

Review Article

Evaluation of Design Techniques for Extra Heavy-duty Flexible Pavements and Other Critical Considerations

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Abstract

The design of heavy-duty flexible pavements for highways is well-established in the United States, Europe, and Australia. However, a standardised design methodology for extra heavy-duty flexible pavements—specifically tailored for ports and intermodal container terminals—remains lacking. These pavements present unique challenges due to significant variations in several load repetitions, load magnitudes, long-term static loads, tyre pressures, wheel and axle configurations, and loading characteristics, with axle loads reaching up to 120 tonnes. Existing design methods are often influenced by industry interests, such as concrete interlocking pavers, concrete, and asphalt, leaving pavement practitioners with limited tools to optimise designs for the extreme load conditions encountered over the pavement's design life. Traditionally, extra heavy-duty pavements are considered high-risk areas due to their high failure rates and the substantial costs associated with such failures. This study provides a comprehensive review of existing design methodologies and software available internationally, critically compares these methods, and discusses other critical considerations to mitigate the risks of extra heavy-duty pavement failure. The literature review reveals that the development of unified design guidelines for extra heavy-duty flexible pavements intended to withstand severe axle loads up to 120 tonnes or more would require further research in this area.

Keywords

Extra Heavy-duty Pavement, Design Methods, Design Tools, Subgrade Failure Criteria

1. Introduction

Flexible pavements, comprising asphalt layer over unbound or bound granular bases, are widely used in highways, airfields, ports and container terminals. While these pavement types may appear similar at first glance, they exhibit significant differences in several critical factors. Notably, ports and container terminals experience higher axle loads, varying wheel and axle configurations, and higher tyre pressure compared to highways and airfields. Additionally, these facilities face unique chal-

lenges, such as number of load repetitions, load magnitudes, long-term static loads, more pronounced vehicle wanders, sharper turning radii, and frequent start and stop movements [1]. These conditions are further complicated by the presence of specialised equipment like self-propelled modular trailers (SPMT) and reach stackers as shown in Figure 1a and 1b respectively, which impose substantial and concentrated loads on the pavement structure.

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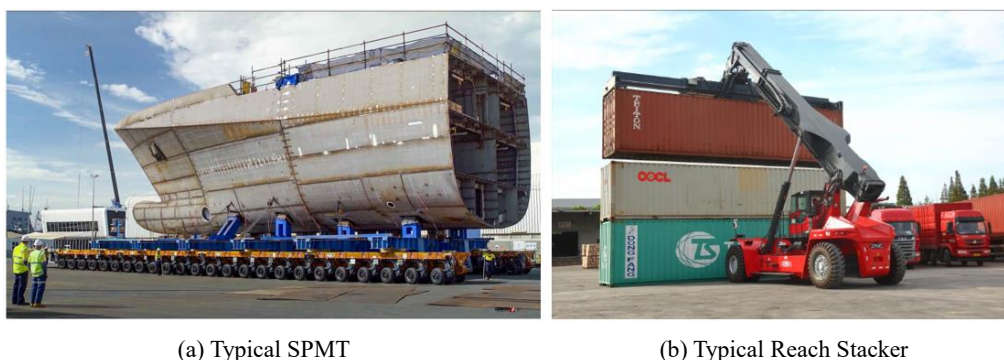


Figure 1. Specialised Equipment (Source: Cometto and Google).

The design traffic loading for container terminals or airports typically experiences a few hundred load repetitions per day, in contrast to 50,000 or more load repetitions observed on highways [2]. The wheel loads and tyre pressures for reach stackers used in container terminals can exceed 30 tonnes and

2,000 kPa respectively, which is significantly higher compared to highway pavements, where typical values are around 2 tonnes and 750 kPa. A comparative overview of the design parameters for a typical port container terminal pavement versus a highway pavement is presented in Table 1.

Table 1. Port Container Terminal Pavement Versus Highway Pavement Design Parameters.

Parameter	Port container terminals	Highways
Design vehicle axle load	120t reach stacker	16.5t Dual tandem axle group 20t triaxle dual tyre group
Tyre pressure	600 – 2400 kPa	500 – 1000 kPa
Design life	10,000 passes	1,000,000 passes
Wander	200 – 800 mm	254 mm
Design pavement thickness	1500 mm	600 mm

Note: Data source from [2-4].

Furthermore, the wheel configurations of the design vehicles can influence how loads and pressures are applied to the pavement. In airfields and container terminals, these configurations differ substantially from those of conventional road vehicles, such as trucks with single, dual and tandem axles, all aligned along the same axis, as illustrated in Figure 2. The conversion of wheel loads from specialised handling equipment into an equivalent standard axle load is problematic. Heavier and slow-moving wheel loads affect pavement materials differently and to a greater depth than the standard axle loads [5]. Consequently, employing the concept of equivalent standard axles as a design traffic loading is inappropriate for extra heavy-duty pavements. Therefore, the design techniques for such pavements must be distinct from those used for standard highway pavements.

The construction requirements for extra heavy-duty pavements can significantly differ from those of standard

highway pavements. For instance, in the United States, state highway specifications may be applicable to airfield pavement projects at non-primary airports servicing aircraft weighing less than 27.2 tonnes, subject to approval by the Federal Aviation Administration (FAA). However, such specifications are not directly transferable to the unique conditions encountered in container terminals and ports. A practical approach for modelling the sensitivity of extra heavy-duty pavements is the sub-layering method developed by Barker-Brabston [9] of the U.S. Army Corps of Engineers (USACE). This method involves two material requirements for the base layer: (1) the high standard granular (HSG) base must achieve 100% modified compaction with a minimum 70% dry back, and (2) the asphalt cover is limited to a maximum thickness of 100 mm. These specifications are detailed in Austroads [3], MRTS05 [10], DIT [11], etc.

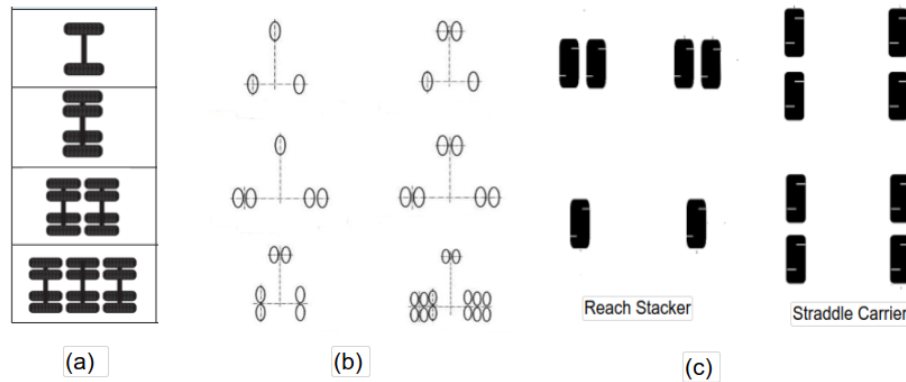


Figure 2. (a) Typical Road Heavy Vehicle Axle Group [6]; (b) Typical Aircraft Landing Gear Type [7]; (c) Typical Container Terminal Vehicles Type Configuration [8].

2. Design Methodologies

While alternative design procedures exist in Australia and internationally for flexible pavements in ports and container terminal pavements, some published methodologies do not adequately address the use of higher-strength subgrade materials, modified and lightly bound cement-treated base materials, polymer-modified binder asphalts or unbound pavements [12].

In Australia, there is currently no standardised guide that comprehensively addresses the design loading analysis, environmental considerations and material specifications pertinent to extra heavy-duty pavements. This gap contrasts with the well-established and widely disseminated methodologies for highway pavement design, which have been refined and made accessible through the collaborative efforts of industry groups and stakeholders. The lack of a unified approach in the design industry is partly attributed to concerns over intellectual property rights. Traditionally, the design of extra heavy-duty pavements has been undertaken using a combination of design approaches and proprietary in-house methods. Notable among these are the British Ports Association (BPA) method, HIPAVE, FAARFIELD, among others. However, this practice has led to a design process that lacks formal validation or calibration. Advances in materials and testing have not been consistently incorporated, performance criteria are often inadequately defined, and benchmarking across different procedures is challenging [8].

The following sections provide an overview of commonly used design methods for extra heavy-duty pavements, focusing on their design approaches, capabilities, advantages, and shortcomings. It is important to note that pavement design heavily relies on engineering judgement in selecting the appropriate methods and input data. The guidance presented herein is intended to complement, not replace professional expertise and experience in the field.

2.1. British Ports Association (BPA) Method

The empirical British Ports Association (BPA) method, first published in 1984, has become the predominant design approach for extra heavy-duty flexible pavements within the port industry. The fourth edition, published in 2012, is based on finite element analysis to generate design charts that determine the base thickness, excluding the surface layer [13, 14]. The fourth edition of the BPA manual simplifies axle loadings into an Equivalent Single Wheel Load (ESWL) for design purposes.

The design process involves converting the design traffic loadings into SEWL. The design methodology is structured into three distinct components: surfacing selection, base selection and thickness determination, and foundation assessment relating to subgrade strength [15]. For a given SEWL and the number of passes, the thickness of a cement bound material C8/10 (characteristic 28-day compressive cube strength of 10 MPa and cylinder strength of 8 MPa) base can be determined by the design charts provided in the manual, but this does not include the surfacing thickness. The selection of surfacing layer is primarily based on its resistance to wearing without contributing to the structural strength of the pavement. This design approach assumes the terminal pavement conditions characterised by surface deformations ranging from 50 mm to 75 mm [14, 16].

The design process necessitates the identification of the critical vehicle and the corresponding design load to calculate the SEWL. However, employing the heaviest design vehicle and converting its load to SEWL to represent all traffic [17] does not accurately reflect full traffic mix and typically results in an overestimation of pavement thickness [18]. BPA method encompasses both static and dynamic loading conditions and was primarily developed for the structural design of Concrete Block Pavers (CBPs) with heavily bound bases, making it particularly suitable for pavements surfaced with concrete block pavers or asphalt surfacing over heavily bound bases. However, this method is less applicable in regions like Australia, where traditional pavement designs often incorporate

materials such as asphalt, unbound granular and lightly bound cement-treated bases.

The standard pavement configuration recommended in the BPA manual comprises 80 mm CBP on 30 mm of bedding sand over cement-bound base (C8/10) on crushed rock or a cement-treated bound subbase, with an underlying capping layer if the subgrade CBR is less than 5%. It is noteworthy that the capping layer thicknesses are considerably higher than standard highway pavement recommendations [14].

The BPA manual asserts its applicability for designing various pavement types by substituting alternative materials with equivalent thicknesses, utilising Material Equivalence Factors (MEFs). This approach enables designers to explore multiple design solutions using different materials when the designs are created using the design charts [16]. However, the use of MEFs is valid only for a limited range of standard materials [19]. Despite the BPA design manual's claim of versatility, its primary focus remains on segmental pavers and asphalt surfacing over cementitious layers. This limitation arises because the method does not directly account for asphalt fatigue as a failure mode. This method adopts an overall damage approach, wherein the pavement is designed to withstand structural failure due to rutting and shape loss. However, this approach may not be suitable for assessing the failure of individual layers within the pavement structure, particularly in cases where the overall pavement has not failed [8].

The BPA design manual uses the Nottingham University failure criterion [20], based on the UK Road Note 29 [21], which defines terminal conditions with rut depths ranging from 12 to 25 mm, applicable to roads and highways [15]. However, this criterion may not be directly applicable to extra heavy-duty pavements, as their loading conditions significantly differ from those of standard road vehicles. Empirical relationships developed for highway loadings may not accurately predict the performance of pavements subjected to higher and more concentrated loads typical in industrial settings [22]. Additionally, BPA method requires the knowledge of the equipment and design vehicle, including parameters such as vehicle's centre of gravity, load distribution, axle load, and overall weight. In practice, obtaining comprehensive technical data for specific vehicles, such as laden and unladen axle weights and maximum lift capacities, can be challenging.

2.2. PCASE

The PCASE (Pavement Computer Assisted Structural Engineering) software, developed by the US Army Corps of Engineers (USACE), is widely used in the US for the design of heavy-duty airport pavements, particularly for military applications. It employs Mechanistic-Empirical (M-E) performance failure models to predict the structural response of concrete and flexible pavements. The software's built-in function for guiding the sequence of data input ensures users follow the correct steps, which is crucial for accurate design outcomes [23]. The design process of PCASE is tailored

specifically for the needs of the US Navy and US Army, which may limit its applicability for civilian use. The PCASE pavement design module includes a comprehensive library of military vehicles as well as military aircrafts and helicopters. The design vehicles and military aircrafts are based on Unified Facility Criteria, UFC-3-250-01 [24] and UFC-3-260-02 [25], respectively. Additionally, the module allows users to modify existing vehicles or add new ones to the database. It supports the design of flexible, rigid and unsealed pavements [23], using either CBR or layer elastic design (LED) parameters.

The Layer Elastic Design (LED) method has several limitations, primarily stemming from its assumptions that the pavement layers are homogeneous, semi-infinite, and linearly elastic with wheel loads applied as axisymmetric, uniform pressure. In LED, unbound granular materials are assumed to behave elastically; however, in reality, they exhibit elasto-plastic behaviour. The LED method further assumes constant elastic moduli within each horizontal layer, disregarding the potential for plastic deformation, and it does not fully account for stress-dependent nature of materials. This assumption may be incorrect as exclusion of permanent deformation can lead to inaccurate predictions of pavement responses, such as strains and deflections. To partially address this issue, the LED method uses sub-layering of materials and assigning specific moduli to each sublayer in an attempt to account for some degree of material stress-dependence behaviour. This approach provides reasonable estimates of pavement stresses and deflections at selected points [26]. A comparative study using finite element analysis to model the elastic and elasto-plastic behaviour of granular materials found no significant difference in pavement deformation between the two approaches [27].

The LED method offers several advantages, including computational efficiency, software availability, and an extensive body of knowledge accumulated through years of research and development in material characterisation. However, the design process is tailored specifically for the US Army and US Navy, making it challenging to apply within Australian practices, where there is limited flexibility to model ground improvements and incorporate higher strength subbases [28]. Additionally, the type of pavement layer materials are restricted to those predefined in the software's library and the design modulus must fall within the range permitted by the software. This restriction limits the use of new materials in pavement design, thereby constraining the flexibility of material selection in pavement options. When designing the pavement subsurface drainage system, which includes the incorporation of a drainage layer beneath the basecourse, the use of geotextile as a substitute for the separation layer is permitted, provided there is adequate subgrade support. However, this substitution does not provide any structural credits or benefits. The stress ratio approach for determining pavement fatigue is not used in PCASE, which infers that pavement thickness increases indefinitely with the

number of load repetitions [28]. Furthermore, the software does not provide a design thickness for cases involving unlimited load repetitions. Since 2021, the software developer has discontinued technical support for user queries [29]. In conclusion, PCASE is better suited for the design of defence airside pavements specifically intended for military aircrafts.

2.3. Finite Element Analysis

Finite Element Analysis (FEA), using software such as ABAQUS, Plaxis and others, offers an alternative to LED method, addressing some of the limitations. FEA is capable of handling complex loadings, intricate geometries, varying material properties, anisotropy, layered soils, and complex stress-strain relationships, which enables a more accurate prediction of pavement responses [30-32]. However, as FEA becomes increasingly sophisticated, the demand for input data preparation, output analysis, computational resources, and accurate material characterization rises significantly. One of the key challenges is the lack of local material characterisation and testing, which results in insufficient input data for FEA. Additionally, the accessibility of FEA software presents difficulties for practitioners, limiting its widespread adoption. Moreover, FEA results can be complex, making it challenging to justify the use of FEA for routine small- to medium-size projects. As a result, FEA is better suited for research and development, rather than practical design applications, and its advantages have not been fully realised in routine practices. Consequently, the LED method remains the most widely used approach for pavement design.

2.4. HIPAVE

Heavy Industrial Pavement Design (HIPAVE) is based on an empirical/mechanistic analysis for flexible pavements subjected to the extra-heavy wheel loads generated by freight handling vehicles in industrial facilities, such as intermodal container terminals. Currently, there is no universally accepted purely mechanistic approach. HIPAVE is specifically designed to model the mix of vehicle types and container loads, calculating the combined damage using the Cumulative Damage Factor (CDF) [33]. This process involves calculating the CDF for each vehicle type, linearly superimposing the results, and comparing the total with the value of 1 to determine the required pavement thickness.

The effects of dynamic loading, which are induced by factors such as braking, cornering, acceleration and uneven surfaces, are accounted for using dynamic load factors (DLF). When multiple conditions apply simultaneously, the DLF is treated as the cumulative factor. This same DLF methodology is also used in the BPA method. In contrast to the BPA method, the HIPAVE program uses simple proportionality approach, based on published data regarding maximum axle load and lift capacity, to calculate axle weight. For asphalt fatigue failure criteria, it uses the laboratory fatigue relationship proposed by

Shell [34].

HIPAVE is based on CIRCLY and APSDS (Airport Pavement Structural Design System) models and offers a range of features designed to streamline pavement design. These include a standard vehicle library or the option for users to define custom vehicles, the ability to define or use prescribed container weight distribution, and automated calculations of axle loads based on vehicle wheel load configurations and container weights. One of the key advantages of this program is that it allows design vehicles to be modelled with their actual wheel configurations. Additionally, analytical-empirical material models can be incorporated for each layer type, enhancing the accuracy of the designs [19]. HIPAVE can be used for various pavement structures, including asphalt over unbound granular materials, asphalt over cement-treated layers and segmental pavers over cement treated roadbase layer.

HIPAVE has referenced highway failure criteria specifically for cement bound structural layer solely for illustrative examples. It is an open system that allows users to input custom material properties for any pavement layer. But in reality, practitioners have limited access to actual cement bound failure criteria calibrated for ports and intermodal container terminals loading conditions to use in practice.

2.5. APSDS

The Airport Pavement Structural Design System (APSDS) was primarily developed for the design of aircraft pavements. APSDS utilises a mechanistic analysis approach for flexible pavements subjected extremely to the extra-heavy wheel loads associated with large aircrafts. It is specifically designed to model combinations of aircrafts and their corresponding take-off weights, calculating the combined damage using the CDF [35].

APSDS is calibrated against the US Army Corps of Engineers CBR Method S77-1 [18] and incorporates data from Federation Aviation Administration (FAA) test facility, using the gear configurations of Boeing B777 and B747 to develop fatigue models based on the permanent deformation of the subgrade. In cases of fatigue failure in bound layers, APSDS uses the layered elastic program CIRCLY to compute the tensile strains at the underside of these bound layers. Given the similarity in load magnitudes between aircrafts and specialist vehicles used in container terminals, the fatigue models developed by APSDS has broad applicability. Like HIPAVE, APSDS automatically sublayers the unbound granular basecourse and subbase layers in accordance with the Barker and Bradston methodology [9]. In contrast to other methods, such as BPA and FAARFIELD, APSDS, like HIPAVE, computes subgrade strains at all points across the pavement to account for the cumulative damage contributed by all aircraft wheels.

APSDS is based on CIRCLY and HIPAVE, offering users the ability to specify a wide range of input data, including

material properties, wander, aircraft loadings, and the damage model. This flexibility allows for customisation to suit specific pavement conditions. The program includes features to expedite pavement design, such as standard aircraft model library, the option for users to define their own vehicles and the ability to define and store take-off weight distributions. Additional features and material selection options are detailed in the APSDS user manual. The program is capable of computing the effects of future aircrafts or design vehicles with any wheel configuration and can incorporate new pavement materials [18, 36].

2.6. FAARFIELD

The Federal Aviation Administration (FAA) developed the FAARFIELD (FAA Rigid and Flexible Interactive Elastic Layer Design) integrated software program for the design of airport pavements. This program employs three-dimensional finite element (3D-FE) methods for the analysis of rigid pavements and a layered elastic approach for flexible pavements [37]. FAARFIELD version 2.2.2 is the standard software tool for designing and evaluating airport pavement thickness in accordance with AC 150/5320-6G [38]. The program's structural analysis engine incorporates two core components: LEAF, which performs multilayered elastic computations, and NIKE3D, which conducts finite element analyses. FAARFIELD integrates engineering-based structural analysis- either through layered elastic theory or finite element modelling- with empirical failure models. FAA has calibrated FAARFIELD to produce significantly larger flexible pavement thicknesses than those obtained using S77-1 design method developed by US Army Corps of Engineers (USACE) [39] which is inconsistent with the ACN-PCN pavement rating system. It produces reasonably similar thickness on average to those given by the old manual or chart-based method. This reflects a degree of conservatism built into the software that FAA has decided is appropriate [40].

The software calculates the CDF across the full spectrum of design traffic to determine the required pavement thickness, under the assumption that pavement failure occurs when CDF equals one. CDF represents the proportion of a pavement's structural fatigue life that has been consumed. It is computed for each 254 mm wide strip across the total pavement width of 20,828 mm, and the maximum CDF along these strips is used for design purposes. This methodology implies that aircraft generating minimal stress or strain have a negligible impact on the final pavement thickness design.

FAARFIELD estimates pavement structural life using two primary predictors: the maximum horizontal tensile strain at the bottom of asphalt layer and the maximum vertical compressive strain at the top of the subgrade. The user interface displays both slab edge stress and slab interior stress for each aircraft included in the traffic mix during thickness design or life analysis of new rigid pavements. It also shows the most

critical (i.e., the most demanding) aircraft in the loading spectrum [37]. For flexible pavement design, the program adopts the asphalt fatigue failure criteria based on the FAA-USACE relationship. FAARFIELD design procedure prescribes a minimum asphalt thickness over cement-treated base based solely on the weight of the heaviest aircraft, irrespective of the overall traffic volume. It does not account for the effects of traffic channelisation, which can lead to concentrated loading patterns and, consequently, adverse impacts on pavement performance.

All pre-defined layer types in FAARFIELD, except for user-defined layers, correspond to materials specified in AC 150/5320-6G [38]. The program enforces several constraints on layer placement. For instance, overlays cannot be placed beneath wearing course, and no more than two aggregate base layers are permitted within the pavement structure- each of a different type. Aggregate layers are not allowed to serve as wearing course, and when both crushed and uncrushed aggregate layers are present, the crushed layer must be placed above the uncrushed once. Only one crushed aggregate layer is allowed in the pavement structure. If the wearing course is asphalt, the pavement type is automatically reclassified as a new flexible pavement. Additional design constraints include specified minimum and maximum allowable moduli and layer thicknesses of various pavement materials. The design modulus for asphalt is fixed at 1380 MPa, while the moduli for granular layers are internally calculated by the program. The subgrade CBR is restricted to a range of 1% to 33%. Furthermore, when the gross weight of any aircraft in the design traffic mix exceeds 45.4 metric tons (100,000 pounds), the use of a stabilized base course becomes mandatory [38].

Upon launching, FAARFIELD automatically downloads the most up to date aircraft library from the FAA's PAVEAIR database, including capabilities for user-defined vehicles. For design purposes, the program utilises the annual departures based on the maximum anticipated gross take-off weight. It calculates cumulative loading by multiplying this weight by the design period, while arrivals are not considered in determining the total number of aircraft passes. Pavement thickness is then determined on the entire design traffic mix. Geosynthetics are used primarily as separation layers at the interface between subbase and subgrade, without serving any structural function. In empirical pavement design, bound base course layers are increasingly used for extra heavy-duty pavement applications, typically incorporated through the use of layer equivalency factors.

2.7. CBR Method

The California Bearing Ratio (CBR) method for flexible pavement design was originally developed by the California Highway Department to determine pavement thickness for single-wheel loads on highways. Due to its procedural simplicity, reliable performance, and adaptability to airfield applications, the method was later adapted by the USACE for

aircraft pavement design [41]. As the aircraft size and complexity increased, the method was further modified to accommodate multiple-wheel loads. This adaptation was based on Boussineq theory, which analyses the effect of uniform circular loads on homogenous, isotropic and elastic half-space [41-42].

Further investigation and testing conducted by USACE revealed that a single wheel load producing the same surface deflection as a multiple-wheel load would result in equivalent or greater strain within the same pavement structure. When the wheels of a multi-wheel system are spaced sufficiently far apart, the stress fields induced by adjacent wheels do not overlap significantly, and the resulting effect on the subgrade is no more severe than that of a single wheel load. This finding led to the development of the Equivalent Single Wheel Load (ESWL) concept within the CBR design method [41]. If the contact area of ESWL remains constant with varying load, the ESWL can be determined by Equation (1).

$$ESWL = \frac{\delta_{mwl}}{\delta_{swl}} SWL \quad (1)$$

where SWL denotes the single wheel load, δ_{mwl} represents the elastic deflection caused by multi-wheel tyre group and δ_{swl} corresponds to the elastic deflection induced by the single wheel-tyre. The deflection-based ESWL approach is used instead of stress-based ESWL approach, as it tends to yield slightly conservative results. In contrast, the stress-based approach has been shown to underpredict vertical stress [43]. The ESWL simplifies the complex analysis of multi-wheel assemblies by representing their effects through an equivalent single load for computational purposes. To account for multi-wheel assemblies, the classical CBR equation was reformulated, allowing for the determination of flexible pavement thickness as in Equation (2).

$$t = (0.23 \log C + 0.15) \sqrt{\frac{ESWL}{8.1 CBR} - \frac{A}{\pi}} \quad (2)$$

where t represents the pavement thickness, C denotes the coverage, CBR is the subgrade strength and A is the tyre contact area of a single tyre. To streamline the design process and eliminate the need for trial-and-error calculations, USACE developed a series of design curves corresponding to various loads, traffic levels, and pavement thicknesses. For asphalt seal pavement, the CBR design method requires a minimum wearing course thickness of 100 mm. Additionally, the basecourse layer must possess a CBR value of 80% or higher. Even when employing mechanistic or Layer Elastic Design methods, the CBR method remains a valuable supplementary check to validate the pavement design [44].

The primary criticism of the CBR design procedure concerns the use of alpha (α) correction factor, which was introduced to compensate for the overestimation of the ESWL and to adjust pavement thickness based on traffic volume. Research by the FAA has demonstrated that the CBR method tends to yield overly conservative results and performs inad-

equately in many engineering applications [45]. In response, the CBR procedure was reformulated to eliminate both the ESWL concept and the α -factor. This reformulation led to a more comprehensive, stress-based mechanistic-empirical approach that explicitly accounts for multi-wheel assemblies, resulting in the development of CBR-Beta (β) criteria, also known as β -fatigue equation [43]. The updated failure model incorporates a concentration factor as a function of the CBR value, providing a more realistic representation of the subgrade response than the original method, which relies on a constant concentration factor [46]. The CBR design method has been increasingly criticized for its empirical nature, overly simplistic assumptions, and obsolescence in light of the adoption of more advanced analytical models, such as layered elastic theory and finite element methods, in contemporary pavement design practice.

2.8. AfPA Method

The Australian flexible Pavement Association (AfPA) developed this method to address the lack of guidance for the design of flexible pavements for ports and intermodal container terminals [8]. The failure criteria characterised in the AfPA manual are tailored specifically for terminal pavement applications and are not intended for use in the design of highway and aircraft pavements. The AfPA method is based on mechanistic-empirical principles and employs Layered Elastic Analysis approach to calculate pavement responses. In this procedure, all pavement materials are assumed to be homogeneous, linear elastic and isotropic [12]. Instead of applying multiple dynamic load factors, the method assigns a single weighted average dynamic load factor to specify operational areas within the terminal. To account for the varying responses of different pavement materials to loading, the method incorporates an incremental damage approach [12, 47]. The AfPA method determines design loading based on Twenty-foot Equivalent Unit (TEU) volume and a standard terminal layout. However, the guidelines are not tailored for non-typical terminal configurations, which may limit their applicability outside of Australia. A simplified proportional approach is used to assign vehicle axle loads, consistent with the methodology employed in HIPAVE procedure. To account for the non-linear and stress-dependent behaviour of base and subbase materials, the method adapts the Barker-Bradston [9] sub-layering technique, originally adopted in USACE [12].

The AfPA method has been calibrated and validated specifically for Australian port and container terminal pavement conditions. The results of this process demonstrated that the procedure provides accurate predictions of pavement performance, particularly in terms of rutting in unbound granular layers, crushing of bound layers and fatigue in bound layers. Furthermore, the calibration findings indicated that the dynamic loading effects are more appropriately applied to terminal operational areas as a whole, rather than being based on individual equipment movements. Based on these findings,

revised static-to-dynamic load ratios were recommended [47]. AfPA developed a spreadsheet tool to facilitate the use of its design method. This tool enables the pavement designers to develop pavement structures comprising a surfacing layer, basecourse, subbase and subgrade overlying bedrock. The design traffic loading is based on the critical vehicle operating in the area, with loadings of up to seven container weights applied to both the front and rear axles. The list of design

vehicles is tailored to Australian practice and is limited to those predefined in the spreadsheet menu, may restrict the method's applicability in broader international contexts.

2.9. Summary of Design Methods

The extra heavy-duty pavements design methods capabilities, advantages, and limitations are summarised in Table 2.

Table 2. Design Methods Summary.

Method	Analysis	Comments
BPA	Empirical chart	Use FEM 2-D axisymmetric pavement model to develop design chart. Primarily develop for port pavements with CBPs on bound bases. Use MEF to substitute alternative materials. Assume surfacing has no structural strength contribution.
PCASE	M-E	Use CBR-based or LED method for flexible pavements. Westergaard solution or LED for rigid pavements. Widely used in military application for heavy duty airport pavements with limited applicability for civilian use. It has comprehensive library of US military vehicles and material characterisation tailored specifically for specifically for the US Army and US Navy which is challenging for other jurisdictions.
FE	FEA	Alternative to overcome LED method limitations. Can handle complex loadings, intricate geometries, varying material properties, anisotropy, layered soils, and complex stress-strain relationships. Lack of local material characterisation data and software accessibility for practitioner.
HIPAVE	M-E	Use LED and offer standard vehicle library or the option for users to define custom vehicles. Open system software and allow user to input custom material properties. But limited access for practitioners to use to actual cement bound base failure criteria for calibrated for extra heavy pavement option.
APSDS	M-E	Use LED and primary use for aircraft pavement design. Have as standard aircraft model library or the option for users to define custom vehicles. Allow wide range of input data, including material properties, wander, aircraft loadings, and the damage model.
FAARFIELD	M-E	3D-FE method and LED for rigid and flexible airport pavements respectively developed by FAA. Prescribed minimum asphalt surfacing thickness over CTB for heaviest aircraft. Use all pre-defined layer types except for user-defined layers. Layer sequencing restrictions including layer thickness and allowable moduli restrictions.
CBR	Empirical	Use ESWL concept. Use prescribed minimum asphalt surfacing 100 mm for seal pavement. Introduce alpha correction factor to adjust pavement thickness to overcome overestimation of ESWL. Later reformulated with CBR-Beta (β) criteria to account for multiple wheels for more realistic result. Empirical nature, overly simplistic assumptions, and obsolescence in comparison with others advanced analytical methods.
AfPA	M-E	Tailored for Australia port pavements and limited applicability outside Australia. AfPA developed spreadsheet to facilitate the design method. Design vehicles are predefined in the spreadsheet menu and may restrict the method applicability outside Australia.

3. Comparison of Design Procedures

For the purpose of comparison, the various design procedures as discussed in the previous section are used to determine the pavement thickness. In all methods, the design traffic

loading is assumed to be identical. The design vehicle is a 90 tonnes axle load reach stacker with the front wheel configuration as shown in Figure 3. The pavement design life is assumed to be 25 years.

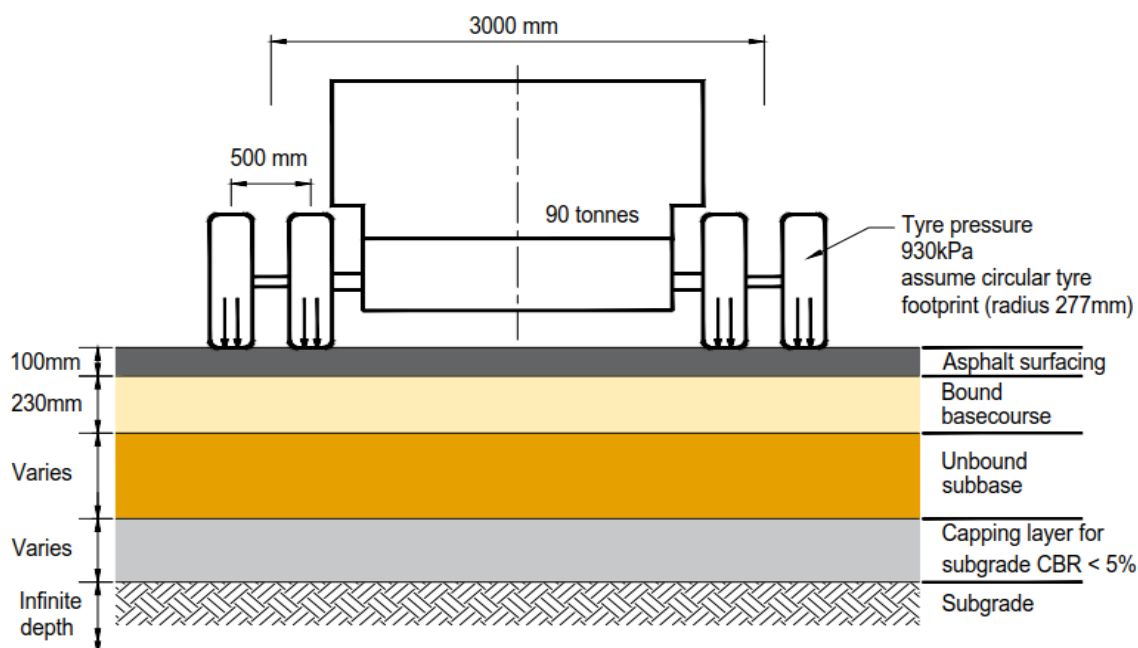


Figure 3. Schematic Diagram of the Extra Heavy-duty Pavement (Vehicle Data Source from Kristjansdottir, 2017).

The input soil parameters used in the comparative study are summarised in Table 3. Except for the BPA and CBR methods, which assume constant values for all thicknesses and subgrade strengths, the other procedures use the Braker-Brabston sublayer method to model the granular subbase material and determine subbase layer strength. For consistency, the surfacing layer is assumed to consist of 100 mm of asphalt and basecourse thickness is fixed at 230 mm throughout the study to facilitate comparison. The effects of the pavement thickness variations resulting from different subgrade CBR values are examined over a range of 2% to 10%. In some jurisdictions, a capping layer is mandated when the subgrade CBR is less than 5% [13, 14]. This layer typically consists of granular material with lower strength than the subbase.

Table 3. Material Properties Used in this Comparative Study.

Layer	Elastic Modulus (N/mm ²)	Poisson's ratio
Surfacing (asphalt)	3000	0.15
Basecourse (C _{8/10})	40000	0.15
Subbase	500	0.30
Capping	250	0.35
Subgrade	10 x CBR	0.40

Data source: Knapton [16].

The required pavement thickness to withstand the design traffic loading decreases as subgrade stiffness increases, as

shown in Figure 4. The results reveal that, for a constant surfacing and basecourse thickness, the subbase thickness is highly dependent on the strength of the subgrade.

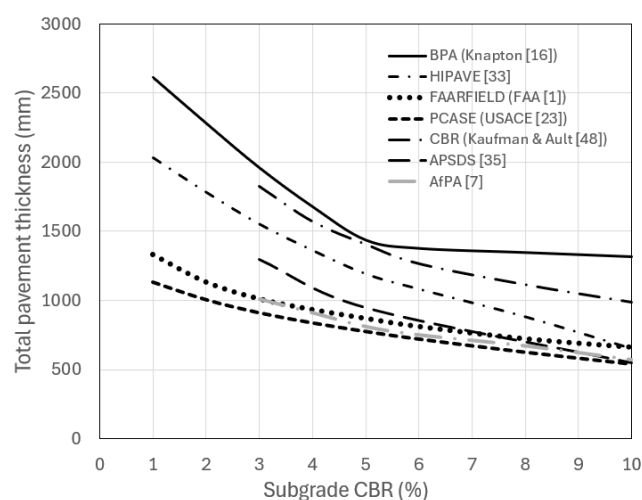


Figure 4. Comparison Among the Design Methodologies Used for Extra Heavy-duty Pavements. (Data Source: Kristjansdottir [27] for BPA and HIPAVE).

In the BPA method, a capping layer of prescribed thickness is required when the subgrade CBR is less than 5%. This requirement contributes to a marked increase in the overall pavement thickness on such subgrades. The comparative study reveals that the BPA method is the most conservative, consistently yielding the thickest pavement designs across all cases. Notably, PCASE, FAARFIELD, AfPA and APSDS methods produce relatively thinner pavements for subgrade

CBR equal or exceeding 5%, compared to the BPA method. It is worth noting that the CBR results are determined from the empirical design chart [48].

In all cases, the APSDS method results in thicker pavement designs compared to those produced by FAARFIELD for subgrade CBR values below 5%. This finding contrasts with the comparative study of the two design methods conducted by Chai et al. [49]. It reveals that the design thickness increases significantly when the subgrade CBR is less than 5%. This discrepancy has implications for pavement thickness design in areas with low subgrade CBR. One possible explanation is that FAARFIELD method considers the full range of aircraft wheel configurations to determine the maximum subgrade strain, while APSDS method uses single-wheel group loadings. Additionally, the study by Chai et al. [49] employed a flexible basecourse (foam-stabilized granular material), whereas this study utilized a cement-stabilized basecourse, which may account for the differing outcomes observed for subgrade CBR values below 5%.

The computational results demonstrate that the HIPAVE method consistently yields a thinner pavement section compared to the BPA method. The difference in pavement thickness is more pronounced when the subgrade CBR value exceeds 5%, where the thickness determined by HIPAVE method decreases significantly, while the thickness derived from the BPA method remains nearly constant, as shown in Figure 4. This suggests that the effect of increasing CBR values is very limited, as the BPA method does not provide alternatives to model an improved subgrade. Furthermore, the surfacing layer is not considered a structural component in the

BPA, whereas, in practice, it contributes to the total required thickness over the subgrade. This explains why the BPA method tends to be more conservative.

The simplified CBR method shows a similar trend to the HIPAVE method, but with more conservative results. This suggests that the CBR method can serve as a simple and efficient approach for independent verification or benchmarking.

4. Subgrade Failure Criteria

In the design of extra heavy-duty pavements, the objective is to limit the vertical compressive strain at the top of the subgrade to a tolerable level throughout the pavement's design life. In this approach, the vertical compressive strain at the top of the subgrade is used as a key determinant for surface deformation in the unbound portion of the pavement structure. It is assumed that most of the surface deformation originates from the subgrade, with minimal contribution from the overlying pavement layers. The pavement performance is characterised by the relationship between the number of allowable repetitions to a standard failure level (N), the vertical compressive strain (ϵ_v) at the top of the subgrade, and the empirical model fitting coefficients (k , b) as in Equation (3).

$$N = \left[\frac{k}{\epsilon_v} \right]^b \quad (3)$$

For airfield pavements, the number of passes to failure is referred to as coverage, and the subgrade failure criteria for the CBR and FAARFIELD methods are presented in Table 4.

Table 4. Rutting Model Coefficients.

Study	k	b	Comments
Austrroads [3]	9150	7	CBR design chart – (refer to Austrroads [3] Figures 8.4 and 12.2 for tyre pressure 750 kPa, radius 92.1 mm, N in ESA unit, 20 mm rut depth) CIRCLY [50] used the same failure criterion
Shell [34]	18000	4	Adopted in DESIGNPAVE CMAA software [51] 95% reliability, based on AASHO road test
BPA (Brown and Brunton [20])	21600	3.57	British conditions for UK practice Road Note 29 [21], rut depth 20 mm.
USACE (Barker and Brabston [9])	5525	6.527	50% reliability, aircraft test pavement
British Airports Authority (Woodman [52])	5820	5.747	50% reliability, based on USACE aircraft test pavement [53]
APSDS (Wardle and Rodway [36])	4276	6.635	50% reliability, based on USACE aircraft test pavement [53]
HIPAVE (Wardle et al. [18])	k	B	Based on USACE CBR method (S77-1 Method [39]) calibrated with aircraft loading. HIPAVE [33] adopted this failure criterion model $k = 1.64 \times 10^{-09} E^3 - 4.31 \times 10^{-07} E^2 + 2.18 \times 10^{-05} E + 0.00289$ $B = -2.12 \times 10^{-07} E^3 + 8.38 \times 10^{-04} E^2 - 0.0274 E + 9.57$
CBR (Gonzalez and Barker [54]; Gonzalez, et al. [43] for USACE)	$\frac{\text{Log}(\beta) = 1.7782 + 0.2397 \text{ Log}(C)}{1 + 0.503 \text{ Log}(C)}$		CBR Beta reformulation procedure with constant concentration factor for all test points to eliminates ESWL concept and the Alpha factor. Use for

Study	k	b	Comments
			CBR airfield pavement design method.
			C = coverage
CBR (Miller [46])	$\text{Log}(\beta) = \frac{1.5586 + 0.0886 \text{ Log}(C)}{1 + 0.0778 \text{ Log}(C)}$		Revised CBR Beta criteria using concentration factor as a function of CBR with a better fit to the test data. Plot curve is 85% reliability. C = coverage, σ = stress at the top of subgrade (psi), $\beta = \frac{\pi\sigma}{\text{CBR}}$
Moffat and Nichol [57]	$N = 10000 \left(\frac{A}{\varepsilon_v} \right)^D$		$A = 0.000247 + 0.000245 \log_{10} E$ $D = 0.0658 e^{0.559}$
FAAFIELD (FAA [55])	$C = \left(\frac{0.00414131}{\varepsilon_v} \right)^{8.1}$		Use Bleasdale function to define coverages to failure ≥ 1000 For $C \leq 1000$, use linear tangent line to the Bleasdale curve ε_v = maximum vertical strain at the top of subgrade
FCAA [58]	$\varepsilon_v = 16000 N^{-0.222}$		French approach to limiting vertical strain of the subgrade

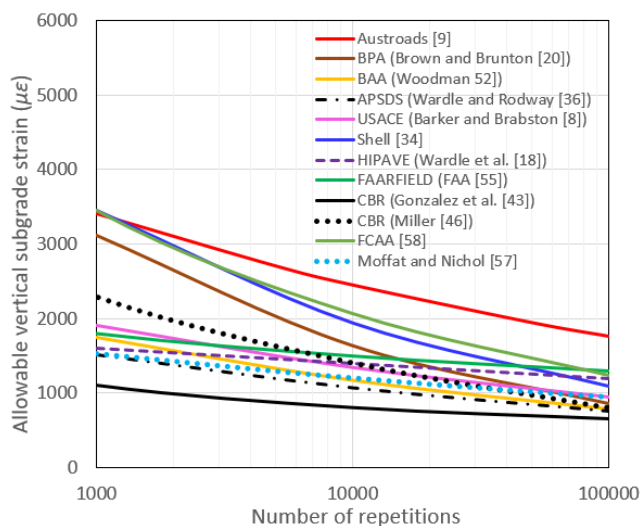


Figure 5. Comparison of Subgrade Failure Criteria.

Numerous subgrade failure criteria have been developed for flexible pavements. Table 4 presents several published criteria relevant to this study. Apart from Shell [34] and Austroads [3], which are applicable to highway pavements, the remaining criteria are intended for aircraft and port pavements. Interestingly, the empirical relationship developed for road models is adopted in the BPA method [56], which incorporates the Nottingham University criterion [20], according to the UK Road Note 29 [21]. A comparison of these criteria is presented in Figure 5. For load repetitions fewer than 10,000, the BPA method exhibits a trend similar that of Shell [34] and Austroads [3]. It is evident that all the failure criteria for aircraft and industrial pavements indicate lower strain values than those of highway pavements. This trend could be attributed to differences in the procedures used for characterising granular materials or the distinct performance criteria

applied to highways, aircraft and industrial pavements. Therefore, direct comparisons of subgrade failure criteria are not meaningful and should be avoided.

The AfPA [12] found that attributing surface deformation solely to the subgrade is not entirely valid for thicker pavements, such as those encountered in extra heavy-duty pavements. The study revealed that rutting could occur in any unbound granular layer, and permanent deformation is more closely related to the deformation within the layer than to the strain at a specific point within the layer. As a result, AfPA modified the traditional model by introducing the Elastic Limit concept, which is defined as the sum of the strain profile with depth above the elastic limit.

It is worth noting that for highways, the allowable rut depth ranges between 12 to 25 mm. In contrast, for ports and container terminal pavements, the allowable rut depth can vary between 25 and 75 mm depending on the equipment and mode of operation [12].

5. Construction Specifications

The quality of an extra heavy-duty pavement system is heavily influenced by factors, such as the asphalt mixture, the quality of the granular base and subbase layers upon which the asphalt surfacing is placed, and the construction practices employed. Achieving optimal performance requires adherence to appropriate construction specifications. However, there are currently no standardised construction specifications using the traditional prescriptive approach for extra heavy-duty flexible pavements for ports and container terminals. Often, highway-standard specifications are modified and applied to extra heavy-duty pavements without a thorough understanding of the material performance requirements and the potential consequences of the pavement failing to meet its design life. Consequently, there is an increasing shift towards performance-based specifications, which allow for innovation, risk

reduction, cost savings, and improved performance in terms of deformation and fracture resistance. Additionally, some asset owners have introduced extended warranty performance guarantees in an attempt to transfer responsibility for asphalt surface performance to suppliers and contractors [59].

In the construction industry, leading asphalt suppliers have invested in research to develop specialised asphalt mixes capable of performing under the severe loading conditions encountered at ports and intermodal terminals. The result of such research has led to the creation of bespoke asphalt mixes, such as PortPhalt, a registered trade product developed by Fulton Hogan [60]. However, the proprietary data for these mixes is not made available to pavement designers for knowledge sharing. Construction specifications are drafted to ensure that a pavement system, once installed, will perform satisfactorily throughout its service life. In the absence of industry-standard construction specifications, there is an increased residual risk for all parties involved in extra heavy-duty pavement projects, regardless of the source of the fault.

6. Pavement Structural Balance, Layering and Material Depth

The concepts of structural balance and layering are critical in designing extra heavy-duty pavements. The structural balance refers to the gradual increase in material quality from the subgrade to the wearing course. Conversely, a well-balanced pavement will exhibit a smooth reduction in material strength

and stiffness with increasing depth, contributing to excellent performance. An unbalanced, shallow pavement system is more susceptible to overlandings than a deeper well-balanced pavement structure. As a general guideline, the elastic modulus of each successive layer should approximately double. Another common rule of thumb is to maintain the classic three-layer pavement structure with basecourse CBR of 80, subbase CBR of 45 and subgrade CBR of 15 [44].

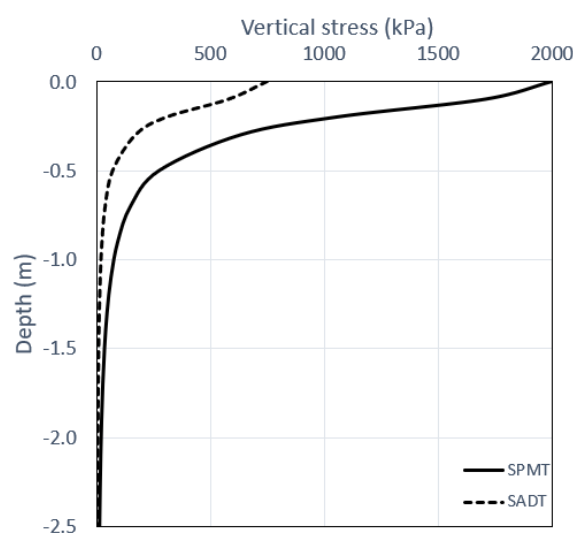


Figure 6. Effect of Wheel Load on Soil Depth.

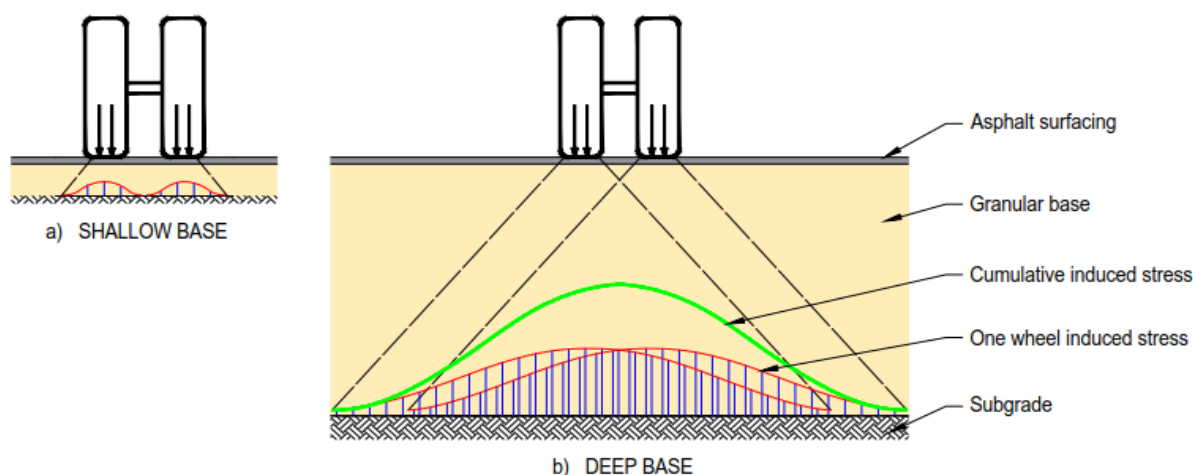


Figure 7. Influence of Depth on ESWL (Adapted from Boyd and Foster [61]).

The depth below the finished level, at which soil characteristics significantly influence pavement behaviour, is referred to as material depth. This means that the strength and density of the soil below this depth can be significantly affected by the applied load. Typically, the material depth for aircraft pavements designed for Boeing 747-400 is between 1700 to 2000 mm, while for road pavements, it is around 800 mm, which corresponds to

minimum cover for a design subgrade CBR of 3%. This implies that the effective subgrade for extra heavy-duty pavements should consider an appropriate material depth up to 2000 mm or more [5] rather than the 1000 mm typically considered for highway pavements. This is illustrated in Figure 6, which shows that the stress resulting from the centre of a uniformly loaded circular area at the surface of a single-layered soil system using

the Boussinesq method to determine vertical stresses beneath a 20 tonne SPMT and a 4-tonne commercial vehicle single axle dual tyre (SADT) wheel load, respectively, against depth. This simple example demonstrates that the extent of stress generated by the wheel load increases with the wheel load itself. It also suggests that the stress impact on weaker subgrades is more severe, with a reduced sensitivity to changes in subgrade strength as it increases.

In the case of wheel groups greater than one, the influence of the multi-wheel loads will be increasing overlap with depth, a phenomenon that can be mitigated by the vehicle model wander factor. This means that the overlap of loads, as well as the degree of wander for non-channelised traffic, must be considered under severe loading conditions. Figure 7 illustrates how the overlap of multi-wheel loads increases with depth. As shown in the figure, the two wheels act independently at shallow base depths, but their influence begins to overlap at greater depths in the case of deep-base pavements. It follows that when two wheels are sufficiently close, the stress under each wheel is increased proportionally owing to the proximity of the other wheels. Knapton [17] developed the concept of effective depth of the slab to account for wheel proximity factor and its relationship with subgrade CBR with the following formula.

$$\text{Effective depth} = 300 \times \sqrt[3]{\frac{35000}{\text{CBR} \times 10}} \quad (4)$$

For a given axle wheel spacing and the calculated effective depth, the proximity factor can be obtained by linear interpolation from Figure 8.

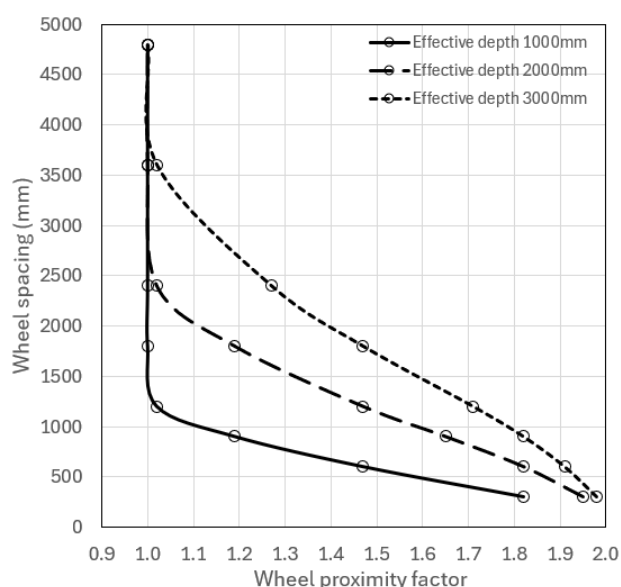


Figure 8. Proximity Factor for Effective Depth Versus Wheel Spacing (Data Source from Knapton [17]).

This underscores the importance of conducting subgrade investigations to assess the properties of the subgrade with the top

2 m or more from the proposed pavement design finished levels. Additionally, the surcharge weight used for extra heavy-duty pavements must accurately reflect the overlying soils and pavement construction. Ministry of Defence in the UK [62] has adopted a standard surcharge weight of 6kg, as opposed to 4.54 kg typically used in the highway CBR test procedure.

7. Basecourse

A flexible pavement structure relies on load-spreading properties mainly through intergranular pressure, mechanical interlock, and cohesion between the particles of the pavement material. Standard crushed rock materials used as road granular base for flexible pavements can fail under the much higher induced stresses found in heavily loaded pavements [63]. Therefore, it is desirable to use high-quality crushed rock materials for the granular base to meet the performance requirements of extra heavy-duty pavements. These materials are often stabilised with geosynthetic materials. Additionally, the compaction for the basecourse and subbase typically follows requirements of 102% and 98% modified AASHTO compaction respectively with 70% dry-back as per AS1289.5.2.1 [64]. These compaction levels align the intend of using the Barker-Brabston [9] sub-layering method. The goal is to achieve higher densities in the aggregate basecourse, which increases in the resilient modulus and compressive strength, thus proving adequate support for the laying and compaction of the asphalt layers. Furthermore, the compaction requirements for extra heavy-duty pavement subgrades are generally stricter than those for highways. The top 300 mm of subgrade should be compacted to at least 100% and 98% of maximum density for non-cohesive and cohesive soils, respectively [65].

Cement-stabilised basecourse layers in extra heavy-duty pavements generally enhance the load-carrying capacity of the pavement. In the case of asphalt-sealed pavements, the use of a cemented layer near the surfacing requires a combination of asphalt and granular thickness, or a minimum cover of 175 mm of dense-graded asphalt, to prevent reflection cracking [66]. Other authorities, such as the Federal Aviation Administration [38] and the Ministry of Defence [62], recommend minimum asphalt thickness of 75 to 100 mm and 100 mm, respectively, over cement stabilised basecourse without the use of asphalt reinforcement or stress absorbing membrane interlayers (SAMI). The rationale for adopting thinner asphalt surfacing is based on the relatively low deflection experienced by heavily bound base pavements, which minimises asphalt fatigue. In this context, the asphalt surfacing primarily serves to restrict the ingress of moisture into the pavement-bound layer [67].

8. Asphalt Layer

8.1. Asphalt Requirements

Heavy-duty asphalt mixtures are required when a pavement

structure is exposed to severe loading conditions, such as high numbers of repetitions, heavy loads, static loads, and high tire pressures, all of which can lead to indentation. It is essential to integrate both the asphalt mixture and the pavement structural design to ensure long-term durability under such extreme loading conditions. Consequently, asphalt mixes must exhibit durability, deformation resistance, and structural stiffness, while also incorporating high-quality aggregates [5]. Durability aspects, such as material quality, adequate binder content, and low in-situ air voids, are typically addressed in state highway specifications. To achieve deformation resistance, a carefully graded aggregate structure with minimal air voids is used to prevent instability, alongside a well-selected binder.

8.2. Bituminous Binder

Recent research has indicated that surface deformation in asphalt surfacing is primarily caused by a lack of cyclic shear resistance in the material [68]. This issue can be mitigated by using polymer-modified and multigrade binders, which increase the softening point and enhance stiffness at higher service temperatures, thereby improving resilience to cyclic loading. Fatigue is generally less of a concern for extra heavy-duty pavements due to the relatively low traffic volumes compared to road pavements. Arguably, bituminous binder is the most critical constituent influencing the performance of asphalt mixtures, as it governs the relationship between asphalt modulus and temperature, including the visco-elastic response of the material under load [68].

8.3. Bituminous Mastic

It is important to note that for extra heavy-duty pavement asphalt surfacing, dense-graded mixtures with high binder contents are typically specified, and these rely heavily on mastic performance to resist deformation [69]. Consequently, mastic properties are critical to the overall performance of the asphalt mixture. Mastic is essentially the effective binder in an

asphalt mixture, composed of a combination of bituminous binder, fine aggregate, and chemical fillers. However, the mastic's response to load is less well understood than that of bitumen, despite general agreement on its importance [70]. Further research is needed to better characterize mastic resistance to deformation. Notably, the traditional prescriptive Marshall mixture design method lacks reliable tools for predicting deformation [71, 72].

8.4. Aggregate

A significant portion of the asphalt mass consists of fine aggregates and coarse aggregates, with the coarse aggregates forming the structural skeleton of the mixture. The properties of the coarse aggregates, such as shape and particle packing, play a crucial role in asphalt deformation. Coarse aggregates are defined as particles larger than 4.75mm. The maximum permissible percentage of coarse aggregate shapes, based on the maximum-to-minimum dimension ratio, is 8% and 20% for ratios greater than 5:1 and 3:1 respectively [65]. Other key coarse aggregate properties, such as gradation, percentage of crushed faces, durability (as assessed by the Los Angeles abrasion test) and, soundness, significantly influence the deformation resistance of the asphalt [73-75].

Fine aggregates should exhibit good durability, soundness, and be free from organic matter and clay. Fine aggregates are defined as particles smaller than 2.36mm. High-angular fine aggregates ensure good internal friction and resistance to rutting [76-78]. However, a high percentage of angular fine aggregates can reduce workability during construction. In practice, a blend of angular (quarried) and rounded natural sands provide a balance between workability during construction and deformation resistance under traffic [59]. For heavy-duty mixtures, the portion of natural sand is limited to 15% by mass of aggregates to minimise the potential for rounded sands to behave like ball bearings, which could destabilise the mix and lead to distortion and lateral flow [78].

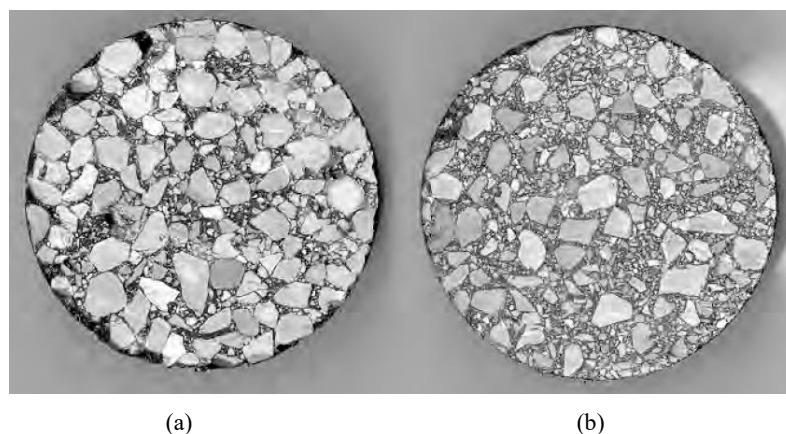


Figure 9. Aggregate Gradations with and Without Stone-on Stone Contact (Source from NAPA [78]).

Fine aggregates play an equally important role in contributing to the asphalt mastic [59]. The coarse angular aggregate skeleton in the asphalt layers bears most of the loads. Therefore, it is essential to use high quality crushed aggregates with the appropriate particle size distribution. The aggregate particle size distribution, or gradation, has a significant role in the asphalt mixtures. Figure 9 shows two asphalt mixtures with different particle size distributions. Figure 8a shows stone-on-stone contact, which Figure 8b demonstrates the coarse aggregates suspended in the matrix of fines, which makes the mixture more susceptible to rutting due to the lack of interlocking between coarse particles [78]. The stone-on-stone matrix provides a deformation-resistant surface, while the high binder content enhances durability [79].

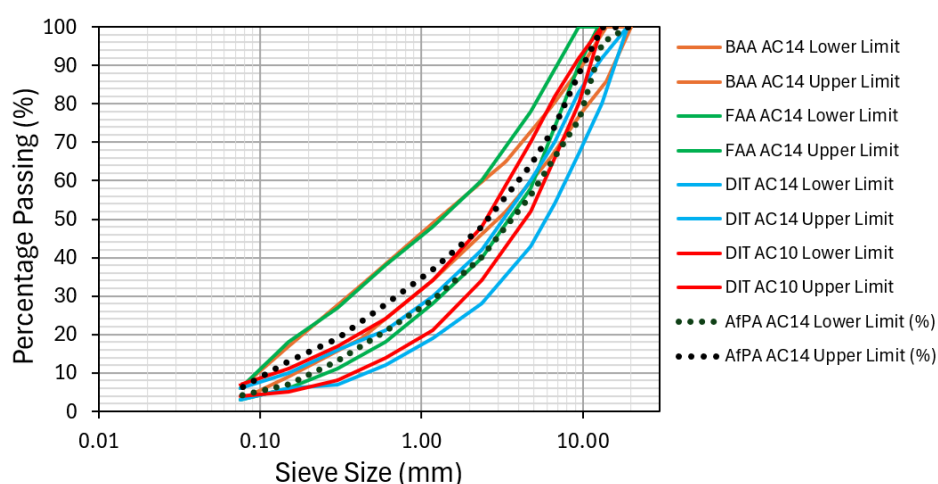
8.5. Fillers

Fillers are added to asphalt mixtures to improve density, strength, viscosity, as well as to stiffen the bitumen, improve bitumen-aggregate adhesion, reduce the risk of stripping, and reduce temperature susceptibility for certain fillers [80-83]. Common fillers include limestone dust, hydrated lime, fly ash, cement, sandstone, and granite dust [70]. However, lime and other fillers are more costly and present logistical challenges

in remote areas. Chemical fillers such as liquid anti-stripping agents, have been shown to be effective compared to active fillers like hydrated lime [84]. In summary, fillers offer a range of benefits, including stiffening the bituminous mastic and increasing resistance to moisture damage.

8.6. Asphalt Mix Gradations

It is important to note that Australian Flexible Pavement Association (AfPA) performance-based airport asphalt mix gradations with a tighter grading envelope can be used with additional requirements to enhance the performance of asphalt in service, compared to typical heavy-duty mixes from the FAA and BAA, as shown in Figure 10. Good production and construction practices, which are beyond the scope of this study, are essential to minimise segregation, aggregate fracture, and slight increase in equipment wear. However, due to the quality control issues and poor selection of virgin binder, the practice of incorporating reclaimed asphalt pavement (RAP) materials in the extra heavy-duty mixtures may lead to premature fatigue or transverse cracking [78]. For this reason, the use of RAP in extra heavy-duty surfacing mixtures is not permitted [78, 85].



Data source: CPEE [44], FAA [65], DIT [86], Emery [87] and AfPA [88]

Figure 10. Particle Size Distribution Grading Curves for Various Asphalt Mixes.

8.7. Asphalt Design Modulus

Sullivan et al. [89] found that design modulus of asphalt derived from flexural modulus test (AGPT-T274 [90]) without confinement yielded unrealistically low modulus values, making them applicable for traffic loading conditions at highway speeds. The compression-based dynamic modulus test (AASHTO-T342 [91]) was determined to be more appropriate for the stress conditions experienced in-service by slow-moving vehicle under severe loading conditions.

8.8. Summary

Asphalt mixes used in extra heavy-duty pavements, subjected to severe loading conditions, such as frequent heavy loads, substantial static loads, and elevated tyre pressures, necessitate specialised mix designs. These conditions demand that the asphalt mixes to have resistance to deformation and fracture to ensure durability and longevity of the asphalt layer throughout its design life. Importantly, the asphalt constitu-

ents and mix gradation contribute to achieving these performance requirements. Table 5 summarises the typical extra

heavy duty asphalt constituents and composition requirements.

Table 5. Typical Extra Heavy-duty Asphalt Mix.

Material	Test property	Limits
Coarse Aggregate	Particle density	$\geq 2300 \text{ kg/m}^3$
	Nominal mix size	14mm
	Water absorption	$< 2.0\%$
	Material Finer than 0.075 mm in Aggregates (by washing)	$< 1.0\%$
	Soundness (using Sodium Sulphate)	$< 3\%$
	Flakiness index	$< 25\%$
	Wet Strength	$\geq 150 \text{ kN}$
	Wet/Dry Strength Variation	$< 30\%$
	Max to min dimension ratio (max.%)	8 with ratio 5:1 20 with ratio 3:1
	Crushed faces with min 2 faces	$\geq 75\%$
	Los Angeles abrasion	$< 25\%$
	Secondary Mineral Content	$< 20\%$
	Friable Particles	$< 0.2\%$
Fine aggregate	Natural sand (% of aggregate by mass)	$\leq 15\%$
Filler	Filler content (% of aggregate by mass)	1.5% hydrated lime
Binder	Polymer modified binders	A5E, A30P or A10E
Asphalt mix	Bitumen content (% of aggregate by mass)	5.0 – 6.0%
	Bitumen content volume	$< 11\%$
	Marshall stability	$\geq 12\text{-}14 \text{ kN}$
	Marshall flow	$< 3 \text{ mm}$
	Marshall air voids target	3.5 - 4.0%
	Gyratory air void	250 cycles $> 3\%$ 120 cycles $< 7\%$
	Air voids tolerance	$\pm 0.5\%$
	Voids filled with bitumen target	75%
	Minimum Voids in mineral aggregate (VMA)	14 – 16%
	Reclaimed asphalt pavement (RAP)	0%
	Mean Indirect Tensile Modulus	6000 – 9500 MPa
	Indirect Tensile Strength Ratio (TSR) (min,%)	$\geq 80\%$
	Wheel Tracking Test (Final rut depth after 10,000 cycles at 65°C)	$\leq 2 \text{ mm}$

Data source: Emery [87], AfPA [88], NAPA [78], FAA [65, 92-94], DIT [11, 86]

9. Conclusions

This study evaluates alternative design techniques for heavy-duty flexible pavements and critically considers several factors impacting the designs. Currently, there are no unified design guidelines for extra heavy-duty flexible pavements intended to withstand severe axle loads up to 120 tonnes or more, which are significantly higher than typical highway design loads. This creates a high-risk scenario for asset owners and pavement designers, often leading to over-design in practice as a precautionary measure to avoid litigation in the event of pavement distress due to structural performance issues. Most existing design guidelines are derived from industry interest groups and lack technical collaboration from stakeholders, which hinders the development of a risk balanced approach for cost-effective pavement solutions. Due

to the severe wheel load conditions and loading characteristics, the design of extra heavy-duty flexible pavements cannot be achieved by extrapolating of highway design methods. Converting the axle loads into equivalent standard highway axles is therefore flawed.

The study reveals that the design of extra heavy-duty pavements requires a deeper understanding of the material performance characteristics, design methodology, input parameters, performance criteria, and operating conditions. This is essential to ensure that the pavement meets both structural and functional requirements without the need for major rehabilitation or reconstruction over its design life.

It is recommended that further research work is undertaken to develop unified design guidelines for extra heavy-duty flexible pavements intended to withstand severe axle loads up to 120 tonnes or more.

Abbreviations

SPMT	Self-Propelled Modular Trailers
RMS	Roads and Maritime Services
NHVR	National Heavy Vehicle Regulator
AfPA	Australian Flexible Pavement Association
FAA	Federal Aviation Administration
USACE	U.S. Army Corps of Engineers
HSG	High Standard Granular
DTMR	Department of Transport and Main Roads
DIT	Department of Infrastructure and Transport
BPA	British Ports Association
BPF	British Ports Federation
ESWL	Equivalent Single Wheel Load
CBP	Concrete Block Paver
CBR	California Bearing Ratio
MEF	Material Equivalence Factor
PCASE	Pavement Computer Assisted Structural Engineering
UFC	Unified Facility Criteria
M-E	Mechanistic-Empirical
LED	Layer Elastic Design
FE	Finite Element
FEA	Finite Element Analysis
HIPAVE	Heavy Industrial Pavement
CDF	Cumulative Damage Factor
DLF	Dynamic Load Factor
CAN	Aircraft Classification Number
PCN	Pavement Classification Number
FCAA	French Civil Aviation Authority
SADT	Single Axle Dual Tyre
AASHTO	American Association of State Highway and Transportation
AS	Australian Standard
SAMI	Stress Absorbing Membrane Interlayers
AC	Asphaltic Concrete
BAA	British Airports Authority
RAP	Reclaimed Asphalt Pavement
VMA	Minimum Voids in Mineral Aggregate
TSR	Tensile Strength Ratio

HMA	Hot Mix Asphalt
AAPA	Australian Asphalt Pavement Association
CPEE	Centre for Pavement Engineering Education
DoD	Department of Defence
MoD	Ministry of Defence
NAPA	National Asphalt Pavement Association
TRRL	Transport and Road Research Laboratory
SWL	Single Wheel Load
δ_{mwl}	Elastic deflection induced by multi-wheel group
δ_{swl}	Elastic deflection induced by the single wheel-tyre
t	Pavement thickness
C	Coverage
A	Tyre contact area of a single tyre
N	number of allowable repetitions to a standard failure level
ε_v	vertical compressive strain at the top of the subgrade
k, b, B, A, D	Empirical model fitting coefficients
E	Elastic modulus
σ	Stress at the top of subgrade
β CBR	Beta criteria

Author Contributions

Boon Tiong Chua: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Writing – original draft, Writing – review & editing

Kali Prasad Nepal: Validation, Writing – review & editing

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Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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