Waterbound Macadam as a Base and as a Drainage Layer

EMILE HORAK and RALPH H. H. TRIEBEL

ABSTRACT

The good performance of this large single-sized granular-base type in wet regions has revived interest in this once labor-intensive form of base construction. Specifications have been improved and guidelines set for the mechanized construction of waterbound macadam bases. Density standards have been set for typical waterbound macadam bases following the construction of four experimental sections, the development of the Rondewel density test, and accelerated testing by the heavy vehicle simulator (HVS). The performance of these waterbound macadam bases is compared with that of other high-quality granular bases. Guidelines are set for effective elastic moduli for typical waterbound macadam bases and the mechanistic analysis of such granular-based pavements. Waterbound macadam-based pavements are also evaluated as a drainage layer and recommendations are made for improvement.

Waterbound macadam is an old construction technique originating with John Loudon MacAdam. The single-sized coarse aggregate is placed and compacted separately on a prepared subbase before the voids are filled with fines, and the material is then compacted and slushed, hence the name waterbound macadam (1).

A considerable amount of waterbound macadam base construction has been done in South Africa, chiefly in the major metropolitan areas. This type of construction reached its climax in the period 1945 to 1955, after which it declined in popularity, primarily because of the high cost of labor-intensive construction. Over the years, however, waterbound macadam bases have distinguished themselves as granular bases with excellent performance. It is particularly in the wet regions of South Africa that waterbound macadam bases have proved to withstand the destructive influence of water and heavy traffic better than other granular base pavements (1). Roads with waterbound macadam bases have shown virtually no signs of shear deformation in wet conditions even after 30 to 40 years of use. For this reason there has been revived interest in waterbound macadam base construction, and the local road authorities and the National Institute for Transport and Road Research (NITRR) cooperated to construct four experimental sections of waterbound macadam near Marianhill, on Main Road 85 (2) and on National Route 3/1 (3). The aim of the work was to establish guidelines for the construction of waterbound macadam bases and to test these sections with the accelerated testing facility, the heavy vehicle simulator (HVS) (4), developed by the NITRR.

Advances made in the specification of materials for waterbound macadam and the objective control of the construction technique are discussed briefly. The accelerated testing of waterbound macadam bases made it possible to evaluate them as structural layers and facilitated the determination of ranges of elastic moduli for the mechanistic analysis of such pavements. Waterbound macadam was also evaluated as a drainage layer during the accelerated testing (4) by monitoring the effects of water introduced into the layer.

MATERIAL CHARACTERISTICS

Waterbound macadam can be defined as a high-quality granular base. The material used should be freshly crushed hard rock. The normal NITRR specification (5) is set out in terms of grading, Atterberg limits, crushing strength, flakiness index, water absorption, and conductivity. It is, however, the grading of waterbound macadam that distinguishes it from other high-quality granular bases (1). The single-sized grading of the coarse aggregate and the maximum stone size of 53 to 75 mm are the factors that ensure granular interlock with high resistance to shear failure. Typical recommended gradings are shown in Table 1.

Although it could easily be defined as an open-graded base (6), waterbound macadam requires that the voids be filled (with fines). Fines contribute mainly to stability and provide some cohesion in the base material. The plasticity index of the fines is limited to 6 percent. The grading merely serves to ensure the free flow of the fines in the dry state to fill the voids between the coarse aggregate. The grading is as follows:

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ADVANCES IN CONSTRUCTION CONTROL AND SPECIFICATIONS

Four experimental sections with waterbound macadam bases were constructed in the vicinity of Pinetown, Natal. The pavement structures all had broken rock subgrades in cuttings where drainage problems normally occur. Adequate subsurface drainage was installed (2). All four experimental sections had a 300-mm thick cemented subbase of a high quality (C3, see Table 2) (2). The waterbound bases were either 150, 170, or 300 mm thick with no-fines concrete edge restraints encasing drainage pipes. The asphaltic-concrete wearing course was 50 to 70 mm thick and the experimental sections were either 100 or 150 m long (2).

### TABLE 2 Definition of Material Symbols Used in Catalogue Designs

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>CODE</th>
<th>MATERIAL</th>
<th>ABBREVIATED SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G1</td>
<td>Graded crushed stone</td>
<td>Dense-graded unweathered crushed stone; Max. size 37.5 mm; 86-88% of apparent density; Fines PI &lt; 4</td>
</tr>
<tr>
<td></td>
<td>G2</td>
<td>Graded crushed stone</td>
<td>Dense-graded unweathered crushed stone, Max. size 37.5 mm; 100-102% mod. AASHTO; Fines PI &lt; 6</td>
</tr>
<tr>
<td></td>
<td>G3</td>
<td>Graded crushed stone</td>
<td>Dense-graded stone + soil binder; Max. size 37.5 mm; Minimum 98% mod. AASHTO; Fines PI &lt; 6</td>
</tr>
<tr>
<td></td>
<td>G4</td>
<td>Natural gravel</td>
<td>CBR &gt; 80; PI &gt; 6</td>
</tr>
<tr>
<td></td>
<td>G5</td>
<td>Natural gravel</td>
<td>CBR &lt; 45; PI: 10 to 15 depending on grading; Max. size 63 mm</td>
</tr>
<tr>
<td></td>
<td>G6</td>
<td>Natural gravel</td>
<td>CBR &lt; 25; Max. size &gt; 1/3 layer thickness</td>
</tr>
<tr>
<td></td>
<td>G7</td>
<td>Gravel-soil</td>
<td>CBR &gt; 15; Max. size &gt; 1/3 layer thickness</td>
</tr>
<tr>
<td></td>
<td>G8</td>
<td>Gravel-soil</td>
<td>CBR &lt; 10; at in situ density</td>
</tr>
<tr>
<td></td>
<td>G9</td>
<td>Gravel-soil</td>
<td>CBR &gt; 7; at in situ density</td>
</tr>
<tr>
<td></td>
<td>G10</td>
<td>Gravel-soil</td>
<td>CBR &gt; 3; at in situ density</td>
</tr>
<tr>
<td></td>
<td>BC</td>
<td>Bitumen hot-mix</td>
<td>Continuously-graded; Max. size 26.5 mm</td>
</tr>
<tr>
<td></td>
<td>BS</td>
<td>Bitumen hot-mix</td>
<td>Semi-gap-graded; Max. size 37.5 mm</td>
</tr>
<tr>
<td></td>
<td>TC</td>
<td>Tar hot-mix</td>
<td>As for BC (continuously-graded)</td>
</tr>
<tr>
<td></td>
<td>TS</td>
<td>Tar hot-mix</td>
<td>As for BS (semi-gap-graded)</td>
</tr>
<tr>
<td></td>
<td>PCC</td>
<td>Portland cement concrete</td>
<td>Mod. rupture &lt; 3.8 MPa; Max. size &gt; 75 mm</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>Cemented crushed stone or gravel</td>
<td>UCS 6 to 12 MPa at 100% mod. AASHTO; Spec. at least 6 MPa or G2 before treatment; Dense-graded</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>Cemented crushed stone or gravel</td>
<td>UCS 3 to 6 MPa at 100% mod. AASHTO; Spec. generally 2 or G4 before treatment; Dense-graded</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>Cemented natural gravel</td>
<td>UCS 1.5 to 3.0 MPa at 100% mod. AASHTO; Max. size 63 mm</td>
</tr>
<tr>
<td></td>
<td>C4</td>
<td>Cemented natural gravel</td>
<td>UCS 0.75 to 1.5 MPa at 100% mod. AASHTO; Max. size 63 mm</td>
</tr>
<tr>
<td></td>
<td>AG</td>
<td>Asphalt surfacing</td>
<td>Ref. TRHB gap-graded</td>
</tr>
<tr>
<td></td>
<td>AC</td>
<td>Asphalt surfacing</td>
<td>Ref. TRHB continuously-graded</td>
</tr>
<tr>
<td></td>
<td>AS</td>
<td>Asphalt surfacing</td>
<td>Ref. TRHB semi-gap-graded</td>
</tr>
<tr>
<td></td>
<td>AO</td>
<td>Asphalt surfacing</td>
<td>Ref. TRHB open-graded</td>
</tr>
<tr>
<td></td>
<td>S1</td>
<td>Surface treatment</td>
<td>Ref. TRH3 single seal</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>Surface treatment</td>
<td>Ref. TRH3 multiple seal</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>Sand seal</td>
<td>Ref. TRH3</td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>Cape seal</td>
<td>Ref. TRH3</td>
</tr>
<tr>
<td></td>
<td>S5</td>
<td>Slurry</td>
<td>Fine grading</td>
</tr>
<tr>
<td></td>
<td>S6</td>
<td>Slurry</td>
<td>Coarse grading</td>
</tr>
<tr>
<td></td>
<td>S7</td>
<td>Surface renewal</td>
<td>Rejuvenator</td>
</tr>
<tr>
<td></td>
<td>S8</td>
<td>Surface renewal</td>
<td>Diluted emulsion</td>
</tr>
<tr>
<td></td>
<td>WM1</td>
<td>Waterbound macadam</td>
<td>Max. size 75 mm; PI of fines &gt; 6 88-90% of apparent density</td>
</tr>
<tr>
<td></td>
<td>WM2</td>
<td>Waterbound macadam</td>
<td>Max. size 75 mm; PI of fines &gt; 6 88-90% of apparent density</td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td>Penetration macadam</td>
<td>Coarse stone + keystone + bitumen or tar</td>
</tr>
<tr>
<td></td>
<td>DR</td>
<td>Dumprock</td>
<td>Ungraded waste rock, max. size &gt; 1/3 layer thickness</td>
</tr>
<tr>
<td></td>
<td>CB</td>
<td>Concrete paving blocks</td>
<td>Wet crushing strength &lt; 30 MPa; Interlocking shapes</td>
</tr>
</tbody>
</table>
The construction technique developed by a process of evolution from labor-intensive to mechanized methods (2,3). The spreading or placing of the coarse aggregate was done, for example, by a heavy grader and the fines were spread with a stone spreader. Alternative means of placing the coarse aggregate include converted bitumen and concrete pavers, spreading boxes towed behind tractors or trucks, and even drip spreaders. These changes made the alternative of waterbound macadam-based construction economically viable (4).

Quality control during construction was advanced by the development of a large sand replacement density test, the Rondawel test (3). This test is shown in Figure 1. The test enabled specifications for waterbound macadam to move away from a recipe method to some measure of objective regulation of construction control. Resulting from the accelerated testing of the experimental sections with the HVS, apparent density specifications could be established, as follows (E80 = equivalent 80-kN axle repetitions):

<table>
<thead>
<tr>
<th>Traffic (E80's)</th>
<th>Material Description</th>
<th>Apparent Density (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 3 x 10^4</td>
<td>Typical coarse WM^a</td>
<td>86-88</td>
</tr>
<tr>
<td>3-50 x 10^4</td>
<td>WM bases (average)</td>
<td>88-90</td>
</tr>
</tbody>
</table>

The traffic classification is an oversimplification of the traffic classes and categories given in the NITR document on pavement structural design, TRH4 (7), indicating that higher density bases are required for higher traffic classes and road categories. This summary specification is shown in Table 3 with the material definition or classification system used in the catalogue of designs in TRH4 (7).

**WATERBOUND MACADAM AS A GRANULAR BASE**

In order to evaluate waterbound macadam as a base course, six HVS tests to date have been completed on the four experimental sections. In each HVS test a large number of specialized measurements of the

<table>
<thead>
<tr>
<th>Material Description</th>
<th>Porosity (n) (%)</th>
<th>Indications of Permeability (L/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical coarse WM^a</td>
<td>25-40</td>
<td>&gt; 1.1</td>
</tr>
<tr>
<td>WM bases (average)</td>
<td>13.5</td>
<td>1.5</td>
</tr>
<tr>
<td>WM base (fines of windblown sand)</td>
<td>21.6</td>
<td>100</td>
</tr>
<tr>
<td>WM2 base</td>
<td>11.1</td>
<td>1.27</td>
</tr>
<tr>
<td>WM1 base</td>
<td>3.3</td>
<td>0.25</td>
</tr>
</tbody>
</table>

^a As for unconsolidated gravel deposits (3,6).
pavement response and behavior were taken. These
measurements are described elsewhere in detail (4).

One of the measurements taken during such an HVS
test in the permanent deformation. This is measured
on the surface by means of a fully automatic, motor-
driven profilometer that tracks over the road surface
or manually by means of a 2-m straight edge. The
def ormation originates in the granular base. This is
true for granular-based pavements with well-protected
subgrades (9) and can be confirmed by profile
trenching across a test section after completion of
such a test.

The terminal rut (permanent downward deformation)
limit for higher-category roads is 20 mm. The number
of repetitions of the dual wheel load used in any
test is calculated and expressed in terms of the
number of standard 80-kN axle repetitions (E80’s).
In order to compare the deformation of different
granular-based pavements tested, a damage coeffi-
cient (d) equal to 3 is used in the relative damage
formula:

\[ D = \frac{P}{80^d} \]  

where

- \( D \) = relative damage value,
- \( P \) = axle load (kN), and
- \( d \) = damage coefficient.

A value of \( d \) equal to 3 rather than 4.2 was found to
be applicable to deep pavement structures with gran-
ular bases (9). In Figure 2 a comparison is made of
various granular-based pavements tested with the HVS.
The behavior of typical WM1 and WM2 quality bases is
compared with the findings of Maree et al. (9).

The WM1 and WM2 bases show the typical rapid ini-
tial deformation of a granular-based pavement. In
WM1, which has the higher density, this initial de-
formation is less than in the lower-density WM2 base.
This indicates that even higher densities could be
specified, which would reduce this tendency to rapid
initial deformation. After the settling-in period,
the rate of increase in deformation becomes constant
for the WM1 base and to a lesser extent for the WM2
base, as for other high-quality bases, such as the
G1 and the G2. The influence of water will be dis-
cussed in the next section; the discussion in this
section is limited to the behavior of dry, well-
drained bases. The highest traffic classes according
to the TRH4 classification (7), even 50 x 10^4
E80’s, are allowed for in the design with a WM1 base,
with the proviso that environmental influences must
be neutralized by an adequate maintenance program
(9). The WM1 base compares well with other high-
quality granular bases such as the G2 and even the G1.
The WM2 base compares well with the weaker-quality
granular base, the G3.

The second measurement used to indicate the
structural capacity of a waterbound macadam base
pavement is the elastic deflection measured at dif-
ferent depths within the pavement. The instrument
used is the multidepth deflectometer (MDD) (10).
Effective elastic moduli were determined by means of
a curve-fitting iteration procedure using the MDD
deflections (1). Waterbound macadam is a typical
stress-dependent granular material; the effective
elastic moduli increase with the applied wheel load,
and density under trafficking increases as well
(1,11). The recommended range of effective elastic
moduli for waterbound macadam base layers, as mea-
sured and calculated, is as follows for various types
of subbase support:

<table>
<thead>
<tr>
<th>Material With Stabilized</th>
<th>With Granular or Cracked Stabilized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class Subbases (MPa)</td>
<td>Subbases (MPa)</td>
</tr>
<tr>
<td>WM1 150-700</td>
<td>100-400</td>
</tr>
<tr>
<td>WM2 120-400</td>
<td>70-250</td>
</tr>
</tbody>
</table>

The stress states in the granular waterbound
macadam layers were calculated on the basis of these
effective elastic moduli by using a linear elastic
layer program developed by the NITTR in 1977 (12).
No laboratory triaxial shear-strength parameters C
(apparent cohesion) and \( \phi \) (angle of internal fric-
tion) of waterbound macadam have yet been deter-
mined, and therefore the values for a G1 base in the
wet to saturated states were assumed as a conserva-
tive guide (1) in the calculation of the safety fac-
tor (11). The maximum stone size for the G1 material
is 37.5 mm.
A safety factor (f) used in the mechanistic analysis of granular bases to predict their structural behavior is calculated as follows:

\[ f = k \left[ \phi \tan^2 \left( \frac{45 + \phi}{2} \right) - l + 2 \tan \left( \frac{45 + \phi}{2} \right) \right] / \left[ \phi_1 - \phi_2 \right] \]

(2)

where

- \( C \) = apparent cohesion,
- \( \phi \) = angle of internal friction,
- \( \phi_1, \phi_2 \) = major and minor principal stresses, and
- \( k \) = constant, depending on the moisture conditions.

An analysis of a typical waterbound macadam base pavement in the wet to saturated states led to the recommendation and incorporation of waterbound macadam bases for wet regions in the new (1984) catalogue of designs. These designs are shown in Figure 3, and the material classification is summarized in Table 2. It is recommended that WM1 bases with stabilized subbases be used for the higher road categories and the higher traffic classes, and granular subbases with WM2 bases can be used for the lower road categories and traffic classes.

**WATERBOUND MACADAM AS A DRAINAGE LAYER**

The emphasis in the construction of waterbound macadams was on achieving a dense granular base with a high shear force resistance due to the coarse granular interlock. The history of waterbound macadams in South Africa and abroad has shown, however, that an open-graded granular base of this kind also provides an excellent drainage layer. The addition of fines to fill the voids between the coarse aggregate reduces the drainage capabilities of such a layer.

Although the experimental sections of waterbound macadam were not designed according to the drainage principles suggested by Cedergren, the influence of water on these waterbound bases was monitored in various ways. During all HVS testing on experimental sections, water was introduced into the WM1 and WM2 bases by means of a system of perforated pipes. The 38-mm diameter pipes were installed right on the higher edge of the trafficked test section (8 m long and 1 m wide), thereby ensuring that water flowed down the cross and longitudinal gradients through the base of the trafficked section. Water was administered normally at atmospheric pressure, and the rate was measured. In one test the water was administered at a pressure head of 1 to 2 m. Water was normally administered toward the end of a test, although in some cases this was done throughout the test.

The typical deformation behavior of a granular-based pavement when the base is soaked is shown in Figure 2. There is a sharp increase in deformation with the increase in trafficking, because of the development of a state of excessive pore-water pressure. This leads to erosion of fines, deformation, and potholing. When a typical WM2 base has adequate drainage, however, there is virtually no change in the rate of deformation. When water is introduced into a WM1 base at a pressure head of 1 to 2 m, it is possible to develop a state of excessive pore-water pressure under trafficking, showing the typical increase in deformation. Under such aggressive soaked conditions the fines are again washed through cracks in the surfacing layer or into untrafficked parts of the test section, where they accumulate between the surfacing and base layer. Shear deformation has not occurred because the granular interlock of the coarse aggregate matrix is still intact.

Indications of permeability of the exposed surface of the waterbound macadam base were measured by means of the in situ falling-head permeability test. Standard material tests and density determinations of the waterbound macadam bases made it possible to calculate the porosity, which can have an important controlling influence on permeability.
Table 3 gives a summary of these results as measured on various waterbound macadam bases.

It is clear from Table 3 that although the addition of fines to the voids of the coarse aggregate leads to a reduction in porosity, the permeability values still indicate an efficient drainage layer. The fact that the small particles influence permeability more than the large particles (15) is clearly illustrated, too. When the fines used to fill the voids are of windblown single-sized sand, porosity values nearly double and the indications of permeability increase 100-fold. This indicates that if the percentage of fines passing the 0.075-mm sieve could be limited to less than 10 percent, the permeability of waterbound macadam bases could be increased significantly. The increase in density from a WM2 standard to a WM1 standard leads to a reduction in porosity and indication of permeability values. In such a dense state the base is comparable with other dense, high-quality granular bases, which are virtually impermeable.

SUMMARY AND CONCLUSIONS

1. The single-sized grading and maximum stone size (75 to 53 mm) of the coarse aggregate characteristic of waterbound macadam material primarily ensure granular interlock and high resistance to shear failure.

2. The possibility of mechanizing the construction of waterbound macadam bases was evaluated by departing from labor-intensive techniques during the construction of the four experimental sections.

3. Quality control and objective specification criteria have been enhanced by the development of the two-way density test and the establishment of recommended density specifications in terms of apparent density.

4. The performance of waterbound macadam bases is typical of granular bases when permanent deformation behavior during accelerated testing is compared. Initial density has a direct influence on the rapid initial deformation.

5. The determination of effective elastic moduli by MOD deflection back-calculation procedures makes it possible to establish ranges of effective elastic moduli. Suggestions for the mechanistic analysis of such bases in relation to the model used for granular materials have been made. Typical catalogue designs for waterbound macadam-based pavements for wet regions have been recommended and incorporated in the NITRR's pavement design document, TRH4 (7).

6. Waterbound macadam, properly constructed to WM1 density and with adequate support, can carry the highest traffic classes, bearing even 50 x 10⁶ EB0's. There is even scope for an increase in the density specification that would offset initial deformation tendencies under trafficking. The stress-dependent material has high resistance to shear failure, which means a better quality of granular base as density increases under trafficking.

7. Waterbound macadam has the potential to be a very efficient drainage layer, especially if coarser fines are specified. Higher densities, however, mean lower permeability. On this point the structural requirements and those for a drainage layer may oppose each other, but the existing density specifications (WM1 and WM2) appear to satisfy both requirements adequately.

8. The importance of providing drainage for any base layer is emphasized by the behavior of waterbound macadam bases. Even in such high-quality granular bases, excessive water in the base can lead to excessive pore-water states and a pumping of fines from any erosion-susceptible layer in the pavement structure.

ACKNOWLEDGMENT

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REFERENCES


Cost-Estimating Model for Low-Volume Roads

FONG L. OU and COLBURN D. SWARTHOUT

ABSTRACT

The Forest Service, U.S. Department of Agriculture, is required to perform accurate and comprehensive road cost estimates to carry out the legislative intent of Congress in the programming, allocation, and use of funds. This study utilizes multiple regression analysis to develop unit-price equations and total project cost equations for cost estimation. A sample consisting of 26 projects from the western United States is used for preliminary model development. The equations developed are applied to a second sample with six projects located in the same area. The results indicate that the model has potential for determining reliable preliminary road cost estimates. Because of its simplicity, this model could reduce the resources spent on this task and lead to the reduction of transportation cost.

One of the major concerns of the Forest Service, U.S. Department of Agriculture, is the accuracy of road cost estimates. Estimates are used to carry out the legislative intent of Congress in the programming, allocation, and use of funds. Two types of preliminary estimates used for this purpose are the office estimate and the field-verified estimate. The former is based on office information such as land use plans, aerial photographs, topographic maps, and other resource information. It is used to support activities such as land use planning, resource management planning, area transportation planning, and long-range (over 5 years) fiscal programming. The second type of estimate is based on all the information available for an office estimate plus more extensive field verification, including some rough field measurements and more detailed resource information gathering. This estimate is used in resource and transportation project planning, short-range (2 to 5 years) fiscal programming, and budgeting.

The accuracy of both preliminary estimates varies in accordance with the reliability of the data base. Deviations can range from 35 to 50 percent for the office estimate and from 20 to 30 percent for the field-verified estimate (1). Two main sources of these deviations are unit-quantity and unit-price predictions. The major concern of this study is unit-price prediction.

Conventionally, road costs are estimated by either constructed costs or historical bids or a combination of both. The constructed-cost method utilizes production rates, labor and equipment costs, profit and risk, taxes, and material costs to estimate the unit price. On the other hand, the unit price derived from the historical-bid approach is estimated by the weighted average of bids submitted by contractors over some period of time. These unit prices are adjusted by a cost trend factor to reflect the cost at the time when the project will most likely be constructed.

The objective of this study is to use regression analysis to develop unit-price estimating models based on historical-bid data. Several other studies have been made along these lines to improve cost estimation (2,3). The results of these studies indicated that by using regression analysis, it is possible to estimate highway construction costs with a higher degree of reliability than can be obtained by simple unit-cost weighted averages. In the present study, a sample of 26 new construction projects was utilized for model development. This model was verified by six projects, including new construction and reconstruction. However, it should be noted that this paper does not suggest weakness or deficiency in current Forest Service policies or practices but is intended to illustrate the potential usefulness.