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Hydraulic conductivity of granular materials

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ABSTRACT: The present paper is an attempt to evaluate the coefficient of hydraulic conductivity of several types of granular materials usually used as base and subbase course materials in pavement construction in Iraq. The selected materials confirmed with S.O.R.B. specifications, (State Organization of Roads and Bridges) issued in Iraq in l986 for granular base and subbase layers. The tests were performed under constant head condition within the range of validity of Darcy’s Law under laminar flow conditions. The regression analysis of the test results revealed an equation that predicts the degree of packing as a function of void ratio and mean particle diameter. The equation can provide quick estimate of the degree of packing which is directly related to the coefficient of hydraulic conductivity of any granular layer.

1 INTRODUCTION

The base and subbase layers in flexible pavements should provide adequate drainage to any excess moisture in addition to their function in increasing the load carrying capacity of the subgrade. Open-graded, highly permeable layers are recommended to be used in these layers to overcome the problem of drainage adequacy and control moister movement and prevention of volume change of subgrade (NCHRP 1998).

The patterns of flow of water through granular material range between saturated flow pattern with all voids filled with water and unsaturated flow where both water and air exist in the pores of soil. In practical conditions it is always assumed that completely fully saturated state is not justified and it is not unusual to expect from (1-12) % of air remaining in voids (Young & Warkentin 1975). However, the analysis is usually made in terms of fully saturated state.

The aim of the present work is to evaluate and predict the coefficient of hydraulic conductivity of granular materials used as base and subbase layers. All samples were prepared at various void ratios and tested under controlled hydraulic gradient within the range of validity of Darcy's law and laminar flow condition.

2 MATERIALS GRADATION AND PHYSICAL PROPERTIES

Table 1 demonstrates the gradation specifications of the base and subbase materials used in flexible pavements (S.O.R.B) and its amendments issued in 1986 by the directorate of roads and bridges, Ministry of Housing and Construction, Iraq. The materials used in this study were brought from Al-Nibai quarry near Baghdad and currently used as pavement construction materials in Iraq. Table 2

Table1. S.O.R.B specification of Base and subbase Course Material Gradation

Sieve Size (mm)	Percent passing by weight for base course materials			Sieve size (mm)	Percent passing by weight for subbase course materials			
	Type A	Type B	Type C		Type A	Type B	Type C	Type D
50	100			75	100			
37.5	90-100	100		50	95-100	100		
25.0	77-95	87-100	100	25	55-90	75-95	100	100
19.0	68-90	80-95	92-100	9.5	30-65	40-75	50-85	60-100
12.5	55-83	70-90	82-95	4.75	25-55	30-60	35-65	50-85
9.5	47-75	65-85	75-92	2.36	15-42	20-45	26-52	42-72
4.75	33-65	50-75	60-82	0.3	7-18	14-28	14-28	23-42
2.0	20-50	33-65	42-70	0.075	2-8	5-15	5-15	5-20
0.425	10-30	17-40	20-45					
0.18	5-22	10-25	10-28					
0.075	3-10	3-10	3-10					

Table 2. Gradation of Material Used in Study as Base and subbase Course

Percent passing by weight for base course materials						Percent passing by weight for subbase course materials				
Sieve size mm	Type A (1)	Type A (2)	Type B (3)	Type B (4)	Type C (5)	Sieve size mm	Type A (6)	Type B (7)	Type C (8)	Type D (9)
50	100	100				75	100			
37.5	97	92	100	100		50	97	100		
25	93	81	98	90	100	25	85	85	100	100
19	83	72	94	85	95	9.5	59	46	65	80
12.5	79	63	81	78	85	4.75	45	35	50	64
9.5	70	53	72	66	80	2.36	34	28	34	53
4.75	59	39	68	50	70	0.3	11	14	21	33
2.0	48	25	57	40	52	0.075	6	5	6	8
0.425	20	19	34	20	29					
0.18	6	7	11	10	22					
0.075	2	1	6	4	3					

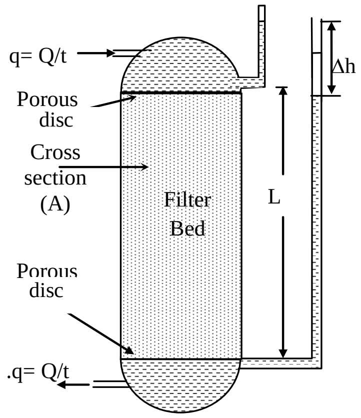
Table 3. Physical Properties of Material Used as Base and subbase Course

Test of specific property	Base course materials					subbase course materials			
	Type A (1)	Type A (2)	Type B (3)	Type B (4)	Type C (5)	Type A (6)	Type B (7)	Type C (8)	Type D (9)
Bulk specific gravity 23/23 ^{0}C	2.649	2.663	2.661	2.658	2.659	2.663	2.649	2.649	2.659
Bulk specific gravity (saturated surface dry)	2.671	2.681	2.687	2.685	2.690	2.681	2.661	2.671	2.662
Apparent specific gravity	2.712	2.721	2.726	2.725	2.731	2.721	2.705	2.712	2.707
Max. density (gm/cm^3)	2.221	2.113	2.241	2.239	2.192	2.113	2.130	2.221	2.23
Min. density (gm/cm^3)	1.529	1.567	1.681	1.639	1.531	1.570	1.547	1.529	1.687
Max. void ratio	0.728	0.693	0.579	0.618	0.731	0.693	0.708	0.728	0.572
Min. void ratio	0.190	0.257	0.184	0.185	0.211	0.258	0.241	0.19	0.19

3 HYDRAULIC CONDUCTIVITY PRINCIPLES AND SET UP

Figure1 shows the testing setup that complies with the ASTM D2434 and AASHTO T215 for determining of hydraulic conductivity of the granular materials. The setup consists of a cylinder 230 mm in diameter and 780 mm in height with two porous discs at top and bottom ends. There are two hemispheres at both ends with piezometers placed at base level for water pressure measurements. The top hemisphere is connected to an outside water reservoir that controls the pressure head at the required level. The bottom hemisphere consists of an out let for measuring the rate of flow.

The sample was prepared by placing the lower porous disc in the cylinder. The granular material was spread in layers with gentle compaction depending on the required void ratio. After the completion of the compaction, the upper porous disc was placed on the top of sample and the upper hemisphere was fitted in position. Water was then allowed to flow and fill gradually and slowly the top hemisphere and then the whole set up. To ensure saturation water was left circulating for 24 hour prior to the commencement of the test. The hydraulic gradients of 0.2, 0.25, and 0.3 were controlled by raising or lowering the position of the outside reservoir. For each specific hydraulic gradient, water from the outlet at the bottom hemisphere was collected at specified time interval of 20 sec. the rate of flow was remained constant indicating the validity of the steady state flow.



According to Darcys' law the volume of water Q flowing through the sectional area of the filter bed in time t is directly proportional to the difference in piezometer levels Δh and the cross sectional area A and inversely proportional to the length L. The constant of proportionality is denoted by the coefficient of hydraulic conductivity K is given according to ASTM, 1969, 1986 as:

$$K = \frac{Q.L}{A.t.\Delta h} \tag{1}$$

To ensure the validity of Darcys' low and preventing the existence of turbulent flow, ASTM D2434, and AASHTO T215 specifications suggested hydraulic gradients of (0.2-0.3) for materials at loose state and of (0.3- 0.5) for dense state. The transition between laminar and turbulent flow is well defined by the dimensionless Reynolds number Re values expressed as (Cedergren 1977):

$$Re = \frac{\rho.v.d}{\mu} \tag{2}$$

where: ρ: Density of fluid (gm/cm^3), v : flow velocity ,μ: dynamic viscosity (gm.sec/cm) and "d" can be taken as a mean pore dimension or as mean grain size diameter. The mean diameter "d" can be estimated using the equation suggested by (Lindly&Elsayed 1998) as:

$$d = \frac{1}{100} * \sum p_i * D_i \tag{3}$$

where: "P_i" is the percentage of aggregate held between two adjacent sieves; "D_i" is the mean of opening size of two adjacent sieves.
A second support for the validation of laminar flow in porous media is the log-log linear relationship between Reynolds number and Fanning friction factor “f” suggested by (Bear, 1972) as:

$$f = \frac{1}{2} d \left(\gamma / \rho . v^2 \right) \tag{4}$$

Another parameter that affects the hydraulic conductivity of porous media is the degree of packing of the granular soil and on the shape of the particles. These are covered by the parameter “c” and the hydraulic conductivity K can then be determined using the equation proposed by (Roger 1969):

$$K = \frac{c.\rho.g.d^2}{\mu} \tag{5}$$

The parameter “c” is determined from the regression analysis of the test results discussed below.

5 RESULTS OF EXPERIMENTAL WORKS

Four samples from base and subbase course materials (types A and B) were selected to check the validity of Darcy’s law. Table 4 illustrates the physical properties of the tested samples within the range of hydraulic gradient 0.05 to 0.5. The resulted relationship between the flow velocity and the hydraulic gradient (v-i) are shown in figure 2.

Table 4. Physical Properties of Material Used in (v-i) relationship

Sample No. Property	Type A No.(1)	Type B No. (4)	Type A No. (6)	Type B No. (7)
specific gravity	2.649	2.658	2.663	2.649
Density (gm/cm^3)	1.952	1.875	1.980	2.079
Temperature (c°)	37	39	21	38
d(mm)	13	8.4	12.6	12.7
Void ratio	0.348	0.407	0.342	0.265

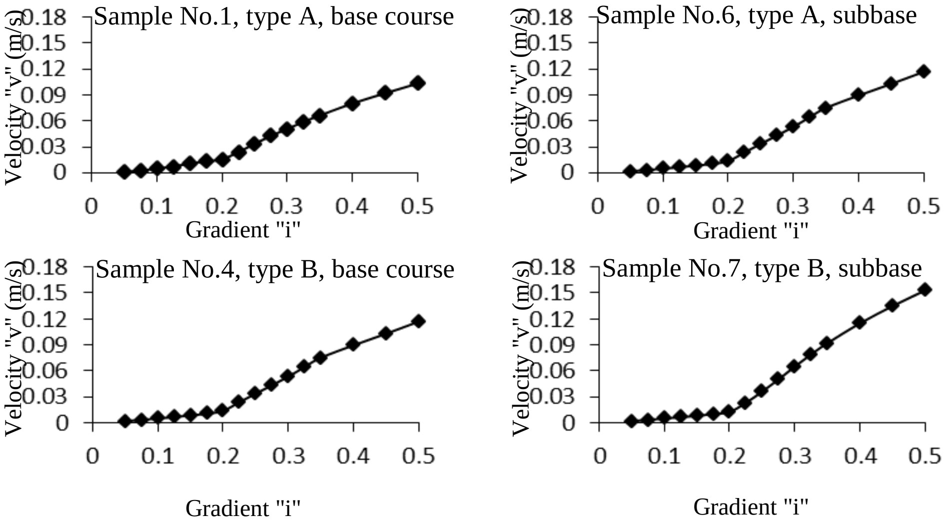
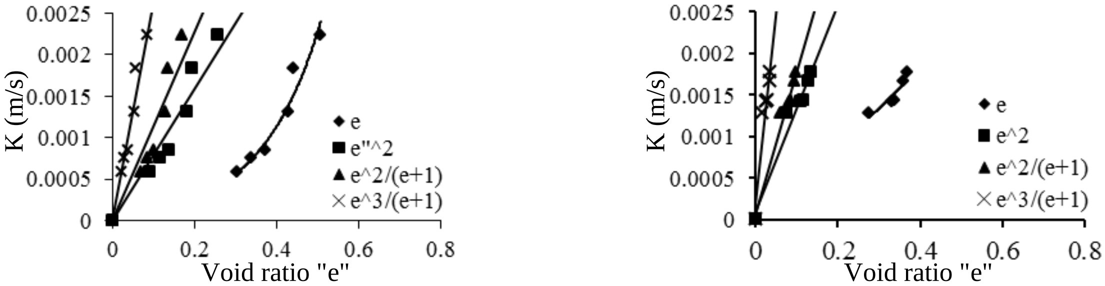


Figure 2. Hydraulic gradient-velocity relationship

The figure illustrates that "v-i" relationship can be divided in to three parts. The first is a slight non linear increase in “v” when “i” is between 0.05 and 0.2. The second is a linear segment when "i" between 0.2 and 0.35. The third when “i” exceeds 0.35 indicating a gradual transition towards turbulent flow demonstrated by the non-linear concave shape. The values of Reynolds number during the second segment were less than 10 validating laminar flow conditions.

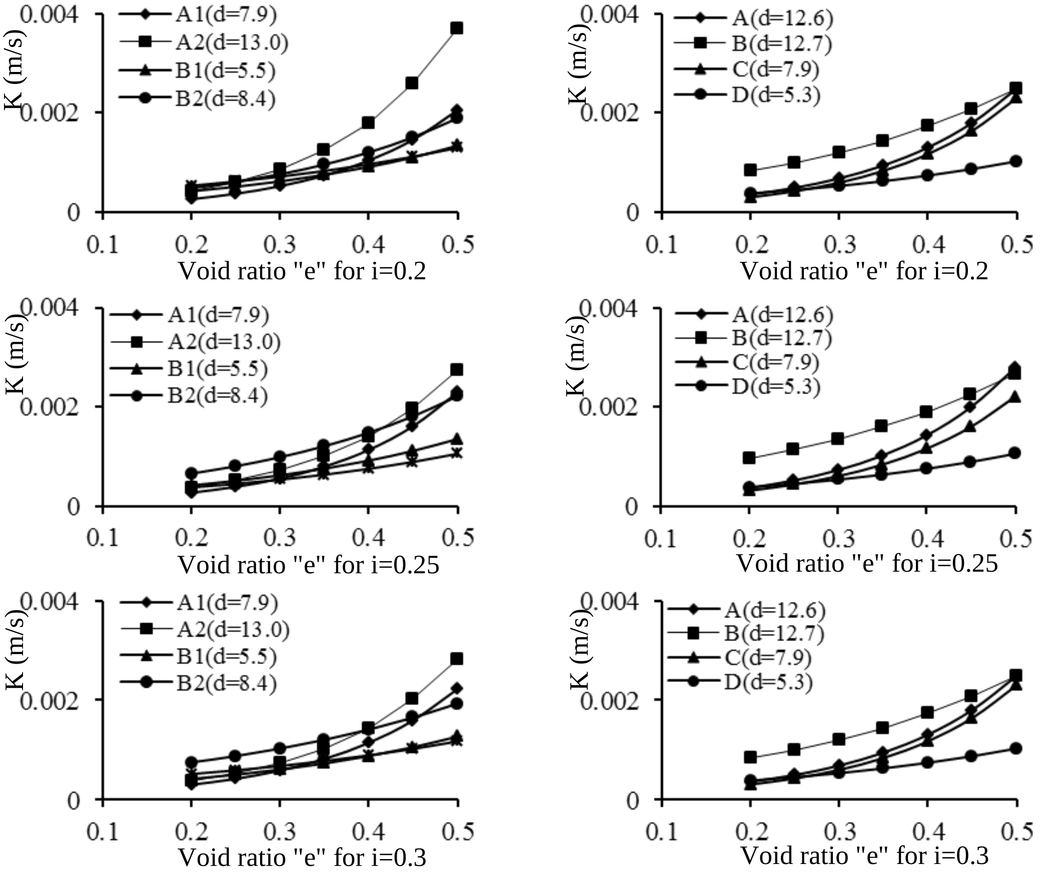
The nine selected samples from the seven types, were tested at different void ratio under three hydraulic gradients i= 0.2, 0.25, and 0.3. The results of the coefficient of hydraulic conductivity are presented as a function of e, e^2, $e^2/(1+e)$, and $e^3/(1+e)$. Typical average results for sample No.1 from type A base course and sample No.7 for type B subbase materials are given in figure 3.



Sample No.1, type A, Base course, d= 7.9mm   Sample No.7, type B, Subbase course, d= 12.7mm

Figure 3. Hydraulic conductivity-void ratio relation for i=0.25

The void ratio - hydraulic conductivity (e-K) relationship is plotted for all base and subbase course selected samples and for all boundary conditions as shown in Figure 4.



Base course materials   Subbase course materials

Figure 4. Hydraulic conductivity-void ratio for tested materials (d mean diameter in mm)

It is clear that the mean particle size has significant effect on the coefficient of hydraulic conductivity in addition to the effect of void ratio, degree of packing, hydraulic gradient, and type of layer. The upper and lower practical sizes shown in each part of figure 4 shows the limits between the upper and lower rates of change of the hydraulic gradient versus the hydraulic conductivity.

A linear regression analysis was performed on the test results obtained from the testing program of base and subbase materials.160 data results each represents (K, i, e, ρ, c, Re, f, and v) values. The best regression results obtained when the degree of packing "c" as a dependent variable is related to ($e^2/1+e$, d, and e) as independent variables providing equation 6 below $R^2=0.912$:

$$c*10^6 = 0.36 - 2.9\ d + 11.2\ e + 0.36\ (e^2/1+e) \qquad (6)$$

This equation combines all parameters affecting the coefficient of permeability of granular materials irrespective of the type base or subbase course. The value of c can be determined from equation 6 substituting d as the mean piratical size determined from equation 3 and the void ratio e from the dry unit weight. The hydraulic conductivity under Darcy's law and laminar flow conditions can then be calculated using equation 5.

6 CONCLUSIONS

The following points are drawn from the hydraulic conductivity tests carried out on five samples of base and four samples of subbase course materials based on the Darcy's law under laminar flow conditions:

1- In general the hydraulic conductivity of all types of base and subbase materials demonstrated an increasing trend with increasing mean particle diameter.
2- Type A base course (d=13mm) and type B subbase (d=12.6 mm) demonstrated the maximum coefficient of hydraulic conductivity values.
3- The best correlation obtained from the linear regression analysis when the degree of packing c is taken as a function of ($e^2/(1+e)$, d and e). Once c is determined from equation 6, K can be estimated for any base or subbase material using equation 5

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