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Effect of fines on mechanical properties of coarse aggregate

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ABSTRACT

Two important factors for the design of pavement structures are resilient modulus (Mr) and permeability (K) of the granular (sub)base. This study addressed the effect of fines on the mechanical properties of four granular materials. The objective was to report the experimental findings regarding the influence of fines on the resilient modulus, permanent deformation and hydraulic conductivity. Mr tended to decrease with an increase in fines content but was found not to be sensitive to the type of fines for the materials. Accumulated strain increased with fines. As the amount of paste increased during specimen fabrication, the Mr for a given confinement decreased. Results from permeability tests confirmed that K decreases with an increase in fines. An important observation with regards to the migration of fines is that secondary effects cannot be captured by Darcy's law.

RÉSUMÉ

Le module d'élasticité (Mr) et la perméabilité (K) de la (sous-) base granulaire sont deux facteurs importants pour la conception des structures de chaussée. Cette étude a porté sur l'effet des fines sur les propriétés mécaniques de quatre matériaux granulaires. L'objectif était de rapporter des résultats expérimentaux concernant l'influence des fines sur module d'élasticité et la conductivité hydraulique. Mr–avait tendance à diminuer avec l'augmentation de la teneur en fines, mais il s'est avéré qu'il n'était pas sensible au type des fines pour les matériaux. La déformation accumulée augmentait avec la teneur en fines au fur et à mesure que la quantité de pâte augmentait pendant la fabrication des échantillons, pour un confinement donné diminuait. Les résultats des essais de perméabilité ont confirmé que K diminuait avec l'augmentation des fines mais ne changeait pas beaucoup pour les échantillons où les fines naturelles étaient remplacées par des fines de substitution.

1 INTRODUCTION

With the development that has taken place in Ontario, the supply of easily accessible, low cost quality aggregate for construction has been decreasing. To help mitigate the effects of this trend for (sub)base construction, a possible solution could be to relax specifications to allow use of quarried aggregate that does not meet current physical property requirements, but can be shown to maintain proper structural and hydraulic performance of the engineered layers.

Important factors for the design of unbound granular base/subbase are the resilient modulus, resistance to permanent deformation and the capability of the granular (sub)base to drain rapidly. The objective of the study reported in this paper was to address the effect of fines on mechanical properties of coarse aggregate.

2 BACKGROUND

The main purpose of the base and subbase layers is to distribute load and reduce the maximum induced stress reaching the subgrade, as well as to provide adequate support for the surface layer. To meet strength and durability requirements the Asphalt Institute (1981) requires CBR > 80 for base and CBR > 20 for subbase (Croney and Croney 1991). Furthermore, both base and subbase must have sufficiently high modulus and resistance to permanent deformation due to repetitive loading, which in turn requires that these layers must be free draining and non-frost susceptible. In the US, the Corps of Engineers criterion stipulates that there should be no more than 3% of particles smaller than 0.02 mm (Janoo et al., 1997). To make it more practical to implement, the Corps also recommended a criterion of no more than 2% of particles passing the #200 sieve (0.075 mm). On the other hand, this criterion has been found to be overly conservative in some cases. These requirements lead to constraints on gradations, most notably less than 10% passing the number 200 sieve (P_{200}) (e.g, OPSS 1010, 2004), with the fine fraction being non-plastic. However, as the percentage of fines increases hydraulic conductivity goes down and the triaxial strength decreases with an increase in the plasticity of the fines (Yoder and Witczak 1975).

2.1 Resilient Modulus of Granular Material

The resilient modulus (Mr) is a fundamental property that is required input for the mechanistic-empirical analysis and design of a pavement structure. The stress state and stress history of a granular material are important factors influencing the resilient modulus, with the impact of these factors being influenced by the physical properties. Most notably, the type and percentage of particles passing P_{200} (gradation), plasticity index (PI), liquid limit (LL) and density, as well as particle shape. The water content (w) and the degree of saturation are factors that also have significant influence on Mr; see, e.g., Maree (1982) and Lakarp et al. (2000).

Barksdale (1991) summarizes the effect of various aggregate properties on engineering properties of granular material in pavement layers. According to Yau and Von Qu (2002), the liquid limit, plasticity index, and the amount of fines are important with respect to the resilient modulus of lower strength unbound aggregate base/subbase materials, while the water content and density are important for higher strength materials. Moisture sensitivity was found to vary depending on specific gradations and the nature of fines (plastic or non-plastic). For materials with limited fines the effect of moisture change is minor. Tutumluer (2013) provides a comprehensive review on the current practice for unbound aggregates used for pavement layers.

The interactions between the variables are quite complex leading to contradictions of research findings in the literature as they relate to the resilient modulus, as well as to permanent deformation. Nevertheless, the consensus is that the mechanical properties of granular material improve with increased confinement and density.

2.1.1 Stress sensitivity of resilient modulus

The stress-dependency of the resilient modulus can be conveniently expressed by the universal model (Uzan 1992)

$$M_r = K_1 p_a \left(\frac{\theta}{p_a}\right)^{K_2} \left(\frac{\sigma_d}{p_a}\right)^{K_3} \quad [1]$$

where p_a = atmospheric pressure (100 kPa); θ = bulk stress; σ_d = deviatoric stress and K_1, K_2, K_3 = regression constants. For Ontario Granular A and B materials, coefficient K_1 ranges from 0.56 to 2.57, with K_2 ranging from 0.013 to 0.727. Given that approximately 80% of the K_3 values are in the range of -0.15 to 0.15, indicating that the resilient modulus for crushed aggregates tend not to be sensitive to deviatoric stress. Guo et al. (2006) show that K_3 tends to decrease with an increase in K_2, even though the data are very scattered. This paper focuses on the use of the K-θ model, in which K_3 is zero.

2.1.2 Influence of fines content on Mr

Inconsistencies have been reported in the literature with respect to the influence of fines contents on the resilient modulus. They are related to the coupled influences of various factors including the type and the fines content, mineralogy, water content and compaction level and how the results are interpreted. Barksdale and Itani (1989) observe that the plasticity of the fines can have an important influence on both resilient modulus and the permanent deformation properties of an aggregate. They note that the resilient modulus was observed to decrease by 60 % as the fines content increased from 0 to 10 %. The plastic strains were also found to increase. These results are consistent with those of Kolisoja (1997) who shows that the resilient modulus of a material can change by 20% by substituting the fines from one source with that of another.

Thornton and Elliott (1988) show a decrease in M_r with an increase in fines from 6 to 12%. Walaa and Hussein (2004) also report that at a water content 2% drier than the optimum value, the resilient modulus increases and the permanent deformation decreases as the fines content is increased. More recent work on the presence of the optimum fines content can be found in Richardson and Lusher (2009). Yoder and Witczak (1975) show that the optimum fines content for the resilient modulus is in the range of 6 to 9%, which is similar to that for maximum CBR.

Mishra and Tutumluer (2012) report that an increase in fines content tends to reduce the resilient modulus of unbound aggregates. For the aggregates tested (crushed dolomite, crushed limestone and uncrushed gravel), the type of fines (plastic or non-plastic) has insignificant effect of Mr. However, both the type and fines content have significant effect of permanent deformation of aggregates. Plastic fines tend to reduce the stability of aggregate structure and results in larger permanent deformation. Non-plastic fines at lower content (~8%) may reduce permanent deformation of crushed rock aggregates.

Guo et al. (2006) suggest that the K-coefficients might be considered as independent of the fines content, when $P_{200} < 5\%$. For a wide range of fines content variation, it is likely that materials with higher fines content tend to have smaller K_1 and K_3 values than “clean materials”, with K_2 increasing at the same time. In other words, an increase in fines content may result in smaller resilient moduli that are more sensitive to the applied stresses owing to the increase in K_2 and decrease in K_3, respectively.

2.1.3 Influence of moisture on Mr

Guo et al. (2006) in their study conclude that an increase in water content tends to decrease the resilient modulus. Aggregates with non-plastic fines were found to be more sensitive to water than those containing plastic fines. They also found the resilient modulus of aggregates to be sensitive to the compaction method used. An increase in the water content by about 4% was observed to induce a significant decrease in the M_r of a specimen compacted by impact method, while only a moderate decrease of M_r for a specimen compacted by vibration. The general conclusion is that M_r appears to be moisture sensitive if the fines in aggregates are non-plastic.

Based on the results of repeated load tests, Kolisoja (1994) find that the influence of the degree of saturation of a material having high fines content is important. This is particularly true for well-graded materials, in which the resilient modulus decreases once the optimum water content is exceeded.

2.1.4 Influence of Fines on accumulated strain

Dry density, which plays an important role for limiting permanent deformation, is influenced by the fines content as reported by Uthus (2007). The dry density of a material with relatively high fines content may be important under dry conditions, but as the content increases, the effect of the degree of saturation (water content) can override the influence of dry density. For equal dry density the permanent deformation is found to increase as the fines content increases, with the resilient modulus and shear strength decreasing. This is particularly true for well-graded materials.

Plastic strain accumulation is sensitive to the deviatoric stress and confining pressure. Strain accumulation increases with an increase in shear, an increase in water and a decrease in the confinement. The mechanisms for strain accumulation due to repetitive loads are, however, different from those for developing resistance during static loading (Holubec 1969). The magnitude of the permanent deformation in cyclic triaxial compression tests tends to increase with an increase in the fines content (Barksdale 1972, 1991; Thom and Brown 1988; Croney and Croney, 1997; Mishra and Tutumluer 2012). Nevertheless, some test results in the literature show that low fines content (up to 8%) may reduce permanent deformation of crushed rock aggregates (Mishra and Tutumluer 2012). Similar findings are reported by Kolisoja (1998) and Belt et al. (1997), who observed significantly higher permanent strains may be expected for aggregates containing extremely high fines content (e.g. > 15 %) or at a low content of fines.

2.2 Hydraulic Conductivity

Water plays an important role in the potential for the deterioration of granular materials, particularly in environments that undergo freeze-thaw cycles. The permeability, which controls drainage, is influenced by gradation. Aggregates with fines have lower hydraulic conductivity. The relation between the mechanical properties and drainage is important as the stress-strain-load cycle behavior is sensitive to the degree of saturation and ability of the granular material to dissipate any generation of excess pore pressure

Cedergren and Godfrey (1974) conclude that 80-90% of severe and premature damage to pavement is caused by excess water. Large numbers of heavy axle weights cause significant damage to pavement structures, particularly when water is present in the unbound granular layers. The movement of water in pavement structures is caused by gravity, capillary action, and/or vapour pressure. In coarse-grained soils the flow of water is largely due to gravity. The build-up of large pore pressures contributes to a loss of shear strength due to reduced effective stress (Dawson 2008). For granular materials there is a residual water content, which is the point at which the granular material is in balance with the hydraulic environment (Huhtala , 2002). When the residual water content is high in a pavement structure, the suction decreases as well as the shear strength. A well-designed pavement provides sufficient drainage to ensure that steady-state saturated flow does not develop.

The permeability, which controls drainage, is influenced by gradation. Aggregates with fines have lower hydraulic conductivity. Emery and Lee (1977) report that the hydraulic conductivity of a Granular A crushed limestone decreases from 3.41×10^{-2} cm/s to 1.26×10^{-4} cm/s when 10% fines are included. Similar findings based on the experiences in Ontario can be found in Senior et al. (2008). There is evidence that permeability is not an issue as long as the fines content is less than 10% (Senior et al. 2008; OPSS 2004).

3. EXPERIMENTAL STUDY

The experimental program reported herein investigated the influence of fines on the mechanical and hydraulic behaviours of four unbound granular materials. These consisted of crushed rock from quarries All Granular A aggregates, according to specifications in OPSS 1010, were provided by the Ministry of Transportation in Ontario (MTO). The physical properties of each aggregate were determined first, including sieve analysis, Atterberg limits and Proctor compaction. California Bearing Ratio (CBR) and resilient modulus (Mr) tests were completed thereafter to evaluate the strength and stiffness characteristics of the aggregates, followed by the hydraulic conductivity tests. Table 1 summarizes the test standards that were used as guidelines.

Table 1: Summary of testing standards

Laboratory Tests	Test Method
Sieve Analysis of Aggregates	AASHTO T27
Determining the Liquid Limit of Soils	AASHTO T89
Determining the Atterberg of Soils	AASHTO T90
Standard Method of Test for Moisture-Density Relations of Soils with a 2.5-kg Hammer and 305-mm Drop	AASHTO T99
Standard Method of CBR Test	AASHTO T193-99
Standard Test Method for Permeability of Granular Soils (Constant Head)	ASTM D2434
Standard Method of Mr test for Soils and Aggregate	AASHTO T307-99

There were a few modifications to the standard procedures:

1. Since the focus was on the influence of fines, the material less than P_{200} was used for the liquid limit testing. Results from tests on source S4, confirmed that the results were similar when including the material less than the P_{40}.
2. When referring to the fines in the text, P_{200} is based on the sieve test by the dry method; the washed P_{200} percent passing is, however, also included in Table 2.

The particle distribution of each aggregate is shown in Figure 1 along with are the limits for Granular A aggregates that are set by the MTO. A summary of the classifications is provided in Table 2. It is noteworthy that the percent fines for S1 and S4 more than doubles when these aggregates are washed rather than dry-sieved. The reported results correspond to those, in which the natural fines were used.

All tests were completed for fines contents ranging from 0% to 10%. The original fines contents were 7.8%, 5.7%, 3.4% and 4.1% for aggregates S1 to S4, respectively. The CBR, Mr and hydraulic conductivity tests were performed at three water contents.

Table 2: Key physical properties.

Property	S1	S2	S3	S4
P_4 (%)	55	48	47	44
P_{200} (%)	7.8	3.4	5.7	4.1
P_{200}* (%)	11.5	5.9	6.1	9.0
LL (%)	27.5	29.5	18.3	21.5
PI	8.2	10	N.P.	6.9
w_{opt} (%)	6.6	6.70	7.95	6.30
$\rho_{d,max}$ (kg/m^3)	2035	2057	2250	2055
CBR	101	49	81	84
USCS	SW-SC	GW	GW-GM	GW

* Washed

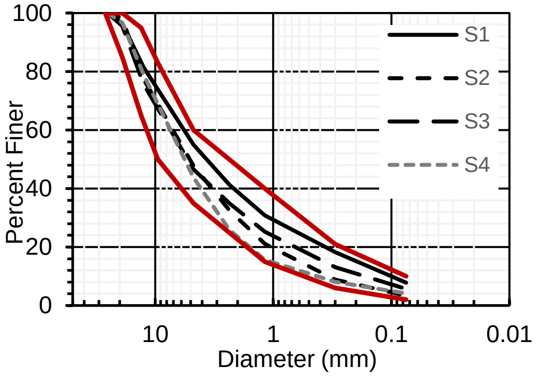

Figure 1: Grain Size distribution for aggregates

3.1 Test Results

3.1.1 Compaction, Optimum Water Content, CBR

The typical trends for compaction and California bearing ratio tests that one observes in textbooks do not necessarily apply for granular base material. For the textbook trends to be realized, sufficiently small particle sizes of the right gradation must be present. At the higher water contents, the water was found to collect at the bottom of some specimens.

Based on the overall trends, at the same compaction effort, the existence of fines tends to increase the achievable density, while 5 to 10% fines are required to achieve maximum CBR values. The optimum water content was in the range of 6 to 8%. Within this range of fines and water contents, Sources 1, 3 and 4 attained CBR values (at natural fines content) that are required by a good granular base, *CBR* > 80.

Figure 2 confirms that higher values of CBR were correlated with higher densities and higher fines content. However, the acutal water contents of the specimens after compaction are seen not have significant influence on the CBR values.

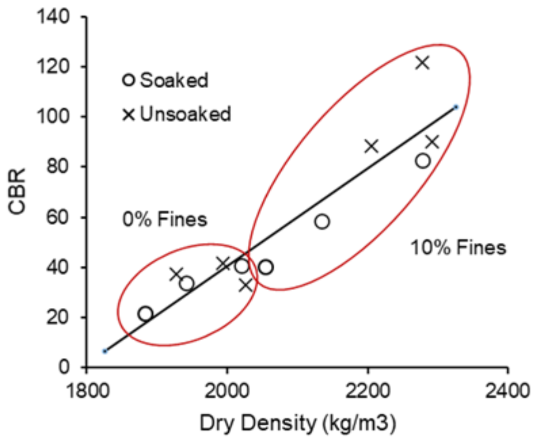

Figure 2: CBR versus dry density for S1, S3 and S4

3.1.2 Resilient Modulus Observations

Optimum water contents (w_{opt}) obtained from standard Proctor test results were used as a guide to estimate appropriate moisture for compacting the M_r test specimens. Given that both the compaction method and the compaction effort for fabricating the M_r test specimens were different from that corresponding to the Proctor compaction tests, specimens compacted at the Proctor optimum water content (w_{opt}) appeared to be wet of optimum when compacted by vibration. In other words, the optimal water content under vibratory compaction was lower (approximately 0.5% to 1%). This difference led to several Mr tests failing due to excessive deformation.

Clear trends with regards to the influence of water and fines on the resilient modulus could not be identified. This was attributed to the coupled effect of these two quantities on resilient modulus. Representative Mr-θ test results are shown in Figure 3. The odd test result for S3 at the fines content of F = 5.7% (and w = 6%) had also shown a sensitivity to deviatoric stress. The paste content (water plus P_{200} material during specimen compaction) is used here to represent the coupled effect of water and fines content. Given that there were certain groupings of results that were similar, the resilient modulus is now plotted against the paste content for all Mr tests of series S1 and S3, shown in Figure 4. One observes that there is a tendency for Mr to decrease with an increase in the amount of paste. When comparing the results at 200 and 400 kPa bulk stresses, shown in Figure 4, the trends are similar, almost parallel, with the values at 200 kPa being lower as expected. Unlike the results for Mr as a function of water (or fines) content, the results for percent paste show a more systematic trend.

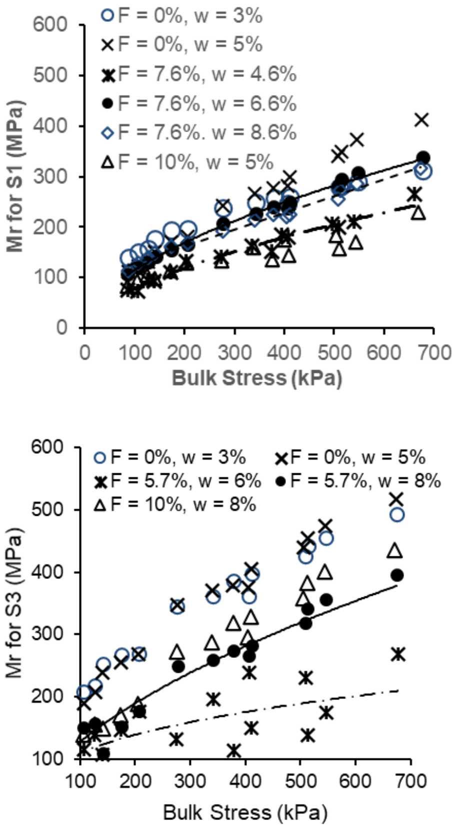

Figure 3: Mr versus bulk stress (θ) for S1 and S3

The variations resilient modulus parameters are also plotted against paste content (instead of fines content) in Figure 5 for the K-θ model. Although there is still some scatter, the trends are better defined. One observes that K2 does not change much in terms of the amount of paste. The parameter K1, however is sensitive, decreasing with an increase in the paste content. Thus, the decrease of Mr can be attributed K1, with K2 being relatively independent. It should be noted that there was a tendency for K2 to decrease as K3 changed from negative to positive in Uzan's model (not shown).

3.2 Permanent Deformation

The development of permanent deformation for the four sources was examined, with the results for Source 3 being presented in Figure 6, which plots the accumulated strain at the end of each confining pressure after stress the repetitions. To make sense of the data, Figure 7 presents the accumulated strain at the end of the cyclic loading versus the percent paste. One observes that the trendline is such that the accumulated strain at the end of a test tends to increase with an increase in the percent paste. The trends for the other source were similar.

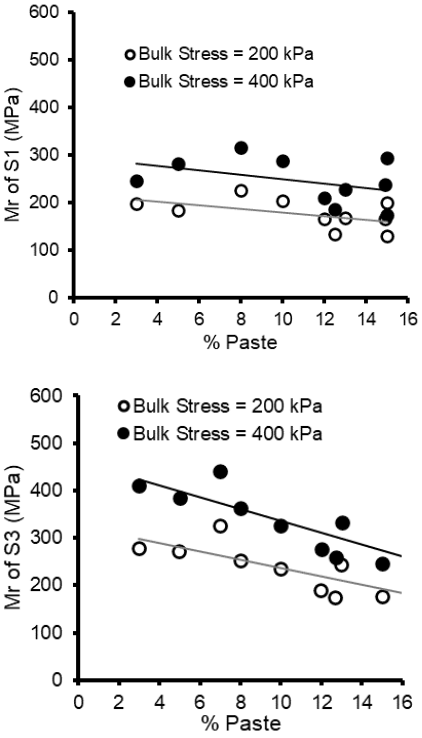

Figure 4: Mr sensitivity to paste content for S1 and S3

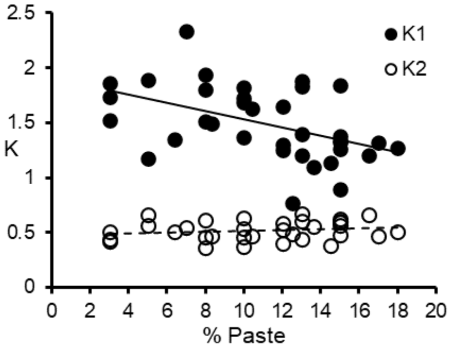

Figure 5: Sensitivity of K-θ parameters to paste content

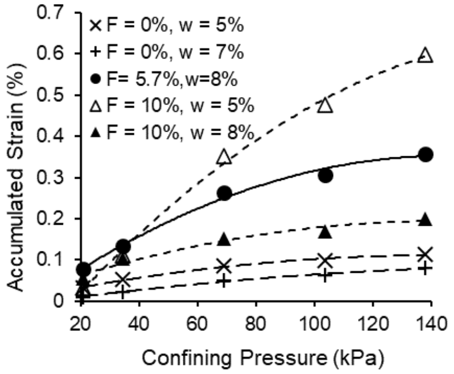

Figure 6: Permanent strain versus cell pressure for S3

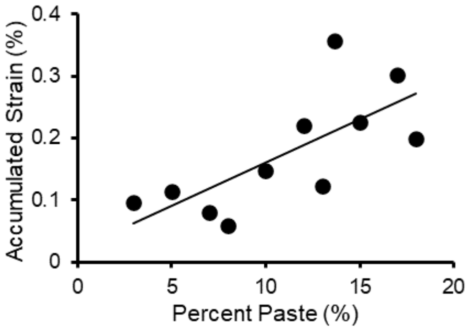

Figure 7: Accumulated strain (S3) versus paste content

3.3 Hydraulic Conductivity

For aggregates densified according to standard Proctor compaction and tested corresponding to hydraulic gradients ranging from 4.4 to 6.6 the permeability did not change. Figure 8 shows that the permeability decreases as the fines content increases. For the same fines content, the denser the specimen, the lower the permeability. The error bars reflect the “standard error” associated with the plotting average permeability.

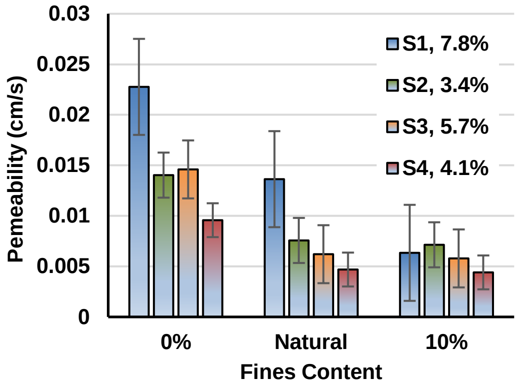

Figure 8: Permeability versus fines content

The particle size distribution of the fine fraction and the mineralogy, both, have some influence on permeability, particularly at high flow rate in coarse aggregates. A close examination of the fines in a transparent cell during a test, revealed that the fines in the voids were in continuous movement (circulation) within the voids and not necessarily moving between voids when the hydraulic gradient (i) exceeded a threshold depending on gradation, fines content and density. At the same time, flow became non-uniform; as shown in Figure 9. The intensity of local fluidization of fines in the voids varies with the hydraulic gradient, which resulted in additional flow resistance and secondary effects that cannot be captured by Darcy’s law. A possible explanation for decreased permeability is that fines acted with the fluid to form a viscous mixture. An increase in effective viscosity would be expected to decrease the hydraulic conductivity.

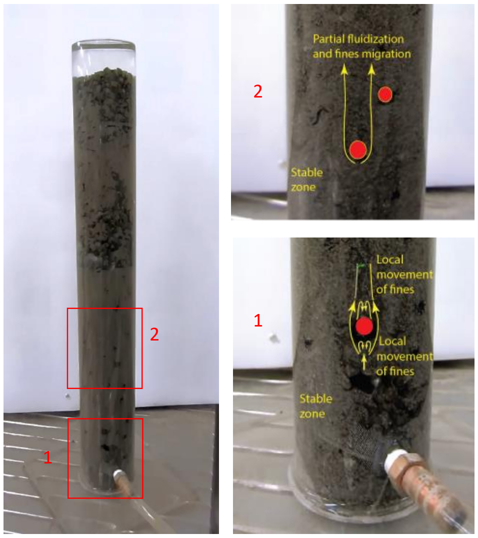

Figure 9: Local movement of fines in the voids

For each of the aggregates the permeability was significantly larger when no fines were present than for those specimens with fines, which was expected because the larger voids in the aggregate structure were “empty”, thus allowing the water to flow more freely. With fines the permeability tends to decrease. These results support the findings of Emery and Lee (1977).

Additional tests were carried out to investigate the influence of fines content and hydraulic gradient. Figure 9 summarizes the test results of Source 4 when the hydraulic gradients were varied in the range of i = 0.008 to 8. Referring to Figure 10(b), when the hydraulic gradient is lower than a critical value i_{cr} with $i_{cr} \approx 0.02$-0.08, the permeability is constant, indicating Darcian flow. The hydraulic conductivity ratio is defined as the permeability relative to the value when it is constant at very low hydraulic gradient. For aggregates containing natural fines with F = 4-10%, permeability tends to decrease with increasing hydraulic gradient (as shown in Figure 10(b), owing to local movement of fines in the voids. On the other hand, when fines passing P_{200} (d > 0.075 mm) were washed away, a different pattern is observed regarding the influence of hydraulic gradient. More interestingly, when all particles smaller than 0.15 mm are removed, the permeability decreases as the hydraulic gradient is increased, similar to the trend for aggregate with F = 4 to 10%. The different patterns of permeability with hydraulic gradients reveals different energy dissipation mechanisms when the fines content and fines type change. In other words, the permeability, which is macroscopic measured property, is sensitive to the flow characteristics within individual pores.

The permeability was found to be sensitive to the compaction level of the aggregates. Figure 11 summarizes the influence of dry density on permeability for different aggregates of various fines contents at low hydraulic gradient of $i < i_{cr}$. Increased compaction can reduce permeability significantly.

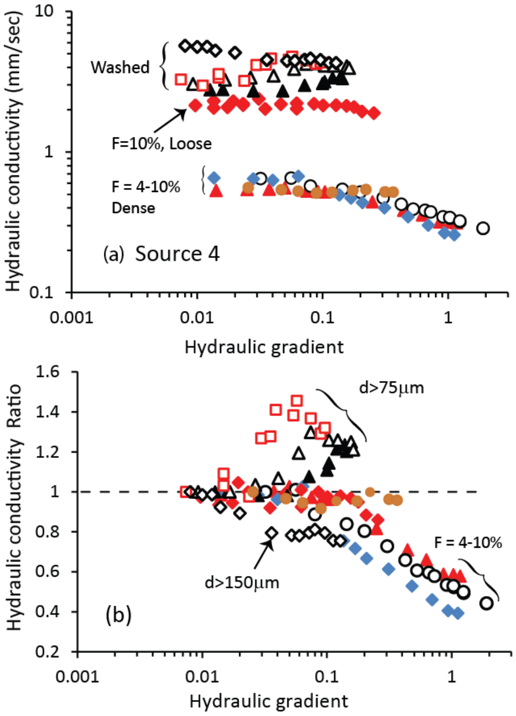

Figure 10: Influence of fines content and hydraulic gradient on permeability (Source 4, ρ_d =1915-2210 kg/m^3)

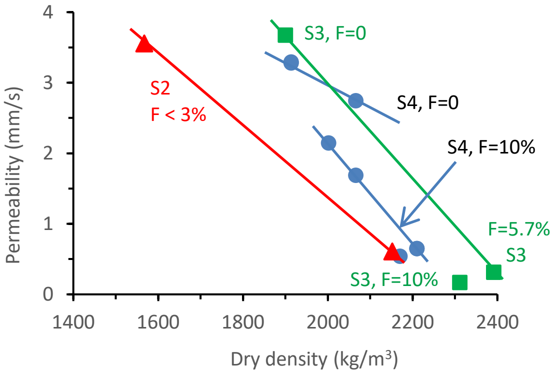

Figure 11: Influence of density on permeability at i < i_{cr}

4 CONCLUDING REMARKS

The M_r was found not to be sensitive to the type of fines for the materials that were considered. Clear trends on M_r with respect to changing fines content or water content could not be identified. On the other hand, the amount of paste (percent water plus percent passing the 75-micron sieve) during specimen fabrication was found to be important.

Results from the permeability tests showed that with zero fines, the hydraulic conductivity was much larger than when fines were present. An important observation with regards to the migration of fines induced by flow under high hydraulic gradients was that secondary effects cannot be captured by Darcy's law, which only considers non-rotational flow. This aspect was addressed by examining the flow of water in the coarse material at various fines content under different hydraulic gradients. Local particle movement or fluidization of fines in the voids was one of the mechanisms related to the non-Darcian flow and influence of fines on permeability in coarse aggregates. Increased fines content reduced permeability significantly.

Based on the results the following conclusions can be drawn:

1. The overall performance of granular materials is affected by the combination of water content, fines content and compaction level.
2. The presence of fines tends to increase the density and CBR value (stability) at a given compaction effort. Soaking does not affect the CBR value of a compacted specimen.
3. Water content and fines contents have coupled effects on resilient modulus of compacted aggregates. Clear trends with regards to the influence of water and fines contents on Mr could not be identified.
4. With increasing paste, K1 tends to decrease for the models, whereas K2 values remain constant with increasing paste. For most of the aggregates tested, the K-θ model appeared to work best.
5. When a specimen is compacted by the same compaction level (or same dry density), the permeability is largest when no fines are present. Presence of fines, either natural or substitute fines, tends to reduce the permeability significantly.
6. Local movement of fines in the voids of compacted coarse aggregates may occur, which causes secondary effects, such as rotational flow.
7. The optimum water content is affected by compaction methods: w_{opt} obtained by using the procedure used to prepare resilient modulus specimens is different from that obtained from Proctor compaction.

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