Inverted Pavement Systems
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Inverted Pavement Systems Background and Overview

Inverted pavement systems are an innovative pavement technology developed in South Africa in the 1970s. The materials used in an inverted pavement system are the same as what is employed in a conventional flexible pavement – only the material layers are rearranged. An inverted pavement is comprised of a cement treated base (CTB) layer, an unbound aggregate base (UAB) layer, and a relative thin layer(s) of hot mix asphalt (HMA). Typically in a flexible system, the UAB layer is placed on the subgrade and thicker HMA layers are placed on top. In an inverted pavement, a CTB layer is placed on the prepared subgrade with the UAB layer placed on top followed by the HMA layer(s).

The components of the system consist of the following:

- Thin HMA layer of 2 to 3.5 inches. (Note: This is a general range of HMA thickness. Field applications in South Africa often utilize less than 2 inches of HMA).
- UAB layer of 6 to 8 inches, compacted to a minimum of 100% modified Proctor density.
- CTB layer of 6 to 12 inches with cement loading of approximately 4%.

An example of an inverted pavement system is shown in Figure 1.

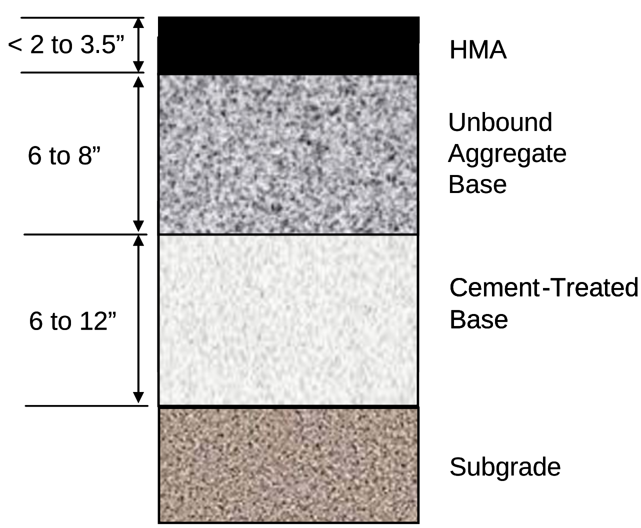

Figure 1 Inverted Pavement Section

South Africa History

South Africa has used inverted pavements (referred to as G1 base pavements) for more than 30 years. G1 is South Africa's designation for a high quality, crushed aggregate base material, which is compacted to approximately 86 to 88% of solid density. Today, approximately 70 percent of flexible pavements in South Africa utilize the inverted design with a thin HMA layer (40 mm or 1.8 inches) placed over a high quality aggregate base (*1*). Inverted sections are often utilized in high volume roadways with design traffic levels sometimes exceeding 30 million ESALs (*2*).

South Africa's inverted pavement technology has not gone unnoticed by the United States. In 1997 a panel of pavement experts participating in a Federal Highway Administration (FHWA) Technology Scan Tour visited South Africa to document South Africa's Pavement technologies. The scan team recommended that inverted pavement technology be tried on a pilot project in the United States (*3*).

In 2002, another FHWA scan tour was conducted which focused on innovative pavement preservation techniques used in France, South Africa, and Australia. The scan report noted that South Africa builds robust pavement structural sections with a long service life. Typical thickness of the subbase and base is 450 mm (18 inches) with 30 to 50 mm (1 to 2 inches) of HMA. A key report recommendation was to initiate demonstration projects with deep subbase and deep base designs in different regions of the country (United States) to determine the effectiveness of this design strategy (*4*).

For whatever reasons, the recommendations from the two scan tours were not acted upon. Therefore, the pace of inverted pavement system evaluation has been slow in the United States, however, there have been several test sections placed. These sections include a quarry entrance road in Morgan County, Georgia (2001) ; a section of the LaGrange, Georgia bypass (2009), and many similar "stone interlayer" projects constructed by the Louisiana Department of Transportation and Design (LaDOTD) , (1997 – present). These test sections/projects, along with future demonstration projects, including the anticipated Virginia DOT/Luck Stone Bull Run Highway 659 project (Summer/Fall 2010) will hopefully guide transportation agencies toward greater use of inverted pavement systems.

How are Pavements Designed? "Empirical versus Mechanistic"

In order to better understand the mechanisms of inverted pavement performance it is helpful to briefly review pavement design approaches. Historically, pavement systems have been designed using mostly empirically based design methods. Such empirical systems are based on observed field performance and are only truly valid for a given set of material, environmental and loading conditions. The AASHTO flexible pavement design procedure, which utilizes the structural number (Sn) concept to design pavements, is essentially an empirical pavement design method. A FHWA Pavement Design user survey conducted from 1995 to 1997, found 80 percent of state departments of transportation (DOTs) use either the 1972, 1986, 1993 AASHTO Guides for pavement design (*5*).

Due to the limitations of empirical design, a mechanistic design component is often used along with the empirical approach. The mechanistic portion consists of evaluating the pavement response (i.e., stress and strain) as a function of the engineering properties (e.g. resilient modulus or stiffness) of the pavement layer materials. Transfer functions are then used to determine the allowable traffic or load repetitions the pavement section can carry as a function of the measured pavement response. One transfer function example is the allowable load repetitions based on the tensile strain measured at the bottom of the HMA layer. All transfer functions are developed using a critical distress threshold value which the user or agency selects. For example, this may be 20 percent of the wheel path with fatigue cracking or a rut depth of 0.5 inch. This highlights the fact that all pavement design procedures must be eventually tied back to observed field performance and there is no 100 percent mechanistic pavement design procedure.

It should be pointed out that the today's commonly used transfer functions have been developed for "traditional" pavement systems. Transfer functions which are unique to inverted pavement systems should be developed to insure proper analysis and design. South Africa recognized this important concept and has developed unique transfer functions for thin and thick HMA "flexible" pavements (*6*).

Unbound Base and Mechanistic Design

A mechanistic design approach provides a way to better understand how base materials respond under loading. With the AASHTO guide for flexible pavements, most DOTs give base materials a structural layer coefficient (SLC) of approximately 0.14. This means that the "structural value" for one inch of base is 0.14. In reality, a base SLC of 0.14 is based on a resilient modulus (stiffness) of approximately 30,000 psi from the AASHO Road Test completed in the early 1960's (7). Also recall that empirical systems are only truly valid for the actual test conditions evaluated. In the AASHO Road Test case, the aggregate type/grading, traffic, in-place density, environmental conditions were all very limited. Regarding in-place density, the target compaction for the UAB at the AASHO Road Test was 100 to 105% of standard Proctor density. Results show an average of 101.5% Proctor density was obtained with 6.3% of the results below 100% (*8*).

Furthermore, a SLC of 0.14 corresponds to a California Bearing Ratio (CBR) of 100. While a CBR of 100 is generally thought of as a typical value for base materials, CBR values in excess of 200 can be obtained on some base materials compacted to modified Proctor density. Therefore, the SLC should be higher, but with the empirical methods, there is no way to capture this increase. With a mechanistic approach, the stiffness of the base can be measured and the appropriate structural value assigned to base materials.

As a note, a new mechanistic empirical pavement design guide (MEPDG) has been adopted by AASHTO with work progressing on the related AASHTO software. It is expected by states will begin implementing the new MEPDG in the near future.

Performance Mechanisms

Inverted pavement systems achieve their performance by taking advantage of the engineering properties of the various pavement layer materials. Each layer is placed in its optimal position to perform and yield the most benefit. A CTB layer placed on the prepared subgrade provides a strong, rigid, “anvil-like” foundation on which to compact the UAB layer. This assists the contractor in obtaining the required density in the UAB layer. Generally, a minimum UAB layer density of 86 percent of solid density is specified, which equates to 100 to 105 percent of modified Proctor (AASHTO T180) density. The exact relationship will vary based on the mineralogy, surface texture, and grading of the base material being used.

Unbound aggregate base is a very unique paving material that becomes stiffer with increased loading (i.e., stress). Because UAB is non-linear stress dependent the stiffness or resilient modulus will be much greater when used in an inverted pavement compared to a conventional flexible system. This is due to the base being closer to the pavement surface where the stresses are greater. In an inverted pavement the overall stress state within the UAB can be 3 to 5 times that seen in a conventional flexible system. In response to this increased stress state, the UAB becomes stiffer. The South Africa design procedure recommends 250 to 1000 Mpa (36,000 to 145,000 psi) as a suggested range of elastic moduli for G1 materials. A value of 450 Mpa (65,000 psi) is presented as the “expected” or average modulus value (*6*). The vertical base modulus on the Morgan County, Georgia quarry project was estimated to be in excess of 100,000 psi when tested in a loaded condition (*9*).

A thin layer(s) of HMA is placed on the UAB layer. Thinner HMA layers are possible because of the increased stiffness and strength provided by the UAB layer. South Africa successfully uses the inverted pavement for high volume traffic application [i.e., 50 million equivalent single axle loads (ESALs) design life]. In South Africa, a 40 to 50 mm (1.8 to 2 inch) layer of HMA is commonly specified as the pavement surfacing (*2*). For design purposes, the structural capacity of the pavement system is designed into the subgrade, CTB, and UAB layers. The HMA surfacing is not considered to add any structural value to the pavement structure from a design standpoint. Periodic maintenance should be conducted on the HMA layer to insure optimal performance (*10*).

Why Use Inverted Pavements?

The motivation behind expanding the use of inverted pavement systems is more than initial cost savings, although that is crucial in these economic times. Doing more with less also means using designs which have reduced life cycle cost and which are sustainable. Optimal utilization of the structural properties of UAB in combination with a thin HMA layer and a CTB layer provides an excellent method of achieving performance, economic savings (initial and life cycle), and sustainability.

Benefits (Field Performance)
South Africa has used inverted pavements for more than 30 years with excellent results. It is commonly specified for their high volume highway applications. Heavy vehicle simulator (HVS) testing has shown that inverted pavements with only 40 mm (1.8 in.) of HMA are capable of accommodating traffic demands up to 50 million standard axles. Testing also found that if a pavement with a crushed stone base (i.e., inverted pavement) is maintained with resurfacings at appropriate intervals, the pavement can provide service for an indefinite time (*11*).

In the United States the most notable inverted pavement was placed on a quarry road in Morgan County, Georgia, in 2001. The section (3" HMA/6" UAB/8" CTB) is performing excellently with no cracking or rutting after 9 years of loaded quarry truck trafficking (approximately 1.1 million ESALs as of November 2009). A conventional quarry road section (3" HMA/ 8" UAB/ 6" Surge Stone) was placed for comparison and is showing substantially more distress than the inverted section. (*12*)

The Louisiana Department of Transportation and Design (LaDOTD) has been successfully using a form of inverted pavement referred to as stone interlayer pavement construction. LaDOTD began investigating stone interlayer construction as a means to reduce HMA reflective cracking from soil cement layers. The initial stone interlayer field test section (~ 1 mile) was placed in 1991 on State Highway 97 near Jennings. The stone interlayer design (3.5" HMA / 4" UAB / 6" cement stabilized base) was compared to a conventional design (3.5" HMA / 8.5" cement stabilized base). After 10 years of service the stone interlayer section had about 50 percent less cracking than the conventional section. Furthermore, the majority of cracking on the stone interlayer section was low severity (i.e., hairline cracks), while almost 50 percent of the conventional section cracks were classified as medium severity with some being classified as high severity (*13*). Between 2003 and November 2007, a total of 54 stone interlayer projects were completed (612 lane miles), let to contract, or being constructed (*14*).

Benefits (Economics)
An economic evaluation of inverted pavements compared to other pavement systems is difficult because of the fluctuation of construction material prices. The initial construction cost for any pavement will vary primarily based on the price of the constituent materials used. In the case of inverted pavements versus a conventional flexible system (i.e., HMA/UAB/Subgrade), the cost of the liquid asphalt binder will be a major determining force in the overall construction costs. In a similar manner, when inverted pavements are compared to concrete pavements, the cost of the cement will likely be a critical factor. Determining an accurate construction cost is further complicated by the possible skewed costs associated with evaluating new technology and the relatively small size of test sections.

The following are some limited cost comparisons (initial construction and/or life cycle) of inverted pavements relative to other pavements.

South Africa

- South Africa has determined that inverted pavements offer a 20 to 25% life cycle savings compared to asphalt base pavements (*10*).

Virginia DOT/Luck Stone Bull Run Bypass (Highway 659), project planned for 2010:

- Conventional Flexible Section: (11" HMA / 3" Open Graded HMA Drainage Layer / 8" CTB)
- Inverted Section: (5" HMA / 6" UAB / 10"CTB)

An initial construction cost savings of 22 percent has been calculated for the inverted section (*15*).

Georgia DOT LaGrange Bypass

- Conventional Rigid Section: (9.5" PCC / 10" UAB)
- Inverted Section: (5" HMA / 6" UAB / 10"CTB)

A life cycle cost analysis conducted by the Georgia DOT found a project savings of $139,000 per lane mile for the inverted section (*16*).

By building the pavement structure strong from the bottom up, any distress is forced to occur in the HMA layers. These distresses should be able to be repaired in a more cost effective manner compared to deeper maintenance or rehabilitation methods. This is very similar to the perpetual pavement design concept in which the HMA layer serves as a sacrificial layer that is maintained or rehabilitated at intervals throughout the pavement life.

Another important item is that with the potential increased economic benefits offered by inverted pavements, there is more funding available for additional new construction or maintenance activities.

Benefits (Energy Demand)

A major benefit with inverted pavement is the potential for reduced energy demand relative to conventional flexible and rigid (i.e., concrete) pavement systems. As seen in Figure 2, the total end use energy demand of unbound "granular materials" or aggregate is about 80 percent less than hot mix asphalt or concrete (*17*). When compared to a conventional flexible system, the overall energy demand of an inverted pavement may be lower as a result of 1) reducing the HMA thickness and 2) utilizing base and CTB (at a low cement loading). When compared to a concrete pavement, the potential energy savings would be gained through the elimination of the concrete pavement layer and replacement with an inverted structure.

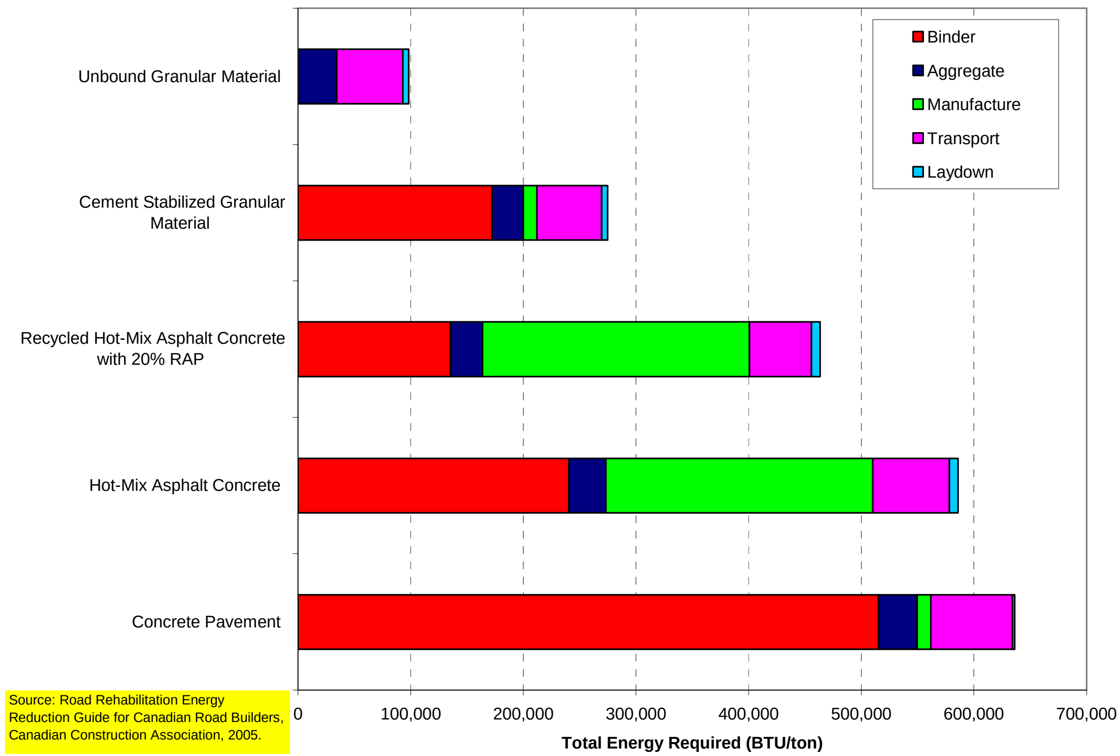

Figure 2 Product Energy Demand Comparison (*17*)

Benefits (Product Mix)

A flexible pavement design will generally utilize more total aggregate than a rigid pavement system. To illustrate the impact of pavement type selection consider the alternate pavement designs shown in Figure 3. These designs are equivalent design based on AASHTO design procedures.

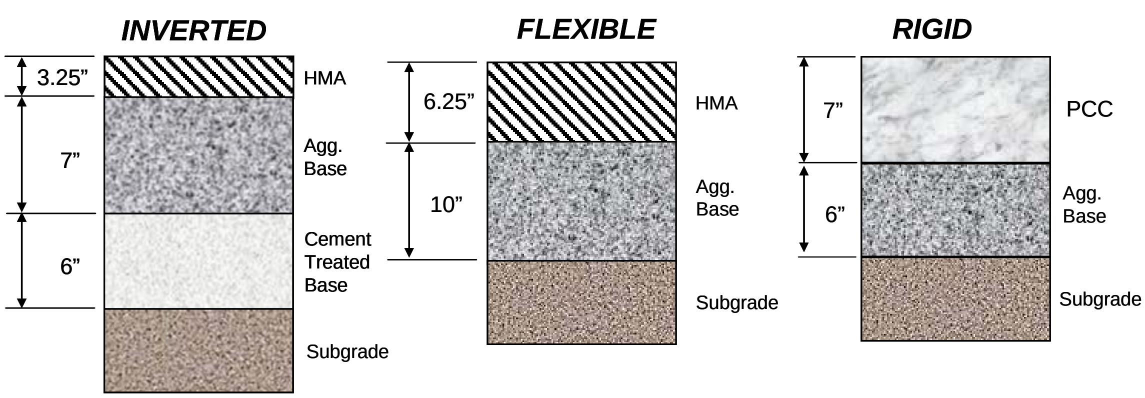

Figure 3 Medium Duty Pavement Design Alternates

Figure 4 shows that the total aggregate demand for an inverted pavement design is very similar to the flexible design; however, the product mix is different. Compared to the flexible design, the base quantity will increase, while the clean stone quantity will decrease. This is due to the CTB layer being used and a reduction in HMA thickness. In many cases this may help the aggregate plant in achieving a more balanced operation and better utilization of resources.

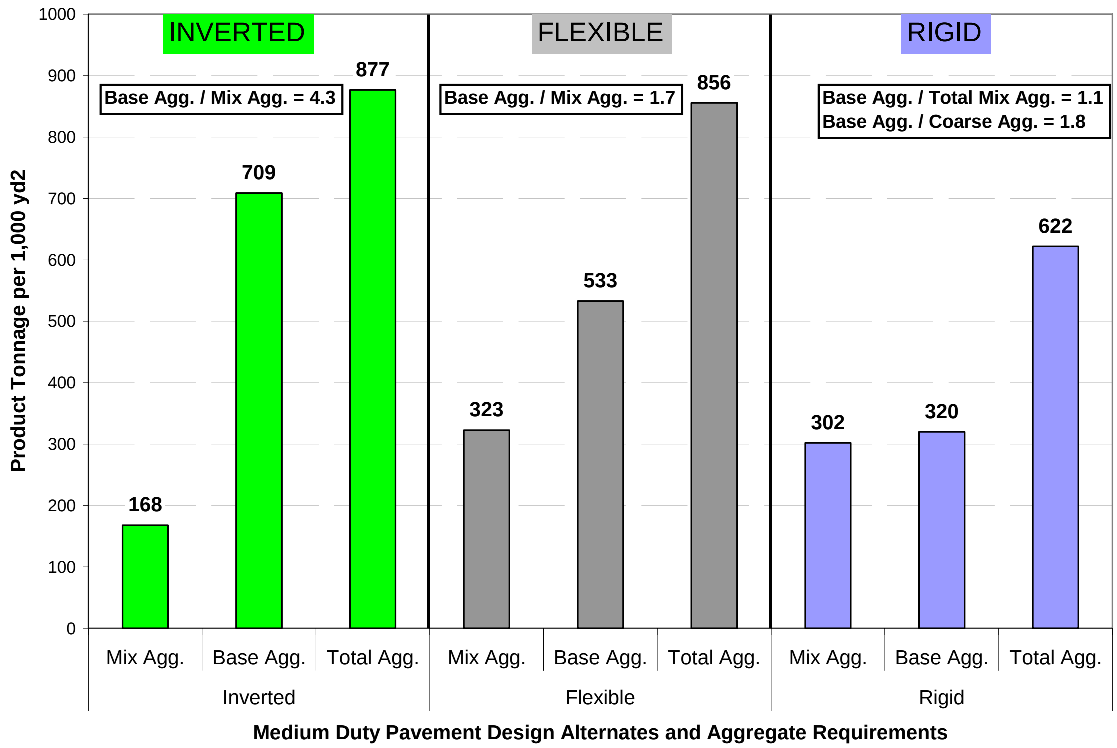

Figure 4 Product Mix for Medium Duty Pavement Alternates

Concluding Thoughts

Unbound aggregate base should be viewed as an engineered product which can be used to economically optimize long lasting pavement designs. Base, as with any product, should be marketed and used to its best technical advantage. Inverted pavement systems offer a great opportunity through which to best utilize the inherent properties of the base material to maximize performance and minimize cost.

In these days of increasing construction costs and decreasing transportation funding the imperative goal of transportation agencies is to construct high quality, cost effective pavements. Inverted pavement systems offer the user agency a viable option to accomplish this goal.

References

1. Rust, F.C., J.P. Mahoney and J.B. Sorenson, *An International View of Pavement Engineering*, Bearing Capacity of Roads and Airfields Conference, Trondheim, Norway, 1998.

2. Technical Recommendations for Highways (TRH) 4, Department of Transport, Republic of South Africa, Pretoria, South Africa, 1996.

3. Study of South African Pavement and Other Highway Technologies and Practices, FHWA Scanning Program, FHWA, U.S. Department of Transportation, May 1997.

4. Pavement Preservation Technology in France, South Africa, and Australia. International Technology Exchange Program. Publication No. FHWA-PL-03-001, FHWA, U.S. Department of Transportation, October 2002.

5. Mechanistic Empirical Pavement Design Guide (MEPDG), Software Version 1.003 Documentation, Part I-Introduction: p. 1.1.2.

6. Theyse, H.L., M. de Beer, F.C. Rust, Overview of the South African Mechanistic Pavement Design Analysis Method. *Transportation Research Record: Flexible Pavement Design and Rehabilitation Issues,* No. 1539, Transportation Research Board of the National Academies, Washington, D.C., 1996, pp. 6-17.

7. AASHTO Guide for Design of Pavement Structures 1993, American Association of State Highway and Transportation Officials, Washington, D.C., 1993.

8. *The AASHO Road Test Report 2 Materials and Construction*, Highway Research Board Special Report 61B, National Academy of Sciences – National Research Council Publication 951, Washington, D.C., 1962.

9. Terrell et al., Field Evaluation of the Stiffness of Unbound Aggregate Base Layers in Inverted Flexible Pavements. *Transportation Research Record: Soils, Geology, and Foundations,* No. 1837, Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 50-60.

10. High Performance Crushed Stone Based (G1) Used on South African Highways, South African National Roads Agency, Pretoria, South Africa, October 1998.

11. Jooste, F.J., and L. Sampson, *The Economic Benefits of HVS Development Work on G1 Base Pavements,* Gauteng Provincial Government, Department of Public Transport, Roads and Works, *July 2005*
http://www.gautrans-hvs.co.za/popup/G1%20economic%20Benefits%20Final2.pdf

12. Buchanan. M.S., *Inverted Pavements: What, Why, and How*, AFTRE Webinar Presentation, National Stone, Sand and Gravel Association (NSSGA), June 1, 2010.

13. Titi, et al., *Long Term Performance of Stone Interlayer Pavement*, Journal of Transportation Engineering, American Society of Civil Engineers, Vol. 129, No. 2, March/April 2003.

14. King, B., *Stone Interlayer Design: Louisiana's Experience*, Presentation Southeastern Asphalt User Producer Group (SEAUPG) Annual Meeting, Aggregate Task Group Meeting, San Antonio, Texas, November 2007,

15. Weingart, R., *Inverted Pavements: Virginia Experience*, AFTRE Webinar Presentation, National Stone, Sand and Gravel Association (NSSGA), June 1, 2010.

16. Cardosa, J., *Inverted Pavements: Georgia Experience*, National Aggregate Base Conference Presentation, National Stone, Sand and Gravel Association (NSSGA), 2008.

17. Road Rehabilitation Energy Reduction Guide for Canadian Road Builders, Canadian Construction Association, 2005.
http://oee.nrcan.gc.ca/industrial/technical-info/benchmarking/roadrehab/Roadhab_eng_web.pdf