The relationship between the crushing compression and the fractal dimension of the fragmented materials is illustrated in the following plots in Figure 5.

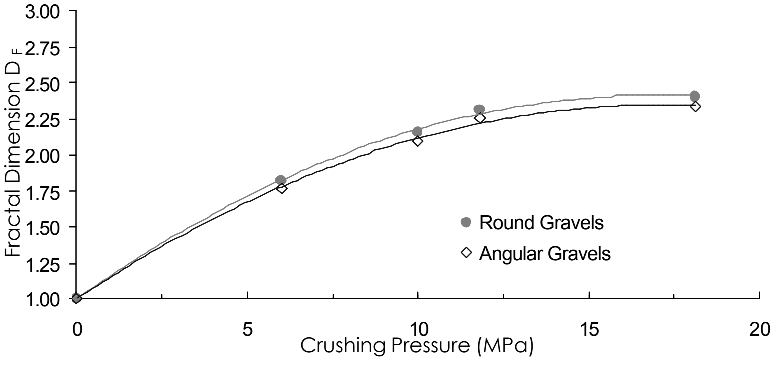


Figure 5: Relationship between the fragmented gravels and the compressive pressure.

4.3 Hydraulic Conductivity of the Gravels

The constant head method of testing that has been found to be suitable for granular materials was adopted in the exercise. The testing procedure follows the recommendations of the ASTM D 2434. The apparatus set up shown in Figure 6 was using the K-605 combination permeameter with the in-flow at the bottom of the test cell.

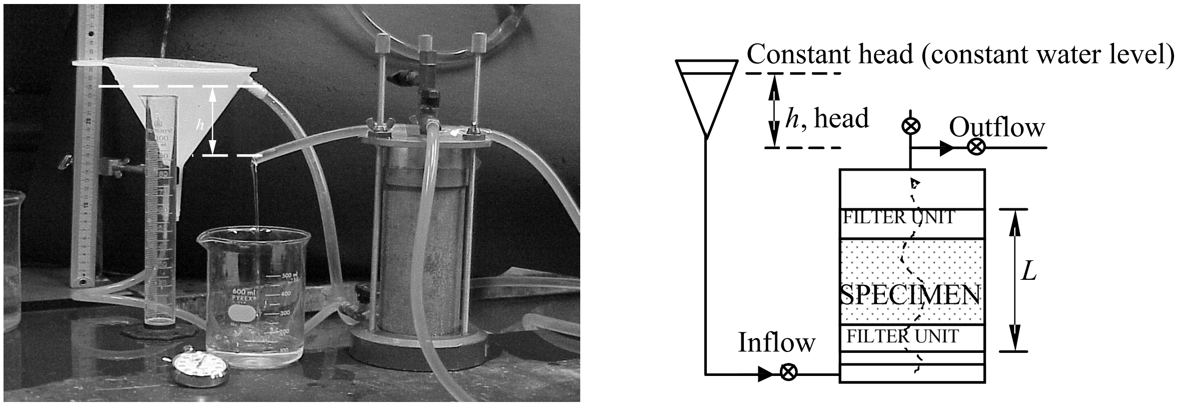


Figure 6: The Permeameter test set-up and a schematic drawing of the Constant Head.

As effects due to the different level of crushing needed to be recorded it was necessary for additional apparatus and measures were introduced in order to obtain a higher accuracy of data. Special precautions were taken for the fragments and the fines produced as a result of the crushed gravel to be kept within the test cylinder and not lost during all the tests until completion. In the permeameter, porous stone filter-units were install at the bottom as well as at the top of the specimen. To avoid clogging of these porous stones by the fines transported outwards by water, a layer of thin durable paper filter was also placed. The filters were wrapped around the porous stone units each with a rubber band in such a way that during the tests flow is forced through these units rather than around them.

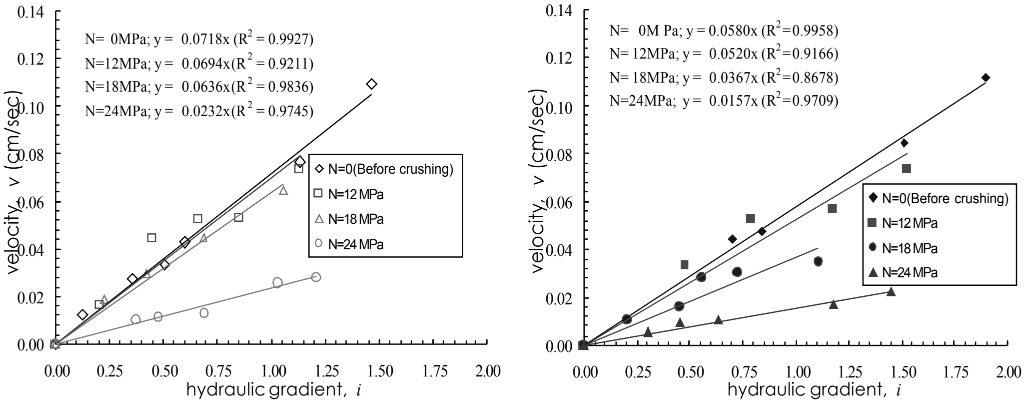
The thickness of the base plug at the bottom of the chamber during which the specimen was crushed was designed to perfectly fit the total thickness required to place the filter unit as the chamber was later set up in the permeameter. The perfect fit was the key to the leak-proof tests. Adequate tests were then carried out to evaluate the hydraulic conductivity of the filter-units. Using equation (4) for equivalent hydraulic conductivity, where, h_1, h_2 and h_3 were the thickness of the filter units and the gravels specimen, the determination of vertical flow in stratified layers the k values for the tested samples were obtained.

$$k_{V(equivalent)} = \frac{L}{\left(\frac{h_1}{k_{V_1}}\right)+\left(\frac{h_2}{k_{V_2}}\right)+\left(\frac{h_3}{k_{V_3}}\right)} \tag{4}$$

At a specific head difference h, at least 3 trial flow discharges were performed in order to obtain a reliable data. Measurement of time was by using a stop clock to indicate the duration to collect 500 ml. of water. Close monitoring against constant interference due to trapped air bubbles and detailed recording of the temperature of the water were some of the important steps taken. If h, is increased a higher value of discharge q is obtained since they are directly proportional to each other. For each specimen, test time of 6 to 8 hours were required to conduct an average of 5 different values of h. A straight-line plot could then be constructed to obtain the equivalent hydraulic conductivity ($k_{V(equivalent)}$) and hence the value for the hydraulic conductivity of the fragmented specimen. After completion of a test, the filter units were carefully extracted from the cylinder while leaving the soaked specimen perfectly intact. The base plug was again fitted at the bottom of the cell and the gravels were oven dried at 300˚C for a period of 24 hours. After a cooling off period of 12 hours for the gravels and the cell, the specimen was subjected to a higher degree of crushing and after which the process of saturation and then the exercise of measuring of the discharges at various heads was repeated for the second set of testing.

5 RESULTS OF HYDRAULIC CONDUCTIVITY OF FRAGMENTED GRAVELS

The first of the four samples from each of the group represented the condition before crushing takes place. The next three represented progressive fragmentation as a result of increased crushing loads in static modes. As the materials break, the finer fragments migrated into the voids and the volume decreased. As a result of reduced void ratio and porosity, the ease at which the water could flow through the specimen was affected. The following plots show the result of the hydraulic conductivity tests for the round gravels in Figure 7 (a) and for the angular gravels in Figure 7 (b) and Tables 1 summarizes results of the tests and the affect of the increased fragmentation evaluated by the fractal dimension number approach. From the data, a relationship between the hydraulic conductivity of the gravels and the fractal dimensions can be established, and this is illustrated in the plots in Figure 8.



(a) (b)

Figure 7: Laboratory evaluation of hydraulic conductivity *k* for fragmented (a) Round gravels and (b) Angular gravels subjected to static loads.

Table 1: Summary of the test result due to static compression.

Static Compression Pressure, *N* (MPa)	Round Gravel			Angular Gravel		
	Fractal D_F	Void ratio e	*k* (cm/s)	Fractal D_F	Void ratio e	*k* (cm/s)
0	1.0000	0.681	0.343	1.0000	0.836	0.150
12	2.3082	0.616	0.329	2.2520	0.711	0.117
18	2.4005	0.530	0.250	2.3372	0.551	0.058
24	2.4200	0.462	0.027	2.3500	0.422	0.016

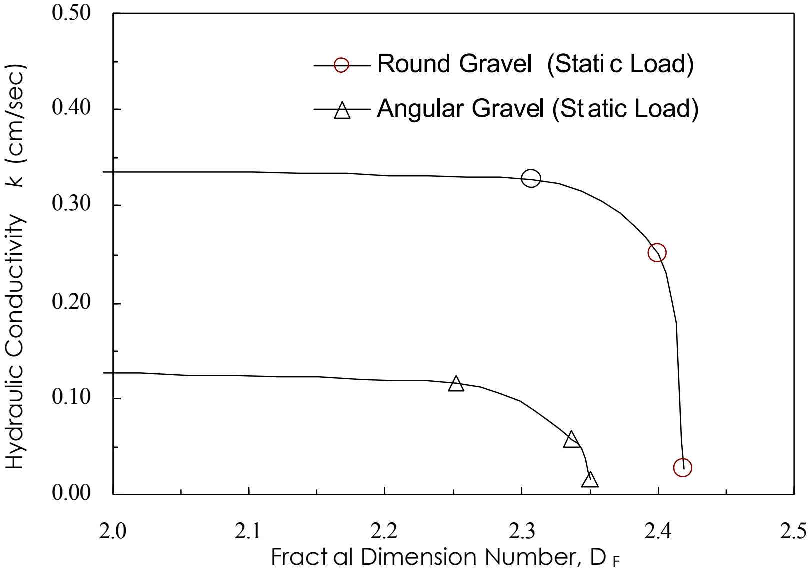


Figure 8: Hydraulic conductivity of round and angular-shaped gravels in relation to fragmentation fractal dimension due to static loads.

The laboratory results show that the values of hydraulic conductivity of fragmented round-shaped grains and fragmented angular-shaped grains each falls within a certain band. Flow of water is more efficient over rounded surface with smooth texture than in bodies with sharp corners and jagged surfaces. The effect of finer fragments in round gravels on the hydraulic conductivity is very significant beyond fractal dimension 2.3 when the permeability is greatly reduced due to an increase in fines as a result of fragmentation. Besides, some of the fragments are in fact angular-shaped grains of various sizes. This explains the less pronounced plot presented by the angular gravels sample since flow of water in them has always been inefficient. On the other hand flow has always been efficient over rounded granulate until fragments were introduced. The reduction in the ease of flow in the round gravels is counter balanced by the efficiency of the fluid flow around smooth rounded grains giving a slightly higher value of *k* in fragments with round gravels.

The effect of the shape of the granular materials (ie. spherical or angular) have been rightly recognized by earlier researchers by factoring in a higher shape factor value (C_s =700) for the angular grains with respect to spherical grains (C_s =360) (Dunn 1980) and as a result, the hydraulic conductivity in soils with round-shaped (spherical) reveals a higher hydraulic conductivity *k* than angular samples and this is verified in the laboratory tests.

5 CONCLUSION

The investigation performed in the laboratory using the constant head permeameter have been improvised in providing the insight into the problems presented by fragmentation phenomenon in granular soils. As a result of fragmentation due to high axial compression, the efficiency of flow in round gravels as well as the angular gravels is affected. Clearly, the increase of the fragments reduces the hydraulic conductivity. The shape of the unbroken gravels remaining in the medium as well as the amount of fragments and fines could therefore be factored into the hydraulic conductivity of the fragmented medium. The hydraulic conductivity of a soil decreases as the fractal fragmentation dimension of the soil D_F increases.

The application of fractal dimension presents an interesting prospect in improvement of the prediction of the hydraulic conductivity property of fragmented granular materials. The main advantage of evaluating a whole population of fragmented material with a number could perhaps be utilized to modify some of the existing empirical equations.

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