Field Performance of Open-Graded Drainage Layers

J. J. Hajek, T. J. Kazmierowski, H. Sturm, R. J. Bathurst, and G. P. Raymond

The results of a field study carried out to investigate the performance of pavements incorporating open-graded drainage layers (OGDLs) are presented. OGDLs are used to ensure rapid and effective drainage of pavement structures and thus to improve pavement performance. Altogether, five paving projects built since 1975 and incorporating OGDLs are described and evaluated. The projects encompass flexible, composite, and rigid pavements, and include both asphalt-cement-treated and untreated OGDL materials. The evaluation was done in terms of (a) pavement performance evaluation, with emphasis, where possible, on comparing adjacent sections with and without OGDLs; (b) occurrence and severity of major pavement distresses investigated by coring and trenching; (c) assessment of in situ drainage done by observing movement of water within the pavement structure; and (d) laboratory analysis of excavated OGDL materials. The results of this study show that the existence of OGDLs alone does not guarantee a better pavement performance. This can be achieved only if the OGDL is a part of a properly designed internal drainage system.

Excess water trapped in the pavement structure can accelerate pavement damage and cause premature pavement failure. In order to remove the excess water, a number of highway agencies have built or are experimenting with free-draining layers or blankets using permeable granular materials (*1–3*). This permeable layer is placed between the pavement surfacing materials and the subgrade and is referred to herein as an open-graded drainage layer (OGDL).

Since 1975, the Ministry of Transportation of Ontario (MTO) has incorporated OGDLs into a number of different paving projects encompassing flexible, rigid, and composite pavements. Five of these projects were built before 1989; an additional three or four projects have been built since or are under construction. The objective of this paper is to review our experience with the five older projects and evaluate the influence of OGDLs on pavement performance. The purpose of this work is twofold:

1. To provide feedback for pavement design practices incorporating OGDLs (*4*). For example, to assess the need for OGDLs, their placement, and physical properties including gradation and protection of OGDLs from infiltration and clogging.
2. To determine if the function and performance of OGDLs can be predicted using the existing design procedures.

J. J. Hajek and T. J. Kazmierowski, Ontario Ministry of Transportation, 1201 Wilson Avenue, Downsview, Ontario M3M 1J8, Canada. H. Sturm, Canadian Portland Cement Association, 1500 Don Mills Road, Suite 501, Toronto, Ontario M3B 3K4, Canada. R. J. Bathurst, Department of Engineering, Royal Military College of Canada, Kingston, Ontario K7K 5L0, Canada. G. P. Raymond, Department of Civil Engineering, Queen's University, Kingston, Ontario K7L 3N6, Canada.

LEARNING FROM THE PAST

The most recent OGDL project evaluated herein was built in 1987 and was probably designed 1 or 2 years before. Since then, our design practices and understanding of what constitutes an appropriate pavement subdrainage design have changed considerably. For example, in the past, the OGDLs were usually not connected directly to longitudinal subdrains, whereas current designs ensure a direct connection between the two elements. The question can be posed: Why study the performance of pavement subdrainage designs that are old and are unlikely to be built again?

The reason for studying the performance of old designs is that we can always learn by evaluating and verifying our theoretical understanding of material behavior and pavement performance using field observations. Although the materials of drainage layers and their arrangement can always change, the basic design principles are universally applicable and change only if they do not adequately explain what happens in the field. In other words, we are studying the field performance to verify our design principles.

GENERAL CONSIDERATIONS IN SUBDRAINAGE DESIGN

Pavement systems, particularly those containing granular base and subbase materials, should not contain free, gravitational water (water that moves because of gravitational force). If free water is present, the effects of dynamic traffic loading can lead to pumping (movement of free water and suspended aggregate particles underneath two adjacent pavement slabs) and to premature loss of riding quality. There is also a concern with the loss of stability due to high pore pressures in saturated dense-graded aggregate layers.

The major design considerations include the permeability and thickness of the OGDL, the collection system, and the protection system. The recommended permeability for OGDLs carrying water across a pavement roadbed on a 2 or 3 percent slope is typically above 1.7 mm/sec (500 ft/day) (*5*). Ridgeway (*6*) implicitly recommends 3.5 mm/sec (1000 ft/day). At any rate, the typical gradation curves for OGDL materials used on past Ministry projects indicate that our materials meet and significantly exceed the recommended permeability criteria (*7*).

FIELD EVALUATION OF OGDLs

In this section we describe pavement structure and subdrainage design of the five projects incorporating OGDLs and evaluate their performance. The evaluation is done in terms of

1. 1990 pavement performance evaluation, with emphasis, where possible, on comparing the performance of the adjacent pavement sections with and without OGDLs;
2. Occurrence and severity of predominant pavement distresses investigated by taking 150-mm-diameter cores and by trenching;
3. Assessment of in situ drainage by observing movement of water within the pavement structure; and
4. Laboratory analysis of OGDL materials obtained by coring, excavating, or both. The analysis included tests for asphalt cement (AC) content (ASTM D 2172), grain size distribution (ASTM C 127-84), bulk density (ASTM 1188-83), and other routine tests. The results are summarized elsewhere (*8*). Only selected results are given in this paper.

The main characteristics of the five projects incorporating OGDLs are summarized in Table 1.

Highway 56

The site encompasses four sections: three test sections with OGDLs and a control section without an OGDL (Table 2). It may be noted that all four sections have the same design thickness of asphalt concrete (130 mm) and the same total thickness of granular materials (535 mm, considering OGDL materials as granular materials). However, on the basis of field investigation by coring and trenching, it appears that the actual asphalt concrete thickness is somewhat higher on sections with untreated OGDLs. This may be attributed to the unevenness or distortion of the untreated OGDLs before paving.

The untreated OGDLs were placed full width across the roadbed with daylighting at the ditch slopes below the shoulder rounding. The AC-treated OGDL was placed below the pavement only and the untreated OGDL was placed on the remaining portion of the roadbed below the shoulders and again daylighted. Where possible, OGDLs were placed on a 3 percent crossfall (*9*).

Pavement Performance Evaluation

After 15 years of service, all four sections exhibit quite similar performance, both in terms of riding comfort rating (RCR = 6.0) and the occurrence and severity of pavement surface distresses. The main distress (on all sections) is frequent severe, full-width transverse cracking. The transverse cracks are often cupped (the depression is about 12 mm on 300 mm straightedge); some are starting to become multiple (transverse cracks) and some to alligator. Sealant bond failure is quite frequent.

Distress Investigation by Coring and Cutting

The investigation by coring (taking 150-mm wet cut cores) and cutting (cutting 600- × 250-mm slabs from the pavement surface) focused on transverse cracks, which are the main distress and the major reason for upcoming pavement rehabilitation.

The OGDL material obtained at locations far from cracks appeared to be undamaged and dry. The AC-treated OGDL material (Section 3) was usually recovered in one piece and was bonded to the overlying asphalt concrete. Its AC content was close to the 3 percent value specified for this section (see Table 1). A quite different situation was observed near transverse cracks where the OGDL material was wet and contaminated with fines from the base material (Granular A).

A composite representative condition of transverse cracks based on coring and cutting is shown in Figure 1. It appears that the existence of OGDLs had no significant influence on the frequency of transverse cracks or on the condition of transverse cracks in terms of crack opening, asphalt concrete stripping at the bottom of the asphalt concrete layer, or cupping. There was noticeable stripping of asphalt cement from the aggregate particles of the treated OGDL material. A low

TABLE 1 MTO Projects Incorporating Open-Graded Drainage Layers

Location	Date of Constr.	Contract No.	89 Traffic		No. of Traffic Lanes	Pavement Structure	Length of ODGL Sect. (m)	Asphalt Content of ODGL (%)	Thickness of OGDL mm
			Volume (AADT)	Truck* %					
Hwy. 56, south of Elfrida	1975	75-02	8400		2 2 2	Flexible	122 122 122	0 3 0	75 75 150
Hwy. 3N, west of Leamington	1982	82-01	8500	9.5	2	Rigid	5200	2	100
E.C. Row near Dominion Blvd.	1987	87-37	25000	12	4	Composite	500	2	100
E.C. Row, near Huron Church Rd.	1987	87-23	11000	13	4	Composite	300	2	100
Hwy. 16N, south of Ottawa	1984	84-22	11000	10	2	Flexible	1000	2	100

* *Estimated*

TABLE 2 Arrangement of Test Sections on Highway 56

Test Section	Thickness of pavement layers, mm			
	Asphalt Concrete		OGDL (Observed)[1]	Granular A (Design)
	Design	Observed[1]		
1 Control	130	140	0	535
2 75 mm untreated OGDL	130	175	75	460
3 75 mm A.C. treated OGDL	130	140	75	460
4 150 mm untreated OGDL	130	175	150	385

Notes: [1]Established by coring or cutting (trenching)
The total thickness of granular materials, considering OGDL to be a granular material, was 535 mm on all sections.

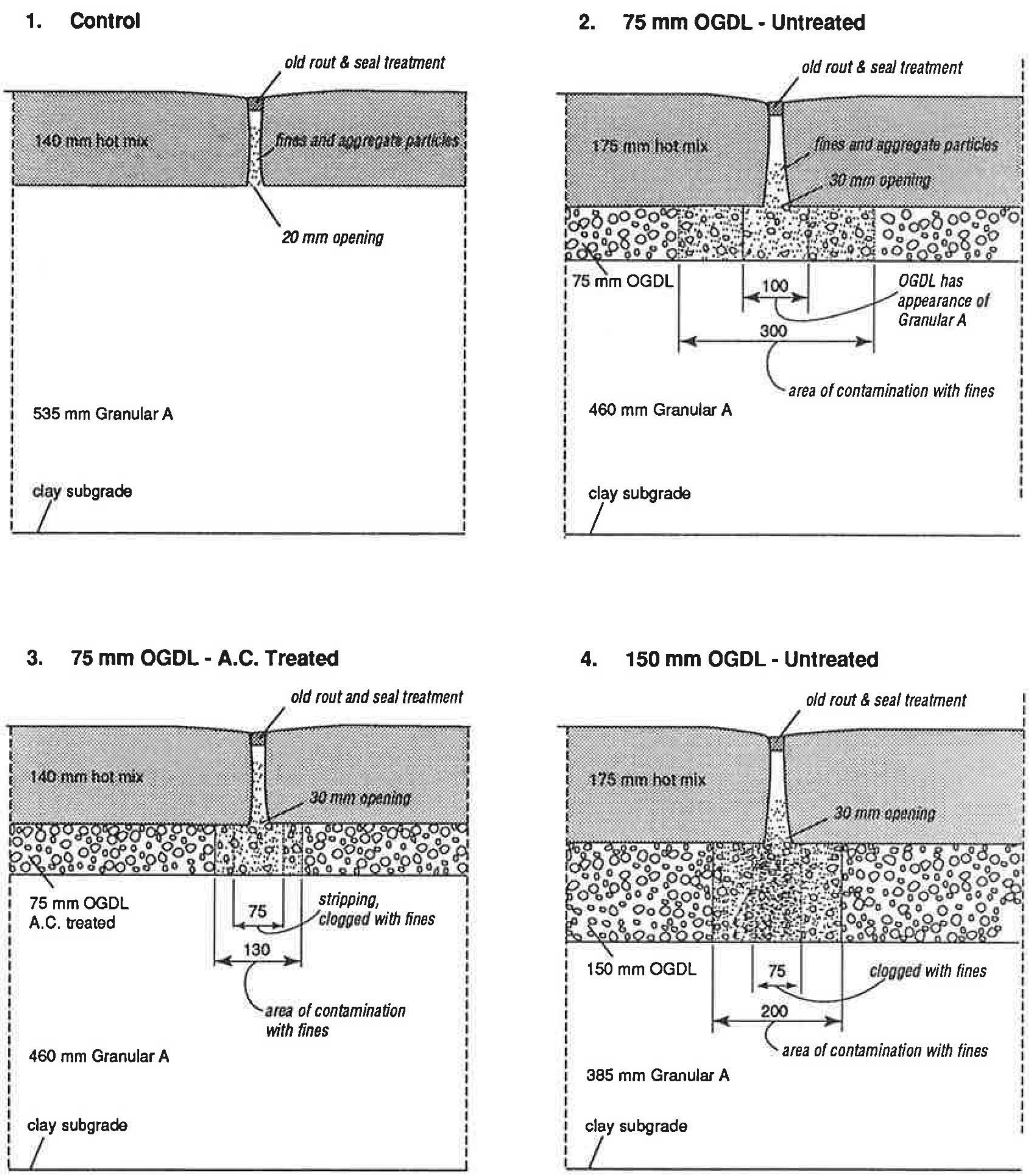


FIGURE 1 Typical condition of full transverse cracks, Highway 56.

value of 1.3 percent AC was obtained from a sample taken below a fully developed transverse crack. Otherwise the type and the area of contamination with fines and the amount of fines in the OGDL materials were quite similar on all three OGDL sections.

Investigation of In Situ Drainage

Daylighting of OGDL The topsoil on the ditch slope was removed at several locations to examine the condition of the OGDL material. The topsoil cover was about 300 mm thick. The OGDL was distinguishable from the surrounding layers of Granular A material even though it was contaminated with topsoil and Granular A material. Underneath the shoulder, the OGDL material was less contaminated and appeared to be free draining.

Crossfall Drainage Water was poured into a 600- × 250-mm cut in the asphalt concrete, and the OGDL material and its propagation towards the ditch were observed using two additional openings between the cut and the ditch daylighting. As indicated by the results given in Figure 2, the crossfall drainage appeared to be sufficient at the location investigated, with an average horizontal permeability of 10 mm/sec (2800 ft/day). This exceeds the recommended minimum by a factor of 3.

Permeability Water was poured into the core holes and cuts, and the drop in the water level was observed. The areas of contamination shown in Figure 1 drained very slowly. Usually, there was no observable water drop in 10 min. Noncontaminated areas drained so fast that no water head could be maintained using a 25-L container.

Highway 3N

The pavement section with an OGDL on Highway 3N is part of a large 1982 experiment investigating the design, construction, and performance of plain-jointed portland cement concrete (PCC) pavements. The experiment encompasses four different pavement designs, including one design with an OGDL (Table 1). The design and performance of all four pavement sections have been described in detail elsewhere (*10*) and will be only briefly reviewed here.

The pavement structure of the four sections, built on a silty-clay subgrade, is summarized below and the arrangement of the OGDL section is shown in Figure 3.

- Section 1: 305-mm plain jointed PCC slab.
- Section 2: 203-mm plain jointed PCC slab, 100-mm open-graded drainage layer.
- Section 3: 178-mm plain jointed PCC slab, 127-mm lean concrete base.
- Section 4: 203-mm plain jointed PCC slab, 127-mm lean concrete base.

The longitudinal drainpipes (installed on all four sections) were plowed in and backfilled with the excavated shoulder material. The highway grade in the vicinity of the OGDL section is mainly at grade.

Pavement Performance Evaluation

A detailed pavement performance evaluation of all four pavement test sections was conducted after 6 years (*10*). Briefly, all four PCC sections have roughly similar pavement roughness. However, the OGDL section and the full-depth PCC section have considerably less cracking distress, approximately five to eight cracks per kilometer, than the remaining two sections with lean concrete bases, which have approximately 60 to 70 cracks per kilometer. Much of the cracking in the lean concrete base sections is related to reflective cracking (from the lean concrete base). It is interesting to note that

1. The OGDL section is marginally less expensive than the full-depth section, but provides comparable performance, and
2. The structural strength of the OGDL section is lowest of the four.

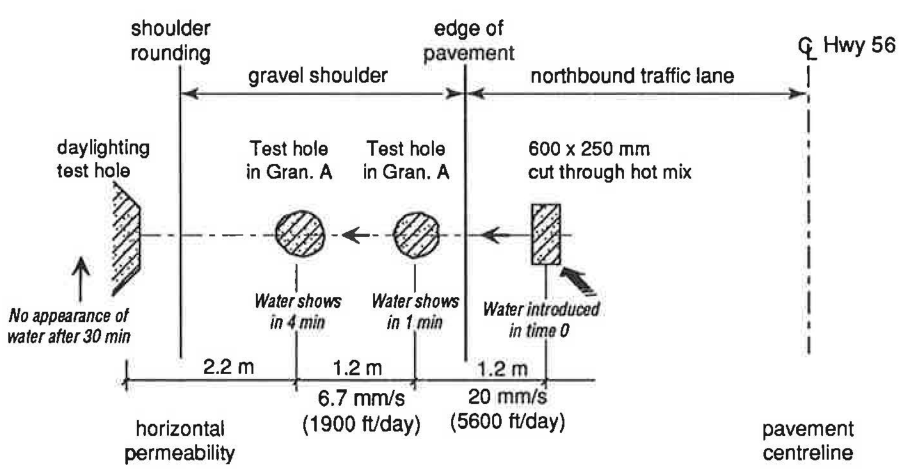


FIGURE 2 Investigation of crossfall drainage, Highway 56, Section 3.

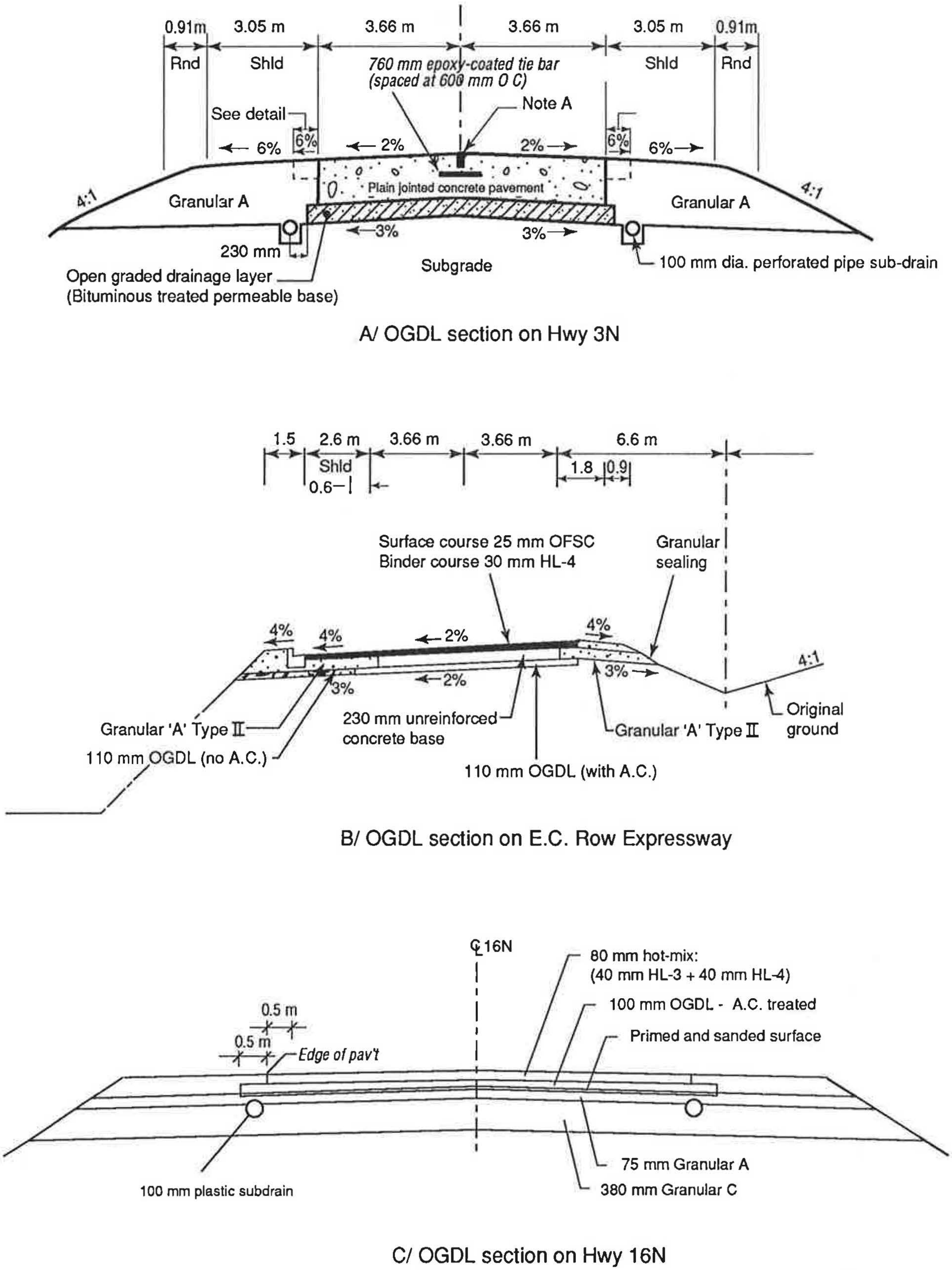


FIGURE 3 Typical OGDL sections.

The major distresses on the OGDL section are faulting of transverse joints and corner cracking. The transverse joints are stepped, on average, by about 3 mm, which is common to all sections. The maximum stepping is about 8 to 12 mm.

Distress Investigation by Coring

The coring was done in June 1989, following a night of heavy rainfall. Before the coring started, pumping action of traffic at transverse joints was clearly observed: small droplets of water were ejected from the joints by passing trucks and squirted upwards, making the pavement surface close to the joints wet and stained with clay and silt particles.

The cores taken at mid-slab (far from the joints) revealed a well-preserved OGDL material. About 80 percent of the material was recovered from the 175-mm bit cylinder in one piece and was bonded to the PCC. It was observed that the OGDL material in the core holes was flooded with water and that soon after the core was removed, the water level rose to within 50 mm of the pavement surface. The bottom 20-mm layer of the OGDL material was contaminated with subgrade (silty clay) and was loose showing signs of stripping. The AC content of the bottom portion of the core was 2.0 percent compared with 2.7 percent obtained for the top portion of the core.

The cores taken at faulted transverse joints near the center of the lane and the outside wheelpath revealed loose, partly stripped OGDL aggregate (AC content ranging from 1.1 to 1.9 percent) heavily contaminated with subgrade material. The OGDL material in all core holes was flooded. There was no loss of material at the bottom on the PCC slabs. Figures 4 and 5 contrast the condition of the OGDL material obtained at a mid-slab location with that close to a faulted transverse joint.

FIGURE 4 150-mm core obtained from cracks or joints, Highway 3N. OGDL material basically in one place and partially bonded to surface layer.

FIGURE 5 150-mm core obtained at transverse joint, Highway 3N. OGDL material loose mixture of stripped OGDL aggregate particles and subgrade soil.

Investigation of In Situ Drainage

Approximately 12 hr after a heavy rainfall, the OGDL was saturated with water at the locations investigated. There was no noticeable drop of the water level during an hour. It appears that the water ponding in the OGDL is caused by relatively impervious granular materials separating the OGDL from the lateral drains and ditch daylighting [Figure 3(*a*)]. Another factor contributing to ponding may be a low hydraulic gradient of the lateral subdrains, which are covered with a geotextile material protecting the perforated plastic subdrain from contamination.

Outlets of the lateral subdrains located on the ditch slopes were in good condition, relatively clean and free of vegetation. Most of them were discharging water, but not in the amounts expected. The rate of water discharge from the outlets seemed to be the same on all four sections. This highlights the need for a drainage collection system in direct contact with the OGDL.

E.C. Row Expressway in Windsor

The original composite pavement design, shown in Figure 3(*b*), was constructed at both locations on E.C. Row Expressway. The OGDL material was placed on the full width of the roadbed with daylighting at ditch slopes. The AC-treated OGDL material was placed underneath the pavement and extended 600 mm beyond the edge of pavement; the untreated material was placed underneath the remaining width of the shoulder.

Pavement Performance Evaluation

The pavement performance of the two OGDL sections is similar. The riding comfort rating is 8.5 (out of 10) and the predominant distress is full-width slight transverse cracks reflected above contraction joints that were precut in the plain PCC base. The transverse cracks have reflected above nearly all contraction joints, resulting in 3- to 6-m spacing. Some of the cracks are starting to spall, particularly on driving (truck) lanes. No crack stepping was observed; however, some rocking of the slabs was noticeable between two adjacent slabs separated by a spalled transverse crack when loaded trucks were passing.

Distress Investigation by Coring

The majority of cores were taken in the vicinity of transverse cracks. One core was taken near the middle of the (paved) right shoulder. The results of coring are shown in Figure 6. In many respects the results are similar to those observed on Highway 3N. The OGDL material at locations far from transverse cracks was in a very good condition with little or no stripping and some contamination by the subgrade material at the bottom. The level of contamination and stripping increased with closeness to transverse cracks. There was no loss of PCC material at the bottom of the PCC base near the contraction joints.

Investigation of In Situ Drainage

Daylighting The removal of granular material and topsoil on the ditch slope (i.e., digging of daylighting test holes) revealed a well-preserved layer of the OGDL material. At the daylighting test holes close to transverse cracks, the OGDL material was quite wet and the underlying subgrade material was saturated. It appears that water is entering the pavement structure through cracks and drains through the OGDL.

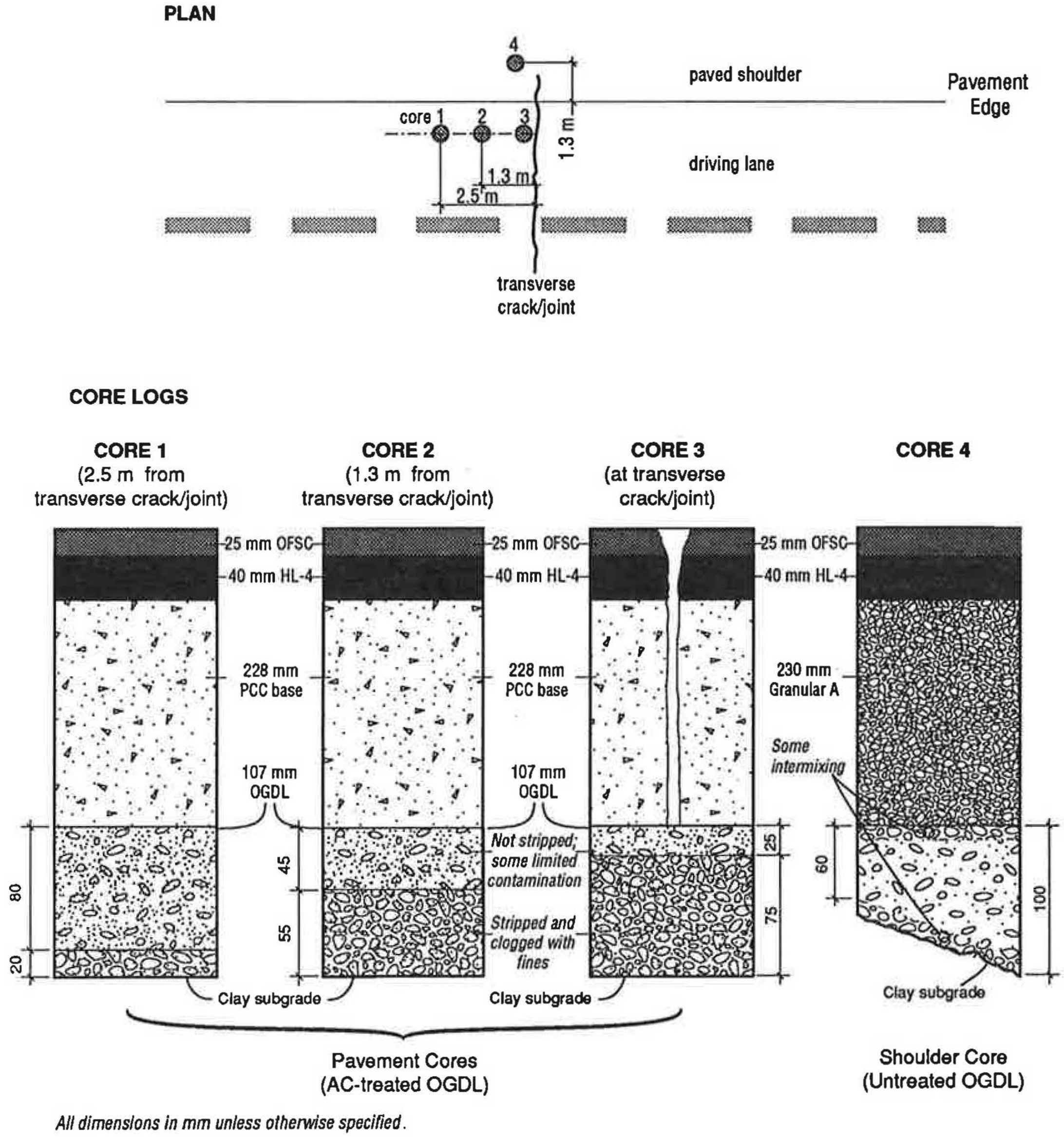


FIGURE 6 Condition of OGDL Material, E.C. Row Expressway.

Crossfall Drainage Water was poured into a 150-mm core hole drilled in the middle of the paved shoulder (Core 4, Figure 6). The rate of water dissipation was quite high (about 0.2 mm/sec), but because of the overall wet subgrade condition and the 3 percent longitudinal pavement grade, it was not possible to observe additional water seepage at the daylighted test hole or holes. The log of Core 4 in Figure 6 also shows uneven thickness of the untreated OGDL beneath the shoulder and some minor contamination.

Permeability The in situ permeability was tested by pouring water into core holes and measuring the rate of water dissipation. The results suggest that only the top portion of the OGDL was free draining in the vicinity of transverse cracks (7). Because of heavy contamination with subgrade fines, the bottom portion of the OGDL was quite impervious.

The two OGDL sections will benefit from an early routing and sealing of transverse cracks, which should prevent free water from entering the pavement structure.

Highway 16N

Three different sections—an OGDL section, a conventional section, and modified granular section—were built in 1984. The structure of the OGDL section is shown in Figure 3(*c*). The conventional section consists of 130 mm of asphalt concrete, 150 mm of gravel base, and about 425 mm of sand subbase. The modified granular section consists of 120 mm of asphalt concrete, 75 mm of gravel base, and about 300 mm of sandy subbase. All unbound granular materials in this section were modified by removing most of the fine aggregate particles. Only the OGDL section has lateral subdrains as shown in Figure 3(*c*).

Pavement Performance Evaluation

The roughness of all three sections is quite similar, as measured by the Portable Universal Roughness Device, whereas the pattern of cracking distresses is somewhat different. In addition to slight longitudinal cracks (midlane, center line, and wheel track cracks), which are found on all three sections, the conventional section has a noticeably higher density of these cracks and also has a few slight half and full transverse cracks. It was also reported that pavement roughness on the OGDL and modified granular design sections, as measured by in-vehicle ride, does not increase during winter, although it is noticeably higher on the conventional design section.

It is still too early to estimate the difference in the lifespan of the three designs. Nevertheless, in addition to its better performance, the OGDL section has also lower granular base equivalency (GBE) thickness (588 mm) than the conventional section (660 to 685 mm). The calculation of the GBE thickness, which relates all materials to an equivalent thickness of crushed gravel (Granular A), assumed that the GBE factor of the OGDL material is equal to 1. The OGDL section was also reported to be somewhat less expensive to construct than the other two sections.

Investigation of Distresses by Coring

The coring revealed undamaged OGDL material even if the cores were taken at (longitudinal) cracks. The OGDL material was usually well bonded to the bottom of the AC layer. The primed and sanded surface of the Granular A material [Figure 3(*c*)] appeared to be undamaged and in very good condition.

The thickness of the OGDL ranged from 70 to 110 mm and its AC content varied from 1.3 to 2.0 percent. Below the shoulder, where the OGDL material was more exposed to moisture, the AC content ranged from 0.7 to 1.1 percent. On the basis of tests conducted on five cores, the average bulk density was 1852 kg/m^3, with a range of 1791 to 1894 kg/m^3. There was no obvious reason for the spread in the bulk density values that could be related to sample location.

Investigation of In Situ Drainage

Crossfall Drainage Water was poured into core holes in the pavement and its progression toward the ditch was observed by using test pits dug in the granular shoulder. The sketch of the experiment given in Figure 7 shows that the crossfall drainage was impeded. A direct connection between the OGDL and the collection system is not provided. The OGDL material is abutted by Granular A material, and the longitudinal subdrains are separated from the OGDL by the primed and sanded surface of the Granular A layer. According to Figure 7, the water that traveled 2 m through the Granular A material on a 3 percent crossfall was detected in 20 min; the water that traveled the same distance through the OGDL on a smaller slope was detected in 1 min.

Permeability No significant water head could be established when water from 25-L containers was poured into 150-mm core holes. It appears that water dissipated very quickly over the primed and sanded Granular A layer.

Subgrade Moisture Content The effect of the OGDL on reducing the moisture at the pavement-subgrade interface was evaluated by time domain reflectometry based moisture gauges

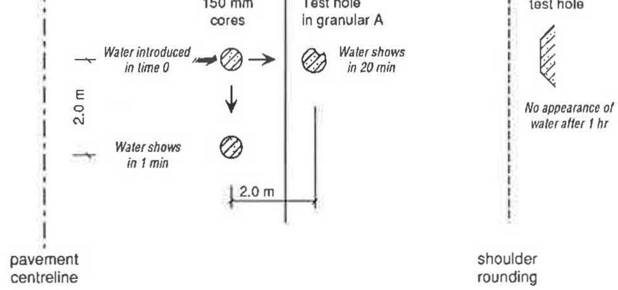


FIGURE 7 Investigation of crossfall drainage, Highway 16N.

(*11*) installed during construction on all three sections. The gauges were installed on the top of the subgrade (*a*) below the edge of pavement and (*b*) below the center line of the northbound lane. The results summarized by Hajek et al. (*7*) indicate that the presence of the OGDL may have somewhat reduced subgrade moisture content.

APPLICATION OF DESIGN PRINCIPLES

Intrusion of Fines

One of the major problems limiting the performance of OGDLs, identified by the field investigation on Highways 56 and 3N and the E.C. Row Expressway, was clogging of the OGDL material with fines. Movements of the fine soil particles can be caused by the movement of water from a fine-grained soil (such as subgrade clay) to the OGDL, by the pumping action of repetitive axle loading, and by penetration of the coarse OGDL material into a fine-grained material during the period of spring thaw. Generally recommended criteria for the design of protective granular filters (*5*) are used in this section for after-construction prediction of the clogging phenomenon.

Fines from Subgrade

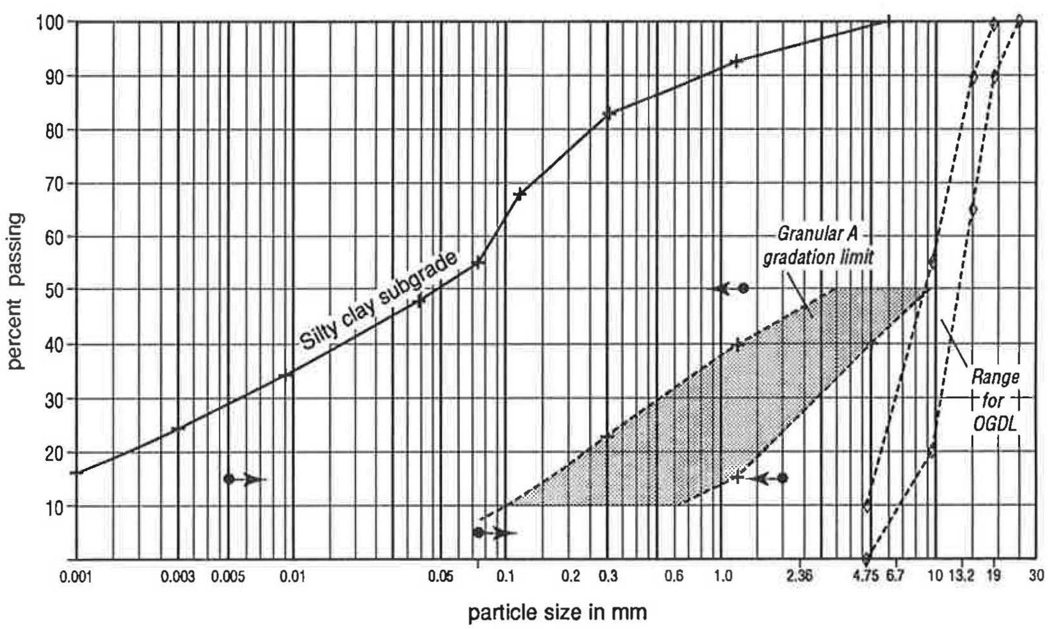
An arrangement similar to that existing on Highway 3N and on the E.C. Row Expressway is considered, in which the OGDL is placed directly on a clay subgrade. Representative gradation curves for the OGDL material and a silty-clay subgrade are given in Figure 8. Also shown as arrows in Figure 8 are gradation criteria for a granular filter based on the report by Moulton (*5*). The gradation range of the OGDL material is completely outside the filter criteria, and it is obvious that a filter layer should be provided to protect the OGDL from clogging. Consequently, in the absence of a filter layer, the observed intrusion of fines in the field is to be expected.

Figure 8 also gives a gradation range for Granular A material, which satisfies the filter requirements for the protection of the OGDL from intrusion of fines from the subgrade and can be thus considered a filter. It now remains to be checked if the OGDL material needs protection from intrusion of fines from the Granular A material. This is done separately in the following section.

Fines from Granular A Material

An arrangement similar to that existing on Highway 56 is considered, in which the OGDL is placed atop Granular A material. The generally recommended filter criteria of Moulton (*5*) were satisfied and no filter was required. However, field observations suggest otherwise: the OGDL was clogged near the transverse cracks where pumping action of traffic took place. This suggests that caution must be exercised when pumping is a possibility.

In addition to granular filters, other measures to reduce the occurrence of clogging include curtailing the amount of fines in the granular base material, priming and sanding the top of the granular base, and the using geotextile filters.



Note: Filter gradation should be within the limits indicated by arrows

FIGURE 8 Filter requirements to protect OGDL from intrusion of fines from subgrade.

Collection System

Another major problem limiting the performance of OGDLs was an inadequate collection system for rapid removal of water carried by the OGDL toward the pavement edge.

In the case of Highway 56 and the E.C. Row Expressway, there is no collection system per se: the removal of water depends on daylighting below shoulder rounding. The lateral drainage through daylighting may be restricted by

1. Contamination from overlying granular shoulder materials and topsoil, and blocking by the layer of topsoil;
2. Uneven or inadequate thickness of the OGDL, or both; an example of uneven thickness is shown in Figure 6 (for Core 4); and
3. Inadequate crossfall grade of the OGDL.

It may be noted that some authorities (*6*), as well as the MTO current guidelines, do not recommended the use of daylighting for draining of the OGDLs.

In the case of Highways 3N and 16N, drainage collection systems are in place, but the OGDLs are not directly connected to longitudinal subdrains. The high permeability of the OGDL material is not utilized if free water must overcome a relatively impervious barrier, for example, that formed by Granular A material, before it can reach lateral subdrains.

CONCLUSIONS AND RECOMMENDATIONS

1. The existence of OGDLs as such does not automatically guarantee improved pavement performance. To achieve improved performance, a comprehensive internal drainage design harmonizing the use of OGDLs (in terms of permeability, thickness and crossfall gradient), a collection system (dimensions and placement of subdrains and outlets), and a protection system (type and placement of filters) is needed.
2. High-permeability OGDLs are susceptible to clogging by fines when they are subjected to pumping at cracks and working joints by repeated traffic loads, particularly if the collection system or the filter system, or both, is inadequate and free water is allowed to linger in the OGDL material. Generally accepted filter criteria may not be sufficient to protect high-permeability OGDL materials from clogging under these circumstances.
3. The clogging and contamination by fines can reduce the permeability of the OGDL material by several orders of magnitude.
4. Stripping of asphalt cement from the bituminous-treated OGDL material does not appear to affect performance of the layer. One hundred percent crushed aggregate is specified to ensure long-term stability of the layer, and the bituminous stabilization is used only to simplify construction.
5. Monitoring of the performance of pavement sections incorporating OGDL materials should continue along the lines outlined in this paper.

ACKNOWLEDGMENTS

The authors wish to acknowledge the effort of all those who designed and constructed the pavement test sections investigated in this study. Their efforts and foresight made this paper possible. Valuable comments and information were received from Sam Cheng. Field work was greatly assisted by M. Stott and A. Weremi.

REFERENCES

1. K. L. Highlands and G. L. Hoffman. Subgrade Permeability and Pavement Performance. In *Transportation Research Record 1159*, TRB, National Research Council, Washington, D.C., 1988, pp. 7–20.
2. D. R. Haughton and A. Davidson. *Open Graded Base Construction—The Pine Pass Project.* Presented at 1987 meeting of the Road and Transportation Association of Canada, Saskatoon.
3. J. S. Baldwin and D. C. Long. Design, Construction, and Evaluation of West Virginia's First Free Draining Pavement System. In *Transportation Research Record 1159*, TRB, National Research Council, Washington, D.C., 1988, pp. 1–6.
4. C. Raymond, H. Sturm, and T. Kazmierowski. *Review of Design, Construction and Performance of Open Graded Drainage Layers.* Internal Report. Surveys and Design Office, Ministry of Transportation, Downsview, Ontario, Canada, Feb. 1990.
5. L. K. Moulton. *Highway Subdrainage Design.* Report FHWA-TS-80-224. Offices of Research and Development, FHWA, U.S. Department of Transportation, Aug. 1980.
6. H. H. Ridgeway. *NCHRP Synthesis of Highway Practice 96: Pavement Subsurface Drainage Systems.* TRB, National Research Council, Washington, D.C., Nov. 1982.
7. J. J. Hajek, T. J. Kazmierowski, H. Sturm, R. J. Bathurst, and G. P. Raymond. *Field Performance of Open Graded Drainage Layers.* Report PAV-91-01. Research and Development Branch, Ministry of Transportation, Downsview, Ontario, Canada, 1991.
8. R. J. Bathurst and G. P. Raymond. *Field Performance of Open-Graded Drainage Layers.* Royal Military College of Canada, Kingston, Ontario, 1991.
9. J. B. McMaster. *Open Graded Bases, Hwy. 56, Contract 75-02.* Internal Report. Geotechnical Office, Ministry of Transportation, Downsview, Ontario, Canada, 1975.
10. T. J. Kazmierowski and G. A. Wong. Six Years Experience with Experimental Concrete Pavement Sections in Ontario. *Proc., 4th International Conference on Concrete Pavement Design and Rehabilitation*, Purdue University, Ind., April 1989.
11. G. M. Stott, D. E. Patterson, and W. A. Phang. *Developments in In-Situ Monitoring of Moisture in Pavement Structures by Time Domain Reflectometry (TRD).* Report PAV-83-02. Research and Development Branch, Ministry of Transportation, Downsview, Ontario, Canada, 1983.