Dynamic Response of Open-Graded Highway Aggregates

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The results are presented of a laboratory study that was carried out to investigate the stability of thin layers of coarse single-sized (open-graded) highway aggregates under dynamic plate loading. The investigation considered a range of aggregates having variable quality as defined by the Aggregate Index Number. The Aggregate Index Number is a quantitative measure of the combined durability of an aggregate that is based on the aggregate's resistance to fracture and abrasion as measured in the Los Angeles Abrasion and Mill Abrasion Tests. Other variables between tests were gradation size and support compressibility. The test results showed that for the coarsest gradation investigated, the semi-logarithmic permanent deformation rate could be reduced significantly by increasing aggregate quality and/or increasing underlying support stiffness. The sensitivity of deformation rate to aggregate quality and underlying support compressibility decreased for parallel but finer gradations. Finally, implications to selection criteria for aggregate used in unbound open-graded drainage layers below highway and airfield pavements are identified.

Infiltration of surface water into pavement cracks and joints is a major source of pavement deterioration in highway and airfield pavements. A strategy becoming increasingly more common in North America to reduce or eliminate this problem is to construct an open-graded drainage layer (OGDL) directly below the surface course that can direct infiltrated water to pavement shoulders or drains (*1–4*). An example of a pavement structure that incorporates an OGDL is given in Figure 1.

The aggregate must have high permeability because of the high volume/short duration flows that may be required of an OGDL layer. A successful OGDL must be capable of removing water at a rate greater than the infiltration rate. For this reason, relatively coarse-grained single-sized (open-graded) aggregates are recommended. The aggregate layer must be protected, using suitable bases or filters, and be provided with outlet drains that ensure positive drainage. Owing to the proximity of any OGDL to the pavement-bearing surface the OGDL must possess adequate stability against traffic-induced shearing stresses. Those shearing stresses may be further amplified near pavement cracks or, in the case of reinforced concrete pavements, joints. Under those conditions traffic wheel loads may not be attenuated through the surface course, and the OGDL may experience overstressing.

The necessity of providing both adequate drainage capacity and adequate stability can lead to conflicting requirements in the specification of the aggregate source because the stability of granular material generally increases if a material has a well-graded particle size distribution (i.e., strength increases with decreasing void ratio). In many instances, a 1.5 to 2 percent asphaltic cement (AC) binder is added to the aggregate to stabilize the layer during construction activities. The AC content is just great enough to coat the aggregate and does not significantly reduce permeability of the material. Nevertheless, unbound open-graded drainage layers have also been successfully constructed (*2,3*). The influence of grain size distribution on aggregate permeability in pavement structures has been the topic of investigation by many researchers [e.g., (*2,5–8*)]. Less well understood is the influence of properties such as fracture resistance (toughness), abrasion resistance (hardness), and grain-size distribution of open-graded aggregates on the stability of materials under repetitive loading [e.g., (*9*)]. Related works (*10*) (*11*) concerned with predicting longevity of ballast aggregates in railway tracks offer guidance to experimental programs for open-graded aggregates in highway and airfield pavements. For example, Canadian Pacific Rail (CP Rail) has adopted a track model that relates longevity of ballast to aggregate fracture resistance, aggregate hardness, and cumulative tonnage on track (*12*). A work by Raymond and others (*13*), concerning the CP Rail track model has, in part, inspired the experimental approach adopted in the current investigation.

SCOPE OF CURRENT INVESTIGATION

A preliminary laboratory investigation that examines, under simulated traffic loading, the influence of aggregate properties on the stability of unbound open-graded drainage layer models is described in this paper. The properties of the aggregates investigated were fracture resistance, hardness, and grain size distribution.

TEST PROGRAM

Three different aggregates from eastern Ontario were examined. The properties used to characterize the aggregates follow:

1. Aggregate gradation (i.e., ranging from a gradation with a top size of 37.5 mm to parallel finer grain size distributions with a top size of 19 and 9.5 mm) and
2. The combination of hardness and resistance to fracturing of the aggregate samples as defined by the Mill Abrasion (MA) value, Los Angeles Abrasion (LAA) value, and the Aggregate Index Number.

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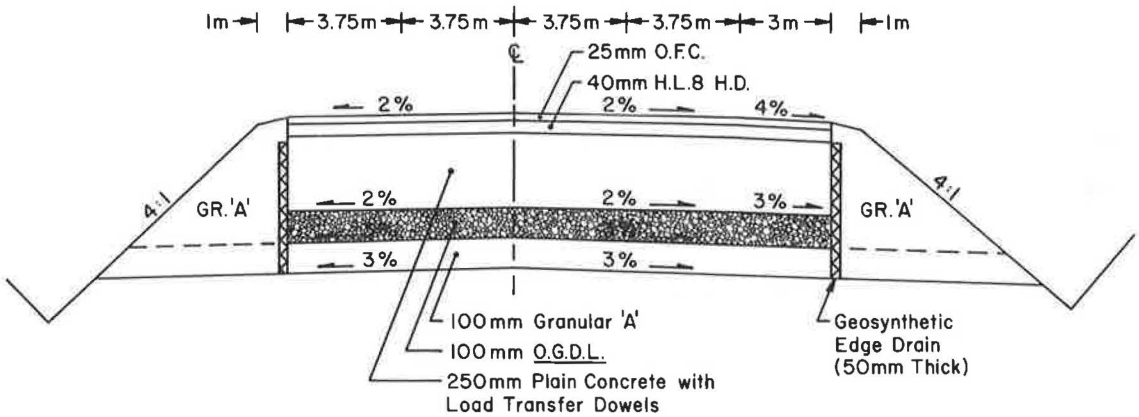

FIGURE 1 Example of highway pavement with open-graded drainage layer.

The relative stability of the aggregate materials was determined by comparing the cumulative load-deformation response of thin layers of aggregate during repeated loading in a laboratory plate-loading apparatus. The principal variable between model configurations with respect to the plate-bearing test was the use of either a rigid or flexible support to model a range of compressibility in the underlying road structure. Experience from similar test programs on the stability of railway ballast has shown that the compressibility of the underlying structure has a very important influence on the cumulative load-deformation response of aggregate materials (*14*). A total of 22 plate-bearing tests were carried out, of which four were replicate tests to examine test repeatability.

Aggregate Sources

The aggregate sources used in this investigation comprised 100 percent crushed rock. The properties are summarized in Table 1. The meaning and significance of the characteristic properties of the aggregates are given in the following sections. The Elginburg limestone and Jasper dolomite have been used as base materials in roadworks by the Ministry of Transportation of Ontario (MTO) in eastern Ontario and the Marmora Trap as ballast in branchline track by CP Rail.

TABLE 1 SUMMARY OF AGGREGATE PROPERTIES

Aggregate Type	Specific Gravity	Mill Abrasion (MA) (%)	Los Angeles Abrasion (LAA) (%)	I_a*	C_u**	C_c***
Elginburg Limestone	2.68	9.1	28.9	74	3.6–4.3	1.0–1.3
Jasper Dolomite	2.76	6.6	20.9	54	3.9	1.1
Marmora Trap	2.98	5.1	14.1	40	4.0–4.4	1.0–1.3

* Aggregate Index Number $I_a = 5 \times MA + LAA$
** Coefficient of Uniformity D_{60}/D_{10}
*** Coefficient of Curvature $D^2_{30}/D_{60}D_{10}$

Gradation

The standard grain-size curves investigated are given in Figure 2. Gradation 1 represents the coarsest material considered and is close to the current OGDL specification presently adopted by MTO (Figure 2a). Gradation 2 (medium) and 3 (fine) have similar slopes and shape to gradation 1 (i.e., similar coefficient of uniformity (C_μ) and coefficient of curvature (C_c)) but are shifted to essentially parallel gradations with finer particle sizes. For comparison purposes, the hatched regions in Figures 2b and 2c correspond to gradation specifications that have been used for OGDL construction in the United States. Gradation 1 is close to the AASHTO 57 specification for coarse aggregate (*1*), and gradations 1 and 2 fall within specifications for OGDLs recently adopted by the Pennsylvania Department of Transport (PennDOT) (*2*). The target gradations were achieved by blending presieved aggregate size ranges taken from laboratory stock piles.

Los Angeles Abrasion Test

LAA tests were carried out on aggregate samples as given in ASTM Designations C535-81 and C131-81 to give a relative measure of particle resistance to fracturing.

The LAA test simulates the effect of high contact forces on aggregate particles, including those generated by impact loading. High impact forces on OGDL aggregates will occur in the vicinity of transverse cracks in asphaltic pavements and below joints in concrete pavements. The ability of an aggregate to survive high contact forces is dependent on the toughness of the aggregate (i.e., particle resistance to fracturing). A low LAA value indicates a material with a high resistance to fracturing under high contact forces.

Because the samples tested covered a range of aggregate sizes, the Standard Test Method ASTM C535-81 was used for materials having a particle size greater than 19 mm, and the test method given in ASTM C131-81 was used for materials with a particle size less than 19 mm.

Mill Abrasion Test

The MA test is a nonstandard test that simulates autogenous grinding and measures the relative resistance to abrasion or

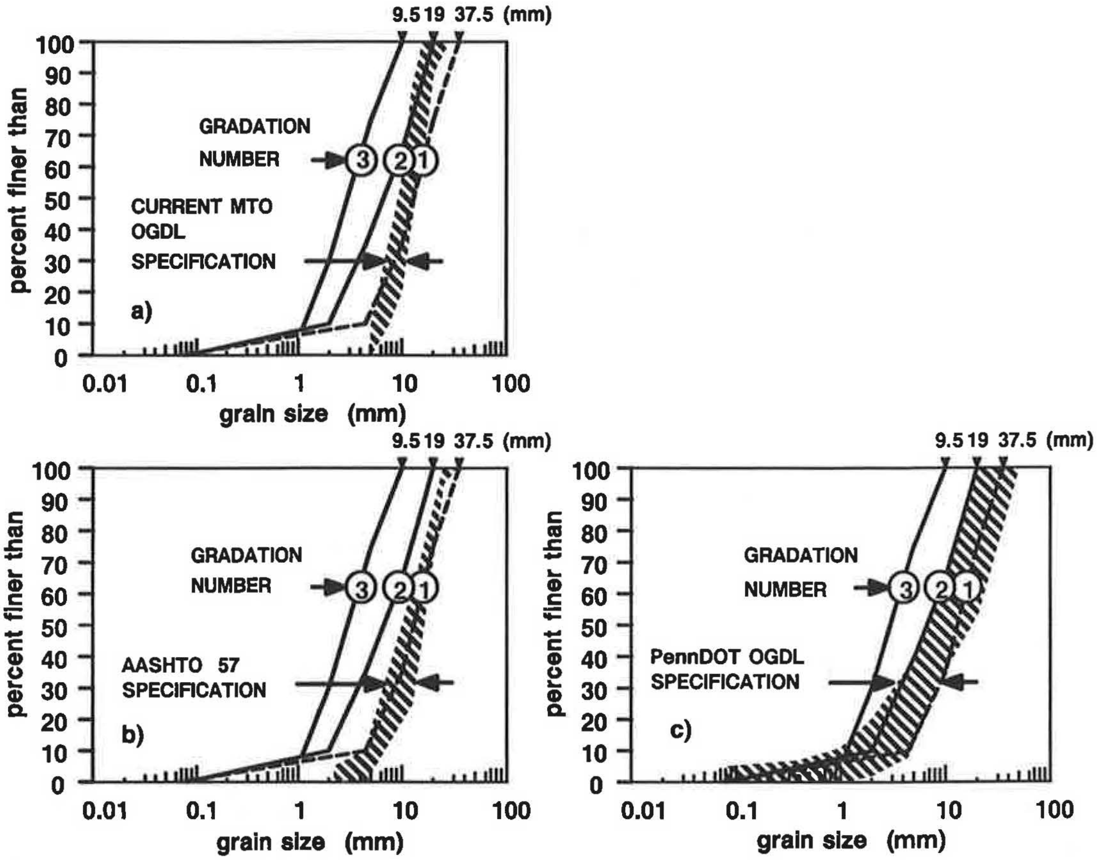

FIGURE 2 Examples of grain size distributions for open-graded drainage layers.

hardness of aggregate materials as a result of the autogenous grinding of the aggregate particles. Abrasion of aggregate particles in an OGDL will result from the constant movement of aggregate particles against each other, particularly near pavement cracks and joints.

The specifications for the MA test follow and are reproduced from the current CP Rail specification (*12*). In the current investigation, the CP Rail method of test was modified for samples having a smaller top-size than that designated in the original specification.

The Mill Abrasion Test (from CP Rail Specification for Ballast 1984):

A representative sample is obtained and sized by using current ASTM Methods of Test. From the coarse aggregate, split a representative portion into a sample consisting of 1.5 kg passing the 38.1-mm sieve and retained on the 25.4-mm sieve plus 1.5 kg passing the 25.4-mm sieve and retained on the 19-mm sieve. The sample shall be washed and oven dried in accordance with the Los Angeles Abrasion procedure. The sample will then be placed in a 4.546-l, 230-mm external diameter porcelain ball mill pot, along with 3 kg of distilled water. The mill pot shall be sealed and rotated at 33 rpm for a total of 10,000 revolutions (5 hours). The sample shall then be wash-sieved through a No. 200 sieve and oven dried before weighing. Mill Abrasion shall be calculated as a percentage loss in weight, using the following formula:

$$\text{mill abrasion} = \frac{\text{loss in weight}}{\text{original weight}} \times 100$$

The Modified Mill Abrasion Test for small-size aggregate: The procedure just described was modified for samples of aggregate having particle sizes less than 19 mm. For those samples, a single 3-kg charge was used composed of particle sizes passing 19 mm and retained on the No. 4 sieve.

Hardness-Toughness Trade Offs and Aggregate Index Number

Experience with railway ballasts (*10,11*) has shown that aggregates that are tough with respect to fracture resistance are not necessarily highly abrasion resistant. Rather, the same longevity of ballast under cumulative tonnage can be obtained by aggregates having different combinations of MA (hardness) and LAA (toughness) values. A parameter that reflects the contribution of both mechanisms to aggregate durability in track is the Aggregate Index Number (I_a) where

$$I_a = 5 \times \text{MA} + \text{LAA}$$

CP Rail has adopted limits on the Aggregate Index Number as a ballast criterion and have correlated the I_a value and aggregate gradation with ballast life (i.e., cumulative tonnage to aggregate fouling). In the CP Rail specification, the Aggregate Index Number is called the Abrasion Number.

The work by Raymond and CP Rail has inspired the current experimental approach and has led to an investigation of the Aggregate Index Number as an indicator of relative stability of coarse single-sized highway aggregates.

The aggregates tested in the current investigation were selected to give a range of hardness and fracture resistance and Aggregate Index Number. The Elginburg limestone was the poorest quality aggregate investigated (i.e., greatest I_a value) and in qualitative terms represents an aggregate with low hardness/low toughness (soft/weak). The Marmora Trap is a metamorphic rock and was the highest quality aggregate (i.e., lowest I_a value) investigated. It has medium hardness/high toughness. Finally, the Jasper dolomite is an intermediate quality aggregate and is defined by medium hardness/medium toughness.

Plate-Bearing Test Procedure

The general arrangement for the plate-bearing test is given in Figure 3; the test system is shown in Figure 4. The OGDL was modeled as a layer of aggregate 100 mm thick and was supported by a rigid or flexible base. The 100 mm thickness is typical of OGDL installations in Ontario (Ministry of Transportation, Personal Communication) and in the United States (*1*). Nevertheless, 100 mm is likely the minimum thickness that would be considered in actual installations to facilitate construction and to ensure adequate flow capacity. The OGDL samples were 1 m by 1 m in plan area and were confined within a rigid thick-walled aluminum tray, which permitted unbound aggregate samples to be placed and compacted away from the loading system. The flexible support condition was created by using a closed-cell gum-rubber mat (12 mm thick). The equivalent subgrade modulus (k_s) of the mat material was determined to be 370 MN/m^3, using a rigid 457-mm diameter steel plate and a static load of 40 kN (i.e., maximum bearing pressure = 244 kPa). The measured mat flexibility is considered to be representative of the compliance because of the combined effect of a good granular subbase overlying a competent cohesive subgrade. In a previous investigation (*14*), the CBR of this artificial "subgrade" was estimated to be equivalent to a granular material with a CBR of 40.

A sinusoidal loading pulse with an amplitude of 2 to 40 kN was applied to the surface of each sample by using the same rigid steel plate. The maximum 40 kN load represents a standard half-axle load. The 457-mm diameter plate (as opposed to, say, a 300-mm diameter plate) was selected to simulate the increased bearing area that would exist in the pavement structure at the elevation of the OGDL as a result of the vertical load that spread through the overlying surface course. The minimum load level of 2 kN was selected to ensure a good contact between the aggregate and the loading plate. The load was delivered to the plate by using an MTS closed-loop electrohydraulic actuator controlled by a DEC PDP11/34 computer. A load cell and linear variable displacement transducer (LVDT) located above the actuator base was used to monitor footing loads and vertical displacements. The load-deformation response of the footing during a loading cycle was recorded and stored by the computer at programmed intervals. The load was applied at a rate of 5 Hz for 1 to 2 million load applications. The plate was maintained in a horizontal position throughout the test by passing the actuator piston through a rigidly supported Teflon® bushing.

A concrete plinth was used to support the aluminum tray that confined the aggregate sample. The purpose of this structure was to provide a catchment system for in-situ permeability tests as part of a related research program.

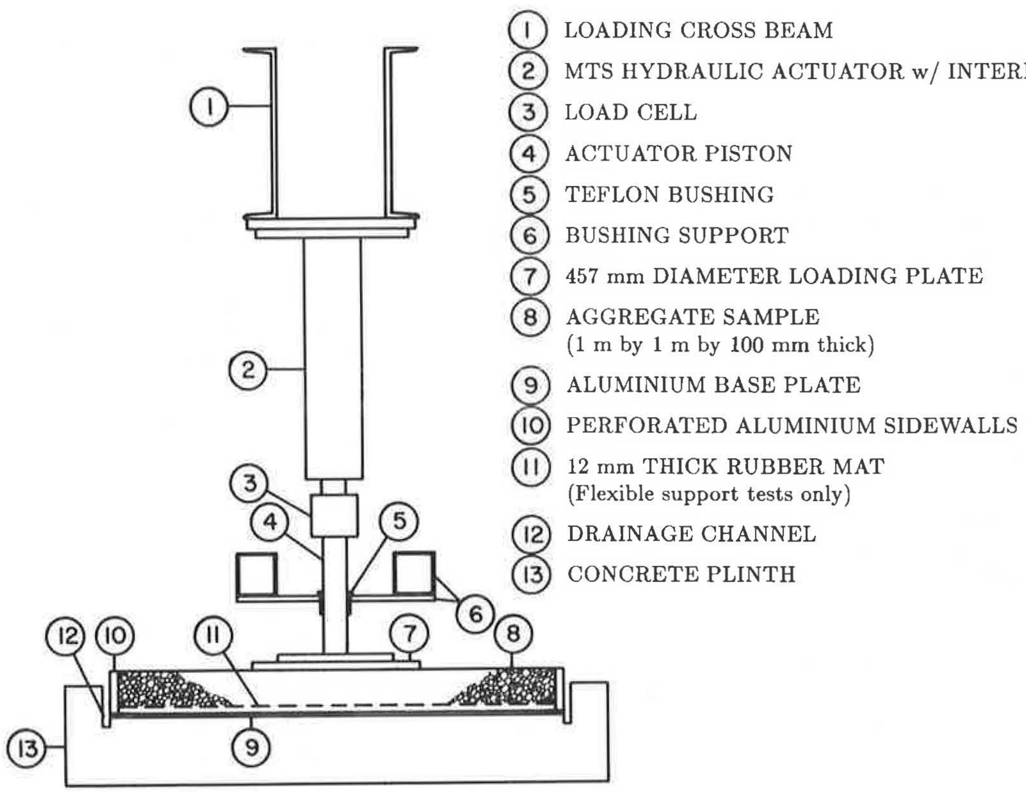

FIGURE 3 Plate-bearing test apparatus.

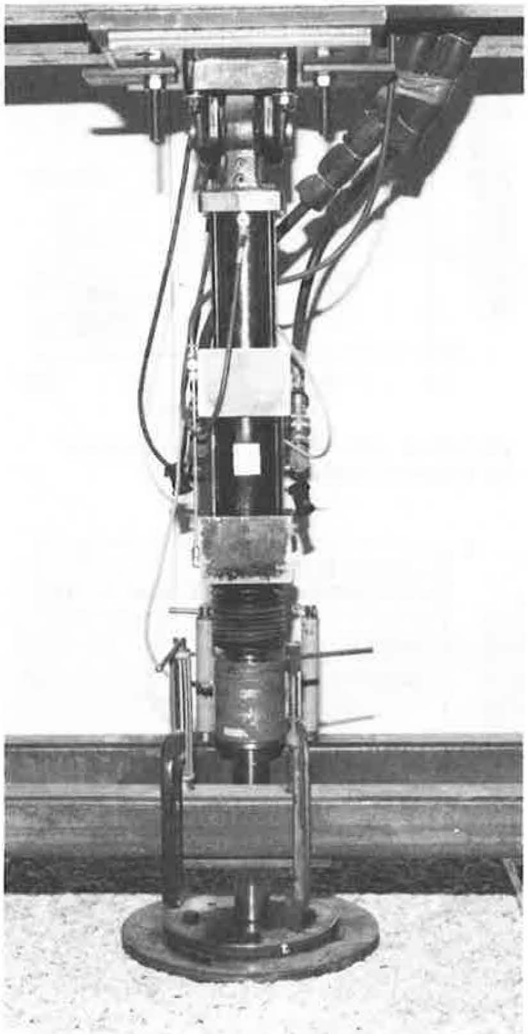

FIGURE 4 Testing system.

The aggregate samples were compacted by using a hand-held tamping plate that weighed 10.4 kg and had a tamping area 250 mm by 250 mm. The same number of passes from the same height were used in the preparation of each specimen.

TEST RESULTS

The results of density measurements showed that void ratios varied from about 0.42 to 0.61 for samples of the Elginburg limestone, Jasper dolomite, and Marmora Trap. Void ratio data were plotted in Figure 5. There was no systematic variation in void ratio between samples constructed with a rigid support. The void ratios for the flexible-support models with the finest gradation were somewhat lower than for the comparable rigid-support configurations. Nevertheless, the mean value of void ratio at a particular gradation was reasonably constant at about 0.49 for both rigid and flexible models. The independence of void ratio from aggregate type was a consequence of similar particle shape for the 100 percent crushed materials and the light compaction effort applied to the samples to prevent particle crushing during construction.

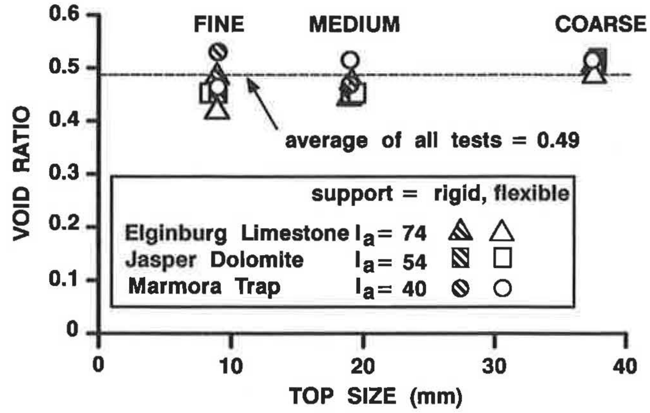

FIGURE 5 Void ratio versus top size.

The results of the plate-bearing tests with the coarsest aggregate (gradation 1) are shown in Figures 6 and 7. The cumulative (permanent) displacement with the number of load repetitions was highly nonlinear, with most of the deformation occurring early in the loading program. The same data were replotted with semi-logarithmic axes. In general, the data show that over a wide range of load repetitions the permanent displacements varied linearly with the log number of load applications. The data from those tests indicate that the magnitude of permanent displacement increases with the value of Aggregate Index Number I_a and with the compressibility of the underlying support.

Permanent deformation as a relative measure of aggregate stability under load can be misleading, because the magnitude

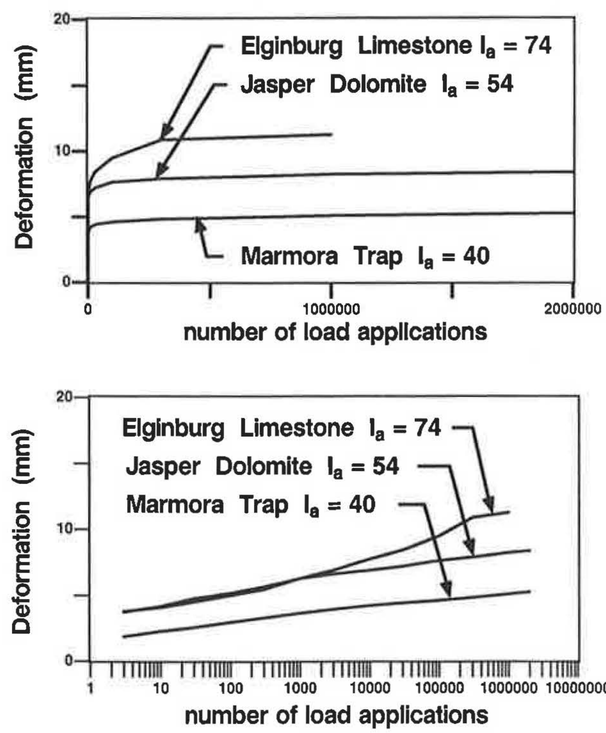

FIGURE 6 Load deformation response of aggregates over rigid support (gradation 1): linear scale (*top*), semi-logarithmic scale (*bottom*).

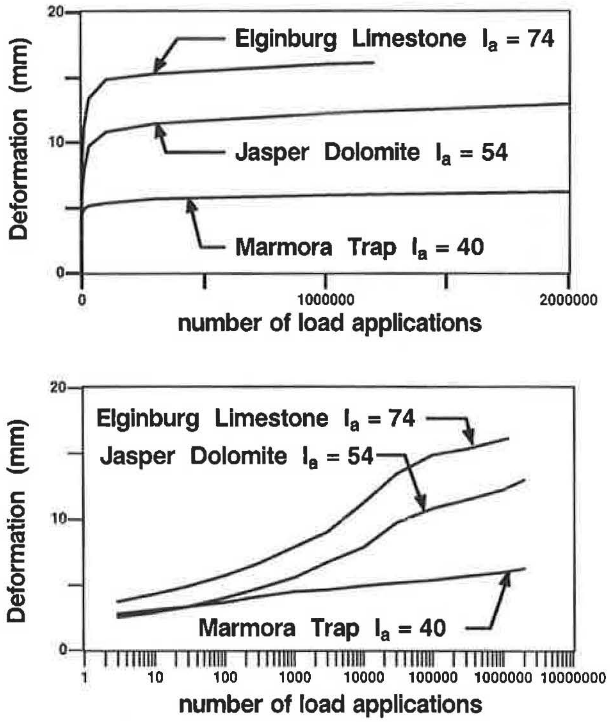

FIGURE 7 Load deformation response of aggregates over flexible support (gradation 1): linear scale (*top*), semi-logarithmic scale (*bottom*).

of permanent deformation after a given number of load applications is sensitive to the effects of initial plate seating. In this investigation the most reliable measure of relative stability between tests was found to be the rate at which permanent deformation had accumulated with respect to the log number of load repetitions (i.e., mm/log cycle) taken over 10 to 10^6 load applications. For brevity, this quantity is referred to as deformation rate.

Deformation rates versus aggregate size for all test configurations are summarized in Figures 8–10 and are based on the three aggregates investigated. For the poorest aggregate (Elginburg limestone in Figure 8), the test results show that deformation rates diminished with finer aggregate size and greater support stiffness. Figure 9 shows that for the intermediate quality aggregate (Jasper dolomite) the deformation rates were essentially insensitive to aggregate size but decreased with lower support compressibility. The same data for the highest quality aggregate (Marmora Trap) show that deformation rates were essentially independent of aggregate size and support condition (Figure 10).

The influence of test parameters on model stiffness can be described by rebound values measured over the course of each test. The rebound values have been calculated as the difference between permanent and peak plate deformations during a load cycle. An average rebound value was calculated for 10 to 10^6 load applications in each test, and those values are plotted in Figure 11, which illustrates that rebound values were essentially insensitive to grain size but (as expected) were dependent on the support stiffness. For the flexible support condition, the rebound values showed a tendency to increase

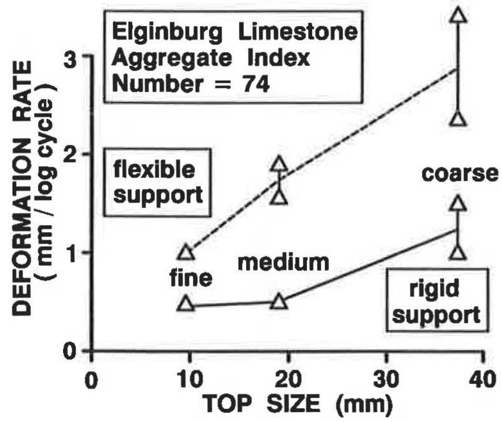

FIGURE 8 Deformation rate versus top size for Elginburg limestone.

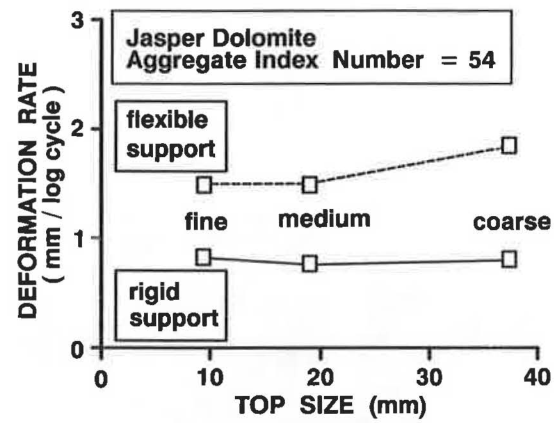

FIGURE 9 Deformation rate versus top size for Jasper dolomite.

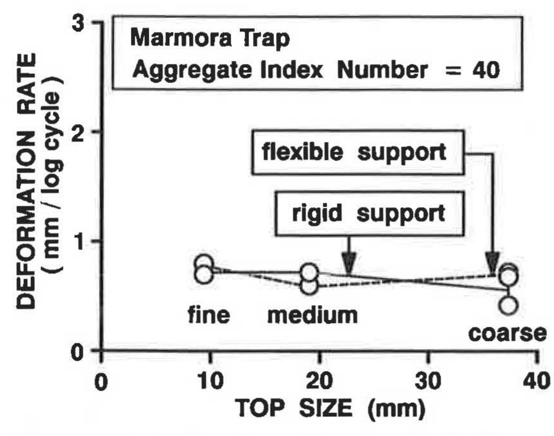

FIGURE 10 Deformation rate versus top size for Marmora Trap.

with decreasing aggregate quality. Nevertheless the magnitude of the values recorded are close to the limit of the instrumentation accuracy, and it is therefore difficult to confidently isolate the influence of aggregate quality on system rebound values.

The deformation rate values from all tests can be replotted against the Aggregate Index Number (I_a), as shown in Fig-

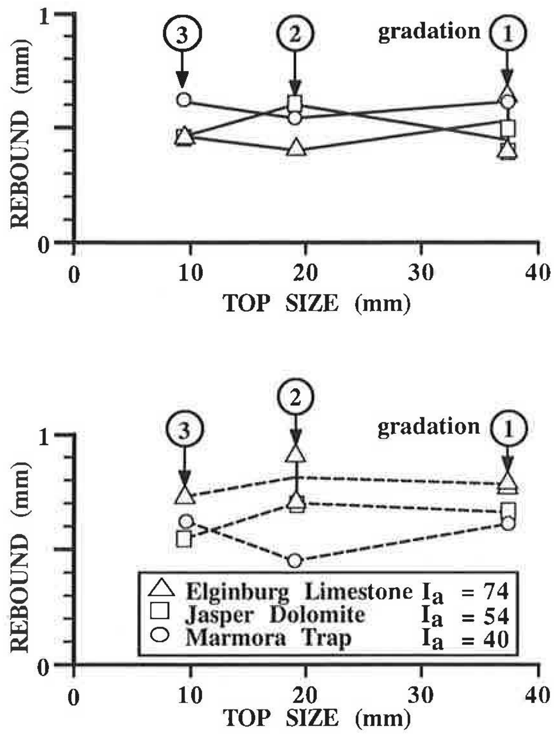

FIGURE 11 Rebound versus top size: rigid support (*top*), flexible support (*bottom*).

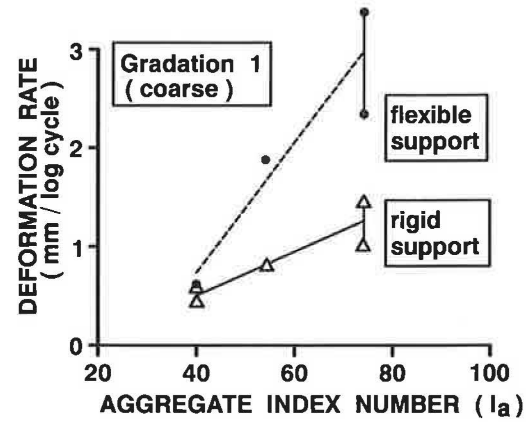

FIGURE 13 Deformation rate versus Aggregate Index Number for gradation 2.

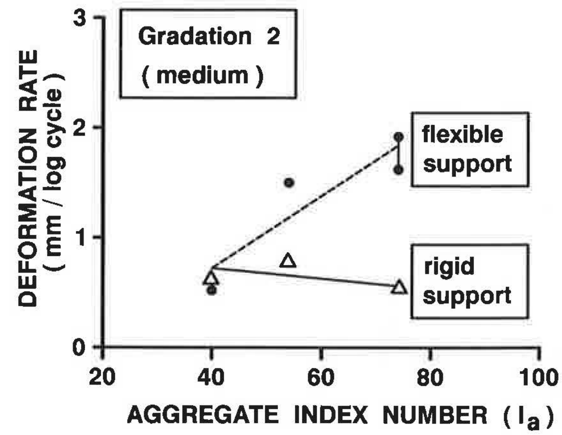

FIGURE 14 Deformation rate versus Aggregate Index Number for gradation 3.

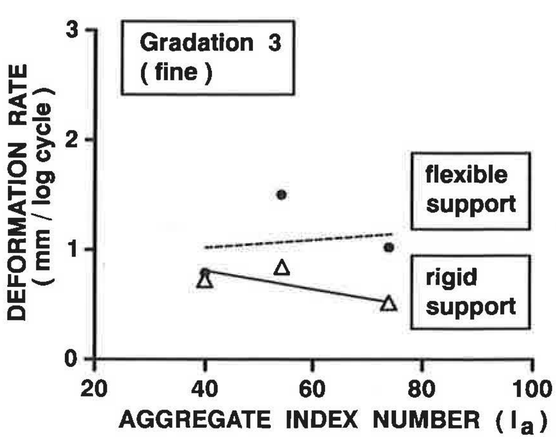

FIGURE 12 Deformation rate versus Aggregate Index Number (I_a) for gradation 1.

ures 12–14 for gradations 1 (coarse), 2 (medium), and 3 (fine). The figures illustrate that the stability of OGDLs meeting the coarsest size specification could be improved by selecting a higher quality aggregate as defined by its Aggregate Index Number. This is particularly true for open-graded aggregates over compressible bases. For example, reducing the Aggregate Index Number from 74 to 40 corresponds to a reduction in the (log) cumulative deformation rate by a factor of three. On a linear scale, this improvement corresponds to a thousand-fold increase in the number of load applications to achieve the same deformation level as for the poorest aggregate. Figure 13 illustrates that the performance of OGDLs having a size distribution corresponding to a medium gradation (gradation 2) could only be improved by selecting a higher quality aggregate if the layer were over a compressible base. Finally, for the finest gradations investigated, Figure 14 shows that the quality of the aggregate did not systematically influence the stability of those systems on the basis of deformation rate.

CONCLUDING REMARKS

The results of the current laboratory investigation have shown preliminary qualitative relationships between aggregate stability under dynamic loading and the quality of the aggregate and the stiffness of the underlying support. The coarse and medium-sized open-graded aggregates investigated cover a range that would be considered in OGDL construction on the basis of a number of current specifications that ensure adequate flow capacity for those aggregates when used as drainage layers below pavement. The tests show that the ability of the unbound aggregate to resist cumulative permanent deformation generally diminishes as the quality of the aggregate decreases (i.e., increasing Aggregate Index Number) and as the compressibility of the underlying support increases. For example, if a coarse aggregation gradation (say, gradation 1) were desirable based on drainage criteria, then an aggregate with a low Aggregate Index Number would be needed to ensure adequate resistance to fracturing and resistance. This is particularly true of OGDLs placed over compliant road support. Under those conditions, the results of the current investigation have shown that a thousand-fold increase in the number of load applications is required for the highest quality aggregate to achieve the same level of permanent deformation as does the poorest aggregate. Highway pavement performance is evaluated in part by the magnitude of surface rut depth. If the number of load applications to achieve an unacceptable level of deformation in the OGDL were to be increased by a factor of a thousand, then pavement repair cycle times would be dramatically reduced. An alternative strategy to selecting a better quality material is to use a finer gradation (say, gradation 2) to improve the stability of the aggregate.

It is current practice in many jurisdictions to use a 1.5 to 2 percent AC binder to stabilize the open-graded drainage layer during construction. The influence of parameters such as grain size distribution, aggregate quality, support compressibility, AC content, and compaction density on those bound systems warrant investigation. Nevertheless, it has been observed in some prototype-scale test sections by the authors that stripping of the OGDL aggregate can occur because of water infiltration, and, therefore, it can be argued that ultimately the stability of the OGDL is dependent on the unbound condition of the aggregate.

In practice, the Aggregate Index Number should not be considered a substitute for petrographic evaluation of highway aggregates. Petrographic analysis is a primary tool in aggregate evaluation particularly with respect to mineral composition (e.g., minerals may be susceptible to weathering), consistency, particle shape, and structure (e.g., foliation, cleavage, and bedding planes). A thorough petrographic evaluation should be carried out to eliminate aggregates unsuitable regardless of their Aggregate Index Number. Nevertheless, as this investigation has shown, the interrelation between Aggregate Index Number, gradation size, and support compressibility does reveal important trends that can assist the engineer to choose between aggregates that are potential candidates for OGDL construction.

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