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Inverted base pavements: construction and performance

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ABSTRACT
Inverted base pavements involve a well-compacted granular aggregate base built between a thin asphalt concrete layer and a cement-treated base. Inverted base pavements can be constructed using conventional equipment and procedures but require proper quality control. This study reviews the extensive South African experience and case histories in the USA. Accumulating evidence suggests that inverted base pavements are a viable alternative and can outperform conventional pavements at a lower cost. Inverted base pavements rely on the complementary interaction between layers. The cement-treated base provides a stiff foundation for efficient compaction and constrains the deformation of the stress-sensitive granular aggregate base. The thin asphalt surface layer deforms as a membrane and develops low tensile stress. Additional large-scale field tests should be conducted to assess the performance of inverted base pavement designs in a wide range of conditions relevant to the USA.

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Inverted base pavements; granular base; pavements; case studies; review

Introduction

Inverted base pavements are flexible pavement structures where a granular aggregate base is placed between a cement-treated base CTB and a thin asphalt concrete surface layer (Figure 1). The main difference from a design perspective between a conventional flexible pavement and an inverted base pavement is in the sequence of the different layers. In conventional flexible pavements, the stiffer layers are typically placed at the top, and layer stiffness is reduced going deeper, all the way to the natural subgrade. On the other hand, inverted base pavement include a layer of compacted aggregate base 'sandwiched' between two stiffer layers of asphalt concrete at the top and a cement-treated base at the bottom. Inverted base pavements rely on the well-compacted granular aggregate base to act as the primary load bearing layer (Cortes 2010, Tutumluer 2013).

Inverted base pavements are extensively used in South Africa to support heavy traffic loads (Jooste and Sampson 2005). The French design guidelines also recommend inverted base pavements to prevent reflective crack propagation between cohesive layers (Corté and Goux 1996).

Recorded construction experience and performance data on inverted base pavements in the US remain scarce. Yet, there is renewed interest driven in part by the increasing construction and maintenance costs and decreasing transportation funds (Tutumluer 2013). This study reviews major findings from the extensive South African experience, and past and present studies in the USA. Practical construction recommendations are presented based on sound engineering principles.

History of inverted base pavements

South Africa

Inverted base pavements were developed in South Africa as a cost-effective alternative to conventional rigid and flexible pavements. Improvements in aggregate base technology and exceptional field performance led to the establishment of inverted base pavements as the primary design for high-traffic roads in South Africa (Freeme *et al.* 1980). Accelerated pavement testing capabilities played a critical role in the development of mechanistic design guidelines. (Freeme *et al.* 1982, Long and Brink 2004, Du Plessis *et al.* 2006, Theyse *et al.* 2011). Inverted base pavements tested using the Heavy Vehicle Simulator are summarised in Table 1.

United States

The first inverted base pavement was constructed during the rehabilitation of rigid pavements in New Mexico in 1954 (Johnson 1961). Subsequently, several researchers studied pavements with an inverted structure (Ahlvin *et al.* 1971, Barker *et al.* 1973, Barksdale 1984, Barksdale and Todres 1983, Grau 1973, Johnson 1961, Tutumluer and Barksdale 1995). Following the FHWA visit to South Africa (Horne *et al.* 1997), research on inverted base pavements has gained renewed interest (Metcalf *et al.* 1999, Rasoulian *et al.* 2000, Titi *et al.* 2003, Terrell *et al.* 2003, Lewis *et al.* 2012, Cortes and Santamarina 2013). Currently, inverted base pavement test projects are being considered in Georgia, North Carolina, Tennessee and New Mexico (Buchanan 2010, Tutumluer 2013). Documented cases in the USA are summarised in Table 2.

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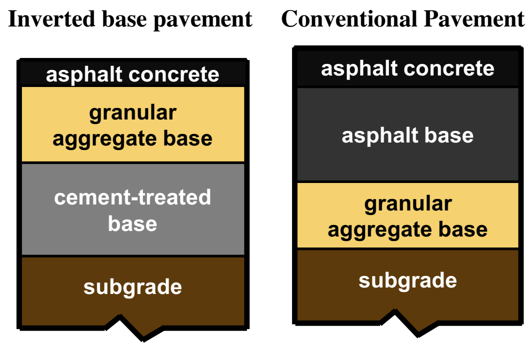

Figure 1. Schematic comparison of an inverted base pavement and a conventional asphalt pavement.

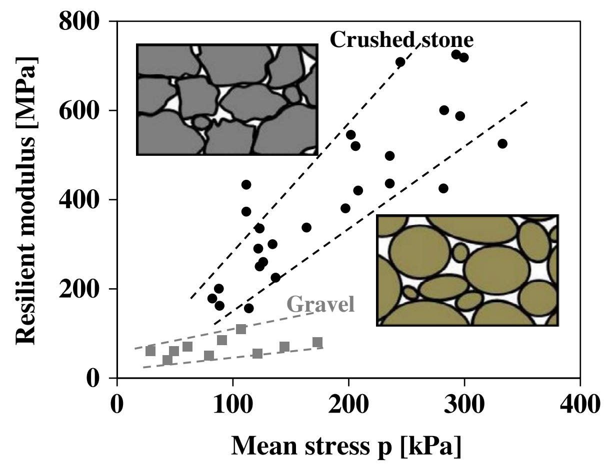

Figure 2. Resilient modulus dependency on mean stress $p = (\sigma_1 + \sigma_2 + \sigma_3)/3$ for crushed stone base and gravel bases. Data from Theyse (2002).

Table 1. Inverted base pavements tested using the Heavy Vehicle Simulator in South Africa.

Location	Year	Layer thickness from top to bottom [mm]
S12 Cloverdene C17	1978	Gap-graded asphalt [70] High-quality crushed stone [320] Lightly cemented base [280] Natural gravel [100]
P157/1 Olifantsfontein	1980	Semi-gap asphalt [30] Crushed stone [200] Lightly cemented base [100] Natural gravel [200]
P157/2 Jan Smuts	1980	Semi-gap asphalt [35] High-quality crushed stone [140] Cemented gravel [255] Natural gravel [125]
N3, Mooi River, Kwazulu-Natal	1982	Gap-graded asphalt [50] High-quality crushed stone [200] Lime-stabilised base [155]
TR86, Macleantown, Eastern Cape (303A2)	1986	Asphalt [40] Crushed stone [150] Drainage layer [150] Cemented gravel [340] Natural gravel
N2–23 Umkomaas, KawZulu-Natal (327A3)	1988	Asphalt [80] High-quality crushed stone [160] Cemented gravel [260]
Road 2388, Cullinan, Gauteng (398A4)	1997	Asphalt [30] Crushed stone [100] Cemented gravel [150]

Note: Data and original references in Theyse 2002, and Jooste and Sampson 2005.

Materials and construction specifications

Construction techniques

Earlier pavements in South Africa were built with granular bases made of natural or stabilised gravel and various forms of Macadam (Jooste and Sampson 2005). As their use extended to high-volume roads, crushed stone became the standard base material for high-traffic roads.

The slushing technique was developed to enhance the interlocking of aggregates in the base. The base is 'slushed' after regular compaction by flooding and compacting it using static rollers; then segregated fines that emerge at the top of the base are brushed away (details in Kleyn 2012). Even though the increase in density due to slushing is only 3–4%, a tightly interlocked matrix of coarse aggregates is formed. The new fabric is cohesion-less and highly stress-sensitive and dilative and justifies the high strength parameters used in the South African guidelines (Theyse *et al.* 2011). The effect of slushing on density was not confirmed in a US-based comparison study (Terrell *et al.* 2003); instead, the very high density achieved in inverted base pavements irrespective of the compaction technique was attributed to the effect of the cement-treated base.

The extensively documented construction of the Lagrange inverted base pavement project shows that no special equipment is required for the construction of inverted base pavements (Cortes and Santamarina 2013). Furthermore, limited field evidence suggests that the cement-treated base withstood the compaction process and did not develop extensive cracks.

Materials – aggregate quality

Cement-treated base CTB

The presence of a cemented substrate provides a stiff foundation support that prevents bending beneath rollers and constrains the deformation of the granular aggregate base during compaction and under traffic load. Cement outperforms lime as a CTB stabiliser (Johnson 1961, Parsons and Milburn 2003). Cement-treaded bases made of crushed aggregate develop higher strength and stiffness and experience lower shrinkage cracking compared to those made using natural soils (Barksdale and Todres 1983).

Granular aggregate base GAB

South African specifications constrain the gradation of the base to maximise attainable density, and impose strict guidelines on attained density, as well as particle origin, shape, grading and fines plasticity (Theyse 2002, Kleyn 2012).

Crushed stone bases develop higher stiffness than natural gravel, as shown in Figure 2 (Maree *et al.* 1981, Theyse 2002). The angular shape and rough surfaces of crushed particles contribute to stability through interlocking (Cho *et al.* 2006, Pan *et al.* 2006, Tutumluer 2013) The superior performance of crushed stone is corroborated with laboratory studies and is reflected in the South African design guidelines (Jooste and Sampson 2005, Cunningham *et al.* 2012).

Granular aggregate bases with non-plastic fines perform better (Johnson 1961, Barksdale and Todres 1983, Jooste and Sampson 2005). In particular, plastic fines make the base

Table 2. Inverted base pavement case histories in the USA.

Location	Year	Layer thickness from top to bottom [mm]		Reference
I-010-1 Road Forks-East Mexico	1960	AC [38] GAB [152] CTB [152]	AC [76] GAB [152] CTB [152]	Johnson (1961)
F-51-1Santa Fe New Mexico	1960	AC [76] GAB [152] CTB [152]		Johnson (1961)
US Army Corps Vicksburg, MS	1971	AC [76] GAB [152] Stabilised clay subbase [381]		Ahlvin *et al.* (1971) Barker *et al.* (1973)
Georgia Tech Atlanta, GA	1980	AC [89] GAB [203] CTB [152]		Barksdale (1984) Barksdale and Todres (1983)
Louisiana	1991	AC [89] GAB [102] Soil-cement [152]		Metcalf *et al.* (1999) Rasoulian *et al.* (2000) Titi *et al.* (2003)
Morgan County quarry haul road, GA	1999	AC [76] GAB [152] CTB [203] Filler [51] Prepared subgrade (CBR 15)		Lewis *et al.* (2012) Terrell *et al.* (2003)
Lagrange, GA	2008	AC [89] GAB [152] CTB [254] Stabilised subgrade [152]		Cortes (2010)
Bull Run, VA	2010	AC [127] GAB [152] CTB [254] prepared subgrade		Weingart (2009)

Note: AC: asphalt concrete, GAB: granular aggregate base, CTB: cement-treated base.

sensitive to moisture changes and can lead to degradation due to moisture cycling (Ekblad and Isacsson 2006, Ashtiani and Little 2007, Ekblad and Isacsson 2008, Bilodeau and Doré 2012). At the same time, a large percentage of fines reduces permeability and may lead to excess pore pressures during traffic loading (Tutumluer 2013).

South African design guidelines specify the required dry density ρ_{dry} as a fraction of the density of the solid mineral $\rho_{mineral}$ rather than relative to the Proctor density. Typical values of $\rho_{dry}/\rho_{mineral}$ for top quality bases range between 85–88% (Theyse *et al.* 1996). This definition of 'relative density' is very intuitive for two reasons. First, it is mathematically equivalent to the ratio of the volume of solids V_{solid} relative to the total volume V_{total}. Second, the definition of mineral density $\rho_{mineral}$ is more robust than the procedurally defined Proctor density, which shows inherent variability due to experimental uncertainties (Donaghe and Townsend 1976, Lee 1976, Shahin 2010).

Asphalt concrete AC

The asphalt surface layer is not critical to the structural capacity of inverted base pavements. Its main role is to provide water sealing and a smooth riding surface as well as restrain the surface of the cohesion-less aggregate base (Jooste and Sampson 2005). As a result, surface asphalt layers in inverted base pavements should remain flexible and ductile in order to accommodate the deflection of the pavement structure. Furthermore, asphalt layers should be impervious to water to prevent the degradation of the granular aggregate base.

Inverted base pavement performance and analysis

Findings based on recorded case histories of inverted base pavements are discussed herein. Details and data can be found in Papadopoulos (2014).

Failure mode

Well-designed inverted base pavements do not develop any preferential failure mode, but a combination of rutting and surface cracks (Barksdale and Todres 1983, Li *et al.* 1999, Titi *et al.* 2003). Surface cracks develop primarily top-down and are of low severity as the granular aggregate base prevents reflective cracks from propagating (Barksdale and Todres 1983, Li *et al.* 1999, Titi *et al.* 2003). Deterioration of the cement-treated base is detrimental to the overall pavement integrity, starting with the degradation of the granular aggregate base.

Inverted base pavements with thick asphalt layers develop permanent deformation that concentrates in the asphalt layer (Barksdale and Todres 1983). On the other hand, recent mechanical analyses show that thin and flexible asphalt layers deform as membranes and develop less tension at the bottom of the layer but higher shear at the load edges (Theyse *et al.* 1996, Papadopoulos and Santamarina 2014). Consequently, signs of distress in inverted base pavements with thin asphalt layers involve top-down hairline cracks, which is more amenable to surface treatment than typical bottom-up cracks (Li *et al.* 1999, Lewis *et al.* 2012).

Comparative studies

Inverted base pavements have outperformed conventional pavements in most comparative studies (Johnson 1961, Barksdale and Todres 1983, Li *et al.* 1999, Metcalf *et al.* 1999, Titi *et al.* 2003, Lewis *et al.* 2012). Notable exceptions are cases where an inferior quality subbase, such as clay, was used instead of a cement-treated base (Johnson 1961, Ahlvin *et al.* 1971) Furthermore, inverted base pavements have been identified as the most economical solution in several cost-comparison studies (Freeme *et al.* 1980, Mitchell and Walker 1985, Titi *et al.* 2003, Weingart 2009, Cortes 2010).

Structural design

South African guidelines suggest a 150 mm-thick granular aggregate base. Thicker granular aggregate bases offer better protection for the cement-treated base (Cortes *et al.* 2012), but cause larger strains in the asphalt concrete layer and are prone to higher permanent deformation (Jooste and Sampson 2005). This is due to the fact that thicker bases are more difficult to compact (in particular slushing) to the required degree, and thus there tends to be less interlocking between the aggregates, as the base resembles a regularly compacted gravel/stone layer.

Inverted base pavements in South Africa are typically constructed using a 50 mm or thinner asphalt layer, even for heavy traffic conditions (Table 1 see also Jooste and Sampson 2005). Numerical simulations show that the threshold thickness for beam-to-membrane transition is between 25–50 mm (Papadopoulos and Santamarina 2014).

The structural capacity of inverted base pavements cannot be analysed using available empirical design guidelines that do not consider the interaction between layers, such as the Structural Number concept. South Africa has employed a mechanistic pavement design process for inverted base pavements for the last 20 years, albeit based on relatively simple constitutive models (TRH 1996).

Granular aggregate base – cement-treated base interaction

The properties of granular materials such as the GAB depend on the state of stress. Field data show that the rigid cement-treated base increases the confinement of the granular aggregate base under the load (Figure 3). The contribution of the CTB is twofold: first, the rigidity of the CTB limits the vertical deformation at the bottom of the granular aggregate base. Second, friction at the CTB-GAB interface provides a lateral constraint that increases the load-induced horizontal stress in the GAB. The higher effective confinement in the granular aggregate base results in a low stress ratio q/p near the CTB which reduces the possibility of a shear failure, and promotes higher stiffness, which lowers the deformation under load.

The interaction between the GAB and CTB layers is demonstrated using finite-element numerical simulations (details in Papadopoulos and Santamarina 2014). The four cases shown in Figure 4 correspond to 'soft' and 'stiff' CTB, with and without sliding along the GAB–CTB interface. Plotted simulations correspond to a circular uniform load q = 550 kPa. Clearly, both the high stiffness as well as the rough surface of the CTB result in higher mean stress in the GAB.

The brittle cement-treated base is susceptible to degradation under repeated high-intensity load applications, particularly when subgrade deterioration also takes place, for example during seasonal moisture changes. Therefore, inverted base pavements that will be used in high-volume US roads should include a cement-treated base that is adequately thick to prevent deterioration, as the cost of comprehensive structural rehabilitation would outweigh construction savings.

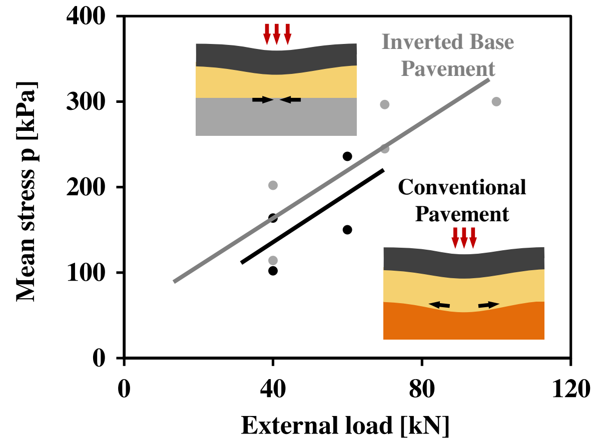

Figure 3. Back-calculated mean stress $p = (\sigma_1 + \sigma_2 + \sigma_3)/3$ in the granular base as a function of the externally applied load for conventional and inverted base pavements. Data from Theyse (2002).

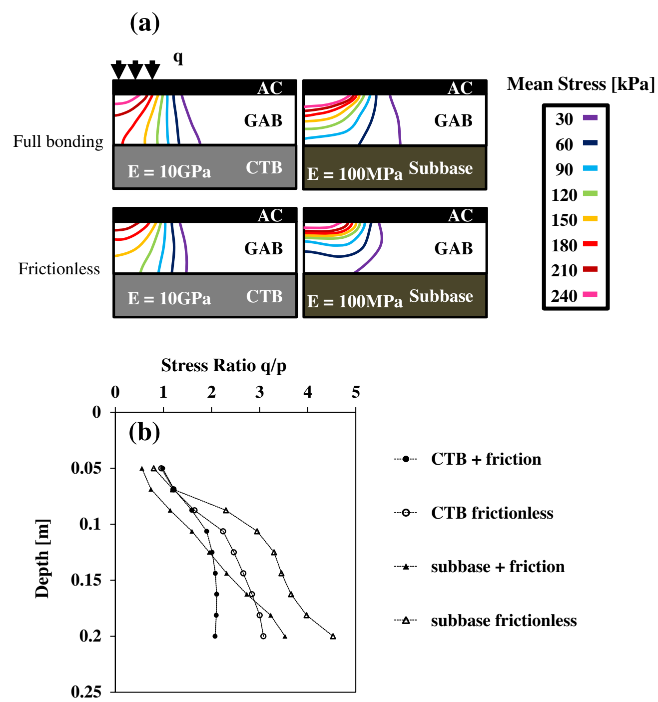

Figure 4. Numerical comparisons between flexible pavements with and without cemented subbase, for both fully bonded and frictionless GAB interface using 3D finite elements. (a) Contours of mean stress in the GAB and (b) stress ratio q/p vs. depth beneath the load centreline.

Note: AC thickness: 50 m, GAB thickness: 150 mm, Subbase/CTB thickness 300 mm. *E*subgrade = 50 MPa. Applied load q = 550 kPa.

Discussion

The mechanical interactions in a three-layer pavement system can be expressed in terms of the relative stiffness between layers. The cohesive asphalt layer and the cement-treated base deform in bending and their stiffness is proportional to Young's modulus E and the cubic power of the layer thickness t:

$$K_{\mathrm{AC,CTB}} = \frac{Et^3}{12(1-\nu^2)} \tag{1}$$

where ν is Poisson's ratio. The stiffness of granular layers such as the subgrade SG and the granular aggregate base GAB is affected by the dimensions of the tire imprint R, the modulus of the layer E and the thickness of the layer H (Gazetas 1983):

$$K_{\mathrm{GAB,SG}} = \frac{3.7E}{\pi R(1-\nu^2)} \cdot \left(1 + 1.28\left(\frac{R}{H}\right)\right) \tag{2}$$

For the subgrade the factor R/H equals zero. Four general pavement systems can be identified (Figure 5(a)). The bending stiffness of the asphalt layer relative to the stiffness of the granular aggregate base defines either a 'beam' or 'membrane' deformation pattern. The striking characteristics of inverted base pavements compared to other flexible pavements are (i) the stiff foundation beneath the granular aggregate base which contributes to its increased stiffness and (ii) the membrane-like asphalt layer behaviour.

Figure 5(b) shows the back-analysis of all inverted base pavements reviewed for this study. This plot highlights the high confidence South Africans have placed on the structural capacity of the GAB, compared to the more conservative designs in most US case histories where a relatively thick AC layer has been used. The range of typical conventional asphalt pavements is also shown for comparison.

The analysis captured in Figure 5 is not all-encompassing and other effects must be considered when designing inverted base pavements. For example, thick CTBs develop lower tensile strain and thus less fatigue cracking. At the same time, an increase in the GAB or subgrade stiffness also reduces bending in the CTB. Finally, a thick GAB reduces the stress imposed at the top of the CTB, but at the same time increases the deformation of the GAB which leads to increased bending of the asphalt concrete layer.

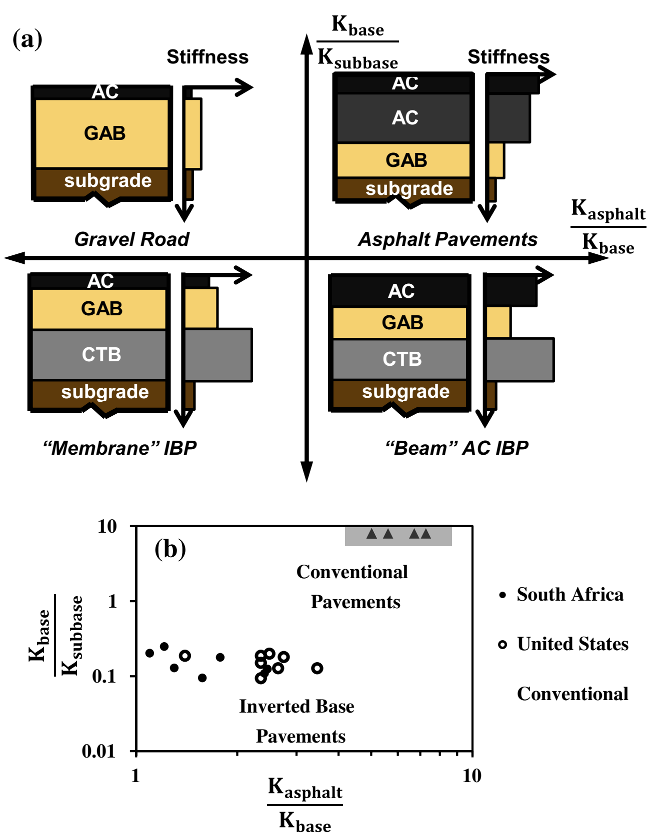

Figure 5. The effect of relative stiffness in pavement response: (a) Conceptual graph of relative stiffnesses in three-layer pavement structures. (b) Results for all inverted base pavements recorded in this study as well as typical range of conventional asphalt pavements. K_{asphalt}, K_{base} and K_{subbase} correspond to the stiffness of the first, second and third layers, respectively, starting from the surface.
Note: Easphalt = 3 GPa, Ebase = 400 MPa, ECTB = 10 GPa, and Esubgrade = 50 MPa.

Summary of findings and construction recommendations

Inverted base pavements are a technically and economically viable alternative to conventional flexible pavements. In fact, inverted base pavements have outperformed conventional pavements in most comparative studies. This report synthesised available data and analysed the published performance of inverted base pavements. Salient observations follow:

- Inverted base pavements benefit from unique interactions between layers: the cement-treated base limits the deformation of the stress-sensitive granular aggregate base which allows the GAB to develop increased stiffness under load.
- A thin asphalt layer is sufficient to provide water sealing and a smooth riding surface. Thin asphalt concrete layers deform as membranes rather than beams, and develop top-down cracks which are easier to identify and treat. Membrane response is typically attained with AC layers thinner than 50 mm.
- Field and numerical results show that the optimal thickness of the granular aggregate base is 150 mm to minimise resilient and permanent deformations.
- High-quality crushed aggregates with non-plastic fines must be used in the granular aggregate base. A high degree of compaction is also required.
- Reflective crack propagation is greatly reduced as a stable granular aggregate base rests between the cement-treated base and the asphalt layer.
- Relatively thick cement-treated base layers are recommended to avoid costly repairs. As long as the CTB performs monolithically, the maintenance of the CTB can be restricted to resurfacing of the thin AC layer. Furthermore, the CTB strength and thickness must be designed to support compaction and traffic loads without long-term deterioration.
- Weak subgrades should be mechanically or chemically stabilised to prevent excessive bending in the cement-treated base.

- Proper construction practices are required to attain the full benefits inverted base pavements have to offer. Inverted base pavements can be constructed using conventional techniques and can be economically advantageous from both construction cost and life-cycle cost perspectives.

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