Principles of Pavement Engineering

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Principles of Pavement Engineering

Third edition

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Foreword

Pavements are built as ground-bearing structures to protect the subgrade from excessive deformation, so that serviceability under vehicular loading is maintained throughout their operational life. Pavement construction has evolved over the past 2000 years since the Romans built the first roads network. Improving ride quality, pavement durability, safety, sustainability and optimising whole-life cost and user expectations are the main factors that have driven the evolution of pavement engineering.

Roman roads provided durable all-weather infrastructure until the introduction of high-speed motor vehicles in the twentieth century. Asphalt surfacing over granular material was introduced to improve high-speed ride quality. Cement- and asphalt-stabilised bases and concrete pavements have been used to provide better bearing capacity for heavy traffic. The need to construct safe, durable, sustainable and low-maintenance pavement infrastructure has become very important in recent years due to environmental legislation and customer expectations. The use of low carbon materials and resilient design and construction has emerged to address environmental pressures and mitigate the risk of climate change. Pavement asset management has become a key to optimise costs, performance and risks. New technologies have recently emerged, such as telematics for data collection, smart materials and innovative constructions. Therefore, modern pavements are expected to meet users' expectation of safety, ride quality, noise and durability to minimise maintenance and avoid traffic delays, congestion and pollution.

Traditionally, pavements are designed using empirical approaches, where performance under traffic loading and environmental attack is monitored to establish the appropriate construction thicknesses. Analytical design from first principles, using an analysis of stresses and strains induced within a pavement, has been used to investigate a wide range of pavement materials, layer combinations and traffic loading. Hence, pavement engineering has become a science that combines structural engineering and geotechnics to model, analyse and design a multi-layered construction over natural ground. It requires good understanding of materials engineering, drainage, traffic loading and design reliability. Designers should consider the expected serviceability level of the pavement as factors such as deformation, cracking, longitudinal profile deterioration and loss of skid resistance occur. Highway pavements require appropriate skid resistance, minimum cracking/rutting and good ride quality for high-speed vehicle movements and should have low maintenance due to the high cost of lane closures and their impact on users and safety. Airfield pavements require limits on foreign object debris (FOD) damaging aircraft and resulting in costs and operational delays. On the other hand, limited cracking, deformation and poor skid resistance might be acceptable in industrial pavements where slow-moving vehicles are expected. Although the structural behaviour and failure mechanisms of airfield pavements are similar to those of roads, there are some major differences in loading and performance requirements. These include the wheel loading magnitude (up to 30 tonnes), wheel configuration (with up to 28 wheels in an undercarriage), tyre pressure (18 bar for civil aircraft and 30 bar for military aircraft), number of load repetitions expected during the design life and FOD damage requirements. Similarly, port container and industrial pavements are expected to carry heavy loads with large dynamic factors.

Pavement engineering is not commonly taught in undergraduate engineering courses and rarely in postgraduate courses. However, considering its significant contribution to sustainable transport, climate resilience and the economy, a good understanding of the theoretical principles and practical application of design and management is essential.

Principles of Pavement Engineering provides a much-needed document to help university students, researchers, graduate engineers, professional designers and asset managers to deliver sustainable transport infrastructure for the betterment of society. Using a simple approach, the book describes fundamental pavement engineering principles, materials characterisation, traffic loading and practical design, maintenance and asset management methodologies. It covers a wide range of pavements (including highways, streets and urban pavements, heavy-duty pavements for airfields, ports and industrial applications and low-volume roads using unbound construction), loading types and performance expectations.

The third edition of *Principles of Pavement Engineering* provides an improved structure with focus on materials and associated pavement categories covering structural design and maintenance. These include unbound, hot and cold asphalts, hydraulically bound and pavement-quality concrete. Part 1 provides a summary of the design principles, pavement types and applications, traffic loading and design reliability. The fundamental engineering properties of unbound material, including non-linear stress and moisture dependency, are not commonly presented in textbooks in the context of pavement design and maintenance.

Part 2 addresses these issues and also covers practical testing and unbound pavement structural design.

Asphalt binder types and characteristics, and the engineering properties of different asphaltic mixes including the effects of aggregate grading, binder content and sensitivity to temperature and loading time and methods of testing with practical examples, are presented in Part 3. This part also details the structural design and construction of flexible pavement, design methods, asphalt surfacing design and materials options including recycling and low carbon asphalt, pavement deterioration mechanisms and maintenance solutions. Theoretical fundamentals and practical examples and illustrations are also presented. To address sustainability, cold-mix asphalt design, testing and specification, and pavement structural design and maintenance are presented in Part 4.

Hydraulically bound material types, engineering properties and testing requirements, as well as the structural design and maintenance of composite pavements (with asphalt surfacing over hydraulically bound base) and heavy-duty modular block pavements are described in Part 5. Pavement-quality concrete types, engineering properties and testing requirements, as well as the structural design and maintenance of rigid pavements are presented in Part 6. The principles of water movement within a pavement structure and its impact on material properties and drainage provision are detailed in Part 7. Finally, pavement asset management, including whole-life cost optimisation based on network- and project-level monitoring, evaluation, surveys and testing to diagnose and propose maintenance and strengthening solutions, is presented in Part 8.

I have known and worked with the author for over 25 years and shared the same professional background in pavement engineering, research and innovation. Dr Thom has unique experience with a very strong academic background in pavement engineering, combined with research, practical design and specification. His understanding of design principles, practical constraints and risks has led to the successful introduction of many research findings into practice, which have improved value and provided better pavements.

In this book, Dr Thom manages to bridge the gap between theoretical pavement design and practical applications in a simple structured approach. The book is a good reference that paves the way for engineering students to understand design principles, for practising pavement engineers to design, specify and plan maintenance with a good understanding of materials and performance expectation, and for researchers to explore innovations such as smart materials, digitisation and pavement solutions in order to fulfil users' expectation of safe, durable, low-maintenance, sustainable and resilient transport infrastructure.

Dr Bachar Hakim
Director of Roads Asset Management, AECOM

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While I take responsibility for the contents of this book, I cannot possibly take all the credit. Life is a continuous learning experience and I continue to learn much from every contact with practitioners, sometimes consultancy clients, sometimes research partners – too many to list. Much of the information in this book comes from the hard work of others, whether my ex-colleagues in industry or the large number of PhD students that I have had the privilege of working with. I have simply taken what others have done and packaged it, sometimes adding my own interpretation. For this third edition, I would specifically like to offer thanks to ex-colleagues at Aecom, Bachar Hakim (to whom additional thanks for the foreword) and Daru Widyatmoko, to current and past colleagues at the University of Nottingham, Gordon Airey, Andrew Dawson and Tony Parry, and to a generation of hard-working researchers, among whom are Kranthi Kunar, Helena Jiménez, Ahmed Nassar, Chibuzor Ojum, Ahmed Abed, Anqi Chen, Monketh Mohammed, Dmytro Mansura, Oluwaseyi Oke, Chris Chu, Imtiaz Ahmed and Van Nguyen.

About the author

Nick Thom started as a general civil engineer with Scott Wilson in 1978, working in bridges and geotechnics before being part of the supervision team for the A180 trunk road into Grimsby. He studied for his PhD (Design of Road Foundations, 1988) at the University of Nottingham and then rejoined Scott Wilson as a pavement engineer, where he was involved in numerous pavement evaluation projects as well as general design consultancy. From 1991, he lectured and supervised research part-time at the University of Nottingham in parallel with consultancy activities, becoming a full-time academic in 2014. His research interests include pavement analysis and design, the behaviour of pavement materials, for example cold-mix asphalt, surface damage, skid resistance, the use of geogrids and stress-absorbing membrane interlayers, and vehicle energy consumption.

Part 1

Principles

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Chapter 1
Introduction

When all is said and done, the pavement industry deals in high-volume, low-cost materials. In the UK alone, there are approximately 14 000 km of trunk roads and motorways with a surface area of some 250 km^2, around 10% of which has to be resurfaced each year. In the USA, this can be multiplied by about six. Furthermore, these are not figures that can be dramatically reduced while motor vehicle transport remains such a key factor in the economy, whether electric or petrol powered. The choice of materials is, therefore, limited to those that can be easily and cheaply produced in large quantities – which inevitably means the raw materials of the earth, namely rock, sand and clay. Any additive used to give extra quality – such as bitumen or cement – has to be used relatively sparingly; otherwise society just could not afford it – to say nothing of the environmental cost of such additives. The job of the pavement engineer, therefore, is to maximise the potential of these cheap, readily processable materials, including their potential to be repeatedly recycled, preferably in-place. The unit cost of the bulk materials may be relatively low, but the quantities required are very high indeed, which means that a modest saving per square metre can multiply up to a very substantial saving overall. To put it another way, if the life of a road pavement can be extended by 10%, this represents a very large contribution to the local economy.

1.1. The long history of the paved highway

It is impossible to know where or when the wheel was invented. It is hard to imagine that Stone Age humans failed to notice that circular objects, such as sections of tree trunk, rolled. The great megalithic tombs of the third millennium BC, notably the pyramids of ancient Egypt, bear witness to ancient humans' ability to move massive stones, and many commentators assume that tree trunks were used as rollers – not quite a wheel but a similar principle! However, it is known for certain that the domestication of the horse in southern Russia or Ukraine in about 4000 BC was followed not long afterwards by the development of the cart. It is also known that the great cities of Egypt and Iraq had, by the late third millennium BC, reached a stage where pavements were needed. Stone slabs on a rubble base made an excellent and long-lasting pavement surface suitable for both pedestrian usage and also traffic from donkeys, camels, horses, carts and, by the late second millennium BC, chariots. Numerous examples survive from Roman times of such slabbed pavements, often showing the wear of tens of thousands of iron-rimmed wheels. Traffic levels could be such that the pavement had a finite life.

Even in such ancient times, engineers had the option to use more than simply stones if they so chose – but only if they could justify the cost! Concrete technology made significant strides during the centuries of Roman rule and was an important element in the thinking of structural engineers. Similarly, bitumen had been used for thousands of years in Iraq as asphalt mortar in building construction. Yet neither concrete nor asphalt was used by pavement engineers in ancient times, for the excellent reason that neither material came into the cheap, high-volume category. As far as the pavement engineer was concerned, economics dictated that the industry had to remain firmly in the Stone Age. Even when the industrial revolution swept through Europe in the days of Thomas

Telford and John Loudon McAdam – the fathers of modern road building in the UK – the art of pavement construction consisted purely of optimising stone placement and the size fractions used.

Times have moved on. The massive exploitation of oil has meant that bitumen, a by-product from refining heavy crude oil, is now much more widely available. Cement technology has progressed to the stage where it is sufficiently cheaply available to be considered in pavement construction. However, there is no way that pavement engineers can contemplate using some of the twenty-first century's more expensive materials – or, at least, only in very small amounts. Steel can only be afforded as reinforcement in concrete; even in such modest quantities, it represents a significant proportion of the overall cost. Plastics and glass fibre find a use in certain types of reinforcement product and polymers can be used to enhance bitumen properties. However, the driving force is always cost, which means that, whether we like it or not, Stone Age materials still predominate.

1.2. Materials for pavement construction

In introducing the various building blocks from which pavements are constructed, it will not be possible to entirely avoid the use of technical terms such as 'load', 'strength' and 'stiffness'. Definitions of such terms are given in Section 1.5.

1.2.1 Soil

Every pavement, other than those on bridges, self-evidently includes soil. The most basic design requirement of any pavement is that the underlying soil is adequately protected from applied loads. Thus, no pavement engineer can avoid the need to understand soil. The following list provides some key facts.

- Soils vary from heavy clays, through silts and sands to high-strength rocky materials.
- Soils are not usually consistent along the length of a road or across any pavement site.
- Soils are very sensitive to water content and so are critically affected by the effectiveness of drainage provision.
- Water content will vary during the life of a pavement, sometimes over quite short timescales, in response to weather patterns.
- Some soils are highly permeable; some clays are virtually impermeable.

All this leads to one thing – *uncertainty*. However clever one tries to be in understanding and characterising soils, it is quite impossible to be 100% sure of the properties at a given time or in a given location.

This uncertainty makes life considerably harder. Nevertheless, it is necessary to categorise each soil type encountered in as realistic a way as possible, and there are two fundamental areas in which soil behaviour affects pavement performance. These are

- stiffness under transient (i.e. moving wheel) load
- resistance to accumulation of deformation under repeated load, likely to be related to shear strength.

The various means of testing, measuring and estimating these properties are covered in Chapter 6 of this book, as are the possibilities of soil improvement by using additives such as cement and lime.

1.2.2 Unbound pavement materials

Unbound materials used in pavement construction include natural gravel, crushed rock and granulated industrial by-products such as slags. Soils are also unbound materials, albeit often with a very small particle size (2 μm or less for clay), but the key difference is that a soil is not, in general, 'engineered' in any way. An unbound pavement layer, on the other hand, will be selected and quite possibly deliberately blended to give a particular combination of particle sizes. It can also be mixed with a predetermined amount of water. One would therefore naturally expect that much of the uncertainty inherent in soil properties is removed in the case of unbound pavement materials. It may still be difficult to predict performance accurately, as different material sources, most commonly different rock types, might be expected to exhibit slightly different properties due to their different responses to crushing or their differing frictional properties. Nevertheless, an unbound pavement material will be a much more controlled and predictable component than the soil. Even the variation in water content will usually be more predictable, in both magnitude and effect, than in the case of soil.

However, the properties of unbound pavement materials of interest to pavement engineers are actually more or less the same as those of soil, namely

- stiffness under transient load
- resistance to accumulation of deformation under repeated load, related to shear strength.

Chapters 6 and 7 of this book will describe the behaviour of unbound materials and the design and performance of unsurfaced pavements.

1.2.3 Bitumen-bound materials

This is a material almost unique to pavement engineering, a material whose beneficial properties were discovered almost by accident, but a material that is now very much at the centre of pavement technology. There are countless stories as to when bituminous products were first used on roads, including the accidental spillage of tar outside Derby iron works in 1901. Although mastics, including natural asphalt, had been used on footways since the 1830s, they were not stable enough for roads, and it was not until around 1900–1901 that the first usages of tar-bound stone occurred at approximately similar dates in the USA and Europe.

While proportions differ around the world, typically some 90% of paved highways have a bitumen-bound surface layer; whatever the make-up beneath the surface, bitumen and bitumen-bound materials (referred to hereafter as *asphalts*) currently play a major role. And bitumen is quite different from the sorts of cement used in concrete. Whereas concrete is a rigid material that cannot deform appreciably unless it first cracks, asphalt can slowly change its shape because bitumen remains a viscous liquid at normal in-service temperatures.

An ability to change shape may seem a rather undesirable quality and it can indeed lead to deformation – hence the phenomenon known as 'rutting' or 'tracking'. However, it also overcomes some of the difficulties encountered with concrete. For a start, the expansion and contraction with day–night temperature variation is accommodated simply by a small viscous strain within asphalt, meaning that no movement joints are required and that thermally induced cracking will only occur under the most extreme temperature conditions (continental winters, deserts). Asphalts are also able to accommodate any moderate movement within the foundation, for example, minor differential settlement in an embankment, movement that might lead to the fracture of a rigid concrete slab.

Furthermore, the tendency of asphalt to change its shape can be controlled by proper mixture design such that rutting is minimised.

However, despite the flexible nature of asphalt, it can still crack. It is impossible to define a tensile strength, as this will vary with temperature and the rate of loading; the relevant parameter is the *fatigue characteristic*, which defines resistance to cracking under repeated load. The key properties required for design are therefore

- stiffness
- resistance to deformation under repeated load
- a fatigue characteristic.

Chapter 9 will explore the properties of asphalt in some detail, leading to the design of asphalt-surfaced pavements in Chapter 11. Chapters 13 and 14 will extend this to cover the increasingly important topic of so-called 'cold-mix' asphalt.

1.2.4 Hydraulically bound materials (HBMs)

Nowadays, the availability of Portland cement, and substitutes such as fly ash or ground granulated blast-furnace slag, means that it can be economical to use such a binding agent to strengthen an unbound material. These binders are known as 'hydraulic' binders, as they require the presence of water for the cementing action to take place. Cement technology is a vast subject in its own right and is evolving rapidly in response to the need to reduce the carbon dioxide emissions associated with its production. The hydration of Portland cement involves several different chemical reactions, the most important of which are the conversion of tricalcium silicate (*c*. 50% of Portland cement) and dicalcium silicate (*c*. 25%) into hydrates (forming strong solids) by reaction with water, also generating calcium hydroxide and heat. The first reaction is rapid; the second is slower. The reader should refer to specialist literature for details.

HBMs, including so-called *pavement-quality concrete* (PQC) at the upper end of the strength spectrum, introduce a quite different type of behaviour and totally different design requirements. They possess a key property that is lacking in soils and unbound materials, namely the ability to withstand *tension*, and they also avoid asphalt's annoying tendency to change its shape. Individual particles are rigidly bonded together by the binding agent, and a definite tensile force is required to break that bond. In the case of a strong concrete, all the large particles are well bonded into a continuous matrix of fine aggregate and cement paste, and the whole material is solid and rigid. It has a stiffness that is still partly governed by the contacts between the large particles, but which is also heavily dependent on the qualities of the surrounding cementitious matrix. In the case of a weaker HBM, the binding effect may be less complete and some of the particle contacts may remain unbound, giving a certain freedom of movement within the material and a reduced stiffness and strength. Nevertheless, even a weak HBM will remain as a solid, with negligible permanent deformation until the bonds are fractured (i.e. until the tensile strength is overcome). The key properties for the pavement engineer are therefore

- stiffness
- tensile strength.

Arguably, a *fatigue characteristic* should be added, as for asphalt. However, the relationship with tensile strength is so close that it is hardly a separate property. It would also have been possible to add the *curing rate* (the rate of strength gain), as this certainly affects the construction process and economics significantly, and the *thermal expansion coefficient*, as this property strongly influences the tendency of a HBM to crack under day–night temperature variation, requiring the introduction of movement joints in most concrete pavements. Chapters 16 and 19 describe all these properties and associated tests, leading to the design of pavements incorporating these materials in Chapters 17 and 20.

1.2.5 Other materials

The four material types introduced so far represent the basic building blocks available to the pavement engineer. However, it is worth referring here to a couple of materials that do not fit so easily into any of the four categories. The first is *block paving*. Blocks are often made of concrete and so could be termed HBMs. On the other hand, they can be cut from natural stone or may comprise fired clay bricks. Moreover, the discontinuous nature of block paving means that the properties of the parent material are less important than the effects of the discontinuities. The blocks themselves may have the properties of concrete, for example, a stiffness modulus of some 40 GPa, but once discontinuities are taken into account, the effective layer modulus may be as little as 500 MPa. In effect, blocks form a perfectly shaped unbound material and block paving is therefore considered in Chapter 7 as a special case of unbound pavement.

The second special case is a hybrid material, known in the UK as *grouted macadam* and in the USA as *resin-modified pavement*; it is also sometimes known as 'semi-flexible' material. This too does not fit neatly into any of the previous categories, as it combines an asphalt skeleton with a cementitious grout filling the voids in the asphalt mixture. It therefore utilises both bituminous and hydraulic binders. Having a two-stage production process, the material tends to be expensive and is used in particular heavy-duty applications such as bus lanes and industrial pavements. However, it actually resembles an asphalt much more than a concrete, and will be included as such in Chapters 9 and 11.

Block paving and grouted macadam are bulk-use materials at the expensive end of the range. There are also specialist products that are only used in small quantities to strengthen, or in some way improve, a pavement layer. Here, one could include concrete reinforcement products, either in bar form or fibres. There are also reinforcing products designed for asphalt – some are steel, others are polymeric or made of glass fibre. A similar range of products is available for the reinforcement of unbound materials. Geotextiles comprise a closely related range of products, produced in various ways and forming continuous layers separating two different pavement materials (commonly the soil and a granular layer). These too can have a reinforcing function, but their most common use is simply as a separator, ensuring that fine soil particles do not migrate up into the pavement and that stones from a granular layer do not lose themselves in the soil. It is obviously the responsibility of the pavement engineer to understand how (and whether) these products work in particular applications rather than relying solely on the, sometimes not unbiased, opinion of a supplier. They will be introduced with each relevant pavement type and also with the topic of pavement rehabilitation in Chapter 27.

1.3. Typical pavement structures

This section is principally included to introduce the relevant terminology. The first terms that should be drawn to the reader's attention are *flexible, rigid* and *composite*, all of which are used to describe certain generic classes of pavement. Basically, a rigid pavement is one with a PQC slab as the main structural layer; a flexible pavement consists entirely of unbound materials and asphalt and a composite pavement has an asphalt surface overlying a hydraulically bound (e.g. concrete) base.

1.3.1 Pavement layers

Figure 1.1 illustrates the case of a heavy-duty flexible pavement.

At first glance, pavements appear to be unnecessarily complicated. However, everything is there for a reason. The *subgrade* is inescapable of course. *Capping*, where needed, is best seen as a subgrade-improvement layer, as it is uneconomical to place high-value materials straight onto a weak soil. Capping itself is generally a cheap, locally available material, sometimes simply the subgrade soil treated with lime, cement or some other hydraulic binder.

Moving to the top, the *surface course* (not present as a separate layer in rigid pavements) is a high-quality (and therefore expensive) material, tough enough to withstand direct loading, and with surface properties designed to achieve adequate skid resistance and, where required, low noise. As it is expensive, it is not generally a thick layer, 20–50 mm being typical.

Somewhere in the middle of the structure, the *base* is the layer that gives the pavement most of its strength. It is usually relatively thick (often 200 mm or more) and therefore has to be as inexpensive as possible within the constraints of the required mechanical properties. The result is that a large aggregate size tends to be used, whether the layer is asphalt, a HBM or an unbound material, and a likely side effect of a large aggregate size in an asphalt or roller-compacted hydraulically bound base is a relatively uneven finish. This means that it is difficult to achieve a good-quality finished road surface if the surface course is applied directly; hence there is frequently a need for an intermediate regulating layer – the *binder course*. The binder course material is often very similar to the base, but with a smaller aggregate size, which means it can be laid to a typical thickness of 50–80 mm.

Finally, the *sub-base* is much more than just a fill-in layer. The performance of an asphalt or concrete base is critically dependent on the stiffness of the layer immediately beneath, because of its influence on the flexure of the base under traffic load. A firm support will limit such flexure.

Figure 1.1 Pavement layer terminology