INTERNAL STABILITY OF ROAD AGREGATES SUBMITTED TO WATER FLOW

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ABSTRACT
The specifications for the gradation of road aggregates of the Quebec Ministry of Transportation (MTQ) are relatively broad, especially for the subbases. They allow the use of materials with concave upward gradations that can be internally unstable. When they are saturated and submitted to water flow, their finer particles can migrate through the interstices of their own skeleton of coarser particles and thereby alter their grain size distribution. A filter testing programme has been undertaken to study the internal stability of five aggregates of which gradations are included in the MTQ limits. The results have emphasized the role of the internal stability when concave upward graded aggregates are involved. The mobility of their finer particles under water flow can result in surface settlements caused by the washout and loss of efficiency by the clogging of the downstream drainage elements.

RÉSUMÉ
Les fuseaux granulométriques du Ministère des Transports du Québec (MTQ) pour les agrégats constituant les assises de chaussées routières sont très étendus pour les sables de sous-fondation. Ils permettent l'utilisation de matériaux à granulométrie très étalée concave vers le haut qui peuvent avoir des granulométries instables. Lorsqu'ils sont saturés et soumis à des écoulements d'eau, les plus fines particules peuvent migrer au travers des interstices de leur propre squelette de particules grossières et en altérer la composition granulométrique. On a effectué un programme d'essais au filtramètre pour évaluer la stabilité interne de cinq agrégats de compositions granulométriques différentes admises dans le fuseau du MTQ. Les résultats ont confirmé l'importance d'évaluer le potentiel d'instabilité interne des agrégats à granulométrie concave vers le haut. La mobilité de leurs particules plus fines sous l'effet de l'eau peut se traduire par des affaissements de la surface de roulement conséquents au lessivage de ces particules ou encore par un perte d'efficacité liée au colmatage des éléments de drainage situés en aval.

1. SELECTION OF ROAD AGGREGATES

The road structure is essentially composed of base and subbase aggregates that minimize the transmission of traffic loads to the subgrade and reduce the pavement deformation. The selection of these materials is vital and they must obey to rigid rules as regards:

<u>their bearing capacity</u>: they must be rigid enough to resist the concentrated and dynamic wheel loads with minimal deflection;
<u>their drainability</u>: they must not retain water infiltrating from the pavement i.e. water has to be evacuated within a minimum period of time to avoid reducing the bearing capacity or heave by frost penetration.

As regards the last requirement, the drainage of the road structure is currently achieved through :

- lateral daylighting of the subbase sand towards the ditch and/or
- wrapped perforated longitudinal pipe at the pavement edge either combined or not with a vertical edge drain.

For the drainage to be fully efficient i.e. induce a downward flow through the base, the subbase has to be more permeable than the overlying base. The gradation limits for these aggregates are given on Table 1.

Table 1 MTQ gradation limits for aggregates (in percent)

sieve opening (mm)	base (MG-20)	subbase (MG-112)
112		100
80		
56		
28	100	
20	90-100	
14	68-93	
5	35- 60	35 min
1.25	19-38	
0.32	9-17	
0.08	2-7	0-10

One can see that the restrictions on the subbase MG-112 are minimal i.e. that except for the 5 mm sieve requiring at least 35% coarser, practically any gradation between 112 and 0.08 mm is acceptable. It should be reminded that the drainage pipe is in contact with this material. The MTQ specifications however, bears on compaction and gradation, fines content and composition, factors that influence at the most the hydraulic conductivity *k* (Savard, 1996). The range in the allowable gradations of the MG-112 is broad, so is the range in k-values that may straddle many orders of magnitude and in some instances, be lesser than that of the base material.

Furthermore, broadly graded soils with concave upward gradation curves are susceptible to be encountered within these limits. It has been shown in the literature (Chapuis et al. 1996) that segregation can take place within the particles constituting these materials can i.e. finer grains can be created and move through the voids of the skeleton of coarser particles. A procedure for evaluating the potential for internal erosion has been proposed by Kenney and Lau (1985, 1986). Since drainage systems are installed in contact with these foundation aggregates, proper filter selection should prevent clogging of drains or drain pipes by finer particles or blinding immediately upstream of the filter. For their selection, Lafleur (1999) has proposed that the retention ratio R_R should be smaller or equal to unity, where

$$R_R = \frac{\text{filtration opening size of the filter } O_F}{\text{indicative size of the aggregate to be retained } d_I}$$

The filtration opening size O_F corresponds to $D_{15}/4$ for a granular filter and to the FOS-value obtained by hydrodynamic sieving for a geotextile filter.

The following values for d_I have been obtained from the interpretation of filter tests (Lafleur et al., 1989) whereby equilibrium conditions were encountered when the amount of washed out particles M_P was less than 2500 g/m^2. They are:

$d_I = d_{85}$ for soils with coefficient of uniformity $C_u \leq 6$
$d_I = d_{30}$ for soils with $C_u > 6$ and concave upward gradation
$d_I = d_{50}$ for soils with $C_u > 6$ and rectilinear gradation
$d_I = d_G$ for gap-graded soils with $C_u > 6$, where d_G =minimum gap size.

2. PARTICLES RETENTION MECHANISMS AT THE INTERFACE BETWEEN AGGREGATES AND DRAINAGE SYSTEM

The risk of particles washout at the interface between two materials with different pore sizes can annihilate the effectiveness of a drainage system. The washed out particles deposit into the drainage pipes and clog it by reducing the area available for free water flow. This washout through a filter can be accelerated by the dynamic effect of the traffic that forces the particles to move towards the drainage system, especially when the road structure is saturated (Lafleur et al. 1996). Three different mechanisms can develop and they are illustrated on Fig. 1 in relation with R_R. The two extreme situations (piping with R_R >> 1 and blinding with R_R << 1) lead to malfunctioning or failure whereas the intermediate (bridging) results in equilibrium flow conditions. Lafleur et al. (2002) have shown that the Gradient Ratio Test can discriminate these three mechanisms. The Figure 1 depicts the hypothetical changes in grain-size distribution. Since there is a direct relationship between k of an aggregate and its fines content, the associated changes in local hydraulic conductivity k have also been plotted as a function of depth.

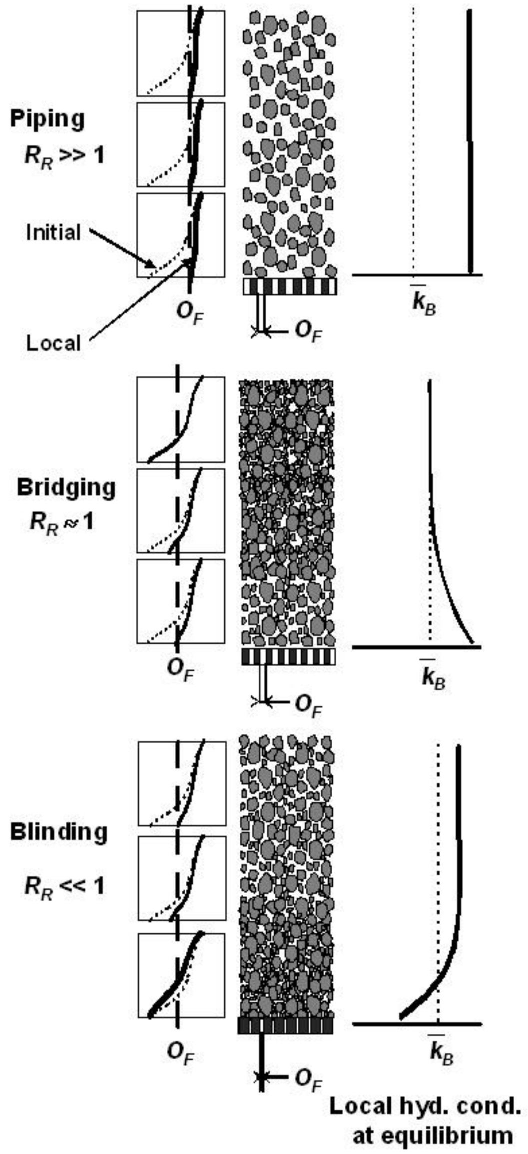


Figure 1. Retention mechanisms at interface between aggregate and drain

piping if R_R >> 1. A large proportion of the aggregate particles fail to be retained since those finer than O_F are progressively washed out into the drainage pipe. This should logically result in an overall increase in k.

bridging if $R_R \approx 1$. Flow equilibrium is reached some time after the installation of the system because of the selective erosion of particles finer than O_F in a restricted zone near the interface that would result in a local increase of k in this zone. This phenomenon is described by Lafleur et al. (1989) and a model has been proposed to evaluate the extent of the so-called self-filtration zone.

blinding with unstable aggregates if $R_R << 1$. The finer particles of unstable aggregates moving inside the coarse skeleton, are blocked if O_F is too small and they are packed immediately upstream of the filter interface by the action of the seepage forces. With an increase in fines content in this zone, the local *k*-value should be decreased.

Since many aggregates inside the MTQ specifications for road base and subbase, are broadly graded and may have concave upward gradation curve, a testing programme was undertaken to verify if these mechanisms could develop in such materials. Furthermore the intervals of validity for R_R given above are not well defined and need further data to support.

3. APPARATUS AND PROCEDURE

The experimental approach consisted of analysing the stability of the particles of aggregates submitted to a downward hydraulic gradient inside a filtrameter cell. These aggregates were reconstituted by mixing grain sizes in different proportions to obtain concave upward gradations contained within the MTQ specified limits for the MG-20 and the MG-112. These mixtures were deposited in the cylindrical cell closed at its base by a filter constituted of a square mesh sieve whose opening size was varied between 0.15 and 4.75 mm

The Fig. 2 gives a schematic view of the filtrameter. Water was supplied at constant head and the upstream gravel layers reduced the presence of air in the feeding water. The hydraulic heads were measured to ±3 mm by six piezometers numbered P0 to P5, at 0, 65, 105, 155, 205 mm from the interface and at the inlet, through open tubes; they allowed evaluation of the local *k*-values. The washed out particles were collected at the bottom of the water tank.

The aggregates were reconstituted by mixing different portions of particle sizes resulting in gradations contained within the MTQ acceptable limits (Fig. 3). Approximately 12 kg of material were used for each test. The aggregates were designated as follows : 1st number = % of the finer portion, 2nd = max. size of the aggregate (mm). The Table 2 summarizes the gradation properties. All of them are classified SP according to U.S.C.S. although the #15-28 with 50% passing the 5-mm sieve, is borderline between GP and SP. One can note that, except for aggregate #7-0.3 which is uniform, the coefficients of uniformity C_u are larger than 6, but with $1 > C_C > 3$, they are all classified as poorly graded, reflecting thereby the concavity of the gradation curve. Their indicative diameter for filtration d_I according to Lafleur et al. (1989) is equal to d_{30}. When applying the Kenney & Lau's method, the Table 2 indicates that the aggregates #7-0.3, #7-5 and #7-28 are stable whereas aggregates #15-5 and #15-28 are internally unstable. The Fig. 4 gives examples of "shape curves" for typical stable and unstable material

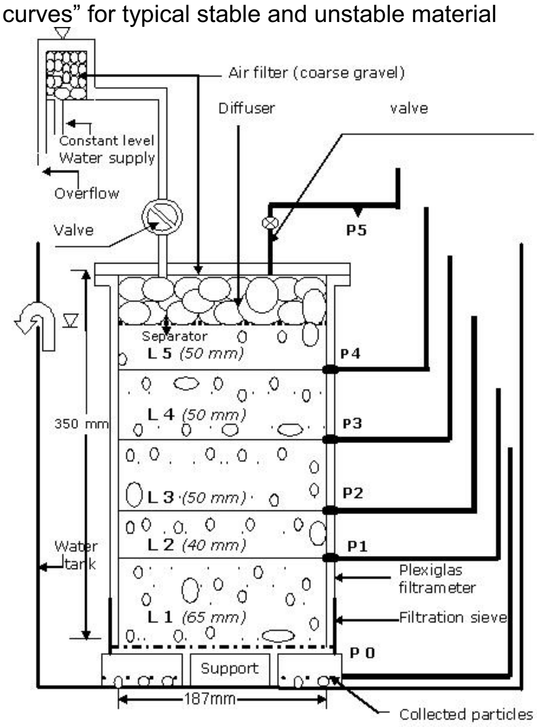


Figure 2. Filtrameter

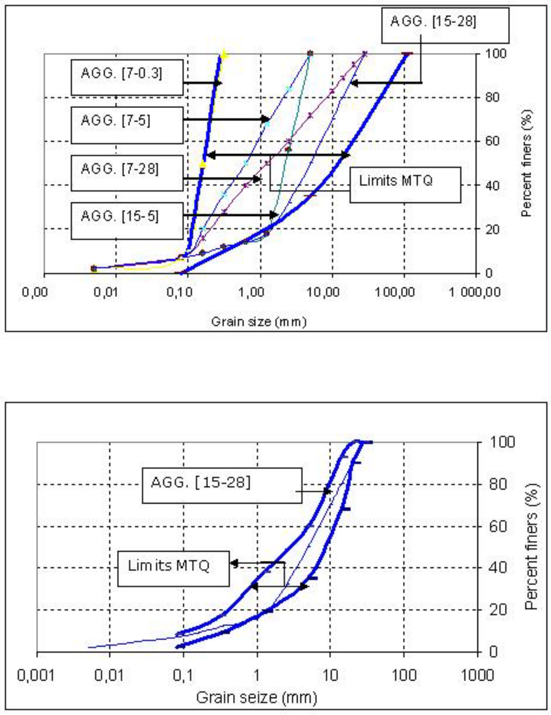


Figure 3. Gradation curves of tested materials and MTQ specifications for MG112 and MG20.

Table 2. Gradation properties

agg. #	7-0.3	7-5	7-28	15-5	15-28
C_u	1.43	6.0	19.2	12.5	35.0
C_C	0.9	0.7	0.3	4.5	5.8
U.S.C.S.	SP	SP	SP	SP	SP
d_I =	d_{85}	d_{30}	d_{30}	d_{30}	d_{30}
d_I (mm)	0.27	0.20	0.30	1.50	2.85
internal stability	Yes	Yes	Yes	No	No

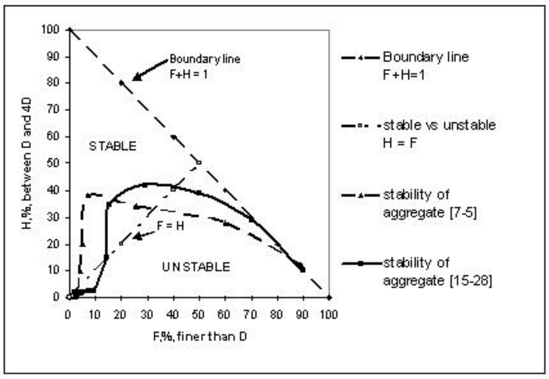


Figure 4. Kenney and Lau's diagram for internal stability of aggregates.

The aggregates were deposited in the filtrameter cell in five layers numbered L1 to L5 on Fig. 2, the top and bottom of which corresponded to the piezometer tips levels. Compaction was minimal and the samples were previously conditioned at a water content of 3% to prevent any segregation of the finer particles. Initial densities of each layer were recorded from mass and volumetric data. The cell was submerged in the water tank to maintain saturation throughout testing. Before applying the hydraulic gradient, saturation of the sample was achieved by vacuum during 3-4 days; the vacuum was partial (-10 kPa) in order to avoid any particles migration before testing. The downward flow with an overall hydraulic gradient of 10 was maintained for 150 minutes. Flow rates and piezometers were evaluated at 10 minute-intervals. Upon dismantling of the sample, final densities of layers were recorded and separate grain size analyses carried on each layer. The mass of washed out particles was collected at the bottom of the container tank and weighed to 0.1 g.

Seven filtration tests (cf. Table 3) were performed with retention ratio ranging between 0.3 and 2.0. Three tests (nos. 1, 2 and 3) were made on the three stable aggregates and four tests, on the two unstable materials which have been paired by R_R–values below and above 1 (tests nos. 4 and 7, and tests nos. 5 and 6).

Table 3. Testing programme

test no.	1	2	3	4	5	6	7
agg.	7-0.3	7-5	7-28	15-5	15-28	15-28	15-5
O_F (mm)	0.15	0.30	0.60	2.38	4.75	0.84	0.84
R_R	0.6	1.5	2.0	1.6	1.7	0.3	0.6

4. TEST RESULTS

The results were analysed and the filtration mechanisms assessed by comparing the changes in the grain size distributions with the ratio k_f / k_o between final and initial average hydraulic conductivity and from the masses of washed out particles M_P. As demonstrated previously, these correlations give good indications of the changes in the soil structure.

The Figs. 5-7 give in the upper part a) the gradation curves of each layer after tests and the arrow gives the opening size of the square mesh filter. In the lower part b) of the Figures, the changes in local k have been plotted as a function of time. The precision of these computations however, depends largely on the sensitivity of piezometer readings which is 3 mm of water ±, representing a margin of error of approximately 8%, since the distance between the piezometers ranges between 40 and 65 mm.

The Table 4 summarizes the test results. One can see that when the stable aggregates (#7-0.3, #7-5 and #7-28) are involved in tests nos. 1, 2 and 3, M_P is less than 2500 g/m^2 and the k_f / k_o ratio is larger than one, indicating that there is an increase in k. With the unstable aggregates (#15-5 and #15-28), M_P is much larger and k_f has decreased, confirming the general pattern given on Fig. 1.

Table 4. Test results – Mass of washed out particles M_P (g/m^2), average hydraulic conductivity k (m/s) and observed filtration mechanisms.

Test no.	**1**	**2**	**3**	**4**
R_R	0.6	1.5	2.0	1.6
M_P	1418	873	1273	25236
k				
k_o initial	$1*10^{-6}$	$1*10^{-4}$	$5*10^{-5}$	$16*10^{-2}$
k_f final	$2*10^{-6}$	$2*10^{-4}$	$7*10^{-5}$	$4*10^{-2}$
k_f / k_o	2.0	2.0	1.4	0.3
mechanism	BR*	BR*	BR*	P*

Test no.	**5**	**6**	**7**
R_R	1.7	0.3	0.6
M_P	18291	7491	22473
k			
k_o initial	$3*10^{-2}$	$40*10^{-4}$	$7*10^{-3}$
k_f final	$3*10^{-2}$	$7*10^{-4}$	$2*10^{-3}$
k_f / k_o	1.0	0.2	0.3
mechanism	P*	BL*	P*

* : BR: bridging P: piping
BL: blinding

4.1 Equilibrium by bridging

The Fig. 5 gives the typical results of a combination (test no.1) where bridging developed within the stable aggregate #7-0.3, resulting in minimal washout (M_P < 2500 g/m^2). The gradation curves shown in Fig. 5a) do not show any appreciable change after test. The gradation curve of washed out particles has a shape similar to that of the material from which they are issued and these particles are smaller than the filter opening size.

In Fig. 5b), the variations of k with time are contained within a narrow band and confirm the absence of changes in the gradations of the different layers. For tests no. 1, 2 and 3 involving stable aggregates, the hydraulic conductivities slightly trend toward an increase. The Table 4 indicates a slight increase in average k, a factor of 2 for tests no. 1 and 2 and 1.4 for test no. 3.

4.2 failure by blinding

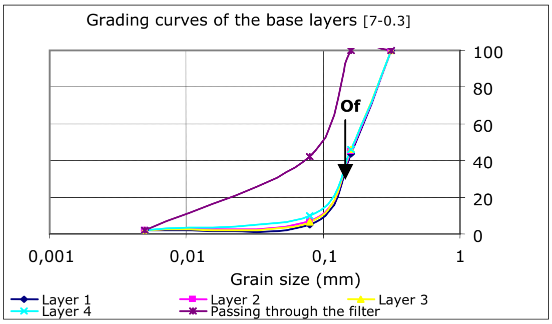
The Fig. 6 gives the result of a failed combination (test no. 6) involving the unstable aggregate #15-28. Given that R_R (= 0.3) is much lower than unity and that the k–values decrease markedly (k_f /k_o = 0.3) during the first 70 minutes, blinding was assessed for this test. This blinding however, was accompanied by a considerable amount of washout (M_P = 7491 g/m^2). The Fig. 6a) shows that only upper layer no. 4 has seen its gradation changed by the water flow whereas the uppermost layer no. 5 disappeared as a consequence of the settlement caused by the substantial washout of particles i.e. all the material settled in a block.

When the retention ratio R_R was increased to 1.7 with the same aggregate in the test no. 5, M_P increased to 18291 g/m^2. The gradations curves of the layers after tests had a similar pattern as for test no. 6 i.e. no changes except the upper layer that had less fines. Given the large value for M_P and the fact that $k_f \approx k_o$, piping was assessed for this combination on Table 4.

4.3 failure by piping

The Fig. 7 gives the results of a failed combination (test no. 4) involving the unstable aggregate #15-5. Piping was encountered (M_P >> 2500 g/m^2) given that R_R > 1. Although washout of finer particles should result in an increase in k, it is seen to decrease (k_f / k_o = 0.3) on Table 4. The Fig. 7a) shows that the gradations of all the layers were affected by the particles instability i.e. each layer lost most of its finer portion. The Fig. 7b) also show that the local k-values are constantly decreasing with time.

The results for test no. 7 also involving the unstable aggregate #15-5, gave similar trends but in this case, M_P was lesser (22473 g/m^2) than in test no. 4 (25236 g/m^2) but also exceeded substantially the threshold value of 2500 g/m^2 even though R_R was inferior to 1.



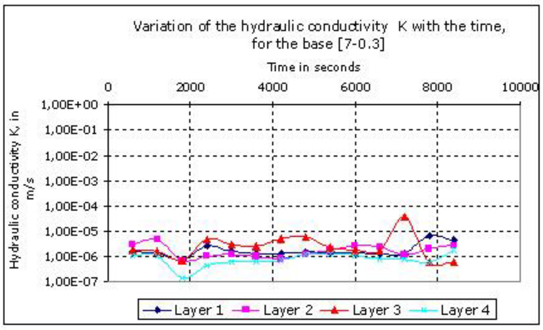
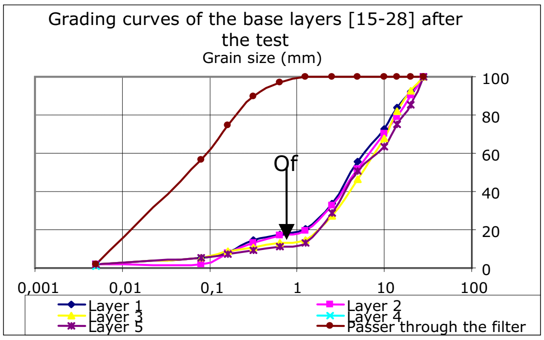


Figure 5 Test results – stable material - bridging.
a) gradation curves; b) hydraulic conductivity vs. time



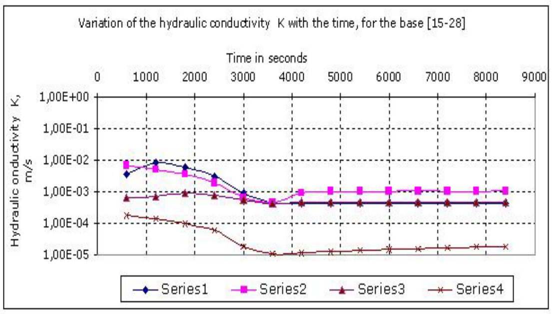
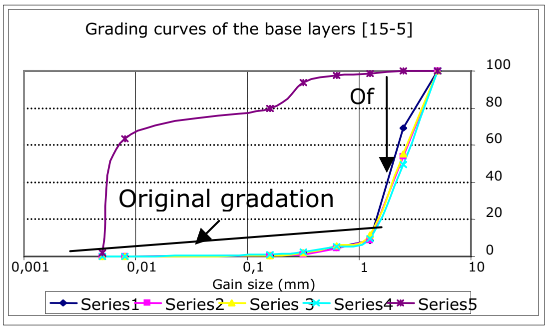


Figure 6 Test results – unstable material – blinding.
a) gradation curves; b) hydraulic conductivity vs. time



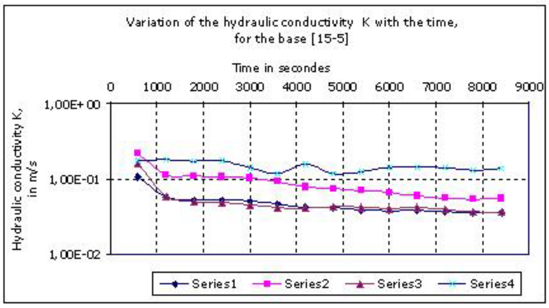


Figure 7 Test results – unstable material – piping.
a) gradation curves; b) hydraulic conductivity vs. time

5. DISCUSSION

5.1- densification during flow and presence of air

The aggregate samples have been placed in the filtrameter at low densities with minimum compaction and it was suspected that some densification could happen as a result of the viscous drag of the water during the flow and reduce the hydraulic conductivity with time. To estimate this factor, a comparison of the densities measured before and after testing has been made on the Table 5. It shows no significant increases, except for test no. 1. For this particular test however, the Table 4 shows a k_f / k_o-ratio of 2, i.e. an increase in *k* despite a 16% increase in density, which should translate into the opposite i.e. a decrease in *k*.

Table 5. Densification of the samples during water flow.

Test no.	1	2	3	4	5	6	7
ρ_{Do} (kg/m^3)	1326	1788	1826	1790	1792	1791	1791
ρ_{Df} (kg/m^3)	1540	1822	1940	1799	1861	1921	1802
% increase	16	2	6	0.5	4	7	0.6

By testing materials in a loose conditions and under relatively high gradients, the results are believed to be conservative for the following reasons. Although the grain size distribution is the main factor in the internal mobility of finer particles, the density also influences to some extent the porometry of the coarse skeleton. The intensity of the hydraulic gradients can also influence the mobility of the finer particles and the distance that they can travel.

Some doubts were also expressed about the influence of incomplete saturation of the samples and on the evolution of hydraulic conductivity with time. It is believed that, given the accuracy of the *k*-measurements, this factor did not influence appreciably the results.

5.2- influence of internal stability on filter retention

The procedure proposed by Kenney and Lau (1985) for evaluating the potential for internal instability disclosed that aggregates 15-5 and 15-28 could be unstable. Our test results confirmed the validity of this approach. Skempton and Brogan (1994) arrived at similar conclusions from results of upward flow piping tests in sandy gravels. However, even though the retention ratio was less than unity in tests no. 6 and 7 with these aggregates, M_P was much higher than the threshold value of 2500 g/m^2.

The aggregate #15-28 fits into the MG-20 MTQ base gradation limits. It has been tested against filters with O_F equal to 4.75 and 0.84 mm i.e. with $0.3 < R_R < 1.7$ and considerable washout was observed. The MTQ standard 13101 (MTQ, 2003) specify that O_F for geotextiles should be less than 0.15 mm. For such a combination, the R_R-value of 0.05, is much lower than unity and the risk of blinding should be evaluated.

5.3- "classical" design of filters based on d_{85}

The test results have shown that the retention ratio R_R based on proper base indicative size d_I gives trends of the amount of washed out particles. It appeared to be conservative with stable soils, since even with $R_R > 1$, $M_P < 2500$ g/m^2. With unstable soils when comparing tests no. 4 and 7 or tests no. 5 and 6 for which even if $R_R < 1$, M_P is always much larger than 2500 g/m^2. More tests would therefore be needed to give a better definition of the indicative filtration size of the soil to be retained d_I for unstable soils. The Table 6 compares the classical retention criterion with $M_P < 2500$ g/m^2. It shows that even though the filtration opening size O_F is much smaller than d_{85}, (i.e. $O_F / d_{85} << 1$) substantial washout has been observed in the present testing programme.

Table 6. Applicability of classical filter retention criterion (R_R with $d_I = d_{85}$)

test no.	O_F (mm)	d_{85} (mm)	O_F / d_{85}	M_P (g/m^2)	
1	0.15	0.27	0.5	1418	Yes
2	0.3	2.5	0.1	873	Yes
3	0.6	12.0	0.1	1273	Yes
4	2.38	4.0	0.5	25236	No
5	4.75	17.0	0.3	18291	No
6	0.84	17.0	0.1	7491	No
7	0.84	4.0	0.2	22473	No

The current practice of selecting filters when comparing of the size of the largest particles to be retained d_{85}, can be therefore unsafe with broadly graded aggregates. A lower indicative size should be used and more experimental evidence is necessary to assess this value.

The test results have also shown that internal instability may take place within broadly graded aggregates and this instability resulted in extensive piping of the finer moving particles through the tested filters.

6. CONCLUSION

Given that drainage is an important factor on the acceptable behaviour of a road foundation, provisions should be made in the selection of aggregates for their susceptibility to internal instability, given that the shape of their gradation curve is often concave upward.

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