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The Construction Cycle of Pavements

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Executive Summary

This report outlines the process for the construction of a pavement. While focus is put on segmental pavements, the broad framework can be applied to any type of pavement project. It is divided into three major phases. A case study is used in each section to identify the key elements.

Site inspections are important to understand the local conditions. The first case study focused on two pavements located in central Sydney, where the construction and performance of the surfacing were compared. One was a stretch of segmental masonry along a highly pedestrianised mixed-use street, and the other, a rigid concrete hardstand/driveway hybrid leading to a loading dock. As these pavements were constructed relatively recently, there were few defects. However, the defects that were present highlighted the differences between the construction and properties of each type. The segmental masonry had localised defects while the continuous concrete had dispersed cracks along its surface, reflecting the distribution of loads. This step gives invaluable information about how types of pavements will perform in the environment.

The design phase used published literature to determine the shape of the pavement as well as its suitability for a designed load. Using the guidelines laid out by Australian authorities, the acceptability of a candidate asphalt pavement was calculated, focusing on fatigue and permanent deformation. This project was found to have failed on both fronts, citing major problems at heavy loads. Other literature was used to find a good starting point for the profile of a segmental pavement that was to be used in an industrial context. These two examples helped give an indication of what the design process is like.

The final section analysed was the construction planning process. Picking materials and choosing a design out of a variety of options are vital steps that engineers must go through. Writing up specifications for contractors to follow also requires a different set of skills. The translation of technical designs and language to simple, utilitarian language is vital to ensuring that a structure is built properly and will reflect the designs. While detailed explanations on design choices are valuable, it can crowd contractors in unneeded information for construction.

Throughout this report, a cohesive narrative about the construction process, from scouting to building, is laid out. Every step is crucial, and idling on one will be a great detriment to the rest of the process. While information is always valuable, it is also important to understand when it is useful and when it is unnecessary.

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1.0 Introduction

Pavements have been a fundamental part of human life, facilitating movement of people from place to place. Starting from simple dirt animal tracks, going to cobblestone pathways, and developing into the concrete and asphalt highways of today, clear transit lanes are central figures in interactions between people. The composition of these pavements has changed over time, adapting to the uses and needs of each period. With the industrial revolution, road infrastructure greatly shifted, not just in physical construction, but also in social construction. The pilfering of public land for private use critically facilitated the evolution of pavement materials as well as the public's perception of what roads are used for. While roads and pavements are not the only way to transport people and goods, it has become the dominant form of transport. Largely due to lobbying by the auto industry and the political popularity of key figures like Robert Moses, roads were moulded around cars in North America, eventually seeping into the rest of the Global North. The Global South is also plagued with cars. 27.5 traffic fatalities per 100,000 were recorded in low-income countries as compared to 8.3 in high-income countries (World Health Organization 2018), highlighting the inequalities inherent in the current shape of transport infrastructure. Pavements are not the primary cause of these deaths but can however play a part in altering these numbers.

This report follows overarchingly covers the life cycle of pavements. The three major components have been individually analysed in the attached appendices, each using a case study to further explore their respective elements. Part 1 investigates site inspections, looking at two sites located within the inner-Sydney suburb of Chippendale. The differences between construction of two pavements, made of segmental masonry and rigid concrete, were compared as well as their failure methods. The second section dealt with pavement design. It goes through the process of designing and calculating the acceptability of an asphalt pavement following the guidelines provided by Austroads. The initial design process was briefly examined using available literature to examine the profiles for segmental pavements in industrial contexts. Finally, part 3 outlines the construction process, using another industrial segmental pavement case study. Specifications were written up, covering the ripping and re-compaction of a base course, and block laying processes that transform theoretical calculations to a physical structure. Detailed analysis of design choices and construction processes were also included. From these three sections, a thorough story of pavements can be attained.

2.0 Pavement Construction Process

This section was divided into three sections to reflect the three major steps analysed in the previous reports. These reports can be found in Appendices A, B and C following a chronological order of the process for building a pavement. Part 1 goes over the initial phase of construction, the site inspection. The gathering of data is vital for the next phase, design. This is covered in section 2.2. After the design is finalised, the final phase for engineers is the construction phase. Specifications need to be drawn up for how the pavement is to be constructed. The process of translating a design into the component steps for contractors to read is crucial in ensuring that a pavement is built properly and reflect the design made by the engineer. Each of these phases are crucial in building any structure, and inadequate effort put into any of these sections may lead to disastrous outcomes.

2.1 Site Inspection

As seen in plate 2.1 (Appendix A - 3), the two sites were located just South-West of Central Station in Sydney. This site was all developed as part of an urban renewal project, dubbed 'Central Park', which gentrified a former brewery with construction finishing roughly around 2015. Several residential buildings as well as a mall were erected as part of the project, creating a mixed-use environment. The first site, Kensington St, was a largely pedestrianised 170m long corridor with restaurants pressing up on both sides of the street. This area, along with a smaller completely pedestrianised alley was collectively called 'Spice Alley', attracting many patrons. Conversely, the second site was a hardstand-driveway hybrid located next to the residential building, 18 Park Lane. It acted as a hardstand for fire trucks during emergencies, but its most frequent use was as an entrance to the loading dock for the nearby mall. Plates 2.1 and 2.2 (Appendix A - 3) give a visual reference for Kensington St and Park Ln respectively.

2.1.1 Construction

Kensington St was designed as an 8m wide flexible segmental block pavement, replacing a previously asphalt residential street. Consisting of three main layers, the sub-base; base and wearing surface (Sharp 2009; Shackel 1990), block pavers were used as the wearing surface due to its aesthetic fit with the local environment. The Austral Hamlet bricks were laid in a 45° herringbone pattern, with stretcher bonds bounding the expansion joints on top of a 30mm compacted sand bed. This laid on top of a 150mm compacted base which sits atop a compacted granular fill sub-base. Some of the trachyte curbs were also reused. On the other hand, the Park

Ln hardstand was a rigid concrete pavement, consisting of two large slabs roughly 11.5m by 10m in dimension. As seen in plate appx 2.1 (Appendix A - 15), steel reinforcements are visible, indicating that it is most likely a Jointed Reinforced Concrete Pavement. Rigid pavements only consist of the compacted sub-base and the reinforced concrete layer. This sub-base can range from a 125mm bound sub-base to a 150mm layer of lean mix concrete. The minimum thickness of the concrete slab can vary between 150mm to 230mm based on the design load. As it could be expected for large class 5 or 9 trucks, a thicker slab can be expected. One of the major factors influencing the construction process was labour and its associated costs. The laying of block pavers requires considerably more labourers to hand-lay each brick and to complete the section on time. The use of a mechanised laying machine can speed up the process, however as highlighted by Shackel (1990, p.209), these machines are best used in large standard areas with little interruption in the pattern. Therefore, it is unlikely that machines could be used at this site. Comparatively, cement requires much fewer labourers at one time. However, constant attention is required during the curing phase. Another problem was material costs. As concrete and the bound sub-base require high-cost materials, arguments for a segmental pavement, which uses generally cheaper materials, can also be made.

2.1.2 Performance

The primary purpose of the site visit was to investigate the condition that these two pavements were in and identifying the types of defects that should occur in each. As both pavements are less than 10 years old, very little degradation was expected, with only minor defects being visible. This was largely true of the Kensington site, where low vehicle traffic meant that there were fewer opportunities for high load impacts on the pavement. Some localised cracking was observed, as seen in plate appx 1.3 (Appendix A – 12). These cracks were also largely located near the expansion joints, suggesting stresses from the movement of the expansion joints may have accelerated the cracking of these blocks. Notably, more defects were observed towards the end of Kensington St, where Dwyer St fed more vehicles onto the road surface. Plate appx 1.6 (Appendix A – 13) illustrates this. This highlights that vehicle traffic is a major factor in the deterioration of pavements. From the time it was constructed, little has changed about the general loading conditions on Kensington St. However, temporary staging may be a new addition, along with the associated trucks that transport them.

The Park Lane hardstand shows more visible signs of wear. This may be due to the different design load combined with the nature of the pavement type. As a continuous pavement is

designed to distribute loads across its whole area, cracks can easily propagate through the whole section. Light cracking can be seen near the 18 Park Lane boundary (plate appx 2.2 & appx 2.3 in Appendix A – 15/16). These light crocodile and parallel cracks may be due to overloading, or an unintended loading structure. Longer, deeper longitudinal cracks that affect the whole slab are also present (plate appx 2.4 & appx 2.5 in Appendix A – 17/18). The visible steel reinforcement as mentioned previously may also be alarming, since exposure may lessen its load-bearing capacity as well as accelerate rusting. Spalling near the gutter and holes under the bollards sandwich the pavement with defects along the edges. Plate appx 2.7 (Appendix A – 19) indicates potentially serious damage, which may need repairs soon alongside the damage seen in plates appx 2.9 and appx 2.10 (Appendix A – 20). The edge spalling may be a result of the drain expanding and contracting in weather, causing the concrete to chip at the edges, especially as heavy vehicles travel across this gap. These defects show signs of wear, which may follow observations made by Sharp (2009), that trucks are frequently loaded over their legal limit. Furthermore, the use of the hardstand as a makeshift stopping zone results in many vehicles, heavy and light, frequently parking on the pavement, accelerating fatigue. This can be partially seen in the greater number of cracks observed under where vehicles regularly park.

2.1.3 Importance of Site Inspections

The comparison of the two sites highlights the benefits of both types of pavements. Firstly, the versatility of block pavements mean that they can be used in a multitude of contexts. Failures are also localised. Combined with the relative ease of replacement, segmental blocks offer longevity as well. Continuous rigid pavements are also useful in industrial and heavy load applications. Their ability to distribute the load allows for heavy loads. However, defects are also more likely to spread, which means that if a major failure were to occur, it can lead to the failure of the whole pavement. The cost of materials is another factor that needs to be considered. As reinforced concrete slabs are expensive materials, it may not be attractive in cases where strength is not entirely necessary.

Through this case study, the process of site inspection can be understood. This involves various important actions. Firstly, gathering data regarding the location of the site is paramount in understanding the local context as well as what the engineering parameters, such as topography or geology, are for a potential project. Secondly, proficiency in assessing the performance of pavement structures is also developed. This allows for engineers to judge the compatibility of

specific designs to different location. Site inspections give invaluable information to engineers, allowing for better designed surfaces.

2.2 Pavement Design

After the analysis of the project site, appropriate designs for new structures can proceed. The first section of Appendix B follows acceptability calculations for a designed asphalt pavement. The properties of the candidate pavement are summarised on pages 1 and 7 (Appendix B). Following the steps laid out in appendix L3 of the *Guide to Pavement Design Technology Part 2 (2017)*, fatigue damage and permanent deformation were analysed. The calculations have been collated from page 7 (Appendix B). As mentioned in the report, both the fatigue and permanent deformation calculations did not meet the acceptability criterion. The main cause of damage appears to be from the high Single Axle Single Tyre loadings. Reducing this damage would be essential to meet the acceptability criterion. Changes to the properties of the pavement, such as increasing the thickness of the cement layer or stabilising the granular sub-base, may be required. The broad steps followed in this section give a glimpse into the design process. Calculations for the acceptability of a design is conducted, which then help to identify problem areas and proper fixes can be implemented.

The second section of this report dealt with the initial design part of the process. The use of published literature is an invaluable asset for finding where to start. A segmental block pavement was to be designed for industrial purposes. Using the readings in Chapter 4 of Shackel (1990), the basic profile of the pavement was calculated. The specifications are summarised on page 2 (Appendix B). Stabilisation of the granular material was also discussed. Binding the granular material using cement or other methods offers a more solid layer that can withstand higher loads without failure. This does come with the drawback of requiring more expensive material. Gravel is a relatively cheap material, and the use of cement to bind it does negate some of the fiscal savings of using this material. As the design brief did not call for stabilisation, it was not used in the design. However, the limitations of literature are also visible in this case study. As the writings are generalised, it has the potential of not accounting for the different environments a project may be in. Therefore, the discussion on stabilisation can be used as a reference for strengthening the pavement. Especially since the literature was limited to a relatively lower loading group, meaning that the design may not be acceptable for the actual designed loads.

By using the two case studies in this report, a more thorough understanding of the design process can be achieved. Design begins with the selection of an initial profile for the pavement. Calculations for acceptability criterion are then required to determine whether the design is sufficient. Alterations can then be made and iterated upon until the design meets specifications. The finalisation of this process can then be handed off to the next stage, where specifications for the construction of the pavement are required before being handed off to contractors and built.

2.3 Road Construction

The final case study centred around the construction of an interlocking segmental pavement that was to be used in an industrial setting. The basic layout of the site is catalogued on pages 1 and 14 (Appendix C). Replacing a previously asphalt pavement, the project covered the ripping; re-compaction; and laying of the new concrete pavers. Specifications for this job were written up (Appendix C – 11), ensuring that only the most essential information regarding the actual construction of the pavement was included. This aids in the smooth operation of the site as well as laying out all the required components for the contractor. Obfuscation via text may result in key information getting missed, thus considerations must be made for a clear, succinct specification document. Analysis of the design choices is also important but can be left in a separate document.

2.3.1 Material

Material selection is a key process for construction and a whole variety of factors need to be considered. This project was to use ‘Unipave 100’ and ‘Techpave 100’ blocks for its wearing surface. Pigmentation being one factor needed to be considered, black pavers were chosen as they may help identify areas with efflorescence, a known problem on the site. A lighter paver was used in the edge course to delineate the pavement, helping with navigation of large vehicles. Sourcing is another factor that needs to be considered. While locational data was assumed, it was very difficult to find any manufacturers that provided interlocking pavers that met the design requirements set out. This may be due to various recommendations and guidelines opting to use 80mm pavers as mentioned in the report (Appendix C – 3). Bedding and jointing sand provide pivotal support to the pavement structure, ‘locking in’ the concrete pavers as well as filling in the gaps between them. These sands increase the strength of the pavement and help to improve longevity as chips and other defects are minimised by somewhat restricting free

movement of individual pavers. The use of a concrete edge restraint also helps to bound the pavers, and therefore require concrete with properties strong enough to withstand the forces exerted from moving heavy vehicles. Importantly, bituminous spray seal was used to negate the problem of efflorescence, highlighting the need to sometimes alter the design from the guidelines to accommodate the local environment.

2.3.2 Equipment

The selection of equipment is also another area where thought must be put in. Machinery streamlines the construction process. The list of equipment to be used on this project can be seen on page 12 (Appendix C). Each piece fulfills a certain role and provides invaluable aid to the workers on site. For example, the excavator massively helps in the ripping of the basecourse material during the first stage of the project. The utility of prior research can also be highlighted in this area. Data regarding the number of passes required for adequate compaction on a roller was available, influencing the choice of rolling equipment. A hand-driven plate compactor was chosen to accommodate the existing structures on the site, highlighting how site investigations can influence the construction method. Labour considerations can also affect the equipment used. Labour-saving devices such as a forklift and mechanised block-laying machines increase the productivity and output of workers, allowing for quicker turnarounds, especially on large projects like this. Screeding machines also save labour as well as allow for a more accurate and consistent finish to the job it carries out.

2.3.3 Site Management

Decisions also need to be made regarding on-site operations. The proper storage of materials is important for maintaining quality control as well as security. Thus, all materials should be inspected prior to accepting and should be stored securely under cover. As the properties of the materials may be altered if left unchecked, it is important to keep them properly stored as required by the manufacturer. The process for the preparation of the base course is analysed on page 5 (Appendix C). Attention should be put on two key aspects. Firstly, that there are restraints on certain types of equipment due to site conditions, meaning that the selection of equipment is paramount. The use of heavy machinery also means that care needs to be taken when moving them around the site. If not planned for properly, it can cause unintended damage to other parts of the site. Secondly, the need to test the adequacy of the job regularly and broadly is highlighted. The compaction levels and associated water levels greatly dictate the properties

of the soil; thus, a lot of attention should be placed in ensuring that the specifications are adhered to.

Scheduling for the construction process is important to ensure timely progress but also for the integrity of the finished structure. Screeding and laying of the pavers are an example of this. As the strength properties of the sand are dependent on the water content, considerations should be made regarding the laying schedule to ensure no changes to the handling characteristics of the pavement. In conjunction with this, the decision to start laying from the bottom of the hill also reflect the geographic context of the site as well as logistical efficiency. As the pavers are stored at the bottom of the site, the completion of the bottom section results in a finished surface that the machinery can then easily traverse and operate on top of. Similarly, the continuous compaction of the pavers allows for the heavy machinery to continuously operate without damaging the surfacing. Using the plate compactor previously used for the final compaction cuts down on the total number of different equipment needed. This final compaction is achieved using 2 cycles of compaction. The first sets the pavers in place while the second ensures the jointing sand has filled the joints and prevents chipping. The laying process is also hastened as the machinery can now operate much closer to the work face. The choice for the 45° herringbone pattern is grounded in the physical properties of the pavers and laying pattern (Appendix C – 6).

2.3.4 Skills

As seen in the previous sections, there are countless factors that need to be considered while designing any structure. This stage cannot be completed without all the work put into the prior phases. The culmination of all the information gathered allow for engineers to translate theory and calculations into a set of instructions that contractors can follow to physically build the pavement. The importance of information could also be seen in the areas where data could not be attained. Locality, climate, water tables, urgency and budgeting were just some of the factors not considered. These parameters may greatly affect the choices made in the specification. For example, information regarding equipment hire costs and the wages of labourers may influence the calculus on the economics of the project. This highlights that the ability to make good assumptions is another skill is required. Decision-making regarding the design as well as the determination of what information is necessary for who is key for cohesionless communication across multiple disciplines. Translation and adjusting language to meet the abilities and needs of others is also displayed.

3.0 Conclusion

Various elements of the pavement construction process have been analysed. This report has especially highlighted the great versatility of segmental pavements. Part 1 illustrated the aesthetic qualities, being used in a predominantly pedestrianised mixed-use corridor. The following parts explored its use in industrial contexts. Different failure modes of materials and its applicability in various situations were observed. The high strength of rigid concrete pavements, owing to its load distribution capabilities, highlighted the use of concrete in industrial applications. However, as the failures will also distribute and propagate throughout the structure, proper calculations are required to ensure that this type of pavement is engineered accurately for its use-case. A similar process can be followed in the use of a mechanistic design method to check the acceptability of an asphalt pavement. The published literature explored in section 2 emphasised the key differences noted in the composition of segmental and continuous pavements. The final case study highlighted another benefit of concrete block pavers as well as explored the process to manifest designs into structures. Repairability becomes a considered factor for block pavers as failures are more localised, reflecting the segmented construction process. The laborious nature of segmental pavement construction may be costly and intensive, as seen in the specifications included. However, it may be worthwhile when considering on a longer timeline.

The interests of the capitalist class have and continue to have influence over urban planning. The early 20th century saw the auto industry instigate various campaigns, from creating the concept of the 'Jaywalker' (Norton 2011, p.78) to the dismantling of trams networks in the US (Marx 2022, p.30) and across the world. Nothing substantive has changed as tech companies continue to hawk *gadgetbahns* such as the 'Loop' by Elon Musk or Uber rideshares or Lime bikeshares. Pavements have shaped the outline between public and private space. Prior to mass adoption of cars, streets were a place for everyone (Marx 2022, p.20). Now Automobiles dominate the decision-making process for everything. This starts on the pavements upon which the foundations of society are built. A lot has changed in material availability and selection since the Belgian block highways of Robert Moses. But the wrong lessons have been learned as the concrete Katy Freeway continues to get clogged in traffic (Cortright 2016). Induced demand was a concept exemplified by the Moses highways (Caro 1975, p.515), yet engineers have repeatedly failed to acknowledge it in their designs, even if traffic flow is made smoother with better materials. Engineering is innately political; it is past due that engineers face that fact.

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APPENDIX A

Site Investigation

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Executive Summary

This report aims to analyse the differences between pavement types. Comparisons between segmental and continuous pavements were made to study the changes in construction material and processes, use-cases, and longevity. Two sites were chosen for a case study to investigate real-world applications of different paving materials. Both sites were in the inner-city suburb of Chippendale, where an urban renewal project was undertaken to transform the former Carlton & United Brewery into a mixed-use neighbourhood. The brick street of Kensington Street and the concrete hardstand/driveway area in front of 18 Park Lane were conveniently located next to each other and thus were chosen for this investigation.

The use-cases of these two sites varied greatly and is reflected in the material used for the pavement. Kensington St is a shared zone that is highly pedestrianised. Commercial businesses line the whole street. Vehicle traffic is kept to a minimum, with mainly delivery trucks stocking the businesses along Kensington St. The Park Ln driveway consists of two 10m by 11m slabs of concrete and serves a multitude of uses. Many trucks utilise this space as there is a loading dock for a nearby mall and the garbage facilities for the whole complex are located within. Fire trucks also use this area to park and respond to emergencies, thus requiring a strong and rigid surface that can withstand these heavy loads.

The construction processes differed quite significantly. Kensington St was formerly a residential street and was able to reuse some material, while Park Ln was an entirely new build. The brick pavers on were laid upon a subbase and base layer of compacted soils and rocks. Only one layer of cemented material beneath the thick jointed concreted surface layer was used for Park Ln. The labour required for construction differed among pavement types. Brick pavers are more labour intensive due to the small size of each brick while concrete pavers require less workers but constant care and maintenance during the curing process.

Both pavements were in good condition, with only minor defects being present. A few bricks were cracked near the expansion joints, indicating that these areas cause faster degradation on the brick component. A few more defects were observed on Park Ln. minor cracking across the whole surface, with some cracks travelling along both slabs were present. Well-developed spalling and the exposure of a steel rebar were some more concerning observations. Spot damages from abnormal sources, such as chemical erosion on the brick surface and holes under

the bollards were also seen but seemed to pose no major threat to integrity. As these pavements are quite new, it is expected that more defects will gradually develop, worsening the already present defects.

The choice to use either pavement type should be done while taking in the consideration of use case, environmental context and labour and material availability. Kensington St exemplifies the use case of brick in shared zones with low load requirements while Park Ln highlights the advantages of a rigid concrete pavement. Proper design and maintenance are crucial in increasing the longevity of a surface and planning for long-term use can help to achieve that goal.

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1.0 Introduction

From the humble beginnings of animal trails, the surfacing of travel paths has greatly changed and developed. Throughout most of human existence, roads have been a mixed-use environment, accommodating all types of users from horses to people to bicycles. Speeds were restricted to much safer limits and the organised chaos resulted in lively environments. With the invention of automobiles and the introduction of mass-production, pedestrians were quickly pushed off to the side of the road, lest they be run down by entitled motorists. To accommodate for the extra strain of these vehicles, pavement technology needed to develop as well. While many different materials were tried and tested, the size and weight of trucks grew rapidly. Traffic engineers have come a long way, going from the Belgian block highways of Robert Moses to the curated landscapes using a myriad of pavement materials today. The dominance of cars in cities has meant that for a long time, pavement research has been focused primarily on car infrastructure. Advocacy by urbanists such as Jane Jacobs and Jan Gehl have slowly been pushing policymakers to reconsider the urban landscape. With space being reclaimed by other road users, interest in different types of pavements has increased.

Pavements are a vital part of any urban environment and can shape how its citizens go about their daily lives. Fundamentally, they help facilitate the transportation of goods and people from place to place. By using different materials and finishes, human behaviour can be further influenced to reflect the desired environmental conditions. Thus, this report aims to analyse the effects of two different pavement types through case studies. Segmental pavements in the form of masonry and continuous pavements were studied. Details of the construction method of both types as well as its performance and loading characteristics are described below. The chosen sites were located right next to each other in the inner-Sydney suburb of Chippendale. The segmental pavement is located along Kensington St while the continuous pavement is situated in front of the residential tower, 18 Park Lane (The Mark).

2.0 Pavement Analysis

2.1 Context

Both sites are located within the Central Park complex. This area was formerly the Carlton & United Brewery (CUB) (City of Sydney 2013) and was redeveloped as part of an urban renewal

project started in 2007. As seen in figure 2.1, the complex is adjacent to Central Station and sits along Broadway, connecting it to the Sydney CBD. Frasers Property purchased and constructed the area to be a mixed-use urban environment (City of Sydney 2013), gentrifying the run-down brewery. The proximity to the CBD as well as multiple educational facilities such as UTS, University of Sydney and Tafe spurred the construction of luxury apartments. The Central Park mall, along with the Broadway and Market City shopping centres provide a plethora of retail stores for essentials as well as discretionary purchases. Wholistically, the precinct is located along a highly mixed-use area, resulting in high levels of mixed traffic.

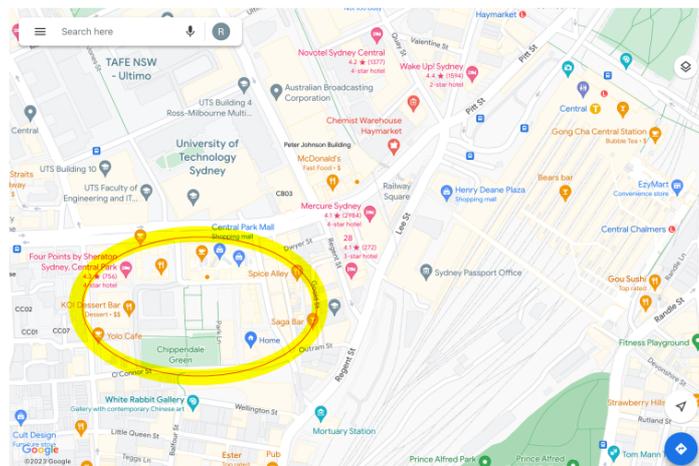


Figure 2.1. Location of Central Park Project

2.1.1 Kensington Street

Kensington St is a highly pedestrianised retail street with various restaurants and cafes along its 170m span. Completed in 2015 (Landscape Australia 2016), the 8m wide street is paved with herringbone pattern brickwork. Vehicle traffic is extremely low, primarily delivery trucks stocking the businesses along the street. There are only a few parking bays, roughly 4 to the left of the throughway. Some private vehicles of customers do travel through this street to park, however infrequently. Traffic is one-way from South to North and the posted speed limit is 10km/hr. Outdoor dining flanks both sides of the throughway, demarcated by planters as seen in plate 2.1. Kensington St connects Outram St to Broadway, with Dwyer St, a short residential street, funnelling some traffic towards the end of Kensington St. A parallel pedestrianised walkway with more eateries called ‘Spice Alley’ is also connected to Kensington St on the West with three entrance points. Due to the pedestrian friendly atmosphere, the street is regularly closed off to vehicle traffic and events are held along this strip. Temporary stages have been erected and performances at these events concentrate an even higher amount of foot traffic



Plate 2.1. Kensington St

2.1.2 Park Lane

Two concrete slabs roughly of equal size make the area in front of The Mark, which was completed in 2014 ('The Mark (Sydney)' 2021). It is approximately 23m by 10m and serves a dual purpose, as a hardstand and driveway entrance to the underground facility. Fire trucks occupy this space during emergencies that occur inside The Mark. Other times, it is mainly used as a driveway to the loading dock for the nearby Central Park Mall. Garbage, delivery and moving trucks that serve the entire Central Park precinct also enter the underground facility seen in the middle of the picture in plate 2.2. Private vehicles picking up and dropping off passengers also regularly use this area to wait. Due to the proximity to the Sydney CBD, the residents of 18 Park Lane also regularly walk along the pavement towards Broadway.



Plate 2.2. 18 Park Ln Hardstand area

2.2 Construction

Precise information on the construction process for these two sites were not available. Therefore, the best estimates were made to detail the makeup of the subsurface materials. The Central Park precinct sits upon Ashfield Shale (Herbert 1983), creating the subgrade foundation which the two project areas were built upon.

Prior to the urban renewal project, Kensington St was paved with regular asphalt surfacing, serving as a local residential street. It was then repaved with segmental masonry, using Austral Hamlet bricks in a Herringbone pattern (Brickworks 2019). A stretcher pattern running perpendicular to the street occasionally interrupts the herringbone pattern to indicate the entrances to Spice Alley. Brick pavers were extensively used along this corridor for a multitude of factors. Firstly, as it was located within a historical site surrounded by heritage buildings that use brick as well, masonry was deemed an aesthetic fit for the local context. Furthermore, segmental pavements have been shown to reduce the speed of vehicles due to the increased noise from driving on the unsmooth surface (Shackel 1990). This subtle accent quietly tells motor vehicles that this is a hostile environment to vehicles. Other pedestrian friendly materials, such as granite were used as a central dish drain (Landscape Australia 2016), 3m from the East boundary of the road. Some of the old trachyte kerbs have been reused in the repaving and runs along the Western edge.

Kensington St is a flexible pavement, due to its segmental masonry build and lack of formal joint system (Sharp 2009). Flexible pavements are comprised of three main layers, the sub-base; base and wearing surface (Sharp 2009). While the standards used at the time of constructing the top three layers was unavailable, the current standards published by the local council (City of Sydney) were easily accessible. Therefore, as the difference between the publishing date of the new standards and the construction date was not too dissimilar, the new codes were used in the analysis. Furthermore, outlines by Shackel (1990) give similar remarks in typical road design standards. The standards require a sub-base layer of compacted fill to CBR4 standard, which equates to 98% std Maximum Dry Density (MDD) (City of Sydney 2019). The base layer should comprise of 150mm of compacted DGB20, a well graded course base as outlined by RMS 3051. Similarly, 150mm of crushed dolomite was used in a brick intersection (Shackel 1990). As Kensington St was formerly a residential street, some of the subsurface layers may have already been there. Re-compaction of these layers may be

necessary but new material might not have been required during the laying process. Finally, a 30mm thick compacted sand bed sits atop the base and creates a surface for the brick to lay upon. The 76mm deep bricks were “bedded in a stiff slurry screed, with a wetter slurry screed broomed into the narrow 5mm joints” (Brickworks 2019). Along the surface, expansion joints are present every 4m, preventing the cracking of the brickwork.

Conversely to the flexible pavement on Kensington St, the Park Ln hardstand is most likely a rigid pavement. Due to the use case of the area, it can be sensibly presumed that this surface will require reinforcements due to the high loads of multi-axle trucks. The use of large concrete slabs also indicates rigid construction, allowing for more distribution of stress across a larger area. Rigid pavement construction only consists of a compacted subbase layer and the concrete base (Sharp 2009) above the subgrade. To help sustain a higher load, rigid pavements will be jointed. Of the four principal types of concrete pavement, Park Ln is likely to be a Jointed Reinforced Concrete Pavement (JRCP). The slabs of concrete at this site are relatively large at roughly 11.5m by 10m, suggesting that by size, only a JRCP design would be standard (Moffatt & Papacostas 2017). The thickness and type of subbase is dependent on the Heavy Vehicle Axle Group (HVAG), ranging from 125mm of bound subbase to 150mm of lean-mix concrete subbase. Thickness of the base concrete slab is also dependent on the HVAG, from a minimum thickness of 150mm to 230mm for high HVAG. With large trucks, possibly class 5 or 9 (4-6 axles), utilising this pavement, a high HVAG value would be predicted, thus a sufficiently thick base and subbase layer is required. Reinforcement is also used to help cope with the tensile stresses applied to this section. These steel reinforcements can be seen in Appendix appx 2.1, where some of the concrete has been eroded away and the inner structure is slightly visible.

The cost of construction is also another key point to consider when comparing different types of paving. While brick pavements may be aesthetically pleasing and safer for pedestrians, the laying of the masonry may be labour intensive. Each layer will need to be compacted well and the small size of the bricks result in large number of hands required to complete laying in a timely manner. The laying of rigid pavements only requires two layers. However, these layers are time consuming as both the base and subbase require a long time to set. The setting of the concrete is comparatively less intensive than the process to lay brick but may take longer and require constant maintenance to ensure proper curing of the concrete. Though these factors should be considered in the design process, the use-case should take priority.

2.3 Performance

The deterioration of pavement is expected from use. Gradual degradation from normal wear-and-tear is the ideal case for defect formations. Deficiencies arising from poor construction should be minimised, as it may drastically exacerbate wear and shorten the lifecycle of the pavement. With both pavements being in service for less than ten years, only minor defects were observed. These defects were in line with the pavement type, reflecting its use case and material properties. While most defects followed the pattern of use deterioration, some other defects were also observed.

As there is very little vehicular traffic, the deterioration upon the Kensington St surface has been kept to a minimum. Plate appx 1.1 depicts the current typical condition of the pavement. No observable defects are present bar minor discolouration of the mortar, similar to plate appx 1.2. The most common defect observed was cracking of the brick near the expansion joints. Plates appx 1.3 and appx 1.4 indicate that the daily heat cycling, and movement of the wearing surface has accelerated the deterioration of the bricks near the joints. Furthermore, it is noted that the bricks that were cracked were all oriented square to the direction of travel. Exemplified by plate appx 1.5, where the chipping on the brickwork is present in the stretcher pattern section. The end section of Kensington St was notably more deteriorated compared to the earlier section. Plate appx 1.6 highlights the faster wear at the intersection to Dwyer St. The larger number of vehicles utilising the pavement has increased the loading, resulting in visible wear on the mortar and brick surfacing. Cracks are also more frequent along this section for similar reasons, while again appearing in the bricks laid perpendicular to travel direction. Deterioration from wear can also be seen in the reused trachyte stones (see Plate appx 1.7). As these stones are much older than the brickwork, there is greater levels of chipping and holing. One abnormal defect was also observed along Kensington St. The patch of roughened brick seen in plate appx 1.7 was only concentrated within this single area. Therefore, it could be theorised that some outside force, possibly chemical erosion, occurred on this spot previously, leading to accelerated loss of smooth surfacing.

Overall, the surface along Kensington Street has appeared to have deteriorated at a reasonable pace given the traffic load. There has only been minor cracking along the high stress points. The section past Dwyer St highlights the effects of higher traffic loads, showing signs of greater wear. Furthermore, with the narrow width of the throughway, rutting may have potentially been

an issue as vehicles drive along the same path. However, no signs of rutting or heaving were observed, indicating proper compaction of sub-surface materials and water removal. As time passes, this may change, and rutting may appear with continued use by vehicles. The cracking of bricks and surface roughening will also continue. While the cracked bricks near the expansion joints may need to be replaced a bit earlier, wholistically the road surface has performed as expected.

Park Lane has fared slightly worse compared to the Kensington St pavers. While design considerations would have factored in the greater traffic and load stresses, the hardstand area has more signs of wear, although still in good shape. Minor aesthetic damage is present throughout the whole section. Various patterns of light cracking can be observed (See plates appx 2.2 and appx 2.3). The crocodile cracking may be a result of repeated over-loading due to increased frequency of “overloaded trucks with axle loads exceeding legal limits” (Sharp 2009) present in Australia. Therefore, any flaws in the curing process of the concrete will quickly develop into a crack. Longitudinal cracks as seen in plate appx. 2.4 underline the toll repeated heavy loads have on concrete pavements. Travelling square to the direction of travel, these cracks can potentially cause a failure in the surface if not treated and managed. Plate appx 2.5 shows deeper cracks that have not been treated and have developed larger gaps, eventually joined other cracks and forming large crack patterns as in plate appx 2.6. Furthermore, construction flaws can also be seen in plate appx 2.1, where the steel reinforcement is visible at the surface. This can be hazardous as it may accelerate and propagate the rusting of the reinforcements, reducing the slab’s ability to hold tensile stresses. Spalling (see plate appx 2.7) is another major issue. The gutter boundary is in a fair to poor condition and will only worsen at a faster rate if not managed properly. This may be due to the thermal expansion properties of the metal gutters, providing an axial stress that may not have been accounted for. The corners of the boundary also provide a nucleation site for cracks to form, creating linear cracks as in plate appx 2.7. Edge faulting can also be observed on the other boundary of the pavement, although to a lesser extent. Plate appx 2.8 shows the very slight change in height between the concrete pavement and the stone pavement. This is not present on other sections of the concrete-stone boundary, indicating potentially some moisture movement. The sealing between the boundary was noted to be split, possibly allowing for water to seep into the subgrade layer. Finally, the last notable defect observed at this site can be seen in plates appx 2.9 and appx 2.10. Located near a bollard with a missing bolt, it may be surmised that the hole was created from the uprooting of the bolt, pulling some of the concrete with it. A similar process may have

occurred at the adjacent bollard (as seen in plate appx 2.11), as the concrete is discoloured and appears to have been patched up. Another observation of this photograph highlights a crack running through the bolted concrete, indicating that these areas provide a structural weakness.

While the Park Lane hardstand shows more signs of wear, it is still in good condition. Many of the defects observed were minor, reflecting the young age of the pavement. This analysis highlights the difference in fault types and the difficulty in comparing the performance of wildly different pavement surfaces. As the concrete is a continuous pavement, defects can propagate throughout a much larger area, whereas cracks in brick will be mostly isolated to the affected brick. This feature may be used in different scenarios, providing a plethora of options for road surfacing.

2.4 Loading

As this area is newly built during the urban renewal project, the loading on the pavement surfaces has not drastically changed from the initial designed loads. It is unlikely for the hardstand area in front of The Mark to have a change in use-case or loading, as the dimensions of the entrance to the loading dock are limited. The aforementioned overloaded trucks may need to be addressed for the longevity of the pavement. Another problem may be the makeshift use of the hardstand area as a waiting zone for private vehicles and unloading zone for small trucks. As seen in plate 2.2, the right side is marked as a 'No Parking' zone that is rarely adhered to.

Kensington St will also likely not have any changes to the load structure. However, as it is a through road and previously being an asphalted residential street, it may at some point be reverted to carry more traffic though unlikely. The temporary staging may be an unforeseen use-case and may also be an unusual loading profile. The staging itself may not present a problem, but the trucks required to transport and set up the stage may cause some issues. These issues may all be exacerbated due to uncharacteristic weather and climate. With Sydney recently experiencing three La Nina events consecutively resulting in the highest annual rainfall recorded in Sydney (Hannam 2022), cracks and defects have the potential to quickly deteriorate as water seeps into them. Quick action should be taken to manage defects and plan for future potential changes to the use of these pavements.

3.0 Conclusion

Through analysis of two different pavement types, the construction process and the benefits of specific paving have been identified. The planning stage has been found to be a crucial step in choosing pavements as use-cases may determine the need to use one type of pavement over another.

The Kensington Street analysis highlighted the use of brick pavers for a highly mixed-use commercial street. The aesthetic charm and low need for strength were the main points discussed in the choice of brick pavers over alternatives such as asphalt or concrete. Labour was recognised as the major issue regarding this choice as it can be intensive on human labour and wages. Conversely, the Park Lane case highlighted the advantages of rigid concrete pavements. High loads require materials that can withstand these stresses, underlining concrete's ability to withstand stress. The labour issue can also be avoided partially as it is not as intensive, only requiring a few workers to constantly manage it during the curing process. If prepared and managed properly, pavements will be able to function for a long time. The flexible nature and small 'grain' size of brick compared to continuous concrete slabs results in defects concentrating in the affected area and not spreading across the whole structure. This can mean that individual bricks can be replaced and continue to be used for a long time. The concrete paver allows for a more distributed load, spreading the stress applied over a larger area and reducing the number of large failures. Thus, the benefits and drawbacks of each method can be identified.

Carefully choosing the right material and construction method is important. However, the use cases identified in this case study are not the only ones. The combination of the two different situations may also be an option. For example, the use of durable brick pavements in an industrial environment may be beneficial as defects are localised and can be quickly replaced. With the industrialisation of the global economy, materials have become cheaper and cheaper while labour costs have gradually increased. More so than previously, the abundance of choice and considerations may seem daunting, yet for a satisfactory and long-lasting result, this process must be undertaken.

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Appendix 1

Observed defects along Kensington St



Plate appx 1.1. Typical state of brick paving as at 1/3/23



Plate appx 1.2. Minor discolouration of mortar: 15cm measure for scale



Plate appx 1.3. Close up of crack at expansion joint. 15cm measure for scale



Plate appx 1.4. Cracking of bricks along the expansion joints



Plate appx 1.5. Chips on brickwork



Plate appx 1.6. Deterioration of the general surface is visibly worse near the Dwyer St intersection. Mortar and brick have higher levels of wear and cracking along joints.



Plate appx 1.7. Patch deterioration of brick surface

Appendix 2

Observed defects on Park Ln hardstand/driveway



Plate appx 2.1. Steel reinforcement visible on surface



Plate appx 2.2. Light crocodile cracking



Plate appx 2.3. Parallel set of cracks. iPad Air for scale



Plate appx 2.4. Longitudinal crack, traverses through both slabs from end to end



Plate appx 2.5. Deeper cracks



Plate appx 2.6. Large crocodile pattern cracks forming



Plate appx 2.7. Edge spalling along the gutter boundary



Plate appx 2.8. Light edge faulting along segmental pavement boundary



Plate appx 2.9. Close up of 1cm deep hole in concrete surface near bollard



Plate appx 2.10. Vertical shot of whole near bollard. 15cm measure for scale



Plate appx 2.11. Adjacent bollard to plate appx 2.10, discolouration of surrounding concrete and long crack through bolts

APPENDIX B

Pavement Design

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Executive Summary

This report discusses various design methods for two different pavement types. A mechanistic design method was used on a flexible asphalt segment following the outlines laid out in the Austroads guideline. This assessment aimed to check the acceptability of the candidate pavement for its designed use. Fatigue and loading were the main factors that were analysed. The candidate pavement was found to be not acceptable due to damage failure of the cemented material leading to the allowable permanent deformation not tolerating the design traffic. Increases in the thickness of the cement and sub-base layer should alleviate this problem. Economically, considerations could be made to stabilise the sub-base or thin out the asphalt material.

The pavement profile for a segmental cement pavement to be used in an industrial setting was also designed. Following the design brief, the segmental pavement would require a 700mm sub-base and 900mm base. The use of a granular base or stabilisation should also be considered for economic purposes as they will greatly reduce the thickness of the pavement as well as utilise a cheaper material. This can save almost 700mm of thickness, drastically reducing the amount of material required. However, applicability may be a concern for higher traffic designs. Stabilisation would also require more labour for installation, which may lessen the savings from reduce costly material use.

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1.0 Introduction

Pavements are fundamental in ensuring smooth and easy access for human activity. This is made possible through proper design of the surfacing. The process starts with the selection of the pavement material, which greatly alters the handling properties of the pavement. Then, calculations regarding the acceptability of the designed pavement are used to determine if it will be able to withstand the loads that will be applied to it when it is in use.

In this report, two different types of surfacing are examined. Firstly, a flexible pavement of asphalt will be designed using mechanistic design methods. A thorough investigation on the acceptability of a candidate pavement will be conducted. Secondly, a segmental pavement in the context of an industrial environment will also be briefly designed and analysed. This section will follow the frameworks of published literature and outline the required thicknesses of the material beneath the segmental pavers. The calculations laid out in both parts are compiled in the attached appendix for wholistic coherence. Through the design of two different types of pavements, a greater breadth of knowledge can be attained about the design process of road surfacings.

2.0 Design

2.1 Flexible Pavement

The acceptability of the candidate pavement was calculated following the guidelines laid out by Austroads. It follows the steps in Appendix L3 in *Guide to Pavement Design Technology Part 2 (2017)*. This procedure examines each component of the road structure independently as well as synergistically, ensuring that the pavement will be able to tolerate the designed loads. The whole procedure has been summarized and assembled in Appendix 3. The profile of the candidate pavement to be assessed was outlined in Table appx 3.1. All three of the asphalt surface, cemented bases and unbound granular sub-base were examined. The design brief outlined some values that were to be used. A CBR value of 3% for the 'Normal standard crushed rock' unbound granular sub-base and a 30-year design traffic of 1.09×10^7 Heavy Vehicle Axle Groups (HVAG) was given for the calculations. The critical strains found in steps 14 and 17 in Appendix 3 were also done externally and given. Finally, the desired reliability factor was 95%.

From the analysis, the candidate pavement will not be acceptable in its current form. As seen in Step 27 of the cemented material and Step 28, the pavement would fail under the given requirements. The fatigue damage in the cemented material greatly exceeds the limit of 1.0 by 2.60. This is mainly concentrated in the high loads of Single Axle Single Tyre (SAST) load calculations, accounting for over three quarters of the damage caused due to fatigue. Additionally, the designed cemented material will cause the failure of the surface due to the permanent deformation caused from cracking. The allowable permanent deformation calculated in step 28 does not exceed the design traffic load calculated in step 11.

2.1.1 Redesign

The biggest failure point in the current design would be the damage caused by SAST loads on the cement material. The high axle group loads contribute the majority of the damage caused to the road surface and if this can be addressed, there will be follow-on effects that will increase the likelihood of acceptability. The allowable group repetitions will need to be increased, which can be done by decreasing the values outputted by CIRCLY in steps 14 and 17. This can possibly be achieved by re-evaluating the profile of the pavement. Increases in the thicknesses of the cemented material may help strengthen the pavement against fatigue, as the cemented material is where the problems are concentrated. Similarly, increasing the subgrade thickness may also help to decrease CIRCLY values used in step 18 for the allowable permanent deformation. As the subgrade is unbound, another option would be to stabilise this layer, increasing the load bearing ability. A smaller design traffic would also achieve a similar outcome. However, this may not be possible as it would drastically change the use-case outlined in the design brief.

2.2 Segmental Pavement

This section dealt with the calculations for the depths of the base and sub-base for a segmental block pavement in an industrial use-case. The design process was taken from Chapter 4 of Shackel's *Design and Construction of Interlocking Pavements (1990)*. Following three main steps, a basic profile for the pavement was made using the design values outlined in Table appx 4.1 (Appendix 4). Firstly, the required sub-base thickness was calculated using the figure 4.16 from Shackel (1990). Similarly, the base thickness was calculated by interpolating from figure 4.19. The design traffic was not given; thus, it was assumed to be 10^6 HVAG. As specified by the brief, the sub-base is to be unbound granular material.

2.2.1 Specifications

As seen in figure appx 4.1, the minimum sub-base thickness required was calculated to be 680mm. This was rounded up to 700mm, as specified by the design brief. Furthermore, as during the actual construction process, some buffer is required to ensure variabilities in the finish will not drastically hamper the functionality of the pavement. Something that should be mentioned is that the given CBR value was a soaked value, which is typically lower than in unsoaked conditions. This would impact the required thickness as evident in figure appx 4.1. However, since the soaked CBR value roughly represents a worst-case scenario, it may be safer to use this value. Furthermore, as no information regarding the water table or the seasonality of the local environment is available, the use of the soaked CBR value should encompass the harshest conditions if there is a high water table or seasonal variability that affects water levels.

Figure appx 4.2 illustrates that the base thickness required for a maximum wheel load of 30 tonnes is to be at least 880mm, rounded to 900mm. For such a low CBR value, the difference between the single and multiple wheels is negligible. As Shackel mentions, figure appx 4.2 is only applicable in an optimal case where only one type of vehicle is operating. This is not representative of a real-world scenario that would see a wide range of vehicles operating at any one time.

2.2.2 Granular Sub-Base and Stabilisation

As seen in the previous section, a substantial thickness is required due to the combination of a low CBR value and high maximum wheel load. If economic considerations were to be considered, figures appx 4.3 and appx 4.4 may be useful in altering the pavement for a cheaper design. Figure appx 4.3 may in fact be more applicable to the outlined design as it analyses an unbound granular base, whereas figure appx 4.2 is generalised across different materials and pavement layouts. From figure appx 4.3, the required thickness would reduce to 500mm of granular material, which is much less than the 900mm specified in figure appx 4.2. Figure appx 4.4 is not applicable to the specified design. As it lays out the statistics for a stabilised sub-base material, it cannot be used in the current design. If, however, the design specifications were to change, then stabilisation may be the ideal candidate for decreasing the depth of the pavement profile. Only 250mm of stabilised material would be required. While the stabilisation process may increase the materials and labour costs, it will greatly reduce the depth of digging required and volume of potentially more expensive material being used to fill, thus providing an economic advantage to other methods. However, since both graphs are only applicable to design

traffics of less than or equal to 1 million, the values may not be as accurate, especially since the assumed traffic was 1 million HVAG. Furthermore, as this is an industrial area, the traffic may be much greater than the assumed traffic, which underscores the questionable applicability of these figures. The recency of Shackel may also be a question to consider. As it was written over 30 years ago, it is highly likely that newer methods were developed that are better.

3.0 Conclusion

Various methods have been established for designing different types of pavements. The two used in this report varied greatly in approach and complexity. This is highlighted in the methodologies of the two texts used as references for this report.

The mechanistic method used to design the flexible pavement was more involved and focused on checking the acceptability of design. This approach required intense calculations regarding fatigue and allowable loading. The candidate pavement in the design brief was found to be inadequate due to the failure of the cemented base. Thus, changes to the thickness of the cement and subgrade layer were recommended. By increasing the thicknesses of these layers, or stabilising the subgrade, the pavement should decrease the damage caused by fatigue.

In contrast, the industrial segmental pavement design focused more on the initial profile design. Shackel's method used various graphs to determine the required thicknesses for the base and sub-base layers. Shackel also highlighted the benefits of bounding the sub-base material. The potential fiscal savings from the use of granular material or binding should not be overlooked when designing pavements. This method is limited however, by its applicability regarding design traffics. High traffic counts may not be reflected in this method.

4.0 Recommendations

Data is crucial in creating models and design. Without sufficient information on the surrounding environment, it is difficult to make accurate assessments on the acceptability of designs. For example, data on the water table or the seasonality of the surrounding area was crucial in the design of the segmental pavement. These factors can potentially result in over-designed specifications and wasted work on unnecessary precautions. Furthermore, the costs associated with the extra safety would also raise concerns on the economic side of construction. Cost

factors can also play a part in optimising the design of pavements. Balancing the need for safety and maximising cost-cutting is important for maintaining a productive business. For example, by relying more heavily on the cheaper granular fill to make up for the failures seen in the candidate pavement while trimming the expensive asphalt layer, the cost effectiveness can be maximised. Considerations for long-term and short-term savings should also be made. While cemented materials may have a higher up-front cost, asphalt will have a higher maintenance cost, which can cost the client more in the long run.

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Appendix 3

Flexible Pavement Design following Appendix L3 (Moffatt & Papacostas 2017)

Step 1

Table appx 3.1. Candidate pavement profile

Material type	Thickness (mm)
Size 14 mm asphalt, E = 2200 MPa	60
Size 20 mm asphalt, E = 2500 MPa	140
Cemented material, E = 3000 MPa	220
Unbound granular material	240
Subgrade, CBR = 5%	Semi-infinite

The design flexural strength of the cemented material is assumed to be 1.2 MPa. Both Modulus and flexural strength of the cemented material were determined from laboratory tests.

As the thickness of asphalt over the cemented material is greater than or equal to 175 mm, the post-cracking phase of the cemented material life may be considered (Section 8.2.6).

$$(0.75 \times \text{thickness of granular material cover}) + (\text{thickness of asphalt cover}) \geq 175 \text{ mm}$$
$$(0.75 \times 240) + (60 + 140) = 380 \geq 175 \text{ mm}$$

Step 2

Subgrade as in Appendix L.1

Subgrade CBR = 3%

$$E_v = 30 \text{ MPa (Section 5.6)}$$

$$E_H = 0.5 \times E_v$$

$$E_H = 0.5 \times 30 = 15 \text{ MPa}$$

$$\nu_v = \nu_H = 0.45 \text{ (Section 5.6)}$$

$$f = \frac{E_v}{1 + \nu_v} = 20.69$$

Step 3

Properties of the top granular sublayer:

E_v top granular sublayer is the minimum of Equation 41 in Section 8.2.3 and the value indicated in Table 6.5 (assuming normal standard crushed rock).

$$E_v \text{ top granular sublayer} = E_v \text{ subgrade} \times 2^{(\text{total granular thickness} / 125)} \text{ (Eqn 41 Section 8.2.3)}$$

$$E_v \text{ top granular sublayer} = 113.53 \text{ MPa}$$

$$E_v \text{ top granular sublayer} = 150 \text{ MPa for Normal Standard crushed rock (Table 6.5)}$$

$$E_v \text{ top granular sublayer} = \text{minimum (113.53 MPa, 150 MPa)} = 113.53 \text{ MPa}$$

$$E_h \text{ top granular sublayer} = 0.5 \times E_v$$

$$E_h \text{ top granular sublayer} = 56.76 \text{ MPa}$$

$$v_v = v_h = 0.35 - \text{Table 6.3}$$

$$f = \frac{E_v}{1 + v_v} = 84.09$$

Step 4- Other granular sublayers

Divide the total granular layer thickness into five equi-thick sublayers (Section 8.2.3) each $240/5 = 48$ mm thick.

Calculate the ratio of moduli of adjacent sublayers:

$$\begin{aligned} R &= [E_{\text{top granular sublayer}} \div E_{\text{subgrade}}]^{1/5} \\ &= [113.53 \div 30]^{1/5} \\ &= 1.30 \end{aligned}$$

Sublayer elastic properties calculation procedure is shown in Appendix L.1.

$$E_v \text{ top of subgrade} = 1.30 \times 30 = 39.15 \text{ MPa}$$

$$E_h \text{ top of subgrade} = 0.5 \times E_v \text{ top of subgrade} = 19.57 \text{ MPa}$$

$$v_v = v_h = 0.35$$

$$f = \frac{E_v}{1 + v_v} = 29.00$$

Elastic properties of other sublayers are calculated similarly using the elastic properties of the underlying sublayer and are listed in table appx 3.2.

Table appx 3.2. Elastic Properties of sublayers

Material type	Thickness (mm)	Elastic modulus (MPa)		Poisson's ratio		f Value
		E_v	$0.5 \times E_v = E_h$	v_v	v_h	
Granular	48	113.53	56.76	0.35	0.35	84.09

Granular	48	87.00	43.50	0.35	0.35	64.44
Granular	48	66.67	33.33	0.35	0.35	49.38
Granular	48	1.30*39.15= 51.09	25.54	0.35	0.35	37.84
Granular	48	1.30*30=39. 15	19.57	0.35	0.35	29.00
Subgrade	Semi- infinite	30	15	0.45	0.45	20.69

Step 5

Cemented Materials–

Pre-cracking cemented material phase:

$$E_v = 3000 \text{ MPa (Table 6.7)}$$

$$\nu_v = \nu_h = 0.2 \text{ (Table 6.7)}$$

Post-cracking cemented material phase:

$$E_v = 500 \text{ MPa (Section 8.2.6)}$$

$$E_h = 0.5 \times E_v \text{ (Section 8.2.6)}$$

$$= 250 \text{ MPa}$$

$$\nu_v = \nu_h = 0.35 \text{ (Section 8.2.6)}$$

$$f = \frac{E_v}{1+\nu_v} = 370.37$$

No sub layering.

Step 6

Asphalt-

Size 14 mm asphalt:

$$E_v = E_h = 2200 \text{ MPa}$$

$$\nu_v = \nu_h = 0.4 \text{ (Section 6.5.8)}$$

Size 20 mm asphalt:

$$E_v = E_h = 2500 \text{ MPa}$$

$$\nu_v = \nu_h = 0.4 \text{ (Section 6.5.8)}$$

Elastic properties of all material, including granular sublayers, are listed in Table appx 3.3.

Table appx 3.3. Elastic properties of pavement with cemented material subbase

Material type	Thickness (mm)	Elastic modulus (MPa)		Poisson's ratio		f Value
		EV	EH	vV	vH	
size 14 mm asphalt	60	2200	2200	0.4	0.4	–
size 20 mm asphalt	140	2500	2500	0.4	0.4	–
Cemented material	220					
Pre-cracked/ Post-cracked		3000/ 500	3000/ 250	0.2/ 0.35	0.2/ 0.35	–/ 370.4
Granular	48	113.53	56.76	0.35	0.35	84.09
Granular	48	87.00	43.50	0.35	0.35	64.44
Granular	48	66.67	33.33	0.35	0.35	49.38
Granular	48	51.09=1.30×39.15	25.54	0.35	0.35	37.84
Granular	48	39.15=1.30×30	19.57	0.35	0.35	29.00
Subgrade	Semi-infinite	30	15	0.45	0.45	20.69

Step 7

Subgrade strain criterion as in Appendix L.1.

Permanent deformation allowable loading (Equation 5.3)

$$N = [9150 \div \mu\varepsilon]7$$

Where:

$\mu\varepsilon$ = the vertical compressive strain (in terms of microstrain), developed under a Standard Axle, at the top of the subgrade

N = the allowable number of repetitions of a Standard Axle at this strain before an unacceptable level of pavement surface deformation develops (units of ESAs)

Step 8- Cemented material fatigue criterion

Calculate the fatigue constant K of the in-service fatigue relationship using the design modulus of 3000 MPa and the design flexural strength of 1.2 MPa

$$\begin{aligned} K &= 240 \times FS + (919300 \div E) - 285 \\ &= 240 \times 1.2 + (919300 \div 3000) - 285 \\ &= 309.43 \end{aligned}$$

Using Equation 13 check the K value does not exceed the maximum values of K

$$K_{\max} = 18880 \div (E)^{0.5}$$

$$= 344.70$$

Using $K = 309.43$ and Equation 10, the in-service fatigue relationship is:

$$N = RF \times (309 \div \mu\varepsilon)^{12}$$

Where:

Reliability Factor, $RF = 1.0$ (Table 6.8)
(For a highway having 95% desired project reliability)

Step 9- Asphalt fatigue criterion

For the sake of brevity, the upper asphalt layer is not examined in this example

Size 20 mm asphalt:

$$N = (SF \div RF) \times [\{6918 \times (0.856 \times V_b + 1.08)\} \div (E_{\text{mix}}^{0.36} \times \mu\varepsilon)]^5$$

$$N = (6 \div 6) \times [\{6918 \times (0.856 \times 11 + 1.08)\} \div (2500^{0.36} \times \mu\varepsilon)]^5$$

(Assuming volume of bitumen (V_b) = 11%)

Shift Factor, $SF = 6$ and Reliability Factor, $RF = 6.0$ (Table 6.16)

Step 10

$$N_{DT} = 1.09 \times 10^7 \text{ HVAG}$$

Traffic Load Distribution TLD is Table G 1 in Appendix G

$$ESA/HVAG = 0.7$$

Step 11

Design traffic loading (ESA), DESA as in Appendix L. 1.

$$DESA = ESA/HVAG \times N_{DT}$$

$$DESA = 0.7 \times 1.09 \times 10^7$$

$$= 7.063 \times 10^6 \text{ ESA (i.e. approximately 7 million HVAG standard axle passes)}$$

Step 12

Standard Axle load as in Appendix L. 1. Represented as:

Tyre-pavement contact stress = 750 kPa

Load radius = 92.1 mm

Four circular areas separated centre-to-centre 330 mm, 1470 mm and 330 mm (Figure 8.2).

Step 13

Critical locations to calculate strains are:

- top of subgrade
- bottom of asphalt layer
- bottom of cemented layer.

All the above strains are calculated directly beneath one of the loaded wheels and midway between the loaded wheels (Figure 8.2).

Step 14

Critical strains resulting from Standard Axle load calculated by CIRCLY as follows:

Pre-cracking cemented material phase:

- Asphalt – maximum horizontal tensile strain of 20 $\mu\epsilon$ located under the inner loaded tyre
- Cemented material – maximum horizontal tensile strain of 85 $\mu\epsilon$ located between the loaded tyres
- Subgrade – maximum vertical compressive strain is 227 $\mu\epsilon$ located between the loaded tyres.

Post-cracking cemented material phase:

- Asphalt – maximum horizontal tensile strain is 163 $\mu\epsilon$ located under the inner loaded tyre.
- Subgrade – maximum vertical compressive strain is 415 $\mu\epsilon$ between the loaded tyres.

Step 15

Single axle with single tyres load as in Appendix L. 2.

Single axle with single tyres represented as:

Tyre-pavement contact stress = 800 kPa

Load radius = 102.4 mm

The two circular areas separated centre-to-centre 2130 mm (Figure 8.2)

Step 16

Critical locations to calculate strains under single axle with single tyres with 53 kN load as follows

Pre-cracking cemented material phase:

- bottom of asphalt
- bottom of cemented material

Post-cracking cemented material phase:

- bottom of asphalt

Step 17

Critical locations to calculate strains under single axle with single tyres with 53 kN load as follows

Pre-cracking cemented material phase:

- asphalt – maximum horizontal tensile strain of 31 $\mu\epsilon$
- cemented material – maximum horizontal tensile strain of 74 $\mu\epsilon$

Post-cracking cemented material phase:

- asphalt – maximum horizontal tensile strain of 142 $\mu\epsilon$

Step 18

Permanent deformation allowable loading – from *Step 7*:

Pre-cracking cemented material phase:

$$N = [9150 \div \mu\epsilon]^7$$

$$\begin{aligned} N_{1stS} &= [9150 \div 227]^7 \\ &= 1.73 \times 10^{11} \text{ ESA} \end{aligned}$$

Post-cracking cemented material phase:

$$\begin{aligned} N_{2ndS} &= [9150 \div 415]^7 \\ &= 2.53 \times 10^9 \text{ ESA} \end{aligned}$$

Step 19

As the post-cracking phase of cemented materials is being considered, the total allowable ESA is determined in *Step 28*.

Step 20

Asphalt and cemented materials are present in the candidate structure; therefore *Steps 21 to 27* must be repeated for both the asphalt and the cemented material.

Step 21 (asphalt)

Steps 22 (asphalt) to 26 (asphalt) are repeated for each axle group type present in the distribution:

- single axle with single tyres – SAST
- single axle with dual tyres – SADT

- tandem axle with single tyres – TAST
- tandem axle with dual tyres – TADT
- triaxle with dual tyres – TRDT

Step 22 (asphalt)

The expected repetitions of each load level for each axle group type as in Appendix L. 2.

Table appx 3.4. Calculation of expected repetitions – single axle/ single tyre (SAST) – full depth asphalt pavement

Axle group load (kN)	Proportion of loads	Proportion of axle group	Design traffic (HVAG)	Expected group repetitions
10	0.002804	0.393	10900000	12011.49
20	0.07827	0.393	10900000	335285.20
30	0.1546	0.393	10900000	662260.02
40	0.1571	0.393	10900000	672969.27
50	0.2994	0.393	10900000	1282539.78
60	0.2329	0.393	10900000	997673.73
70	0.06502	0.393	10900000	278526.17
80	0.007943	0.393	10900000	34025.43
90	0.001087	0.393	10900000	4656.38
100	0.000354	0.393	10900000	1516.43
110	0.000174	0.393	10900000	745.36
120	0.000174	0.393	10900000	745.36
130	0.000174	0.393	10900000	745.36

Table appx 3.5. Calculation of expected repetitions – single axle/ dual tyres (SADT) – full depth asphalt pavement

Axle group load (kN)	Proportion of loads	Proportion of axle group	Design traffic (HVAG)	Expected group repetitions
10	0.03473	0.191	10900000	72304.39
20	0.08696	0.191	10900000	181042.02
30	0.2346	0.191	10900000	488413.74
40	0.2193	0.191	10900000	456560.67
50	0.168	0.191	10900000	349759.20
60	0.09606	0.191	10900000	199987.31
70	0.065	0.191	10900000	135323.50
80	0.04623	0.191	10900000	96246.24
90	0.02969	0.191	10900000	61811.61
100	0.01393	0.191	10900000	29000.87
110	0.004098	0.191	10900000	8531.63
120	0.001158	0.191	10900000	2410.84
130	0.000244	0.191	10900000	507.98

Table appx 3.6. Calculation of expected repetitions – tandem axle group/ single tyre (TAST) – full depth asphalt pavement

Axle group load (kN)	Proportion of loads	Proportion of axle group	Design traffic (HVAG)	Expected group repetitions
10	0.000354	0.009	10900000	34.73
20	0.002377	0.009	10900000	233.18
30	0.002763	0.009	10900000	271.05
40	0.005755	0.009	10900000	564.57
50	0.02889	0.009	10900000	2834.11
60	0.1027	0.009	10900000	10074.87
70	0.1681	0.009	10900000	16490.61
80	0.1661	0.009	10900000	16294.41
90	0.1595	0.009	10900000	15646.95
100	0.1442	0.009	10900000	14146.02
110	0.09774	0.009	10900000	9588.29
120	0.05903	0.009	10900000	5790.84
130	0.02943	0.009	10900000	2887.08
140	0.01539	0.009	10900000	1509.76
150	0.008439	0.009	10900000	827.87
160	0.004279	0.009	10900000	419.77
170	0.002308	0.009	10900000	226.41
180	0.001367	0.009	10900000	134.10
190	0.000723	0.009	10900000	70.93
200	0.000555	0.009	10900000	54.45

Table appx 3.7. Calculation of expected repetitions – tandem axle group/ dual tyres (TADT) – full depth asphalt pavement

Axle group load (kN)	Proportion of loads	Proportion of axle group	Design traffic (HVAG)	Expected group repetitions
10	0.001444	0.259	10900000	4076.56
20	0.005755	0.259	10900000	16246.94
30	0.006242	0.259	10900000	17621.79
40	0.01977	0.259	10900000	55812.69
50	0.06496	0.259	10900000	183388.58
60	0.09511	0.259	10900000	268505.04
70	0.1094	0.259	10900000	308847.14
80	0.09769	0.259	10900000	275788.64
90	0.07611	0.259	10900000	214866.14
100	0.7242	0.259	10900000	2044489.02
110	0.06267	0.259	10900000	176923.68
120	0.05952	0.259	10900000	168030.91

130	0.05878	0.259	10900000	165941.82
140	0.06534	0.259	10900000	184461.35
150	0.0803	0.259	10900000	226694.93
160	0.05717	0.259	10900000	161396.63
170	0.03554	0.259	10900000	100332.97
180	0.0186	0.259	10900000	52509.66
190	0.008535	0.259	10900000	24095.16
200	0.003331	0.259	10900000	9403.75
210	0.000801	0.259	10900000	2261.30
220	0.000322	0.259	10900000	909.04
230	0.00016	0.259	10900000	451.70

Table appx 3.8. Calculation of expected repetitions – triaxle group/ dual tyres (TRDT) – full depth asphalt pavement

Axle group load (kN)	Proportion of loads	Proportion of axle group	Design traffic (HVAG)	Expected group repetitions
10	0.00005	0.148	10900000	80.66
20	0.0001568	0.148	10900000	252.95
30	0.00329	0.148	10900000	5307.43
40	0.01317	0.148	10900000	21245.84
50	0.04167	0.148	10900000	67222.04
60	0.07419	0.148	10900000	119683.31
70	0.09777	0.148	10900000	157722.56
80	0.08338	0.148	10900000	134508.62
90	0.0615	0.148	10900000	99211.80
100	0.05029	0.148	10900000	81127.83
110	0.03701	0.148	10900000	59704.53
120	0.03298	0.148	10900000	53203.34
130	0.03147	0.148	10900000	50767.40
140	0.03361	0.148	10900000	54219.65
150	0.04008	0.148	10900000	64657.06
160	0.04115	0.148	10900000	66383.18
170	0.04819	0.148	10900000	77740.11
180	0.06097	0.148	10900000	98356.80
190	0.07733	0.148	10900000	124748.76
200	0.08433	0.148	10900000	136041.16
210	0.05136	0.148	10900000	82853.95
220	0.02339	0.148	10900000	37732.75
230	0.007764	0.148	10900000	12524.88
240	0.002503	0.148	10900000	4037.84
250	0.000905	0.148	10900000	1459.95
260	0.00008	0.148	10900000	129.06

Table appx 3.9. Calculation of asphalt damage – single axle/ single tyre (SAST) – full depth asphalt pavement

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	12011.49	1	5.849	2.26E+14	5.32E-11
20	335285.20	1	11.698	7.05E+12	4.76E-08
30	662260.02	1	17.547	9.28E+11	7.13E-07
40	672969.27	1	23.396	2.20E+11	3.05E-06
50	1282539.78	1	29.245	7.22E+10	1.78E-05
60	997673.73	1	35.094	2.90E+10	3.44E-05
70	278526.17	1	40.943	1.34E+10	2.08E-05
80	34025.43	1	46.792	6.88E+09	4.94E-06
90	4656.38	1	52.642	3.82E+09	1.22E-06
100	1516.43	1	58.491	2.26E+09	6.72E-07
110	745.36	1	64.340	1.40E+09	5.32E-07
120	745.36	1	70.189	9.07E+08	8.22E-07
130	745.36	1	76.038	6.08E+08	1.23E-06
				Total SAST damage	8.61E-05

Table appx 3.10. Calculation of asphalt damage – single axle/ dual tyres (SADT) – full depth asphalt pavement

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	72304.39	1	2.92	3.61E+15	9.62E-15
20	181042.02	1	5.85	1.13E+14	2.07E-12
30	488413.74	1	8.77	1.49E+13	1.82E-11
40	456560.67	1	11.70	3.52E+12	1.60E-10
50	349759.20	1	14.62	1.15E+12	2.45E-09
60	199987.31	1	17.55	4.64E+11	2.17E-08
70	135323.50	1	20.47	2.15E+11	7.68E-08
80	96246.24	1	23.40	1.10E+11	1.48E-07
90	61811.61	1	26.32	6.11E+10	2.56E-07
100	29000.87	1	29.25	3.61E+10	3.92E-07
110	8531.63	1	32.17	2.24E+10	4.28E-07
120	2410.84	1	35.09	1.45E+10	3.99E-07
130	507.98	1	38.02	9.72E+09	2.97E-07
				Total SADT damage	1.10E-06

Table appx 3.11. Calculation of asphalt damage – tandem axle/ single tyre (TAST) – full depth asphalt pavement

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	34.73	2	2.50	1.58E+16	4.57E-12
20	233.18	2	5.00	4.94E+14	3.66E-10
30	271.05	2	7.50	6.51E+13	7.51E-09
40	564.57	2	10.00	1.54E+13	2.96E-08
50	2834.11	2	12.50	5.06E+12	6.91E-08
60	10074.87	2	15.00	2.03E+12	9.83E-08
70	16490.61	2	17.50	9.41E+11	1.44E-07
80	16294.41	2	20.00	4.83E+11	1.99E-07
90	15646.95	2	22.50	2.68E+11	2.31E-07
100	14146.02	2	25.00	1.58E+11	1.83E-07
110	9588.29	2	27.50	9.82E+10	8.69E-08
120	5790.84	2	30.00	6.36E+10	3.79E-08
130	2887.08	2	32.50	4.26E+10	1.19E-08
140	1509.76	2	2.50	1.58E+16	4.57E-12
150	827.87	2	5.00	4.94E+14	3.66E-10
160	419.77	2	7.50	6.51E+13	7.51E-09
170	226.41	2	10.00	1.54E+13	2.96E-08
180	134.10	2	12.50	5.06E+12	6.91E-08
190	34.73	2	15.00	2.03E+12	9.83E-08
200	233.18	2	17.50	9.41E+11	1.44E-07
				Total TAST damage	2.80E-06

Table appx 3.12. Calculation of asphalt damage – tandem axle/ dual tyres (TADT) – full depth asphalt pavement

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	4076.56	2	1.25	2.53E+17	1.61E-14
20	16246.94	2	2.50	7.91E+15	2.05E-12
30	17621.79	2	3.75	1.04E+15	1.69E-11
40	55812.69	2	5.00	2.47E+14	2.26E-10
50	183388.58	2	6.25	8.10E+13	2.27E-09
60	268505.04	2	7.50	3.25E+13	8.25E-09
70	308847.14	2	8.75	1.51E+13	2.05E-08
80	275788.64	2	10.00	7.72E+12	3.57E-08
90	214866.14	2	11.25	4.28E+12	5.01E-08
100	2044489.02	2	12.50	2.53E+12	8.08E-07
110	176923.68	2	13.75	1.57E+12	1.13E-07

120	168030.91	2	15.00	1.02E+12	1.65E-07
130	165941.82	2	16.25	6.81E+11	2.44E-07
140	184461.35	2	17.50	4.70E+11	3.92E-07
150	226694.93	2	18.75	3.33E+11	6.80E-07
160	161396.63	2	20.00	2.41E+11	6.69E-07
170	100332.97	2	21.25	1.78E+11	5.63E-07
180	52509.66	2	22.50	1.34E+11	3.92E-07
190	24095.16	2	23.75	1.02E+11	2.36E-07
200	9403.75	2	25.00	7.91E+10	1.19E-07
210	2261.30	2	26.25	6.20E+10	3.65E-08
220	909.04	2	27.50	4.91E+10	1.85E-08
230	451.70	2	28.75	3.93E+10	1.15E-08
				Total TADT damage	4.56E-06

Table appx 3.13. Calculation of asphalt damage – triaxle/ dual tyres (TRDT) – full depth asphalt pavement

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	80.66	3	0.83	1.28E+18	6.30E-17
20	252.95	3	1.67	4.00E+16	6.32E-15
30	5307.43	3	2.50	5.27E+15	1.01E-12
40	21245.84	3	3.33	1.25E+15	1.70E-11
50	67222.04	3	4.17	4.10E+14	1.64E-10
60	119683.31	3	5.00	1.65E+14	7.27E-10
70	157722.56	3	5.83	7.62E+13	2.07E-09
80	134508.62	3	6.67	3.91E+13	3.44E-09
90	99211.80	3	7.50	2.17E+13	4.57E-09
100	81127.83	3	8.33	1.28E+13	6.33E-09
110	59704.53	3	9.17	7.95E+12	7.51E-09
120	53203.34	3	10.00	5.15E+12	1.03E-08
130	50767.40	3	10.83	3.45E+12	1.47E-08
140	54219.65	3	11.67	2.38E+12	2.28E-08
150	64657.06	3	12.50	1.69E+12	3.83E-08
160	66383.18	3	13.33	1.22E+12	5.43E-08
170	77740.11	3	14.17	9.02E+11	8.62E-08
180	98356.80	3	15.00	6.78E+11	1.45E-07
190	124748.76	3	15.83	5.17E+11	2.41E-07
200	136041.16	3	16.67	4.00E+11	3.40E-07
210	82853.95	3	17.50	3.14E+11	2.64E-07
220	37732.75	3	18.33	2.49E+11	1.52E-07
230	12524.88	3	19.17	1.99E+11	6.29E-08
240	4037.84	3	20.00	1.61E+11	2.51E-08

250	1459.95	3	20.83	1.31E+11	1.11E-08
260	129.06	3	21.67	1.08E+11	1.20E-09
				Total TRDT damage	1.49E-06

Step 23 (asphalt)

Pre-cracking cemented material phase

The allowable loading of each axle group type and load level is calculated in Table appx 3.9. As a first stage the critical asphalt strain for each load level is estimated for a single constituent axle of each axle group type using Equation 43 (Section 8.2.4).

$$\mu\varepsilon_{ij} = \frac{L_{ij}}{n} \times \frac{\mu\varepsilon_{SAST,53}}{53} = \frac{L_{ij}}{n} \times \frac{31}{53} \text{ for axles within SAST, TAST groups}$$

$$\mu\varepsilon_{ij} = \frac{L_{ij}}{n} \times \frac{\mu\varepsilon_{SADT,80}}{80} = \frac{L_{ij}}{n} \times \frac{20}{80} \text{ for axles within SADT, TADT \& TRDT groups}$$

For example, the critical asphalt strain developed under an axle within a triaxle group (TRDT) with a total group load of 120 kN is calculated as:

$$\mu\varepsilon_{TRDT,120} = \frac{120}{3} \times \frac{20}{80} = 10.00 \mu\varepsilon$$

The allowable repetitions of each axle group and load magnitude are then calculated using Equation 44 (Section 8.2.5):

$$N_{ij} = \frac{1}{n} \times \frac{SF}{RF} \times \frac{[6918 \times (0.856 \times V_H + 1.08)]^5}{E_{mix}^{0.36} \times \mu\varepsilon_{ij}}$$

For example, the allowable repetitions of a triaxial group (TRDT) with a total group load of 120 kN is calculated as:

$$N_{TRDT,120} = \frac{1}{3} \times \frac{6}{6} \times \frac{[6918 \times (0.856 \times 11 + 1.08)]^5}{2500^{0.36} \times 10.00} = 5.15 \times 10^{12}$$

The allowable repetitions of all axle group/ load combinations are shown in Tables appx 3.9 to Table appx 3.13.

Post-cracking cemented material phase

The allowable loading of each axle group type and load level is calculated in Table appx 3.9. As a first stage the critical asphalt strain for each load level is estimated for a single constituent axle of each axle group type using Equation 43 (Section 8.2.4).

$$\mu\varepsilon_{ij} = \frac{L_{ij}}{n} \times \frac{\mu\varepsilon_{ij}}{53} = \frac{L_{ij}}{n} \times \frac{142}{53} \text{ or axles within SAST, TAST groups}$$

$$\mu\varepsilon_{ij} = \frac{L_{ij}}{n} \times \frac{\mu\varepsilon_{SADT,80}}{80} = \frac{L_{ij}}{n} \times \frac{163}{80} \text{ or axles within SADT, TADT \& TRDT groups}$$

The allowable loading of each axle group type and load level is calculated in Table appx 3.14 to Table appx 3.18.

Table appx 3.14. Calculation of asphalt damage for post-cracking cemented material phase – SAST

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	12011.49	1	26.79	1.12E+11	1.07E-07
20	335285.20	1	53.58	3.50E+09	9.59E-05
30	662260.02	1	80.38	4.60E+08	1.44E-03
40	672969.27	1	107.17	1.09E+08	6.16E-03
50	1282539.78	1	133.96	3.58E+07	3.58E-02
60	997673.73	1	160.75	1.44E+07	6.94E-02
70	278526.17	1	187.55	6.66E+06	4.18E-02
80	34025.43	1	214.34	3.41E+06	9.97E-03
90	4656.38	1	241.13	1.89E+06	2.46E-03
100	1516.43	1	267.92	1.12E+06	1.36E-03
110	745.36	1	294.72	6.95E+05	1.07E-03
120	745.36	1	321.51	4.50E+05	1.66E-03
130	745.36	1	348.30	3.01E+05	2.47E-03
				Total SAST damage	1.74E-01

Table appx 3.15. Calculation of asphalt damage for post-cracking cemented material phase – SADT

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	72304.39	1	20.38	4.40E+11	1.64E-07
20	181042.02	1	40.75	1.37E+10	1.32E-05
30	488413.74	1	61.13	1.81E+09	2.70E-04
40	456560.67	1	81.50	4.29E+08	1.06E-03
50	349759.20	1	101.88	1.41E+08	2.49E-03
60	199987.31	1	122.25	5.66E+07	3.54E-03
70	135323.50	1	142.63	2.62E+07	5.17E-03
80	96246.24	1	163.00	1.34E+07	7.17E-03
90	61811.61	1	183.38	7.45E+06	8.30E-03
100	29000.87	1	203.75	4.40E+06	6.59E-03
110	8531.63	1	224.13	2.73E+06	3.12E-03
120	2410.84	1	244.50	1.77E+06	1.36E-03
130	507.98	1	264.88	1.18E+06	4.29E-04

				Total SADT damage	3.95E-02
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Table appx 3.16. Calculation of asphalt damage for post-cracking cemented material phase – TAST

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	34.73	2	13.40	1.79E+12	1.94E-11
20	233.18	2	26.79	5.59E+10	4.17E-09
30	271.05	2	40.19	7.37E+09	3.68E-08
40	564.57	2	53.58	1.75E+09	3.23E-07
50	2834.11	2	66.98	5.73E+08	4.95E-06
60	10074.87	2	80.38	2.30E+08	4.38E-05
70	16490.61	2	93.77	1.06E+08	1.55E-04
80	16294.41	2	107.17	5.46E+07	2.98E-04
90	15646.95	2	120.57	3.03E+07	5.16E-04
100	14146.02	2	133.96	1.79E+07	7.90E-04
110	9588.29	2	147.36	1.11E+07	8.63E-04
120	5790.84	2	160.75	7.19E+06	8.05E-04
130	2887.08	2	174.15	4.82E+06	5.99E-04
140	1509.76	2	187.55	3.33E+06	4.54E-04
150	827.87	2	200.94	2.36E+06	3.51E-04
160	419.77	2	214.34	1.71E+06	2.46E-04
170	226.41	2	227.74	1.26E+06	1.80E-04
180	134.10	2	241.13	9.47E+05	1.42E-04
190	70.93	2	254.53	7.23E+05	9.81E-05
200	54.45	2	267.92	5.59E+05	9.73E-05
				Total TAST damage	5.64E-03

Table appx 3.17. Calculation of asphalt damage for post-cracking cemented material phase – TADT

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	4076.56	2	10.19	7.04E+12	5.79E-10
20	16246.94	2	20.38	2.20E+11	7.39E-08
30	17621.79	2	30.56	2.90E+10	6.09E-07
40	55812.69	2	40.75	6.87E+09	8.12E-06
50	183388.58	2	50.94	2.25E+09	8.14E-05
60	268505.04	2	61.13	9.05E+08	2.97E-04
70	308847.14	2	71.31	4.19E+08	7.38E-04
80	275788.64	2	81.50	2.15E+08	1.28E-03
90	214866.14	2	91.69	1.19E+08	1.80E-03

100	2044489.02	2	101.88	7.04E+07	2.91E-02
110	176923.68	2	112.06	4.37E+07	4.05E-03
120	168030.91	2	122.25	2.83E+07	5.94E-03
130	165941.82	2	132.44	1.90E+07	8.76E-03
140	184461.35	2	142.63	1.31E+07	1.41E-02
150	226694.93	2	152.81	9.27E+06	2.45E-02
160	161396.63	2	163.00	6.71E+06	2.41E-02
170	100332.97	2	173.19	4.96E+06	2.02E-02
180	52509.66	2	183.38	3.72E+06	1.41E-02
190	24095.16	2	193.56	2.84E+06	8.48E-03
200	9403.75	2	203.75	2.20E+06	4.28E-03
210	2261.30	2	213.94	1.72E+06	1.31E-03
220	909.04	2	224.13	1.37E+06	6.66E-04
230	451.70	2	234.31	1.09E+06	4.13E-04
				Total TADT damage	1.64E-01

Table appx 3.18. Calculation of asphalt damage for post-cracking cemented material phase – TRDT

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	80.66	3	6.79	3.56E+13	2.26E-12
20	252.95	3	13.58	1.11E+12	2.27E-10
30	5307.43	3	20.38	1.47E+11	3.62E-08
40	21245.84	3	27.17	3.48E+10	6.11E-07
50	67222.04	3	33.96	1.14E+10	5.90E-06
60	119683.31	3	40.75	4.58E+09	2.61E-05
70	157722.56	3	47.54	2.12E+09	7.44E-05
80	134508.62	3	54.33	1.09E+09	1.24E-04
90	99211.80	3	61.13	6.03E+08	1.64E-04
100	81127.83	3	67.92	3.56E+08	2.28E-04
110	59704.53	3	74.71	2.21E+08	2.70E-04
120	53203.34	3	81.50	1.43E+08	3.72E-04
130	50767.40	3	88.29	9.59E+07	5.29E-04
140	54219.65	3	95.08	6.62E+07	8.19E-04
150	64657.06	3	101.88	4.69E+07	1.38E-03
160	66383.18	3	108.67	3.40E+07	1.95E-03
170	77740.11	3	115.46	2.51E+07	3.10E-03
180	98356.80	3	122.25	1.89E+07	5.22E-03
190	124748.76	3	129.04	1.44E+07	8.67E-03
200	136041.16	3	135.83	1.11E+07	1.22E-02
210	82853.95	3	142.63	8.72E+06	9.50E-03
220	37732.75	3	149.42	6.91E+06	5.46E-03

230	12524.88	3	156.21	5.53E+06	2.26E-03
240	4037.84	3	163.00	4.47E+06	9.03E-04
250	1459.95	3	169.79	3.65E+06	4.00E-04
260	129.06	3	176.58	3.00E+06	4.30E-05
				Total TRDT damage	5.37E-02

Step 24 and 25 (asphalt)

The asphalt fatigue damage resulting from each axle load is calculated as the number of expected repetitions of the load divided by the allowable number of repetitions, as shown in the last column of Table appx 3.9 to Table appx 3.13 for the pre-cracking phase, and Table appx 3.14 to Table appx 3.18 for the post-cracking phase.

Step 26 (asphalt)

The asphalt fatigue damage resulting from each axle group type is the sum of the damage caused by each load level of the group. These are summarised for both cemented material phases in Table appx 3.19.

As the post-cracking phase of cemented materials is being considered, the total allowable ESA is determined in *Step 28*.

Table appx 3.19. The total asphalt fatigue damage for both cemented material phases

Axle group type	Total group asphalt fatigue damage	
	Pre-cracking phase	Post-cracking phase
SAST	8.61E-05	1.74E-01
SADT	1.10E-06	3.95E-02
TAST	2.80E-06	5.64E-03
TADT	4.56E-06	1.64E-01
TRDT	1.49E-06	5.37E-02
Total	9.61E-05	4.37E-01

Step 27 (asphalt)

The total asphalt fatigue damage is the sum of the damage resulting from each axle group type as seen in Table appx 3.19.

Step 21 (cemented material)

Steps 22 (cemented material) to 26 (cemented material) are repeated for each axle group type present in the distribution:

- single axle with single tyres – SAST
- single axle with dual tyres – SADT
- tandem axle with single tyres – TAST
- tandem axle with dual tyres – TADT

- triaxle with dual tyres – TRDT

Step 22 (cemented material)

The expected repetitions of each load level for each axle group type as in Appendix L. 2.

Step 23 (cemented material)

Pre-cracking cemented material phase

The allowable loading of each axle group type and load level is calculated in Table appx 3.20. As a first stage the critical cemented material strain for each load level is estimated for a single constituent axle of each axle group type using Equation 43 (Section 8.2.4).

$$\mu\epsilon_{ij} = \frac{L_{ij}}{n} \times \frac{\mu\epsilon_{SAST,53}}{53} = \frac{L_{ij}}{n} \times \frac{74}{53} \text{ for axles within SAST, TAST groups}$$

$$\mu\epsilon_{ij} = \frac{L_{ij}}{n} \times \frac{\mu\epsilon_{SADT,80}}{80} = \frac{L_{ij}}{n} \times \frac{85}{80} \text{ for axles within SADT, TADT \& TRDT groups}$$

For example, the critical asphalt strain developed under an axle within a tandem group with dual tyres (TADT) with a total group load of 130 kN is calculated as:

$$\mu\epsilon_{TADT,130} = \frac{130}{2} \times \frac{85}{80} = 69.06\mu\epsilon$$

The allowable repetitions of each axle group type and load magnitude is then calculated using Equation 45 (Section 8.2.5):

$$N_{ij} = \frac{1}{n} \times RF \times \frac{K^{12}}{\mu\epsilon_{ij}}$$

For example, the allowable repetitions of a tandem group with dual tyres (TADT) with a total group load of 130 kN is calculated as:

$$N_{TADT,130} = \frac{1}{2} \times 1 \times \frac{309^{12}}{69.06} = 3.22 \times 10^7$$

The allowable repetitions of all axle group/ load combinations are shown in Tables appx 3.20 to Table appx 3.24.

Table appx 3.20. Calculation of cemented material damage for pre-cracking phase – SAST

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	12011.49	1	13.96	1.38E+16	8.70E-13
20	335285.20	1	27.92	3.37E+12	9.95E-08
30	662260.02	1	41.89	2.60E+10	2.55E-05

40	672969.27	1	55.85	8.23E+08	8.18E-04
50	1282539.78	1	69.81	5.65E+07	2.27E-02
60	997673.73	1	83.77	6.34E+06	1.57E-01
70	278526.17	1	97.74	9.97E+05	2.79E-01
80	34025.43	1	111.70	2.01E+05	1.69E-01
90	4656.38	1	125.66	4.89E+04	9.53E-02
100	1516.43	1	139.62	1.38E+04	1.10E-01
110	745.36	1	153.58	4.40E+03	1.69E-01
120	745.36	1	167.55	1.55E+03	4.81E-01
130	745.36	1	181.51	5.93E+02	1.26E+00
				Total SAST damage	2.74

Table appx 3.21: Calculation of cemented material damage for pre-cracking phase – SADT

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	72304.39	1	10.63	3.66E+17	1.98E-13
20	181042.02	1	21.25	8.94E+13	2.03E-09
30	488413.74	1	31.88	6.89E+11	7.09E-07
40	456560.67	1	42.50	2.18E+10	2.09E-05
50	349759.20	1	53.13	1.50E+09	2.33E-04
60	199987.31	1	63.75	1.68E+08	1.19E-03
70	135323.50	1	74.38	2.64E+07	5.12E-03
80	96246.24	1	85.00	5.33E+06	1.81E-02
90	61811.61	1	95.63	1.30E+06	4.77E-02
100	29000.87	1	106.25	3.66E+05	7.92E-02
110	8531.63	1	116.88	1.17E+05	7.31E-02
120	2410.84	1	127.50	4.11E+04	5.87E-02
130	507.98	1	138.13	1.57E+04	3.23E-02
				Total SADT damage	3.16E-01

Table appx 3.22. Calculation of cemented material damage for pre-cracking phase – TAST

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	34.73	2	6.98	2.83E+19	1.23E-18
20	233.18	2	13.96	6.90E+15	3.38E-14
30	271.05	2	20.94	5.32E+13	5.09E-12
40	564.57	2	27.92	1.69E+12	3.35E-10
50	2834.11	2	34.91	1.16E+11	2.45E-08
60	10074.87	2	41.89	1.30E+10	7.76E-07

70	16490.61	2	48.87	2.04E+09	8.07E-06
80	16294.41	2	55.85	4.11E+08	3.96E-05
90	15646.95	2	62.83	1.00E+08	1.56E-04
100	14146.02	2	69.81	2.83E+07	5.00E-04
110	9588.29	2	76.79	9.01E+06	1.06E-03
120	5790.84	2	83.77	3.17E+06	1.83E-03
130	2887.08	2	90.75	1.21E+06	2.38E-03
140	1509.76	2	97.74	4.99E+05	3.03E-03
150	827.87	2	104.72	2.18E+05	3.80E-03
160	419.77	2	111.70	1.00E+05	4.18E-03
170	226.41	2	118.68	4.85E+04	4.67E-03
180	134.10	2	125.66	2.44E+04	5.49E-03
190	70.93	2	132.64	1.28E+04	5.55E-03
200	54.45	2	139.62	6.90E+03	7.89E-03
				Total TAST damage	4.06E-02

Table appx 3.23. Calculation of cemented material damage for pre-cracking phase – TADT

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	4076.56	2	5.31	7.50E+20	5.44E-18
20	16246.94	2	10.63	1.83E+17	8.88E-14
30	17621.79	2	15.94	1.41E+15	1.25E-11
40	55812.69	2	21.25	4.47E+13	1.25E-09
50	183388.58	2	26.56	3.07E+12	5.97E-08
60	268505.04	2	31.88	3.44E+11	7.80E-07
70	308847.14	2	37.19	5.42E+10	5.70E-06
80	275788.64	2	42.50	1.09E+10	2.53E-05
90	214866.14	2	47.81	2.65E+09	8.09E-05
100	2044489.02	2	53.13	7.50E+08	2.73E-03
110	176923.68	2	58.44	2.39E+08	7.41E-04
120	168030.91	2	63.75	8.41E+07	2.00E-03
130	165941.82	2	69.06	3.22E+07	5.16E-03
140	184461.35	2	74.38	1.32E+07	1.39E-02
150	226694.93	2	79.69	5.78E+06	3.92E-02
160	161396.63	2	85.00	2.66E+06	6.06E-02
170	100332.97	2	90.31	1.29E+06	7.80E-02
180	52509.66	2	95.63	6.48E+05	8.10E-02
190	24095.16	2	100.94	3.39E+05	7.11E-02
200	9403.75	2	106.25	1.83E+05	5.14E-02
210	2261.30	2	111.56	1.02E+05	2.22E-02
220	909.04	2	116.88	5.83E+04	1.56E-02

230	451.70	2	122.19	3.42E+04	1.32E-02
				Total TADT damage	4.57E-01

Table appx 3.24. Calculation of cemented material damage for pre-cracking phase – TRDT

Axle group load (kN)	Expected group repetitions	Axles in group	Critical strain (microstrain)	Allowable group repetitions	Damage
10	80.66	3	3.54	6.48E+22	1.24E-21
20	252.95	3	7.08	1.58E+19	1.60E-17
30	5307.43	3	10.63	1.22E+17	4.35E-14
40	21245.84	3	14.17	3.87E+15	5.50E-12
50	67222.04	3	17.71	2.66E+14	2.53E-10
60	119683.31	3	21.25	2.98E+13	4.02E-09
70	157722.56	3	24.79	4.69E+12	3.37E-08
80	134508.62	3	28.33	9.44E+11	1.43E-07
90	99211.80	3	31.88	2.30E+11	4.32E-07
100	81127.83	3	35.42	6.48E+10	1.25E-06
110	59704.53	3	38.96	2.07E+10	2.89E-06
120	53203.34	3	42.50	7.27E+09	7.32E-06
130	50767.40	3	46.04	2.78E+09	1.82E-05
140	54219.65	3	49.58	1.14E+09	4.74E-05
150	64657.06	3	53.13	5.00E+08	1.29E-04
160	66383.18	3	56.67	2.30E+08	2.88E-04
170	77740.11	3	60.21	1.11E+08	6.98E-04
180	98356.80	3	63.75	5.61E+07	1.75E-03
190	124748.76	3	67.29	2.93E+07	4.26E-03
200	136041.16	3	70.83	1.58E+07	8.59E-03
210	82853.95	3	74.38	8.82E+06	9.40E-03
220	37732.75	3	77.92	5.04E+06	7.48E-03
230	12524.88	3	81.46	2.96E+06	4.23E-03
240	4037.84	3	85.00	1.78E+06	2.27E-03
250	1459.95	3	88.54	1.09E+06	1.34E-03
260	129.06	3	92.08	6.80E+05	1.90E-04
				Total TRDT damage	4.07E-02

Step 24 and 25 (cemented material)

The cemented material damage resulting from each axle load is calculated as the number of expected repetitions of the load divided by the allowable number of repetitions, as shown in the last column of Table appx 3.20 to Table appx 3.24.

Step 26 (cemented material)

The cemented material damage resulting from each axle group load is the sum of the damage caused by each load level of the group. These are summarised for both cemented material phases in Table appx 3.25.

As the post-cracking phase of cemented materials is being considered, the total allowable ESA is determined in *Step 28*.

Table appx 3.25. The total group cemented material fatigue damage for pre-cracking phase

Axle group type	Total group asphalt fatigue damage
SAST	2.74
SADT	3.16E-01
TAST	4.06E-02
TADT	4.57E-01
TRDT	4.07E-02
Total	3.60

Step 27 (cemented material)

Total damage to cemented material is the sum of the damage resulting from each axle group type as seen in Table appx 3.25.

As this damage exceeds 1.0, design loading exceeds the allowable loading for the cemented material.

Allowable Loading in ESA

Step 28

As the thickness of asphalt over the cemented material is greater than or equal to 175 mm, the post-cracking phase of the cemented material life may be considered (Section 8.2.6). That is, the allowable loading is the sum of the loading to fatigue cracking of the cemented material plus the loading for each distress mode (i.e. asphalt fatigue, permanent deformation) post-cracking (Section 8.2.6). This calculation requires the allowable loadings to be converted into units of ESA.

Pre-cracking phase:

Cemented material fatigue:

Equation 51 is used to estimate the allowable ESA loading (A_{ESA}) for the cemented material using the total damage, D , calculated in *Step 27* (cemented material), the design traffic, N_{DT} , (HVAG) of 1.09×10^7 and the average $ESA/HVAG$ determined for the traffic load distribution of 0.7:

$$N_C = \frac{N_{DT} \times ESA/HVAG}{D} = \frac{1.09 \times 10^7 \times 0.7}{3.60} = 2.12 \times 10^6 \text{ ESA}$$

Asphalt fatigue:

$$N_{1stA} = \frac{N_{DT} \times ESA/HVAG}{D} = \frac{1.09 \times 10^7 \times 0.7}{9.60 \times 10^{-5}} = 7.94 \times 10^{10} \text{ ESA}$$

Permanent deformation: from *Step 18*

$$N_{1stS} = 1.73 \times 10^{11} \text{ ESA}$$

Post-cracking phase:

Asphalt fatigue:

$$N_{2ndA} = \frac{N_{DT} \times ESA/HVAG}{D} = \frac{1.09 \times 10^7 \times 0.7}{4.37 \times 10^{-1}} = 1.75 \times 10^7 \text{ ESA}$$

Permanent deformation: from *Step 18*:

$$N_{2ndS} = 2.53 \times 10^9 \text{ ESA}$$

As discussed in Section 8.2.6, the total allowable loading of the pre-cracking and post-cracking phases are:

Permanent deformation allowable loading using Equation 53

$$\begin{aligned} N_S &= N_C + \left(1 - \frac{N_C}{N_{1stS}}\right) \times N_{2ndS} = 2.12 \times 10^6 + \left(1 - \frac{2.12 \times 10^6}{1.73 \times 10^{11}}\right) \times 2.53 \times 10^9 \\ &= 2.09 \times 10^6 \text{ ESA} \end{aligned}$$

Asphalt fatigue allowable loading using Equation 52:

$$\begin{aligned} N_A &= N_C + \left(1 - \frac{N_C}{N_{1stA}}\right) \times N_{2ndA} = 2.12 \times 10^6 + \left(1 - \frac{2.12 \times 10^6}{7.94 \times 10^{10}}\right) \times 1.75 \times 10^7 \\ &= 1.96 \times 10^7 \text{ ESA} \end{aligned}$$

The design number of ESA, DESA from *Step 11*:

$$DESA = 7.63 \times 10^6$$

The allowable loading for only the asphalt fatigue exceeds the design loading, thus the candidate pavement is not acceptable due to the permanent deformation.

Appendix 4

Design of Segmental Pavement Workings

Table appx 4.1. Segmental Pavement specifications

Soaked CBR	3%
Maximum wheel load (tonnes)	30
Depth of concrete paver	100

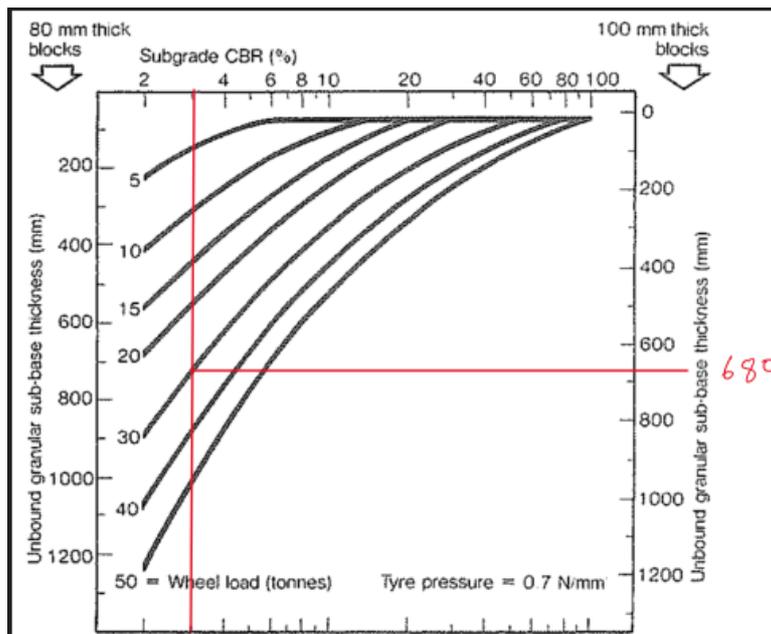


Figure appx 4.1. Annotated figure for sub-base thickness (Shackel 1990)

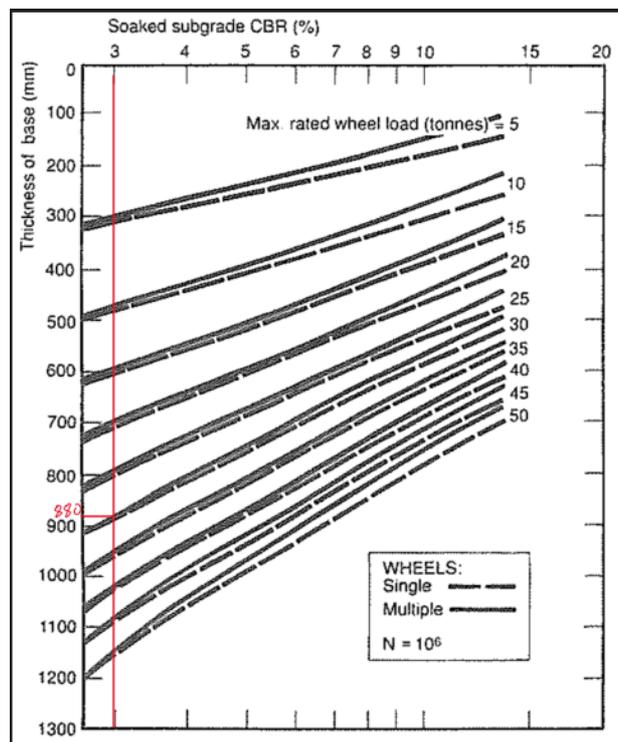
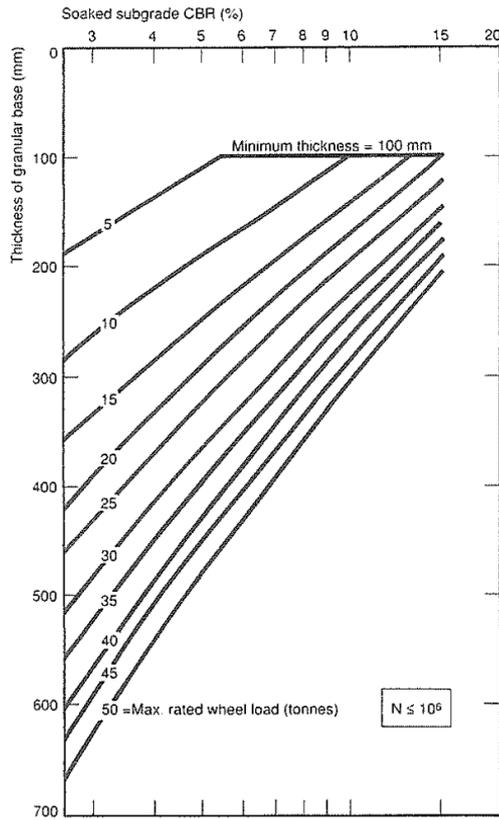
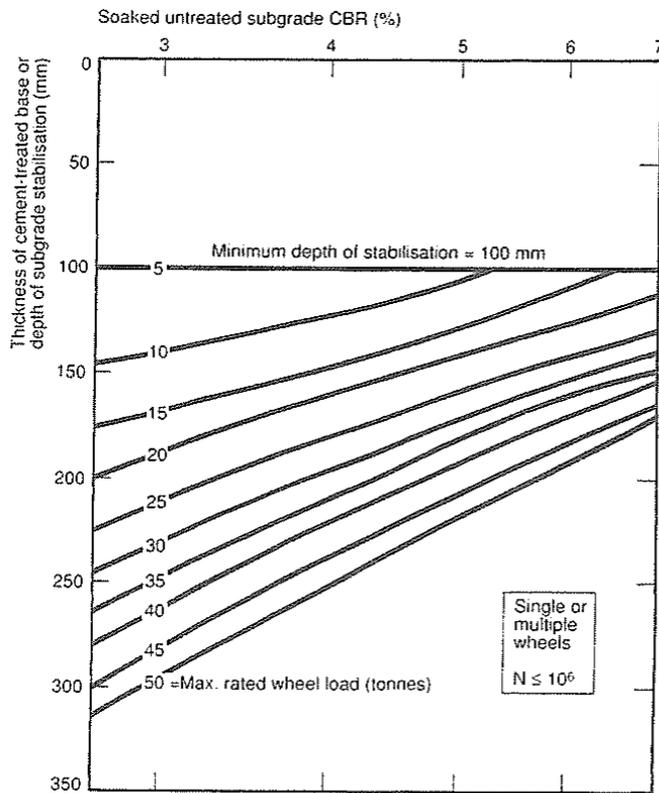


Figure appx 4.2. Annotated figure for the thickness of the base (Shackel 1990)



Nomograph for the selection of the thickness of an unbound granular sub-base

Figure appx 4.3. Thickness required for unbound granular sub-bases (Shackel 1990)



Nomograph for the selection of the thickness of a stabilised sub-base

Figure appx 4.4. Thickness required for stabilised bases/sub-bases (Shackel 1990)

APPENDIX C

Pavement Construction

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Executive Summary

This report explores the construction process of an interlocking segmental pavement using a case study. The project aimed to replace an old asphalt pavement on an industrial driveway. The construction process included the excavation and re-compaction of a part of the base course as well as the installation of the new concrete pavement. This process was summarised in the specifications attached within the appendix.

Black Unipave 100 interlocking pavers were selected as the main pavers with ‘natural’ Techpave 100 pavers being used for the edging course. For the excavation and compaction phase, excavators, heavy rollers, and plate compactors helped in quickly ripping the base course to the desired 130mm depth. The Sand Replacement Test was used to ensure that an acceptable compaction was achieved. In the block laying phase, a screeding machine and a mechanised block layer were pivotal. A herringbone pattern rotated 45° was chosen as the pattern in compliance with the performance-first approach adopted by the standards for industrial contexts. Laying was conducted up the slope as to avoid creep. To finish the pavement, a final compaction was conducted to set the pavements in place along with a jointing sand sweep. This compaction was done continuously to avoid variability caused by the loads applied during construction.

Through this project, the versatility of segmental pavements was highlighted. Further, the meticulous planning of the construction process was vital for a proper finish. More information regarding the location may have been useful in the determination of acceptability of the product as well as for material sourcing purposes. Finally, this project shone light on the relationship of capital to construction and the questionability of who benefits from labour.

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1.0 Introduction

Segmental pavements are highly versatile and can be used in a variety of different applications. As opposed to rigid pavements, segmental pavements do not spread the impact load across the whole structure and largely contain the load to the localised area. As each piece of the pavement is not directly connected, failures in the pavement, such as cracks are kept contained, maintaining the integrity of the whole pavement. The segmental nature also allows for easier maintenance as localised damage can be easily replaced, quickly returning the pavement to an uncompromised state. This can be advantageous in industrial applications as failures of the road surface do not majorly disrupt operation as repairs can be quickly finished.

This report explores the use of interlocking concrete pavers in an industrial driveway context. An old driveway that was previously laid with asphalt is to be replaced with the concrete pavers. The basic geography of the site has been visualised in the simple diagram in figure appx 5.1. The scope of the project comprises of the excavation and re-compaction of the existing base course as well as the laying of the new pavement. While the construction specification has been collated in the Appendix, this report will outline the factors and influences of certain choices made for the project. Details on material choice, equipment use, site management and construction techniques will be thoroughly examined in the main body. Through this project and report, understanding of the pavement construction process as well as the applicability of segmental pavements in industrial contexts will be expanded.

2.0 Specification Outline

This section meticulously outlines the logic behind the choices made regarding crucial elements of the project. The specification for this project was written to be concise and easily understandable by the contractors that are to be used for the actual construction. While detail regarding the reasons for each choice is important in understanding the project holistically, it may be unnecessary for on-site operation and hide crucial details behind walls of text. Thus, the specifications remain concise for easier legibility and the detailing has been left in the overall report.

The concrete pavers will replace the 100mm of asphalt that was previously used as the wearing surface. The 100mm pavers will require a 20mm layer of compacted bedding sand, resulting in

a need for 130mm of the base course to be excavated and re-compacted at a moisture content of 5.4%. As outlined in figure appx 5.1, the driveway is 50 metres long on a 5% downward slope from the road and 8 metres wide to accommodate the large industrial traffic. One side of the road is bound by the wall of the neighbouring property, with the other side free of any physical structures. Two 300mm concrete drains are located along the width of the driveway, halfway down and at the bottom of the driveway. The drains connect to a collector pipe that runs adjacent to the driveway beneath the free edge. The edge adjacent to the road connection is a 170mm concrete slab.

2.1 Materials

Choosing the appropriate material is integral in the proper operation of the pavement once heavy traffic starts to travel across it. With a plethora of choices, it may be difficult to find ideal option for the specific site. However, the restraints given in the design brief have greatly narrowed the available options, allowing for a more straightforward selection process.

Sampling is crucial in the material selection process as it ensures that the actual product will be suitable for the site in real-world applications instead of idealistic rendered conditions. Continuous sampling is also important to maintain quality control in the delivered products. Due to the large amounts required in industrial projects, the consistency of the materials may be affected. Therefore, it is vital to continuously check the condition of the materials throughout the manufacturing process.

Another factor that needs to be addressed is the need to follow established standards and maintain quality control for the finished product. As visually similar materials can have different physical properties, it is important that the properties of the materials can withstand the designed use-case. In worst-case scenarios, failure of the structure from the use of materials not suited to the use-case can result loss of life, especially in industrial contexts where heavy machinery is constantly in proximity to workers.

2.1.1 Concrete Pavers

Unipave 100 blocks were chosen as the main pavers to be used in this project. The dentated shape of the pavers provide much greater resistance to movements in both longitudinal and lateral directions (CMAA 2014), allowing for better pavement performance as noted by Shackel

(1990, p.175). However, one major problem arose during the sourcing of these blocks, as no manufacturer of blocks in Australia were manufacturing 100mm blocks according to the research conducted. This may be due to the recommendations laid out by the Concrete and Masonry Association of Australia (CMAA) opting for 80mm blocks. However, since the 80mm version of the blocks are readily available within NSW, it can be assumed there should be no major issues regarding the production of the 100mm versions due to similarity of the blocks (BA Contracts 2020). No particular reasoning was used in the choice of colour, as aesthetics take a lower priority in industrial use-cases and pigmentation has little effect on performance of the blocks (Shackel 1990, p.164). However, as efflorescence may be a problem at the site, it may make it easier to identify spots where seepage may be occurring as the white may contrast with the black blocks. Techpave 100 bricks were also chosen for the edge course of the pavement as they were suitable for the project and stock was available in NSW (australmasonry 2016). Edge coursing provide a strong boundary for the blocks, resisting movement (McCormack n.d.). The 'Natural' colour offers a lighter colour that can help to outline the edges of the road structure.

2.1.2 Other Materials

Sands specifically provided for bedding sand and jointing sand are important to the integrity of the structure as well as for ease of use in their intended application. The finer jointing sand can be more easily swept into the joints and fill the voids. As previously mentioned, efflorescence was noted to be a problem in the design brief, thus a bituminous spray seal was chosen as a waterproofing membrane to prevent the seepage of the water and salt (Boral 2018), which may lead to reduction in skid resistance in extreme cases (Shackel 1990, p.165). It can also help to prevent seepage through the blocks altering the moisture content and strength properties of the load bearing layers in the road. A high strength concrete is also important in the laying of the edge restraints of the pavement, needing to withstand the horizontal thrust developed under load (Shackel 1990, p.193).

2.2 Equipment

Machinery is important for the efficient and smooth operation of the construction site. As machines enable a single worker to achieve a much higher output of work, it can speed up the construction process. It can also be more accurate and consistent in certain circumstances as

outlined below. This section details the reasoning for the use of specific machinery and is divided into machinery used in the base course work and pavement laying.

2.2.1 Base Course

The excavator is vital in the initial phase of the driveway project, greatly aiding in the ripping of the base course. As noted in the design brief, 130mm of base course material needs to be removed. This can be quickly achieved with a small excavator as the depth is not great, but the surface area is large, resulting in a lot of material needed to be ripped. The compacted nature of the material may also make it difficult to hand rip the material. This also expedites the material removal process as they can easily place the materials into a heap or directly fill the removal trucks with unneeded soil. The next phase of the construction process is also made much easier with the use of a roller compactor. The choice of the CB7 roller was based on prior use of an equivalent vehicle, meaning that previous data regarding the number of passes required for adequate compaction is available as a guide. Rollers also cover a much larger area more quickly, saving on labour. However, the weight of the vehicle restricts its use to areas without structures nearby. Therefore, plate compactors were chosen to compact the areas where heavy machinery could not compact. As these devices are not as impactful, they should be able to compact the surface without damage to existing structures such as the drains or property walls. Furthermore, this device can also be used for the final compaction of the sand bed and pavers, allowing for mixed use.

2.2.2 Pavement Construction

This section of the construction process can be the most labour intensive of the project, highlighting the need for mechanised aid. Forklifts are one such example that aid the productivity of laying. Forklifts can easily supply multiple block laying machines and reduce handling. Furthermore, as mentioned in chapter 6 by Shackel (1990, p.196), pallet stacked bricks can increase productivity by 60%. A screeding machine also increases the efficiency of the laying process while concurrently increasing consistency across such a large surface area. As it only requires a few workers to operate, much more area can be quickly screeded with fewer workers. However, the most important machine in the laying process is the mechanised block layer. Hand laying the bricks requires many labourers to finish in a reasonable time frame. It is also very physically demanding work, with bricks weighing 5.5kg each (BA Contracts 2020). The machines can allow for a more laying to be conducted, increasing output five-fold

to 500m² in a single shift compared to hand laying (Shackel 1990, p.209). This has advantages as the project can be finished much quicker. Variations and stoppages due to weather can also be minimised as it can be finished in a much shorter time frame. Industrial driveways also have fewer structures in the way compared to urban pedestrian walkways that require hand paving around, maximising output. Furthermore, machine laying also has the advantage of consistency in joint widths. This is aided by the interlocking block shape and the spacer nibs on the blocks.

2.3 On-Site Action

Divided into the major construction processes, this section outlines the reasoning behind the construction process chosen in the specification. Before work begins, it is important to secure the site. Fencing protects the site from theft and damage of components within the site as well as preventing unrelated entities from getting injuries. With a large amount of heavy machinery operating, safety should be the highest priority. However, developers and employers are antithetical to worker safety due to their relationship with capital. As interest rates rise, “speed is what employers mostly look for” (Watts, Burgmann & Burgmann 1998, p.104) to ensure quick turnaround, resulting in worksites “allowed to be in unsafe conditions” as Master Builders Association senior Rocher (1980) notes. As contemporary material conditions parallel the conditions of the 1970’s, workplace accidents may rise just as they did previously. Organised labour is quintessential to confront “employers’ seeming indifference” (Burgmann & Burgmann 1998, p.106) to unsafe conditions. Militant action has been the driving force in ensuring worker safety, harkening back to the 8-hour movement in the 1850’s.

2.3.1 Storage

Setting up a storage section on the site allows for easy, organised, and centralised access to the required material and machinery. Furthermore, it is important that materials are stored under cover as exposure to the weather and atmosphere can change the moisture content of the material, thus changing the physical properties which can greatly weaken the driveway and cause failure.

2.3.2 Base Course

As mentioned previously, the use of the plate compactor for perimeter compaction is important to maintain integrity of existing structures. Once the perimeter is compacted, the roller can be used to compact the rest. Information regarding the previous construction process for

compaction is relevant, meaning that it can be used as a guide for the re-compaction of the base course. Density checks at random sections across the whole driveway is essential to ensure proper wholistic compaction. The tolerances for compaction reflect the required compaction as outlined in the brief. With the minimum acceptable compaction at 95% of the Standard Compaction Test result at Optimum Moisture Content (OMC), it is not acceptable to be below the given figure. The upper bound reflects the compaction at OMC. Another issue regarding the roller relates to the damage caused to the underground drainage pipe. This can hopefully be mitigated using a protective plate to distribute the load of the roller across a wider area to reduce strain. The concrete edging should be then placed after compaction and before the sand bedding to ensure the edge has a solid base rather than the loose sand. The bituminous spray then creates a seal between the sand layer and the ground, preventing efflorescence as mentioned previously.

2.3.3 Bedding Layer

To keep the sand at its optimum moisture content for compaction, it should not be placed till right before use. The screeding of 30mm of loose sand reflects the amount required for a 20mm compacted layer (Shackel 1990, p.195). While tolerances are given to reflect acceptable variance coming from the extra rip depth of the base course, the use of the screed machine should create a consistent and accurate screed. Pavement laying should start at the bottom of the slope to prevent block creep. The sequential method for block laying also allows for easier scheduling as segmentation of work to two sections creates a physical gap.

2.3.4 Pavement Laying

The laying of the edge course prior to the main body helps to maintain line and shape for the large main body area (McCormack n.d.). A herringbone pattern was chosen due to the superior strength properties compared to other patterns (CMAA 2014; CMAA n.d.; Shackel 1990). The orientation was chosen to reflect the direction of travel as well as a secondary purpose to help drain water. The rotation of the herringbone by 45° to reduce the need for longitudinally cut pavers. Hand laying of these cut pavers will be required to finish and lock the complete pavement in place.

2.3.5 Final Compaction

The final compaction procedure for the bedding sand was outlined by Shackel (1990, p.210-211). The first compaction sets the stone in place and allows for the bedding sand to rise into

the joints. The second compaction happens after the sweeping of the jointing sand, which fills in the rest of the joint, further solidifying the pavement structure. Continuous compaction of the pavements as soon as the blocks are laid is important as the heavy loads of the block pallets and machinery may disturb the pavement prior to compaction, resulting in poorer longevity.

3.0 Conclusion

This report lays out the method for the construction of an interlocking segmental pavement that is to replace an old asphalt surfacing. Some excavation of the base course was required to accommodate the new pavement and bedding layer. The construction process was succinctly outlined in the specification attached within the appendix. The main body of the report meticulously analysed the major sections contained within the specification. Explanations regarding material selection, the required heavy equipment and work methodology were carried out in the relevant sections. The use of interlocking pavements was core to this project as the industrial application requires a performance first approach. To aid with the prompt construction of this driveway, equipment such as a heavy roller and pavement laying machine were used. Following various standards and guides, a 45° herringbone pattern pavement was constructed with an edging course. Proper care was taken to ensure acceptable compaction of all layers to maximise performance. Details regarding the efficient flow of work were also explored.

Through the research conducted for this report, the versatility of segmental blocks was emphasised. The shear range of products that can be used for a variety of different applications, especially within urban and pedestrian environments highlight the many benefits of segmental pavements. Aesthetics, durability, and ease of maintenance are just some of the qualities that make segmental masonry stand out from other types of pavements. To fully appreciate these pavements, proper construction detailing is vital for longevity.

4.0 Recommendations

As the design brief omitted a specific geographic location, key information was missing that could affect the design. Climate data and water table information can be greatly influenced by local geology. Assumptions regarding acceptability of the basecourse were made as per the design brief, however this may not be fully accurate. Furthermore, the threat of global warming

has caused massive changes in the climate, resulting in more volatile and harsher weather. This should be considered. Location also affects the availability of materials. As concrete pavers have a relatively low value to weight ratio, it may not be economical to transport interstate in such a large country such as Australia. Blocks are produced within each state and transported a relatively shorter distance. While it was assumed that the site was in NSW, this may not be an accurate assumption, which would alter the availability of some types of pavers. As mentioned, no 100mm interlocking pavers could be sourced within Australia according to the internet research conducted. Potentially substituting for the more readily available 80mm paver may be suitable, especially considering the guideline outlined by the CMAA (2014; 2010) recommend using an 80mm thick paver.

Another consideration that may need to be addressed is economics. Quotes regarding labour and machinery hire were not considered. Material costs were also not considered during the selection process. These factors may greatly influence the construction process. The method outlined in the specification has been optimised for time, minimising the amount of human labour required. Calculus regarding equipment rental may find that a different ratio of human labour and machine hire may be more optimal for the contractor. While labour saving devices can be used for good, it is more often used to accrue wealth by reducing costs. More should be questioned regarding whether these labour-saving devices are providing a social benefit to society, considering they are being used to de-skill labour and reducing the ability for workers to organise. Technology can be used to improve the quality of life for workers, if only the benefits were shared equally across society.

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Appendix 5

Pavement Construction Specifications

I. Scope See figure appx 5.1 for outline of worksite

Perform work described here including but not limited to:

Supply and install segmental block pavement with bedding and jointing sands.

Install compliant waterproof membrane to basecourse.

Compaction of basecourse

Complete all contract Works in accordance with instructions.

II. Standards

Comply with applicable clauses in current editions of building standards:

AS/NZS 4455.2 2010 Masonry units, pavers, flags and segmental retaining wall units

AS 2008 2013 Bitumen for pavements

III. Quality Control

All materials should be checked for the required level of finish and performance prior to leaving the manufacturer. Samples should be submitted, approved, and archived in a timely manner.

Samples need to be approved prior to commencement of work.

IV. Materials

Item	Description
Unipave 100 concrete pavers	Dimensions: 225L x 111W x 100 H mm Colour: Black Purpose: Main interlocking pavement
Techpave 100 concrete pavers	Dimensions: 210L x 105W x 100 H mm Colour: Natural Manufacturer: australmasonry Purpose: Edging course
Bedding Sand	
Jointing Sand	
Bituminous Spray	Purpose: Waterproofing
Concrete	28-day characteristic strength $\geq 30\text{MPa}$

V. Machinery

Equipment	Description
Small Excavator	Remove basecourse, e.g Caterpillar 313
Catepillar CB7 Compactor Roller	Base course compaction
Sand Screeding Machine	Similar to Ultrascreed manufactured by Probst
Forklift	Transport pallets of pavers and bedding sand
Mechanised Pavement Layer	Similar to Pavemax series from Probst
Plate Compactor	Used to compact bedding sand and boundary of base course

VI. On-Site Actions

Work Methodology: Ensure delivery of materials and work is compliant with relevant Work Health and Safety requirements. Ensure work site is packed and secured after every shift.

Delivery & Storage: Construct fencing facing road and other open boundaries to secure site. Prepare the bottom of the site/driveway and set up areas for equipment and material storage. Materials should be kept under cover, protected from rain.

Base Course: Use excavator to excavate base course till 130mm depth on both sections of driveway. Test moisture content of basecourse and adjust to achieve 5.4%. Use plate compactor to compact the base course within 0.5m of the drainage pipe and building wall. Compact till density of 2024 kg/m³ (-0 + 100 kg/m³) is achieved. Test using Sand Replacement Method (SRM) for density. Place protective plates over the drainage pipes on the side of the driveway and then use the CB7 roller to compact the rest of the base course in the bottom section of the driveway. Commit 10 passes over the uncompacted perimeter basecourse in static mode. 5 passes are necessary for the remaining inner base course using the vibration mode after 1 pass in static mode. Test multiple random sections of the base course to ensure density meets requirements using SRM. Compact further if necessary. Move roller to the top section of driveway using the side of the road again, then repeat compaction procedure. Lay and set the combined bed and haunch concrete edge restraint on the free side of driveway. Spray a thin layer of bituminous seal once concrete is sufficiently dry.

Bedding Sand: Only prepare enough sand for each day's work. Use the sand screeder to lay a consistent 30mm (-5 +15mm) of level loose bedding sand. Start work on the bottom section of

the driveway and do not start on the upper section prior to the completion of the bottom driveway.

Pavement Laying: As in figure appx 5.2, prepare the Unipave 100 into square layers on pallets in a 45° herringbone pattern. Hand lay the edge course using the Techpave 100 in soldier row formation along the bottom drain then working up the perimeter along the wall and concrete edge restraint, with average joint width of 3mm (± 1 mm). Transport the pallets of Unipave 100 as close as practicable to the work face with the forklift. Starting from the bottom of the slope, lay the pavers down, arrow pattern pointing down the slope, using the mechanical paver. Hand lay pavers to fill empty spots on the interface with the edge course, cut pavers to necessary size. Continuously compact the freshly laid pavers as outlined below to within 1m of the work face. Finish the section with Techpave 100 edge course along the upper drain. Repeat the process for the upper section of the driveway.

Final Compaction: Commit one pass of the plate compactor over the laid pavers. Spread the jointing sand above the compacted pavers and broom the sand into the joints. Remove excess jointing sand then compact the pavers once more with another pass with the plate compactor.

END OF SPECIFICATION

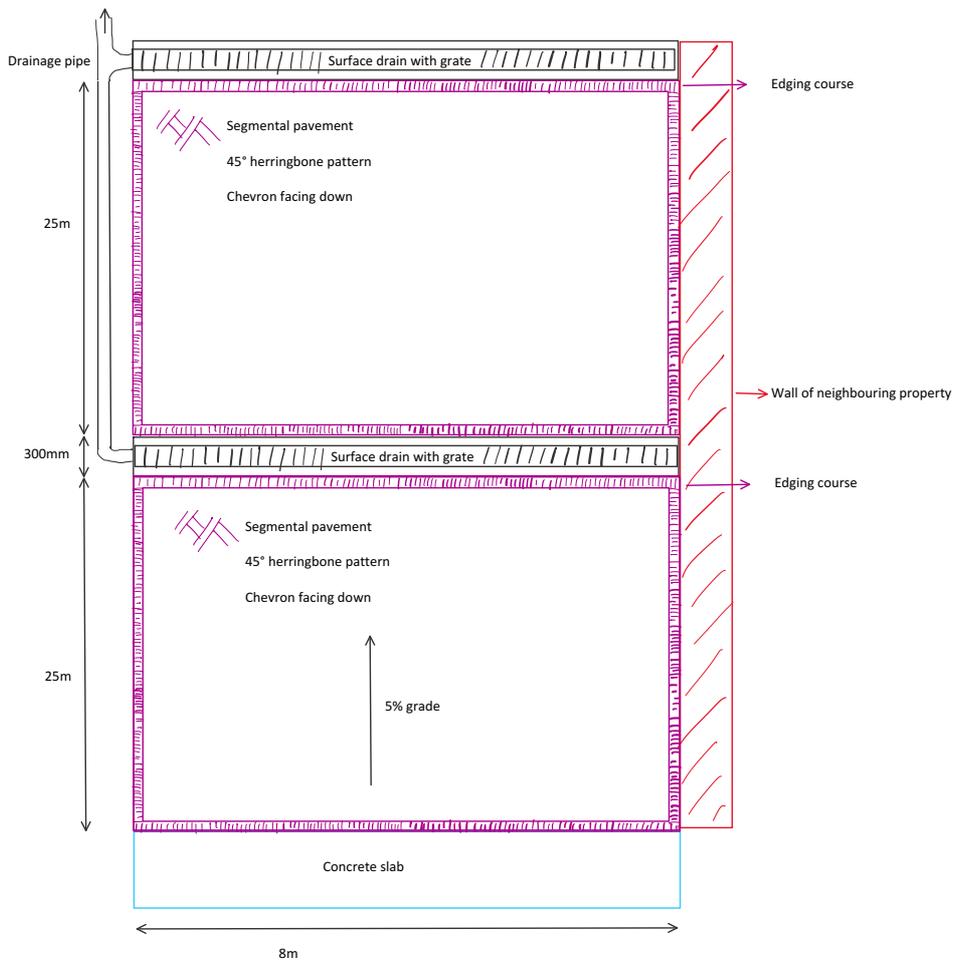


Figure appx 5.1. Simple Plan of Site



Figure appx 5.2. 45° Herringbone pallet (Probst n.d.)