NEW PAVING DESIGNS AND MATERIALS - BREAKING AWAY FROM TRADITION

Nigel Nixon
Nigel Nixon and Partners, Inc.

ABSTRACT

This paper addresses recent developments in design methods for heavy-duty port paving and the cost-effectiveness of new technologies in pavement materials. The process of pavement design require's a comprehensive study of all factors that relate to the pavement's performance. These considerations are reviewed by citing examples of ongoing work undertaken by Nigel Nixon and Partners, including projects at the Port of Virginia, Port of Oakland, Port of Seattle, and Port of Jamaica.

INTRODUCTION

In heavy-duty paving for port and intermodal terminals, the current approach is to design concrete and asphalt pavements by using empirical methods. In recent years considerable research has been undertaken on the development of new design methods for heavy-duty paving. These methods require a detailed knowledge of the full range of container-handling equipment, subgrade conditions, and pavement materials. Developments in paving material technology enable the pavement engineer to produce a number of alternative design solutions so that the most cost-effective pavement can be selected. Using life-cycle costing techniques, the choice of pavement can be based on the initial capital expenditure and ongoing maintenance costs.

OPERATIONAL BACKGROUND

With the continuing growth of containerized cargo trade, there is increasing competition among paving companies for business from shipping lines and railroad companies. As a result, many terminals are expanding or upgrading their container-handling facilities and operations to achieve greater throughput and efficiencies. The opportunity exists to consider all the latest state-of-the-art, container-handling systems to determine the most suitable form of operation for expedient unloading and loading, low container-handling costs, and optimum container selectivity.

The container-handling method has a considerable implication on pavement design. Vehicles such as straddle-carriers and highway trailers have relatively low wheel loadings, which makes it possible to adopt an economical pavement form. Heavier port equipment, such as front-lift trucks, port packers, and reach stackers have more onerous wheel loadings and consequently require thicker pavements. It is beneficial, therefore, to be able to determine specific areas for operation of each type of equipment so that areas where only lighter wheel loads occur can be designed for thinner pavements.

SITE CONDITIONS

To undertake satisfactory pavement design, it is essential to determine the likely ground conditions that will be encountered during construction and how underlying materials will affect performance of the pavement. Pavement design can begin after subgrade conditions are determined. However, if the subgrade is of poor-quality material, benefits can be derived from making improvements to the existing pavement. These include a range of mechanical or additive treatments for the top layers to form a more uniform support condition. For deeper improvement to reduce consolidation settlement, there are several ground-improvement techniques available, whose selection depends on soil types.

Subgrade modifications can be performed by treating pavement foundation materials to enhance their engineering properties. Subgrade materials can be improved by increasing their state of compaction by preloading, or mechanical, means or by changing their constituent makeup by using additives. Examples of these techniques include consolidation by preloading, dynamic consolidation, mechanical stabilization, and additive modification.

In consolidation by preloading, soil is stockpiled on the ground to simulate the final loading conditions arising from additional fill to achieve final levels and superimposed loadings. A surcharge can be made in excess of anticipated loadings to accelerate consolidation. The provision of vertical or horizontal drains speeds up the process. In all cases stability checks should be made to ensure that the soils are not over-stressed.

Dynamic consolidation involves the repeated dropping, under carefully controlled conditions, of a heavy weight from a set height onto the surface of the soil in a predetermined spacing and timing pattern. This produces high stresses that lead to compression of the voids in the soils.

The previous two methods may not produce the required density in the top layers of the subgrade. It may be necessary, therefore, to compact the upper materials by deadweight or vibratory rollers or other compaction equipment. It may be necessary to remove the existing soil and replace it with a suitable material in certain cases.

There are many additives that can be mixed with the subgrade soils to improve their engineering properties. These additives include lime, flyash, and cement. The choice of additive depends on the soil type. Laboratory testing on samples should be conducted before full-scale site trails are undertaken.

PAVEMENT DESIGN

Container weights follow a wide distribution. The heavier the container, the more damaging it can be to the pavement. Because few containers get loaded to their maximum capacity, using the maximum container weight, and hence maximum wheel loads, can lead to overdesign of the pavement structure. It is important, therefore, to investigate the frequency of all container weights the pavement is likely to endure and to determine the container weight and frequency that causes the most damage to the pavement. Analysis also should be carried out for all items at a facility that are likely to traffic the pavement to determine the most damaging item, which will form the basis for the design. The British Ports Association design manual, *The Structural Design of Heavy Duty Pavements for Ports and Other Industries,* provides comprehensive guidance for this stage of design, which also can be applied to other design methods.

Once a full analysis of the traffic to which the pavement will be subject has been completed and the final design properties of the subgrade have been determined, pavement design can begin. Strains are calculated at the boundary of each pavement layer, which are compared with allowable strains for the material. Material equivalence factors are used to develop different constructions that depend on material properties.

This method also can be used to design overlays that extend the life of existing pavements. Existing pavement construction is analyzed and equivalent thickness of cement-bound base material is calculated, following which an overlay is designed.

MATERIALS

All materials used within a pavement have different characteristics that determine their performance. The properties of similar materials also can vary widely, depending on their constituents, workmanship, and environmental factors. The availability of materials, experience with their use, and with their installation cost have a large impact on the final pavement specification. Installation cost too often is used as the sole selection criterion.

Surfacing materials are selected based on their ability to resist the loading imposed by the handling equipment and cargo. They must resist high-contact stresses such as those from trailer dolly wheels and the scrubbing action of the tires. Traditional pavement materials, such as Portland Cement (PC) concrete, and asphalt concrete respond to these stresses in different ways. The high compressive strengths of PC concrete can withstand high-contact stresses. PC concrete slabs can be strengthened in many ways, including rebar, continuous, and or steel-fiber reinforcement. Asphalt concrete, however, is prone to indentation under such loading conditions, particularly during hot weather. Highway mixes may not be suitable to reinforce asphalt concrete; therefore, modified mixes may have to be developed. Mixes can be modified by refining the aggregate requirements or using harder or modified binders. Several proprietary modifiers are available, but their use is not as extensive in the United States as in other parts of the world. Another alternative is to incorporate a reinforcement grid within the asphalt layer. A material that combines the high compressive strengths of PC concrete with the flexibility of asphalt concrete is concrete pavers. These are used extensively overseas for heavy-duty pavements and their use is growing in the United States.

Base layers in pavement provide the majority of the load-spreading ability. A wide variety of materials are available for base layers, including bound and unbound aggregates. Binding agents such as Portland cement and asphalt can be used in many forms. Alternatives exist through the use of two- and three-dimensional geo-grid systems that can be used with otherwise unbound aggregate materials. Base layers also can be constructed using by-product materials, particularly those with some cementitious properties. Phosphoric slag and fluorite, examples of the latter materials, can provide very high strengths. For successful pavement design, therefore, it is essential to know how well these materials will perform. Laboratory testing can provide a considerable amount of information on strengths, elastic moduli, poissons ratio, and fatigue characteristics. When these data are known, the materials can be considered. If laboratory testing is not undertaken, there are many relationships that an experienced pavement engineer can use when considering these materials.

Where ground conditions are adequate, it is possible to construct the base layer directly on top of the subgrade. If ground conditions are inadequate, a subbase is required. The subbase can take the form of an unbound granular layer or be composed of modified subgrade materials. Modification can be undertaken in situ by lime or lime/fly ash for clayey materials; cement for sandy, gravelly materials; or by a combination for mixed materials. Three-dimensional geo-grids also can be used to provide a suitable subbase using low-grade granular fill. Geo-textiles are used to a separate fine-grained subgrades and granular subbases and to reinforce the subbase.

With any pavement design, the more information known about the properties of the pavement materials and the subgrade, the more accurate the design will be. A detailed testing program, therefore, should be undertaken at the beginning of any pavement design.

PAVEMENT PERFORMANCE

After a list of potential pavements for the proposed development is produced, it is possible to consider the whole-life costs of each pavement system so that the most cost-effective pavement can be established for the terminal. This is achieved by assessing the likely maintenance requirements for each form of pavement.

A properly designed and constructed pavement can be expected to achieve its design life if it is maintained satisfactorily. When trafficking is random, some areas of the pavement will degarde quicker than others; therefore, to carry out effective maintenance, a monitoring system must be introduced. Maintenance not only should include the day-to-day patching and repair of defects and failures, but also the undertaking of preventive measures, rehabilitation, and upgrading to minimize potential disruption to facilities operations, by avoiding the need to resort to full-depth demolition and reconstruction of sections of the pavement.

Deterioration of the pavement at a facility can arise for many reasons, including overloading, abuse, settlement, accidents, weathering, poor construction, and old age. Deterioration will manifest itself in many forms, depending on the selection of the paving system.

Once the anticipated forms of maintenance have been determined, it will be possible to estimate an annual budget for the area. This information can be used to conduct a life-cycle cost analysis to determine the whole-life cost of alternative pavements. Such an analysis will consider the initial cost of the pavement and the cost of annual maintenance, expressed in equivalent present-day values. The process involves assessing a discount rate to be applied to all future costs for maintenance, repair, and replacement. The discount rate represents the difference between the cost of capital and inflation rates.

There are several hidden costs that cannot be included in the analysis, but should be considered. Each repair to the pavement may require considerable disruption of operations. Concrete blocks tend to have a lower maintenance requirement, which may increase the attractiveness of this solution. In addition, because competition between operators is great, there may be a potential marketing edge by using an aesthetically pleasing pavement form.

CASE STUDIES

Norfolk International Terminal

The Virginia Port Authority is proposing an extension to its Norfolk International Terminal. This will be undertaken on land that is not extensively developed at present. The final scheme will include a new two-berth quay with quay cranes and up to 42.4 ha (80 acres) of storage area for grounded containers and trailer parking.

Nigel Nixon and Partners undertook a study to identify alternative forms of pavement construction for the new facility. This study was conducted to develop designs, produce specifications, and investigate the cost implications of using different methods to produce flexible pavement. These methods included full-depth asphalt construction and asphalt- and concrete-block surfacing on various base and subbase layers. The study also investigated the benefits of using geo-textiles and two- and three-dimensional geo-grids. In addition, the long-term performance of the pavement was assessed, both in terms of likely maintenance requirements and life-cycle costs.

The terminal as proposed will use a new concept of a bridge crane operation, using straddle-carriers for container movement at ground level. In the short term, however, the terminal will be operated by more conventional means, using only straddle carriers.

All operations will be conducted by straddle-carriers with a high extent of channelized movement along individual container strings within the stacks. The bridge crane operation will provide very high stacking densities and will cover approximately half of the terminal. In the short term, however, the straddle-carrier operation will achieve lower stacking densities and will occupy approximately two-thirds of the development.

The straddle-carriers to be used at the terminal will have a load capacity of up to 36.3 tonnes (40 tons) with wheel loads of up to 11.3 tonnes (12.5 tons). The maximum axle loads on the trailers generally will be limited by state law, although some overloading is anticipated when containers are to be moved within the port areas and axle loads of up to 9 tonnes (10 tons) occur. The critical container weight was 25 tonnes (28 tons).

Extensive investigations were undertaken for the Norfolk International Terminal project, including 40 soil borings and 15 test pits, with associated in situ and laboratory testing. The investigation indicates that the ground comprises man-made fills overlying natural sand and clay formations. The investigation shows a significant difference between the materials below the grounded storage area and the wheeled storage area. In the grounded storage area, the ground consists of heterogeneous, highly plastic clays, silts, and sands, with high moisture contents and equivalent California bearing ratios (CBRs) of less than 2 percent. In the wheeled storage area, the ground consists of sand and low plasticity clay in a more homogeneous condition. Typical equivalent CBRs are between 2 and 3 percent.

The potential for consolidation settlement at the site is high, because of the low relative densities of the soils. To minimize this potential, a surcharging program to reduce the ultimate settlement following construction of the terminal is proposed. Because existing ground levels will be increased marginally to achieve the final designed pavement profiles, it is likely that some of the surcharge material will form a capping layer under the proposed pavement construction. Accommodating the consolidation effort, together with scarification and recompaction of the subgrade and surcharge material, should make it possible to increase the CBR values of the subgrade to 5 and 7 percent, respectively, for the grounded and wheeled storage areas. It will be possible to reduce the pavement construction thickness by providing a more uniform support condition of higher strength. Because potential long-term settlement will be reduced, the pavement will suffer fewer distortions, which can amplify the dynamic affect of a port facility, thus reducing the potential for premature failure of the pavements.

The design was undertaken using the British Ports Association and Asphalt Institute design procedures. When necessary, standard equivalency factors or those obtained by empirical testing were used to proportion other layers. This was particularly the case when geogrid systems were used to modify the granular subbase and base layers.

Many different forms of pavement were produced in the design process for further consideration by the Virginia Port Authority. Material specifications suitable for port use were produced, particularly with regard to the long loading times of container-handling facilities and the high contact pressures of container corner castings and trailer dolly wheels. Each pavement system was then costed, together with any differences in earthwork quantities, to achieve the final pavement levels. Following a cost analysis of all of the different forms of pavement, a short list was drawn up with the preferred solution from each of the main forms of construction.

In regard to maintenance, of particular relevance to the Norfolk International Terminal is the ownership of a specialized asphalt repair machine that has proven to be very economical in repairing localized failures. When this is combined with the very low costs of asphalt in the United States, the full-depth asphalt pavement becomes the preferred option. The concrete-block option is more expensive in terms of initial capital cost, but it exhibits lower ongoing maintenance costs and, as a result, has whole-life costs similar to asphalt pavement.

Port of Oakland

Nigel Nixon and Partners undertook a study to investigate various forms of construction for the paving of the rubber-tired gantry (RTG) grounded area at the proposed Berth 30 container-handling facility at the Port of Oakland.

The terminal was to be operated either by a chassis-based system of container handling or by an RTG system. Initial operations were to involve chassis traffic only, but the RTG system would be commissioned a few years after completion of the construction. To minimize later disruption, the pavement for the RTG grounded area was to be constructed during the current project.

The scheme includes three RTG runways, parallel to the wharf, each divided into two sections with 78 ground slots for 40-ft containers. The RTGs will be capable of lifting one container over four. Average stack height will be two containers high, and the average dwell time of containers in the stacks will be 5 days.

The ground at the RTG grounded area predominantly consists of granular fill overlying bay mud on silty sand. Filling operations on the site have been going on since 1915. The fill materials generally consist of loose to dense sand and gravel with various amounts of silt and clay and firm to stiff clay and silt extending to depths of about 2.6 m (8.5 ft) to more than 6.1 m (20 ft). The fill materials are of variable density and consistency in part because of the various methods used to place materials during historic site development. Much of the surface material is of an engineering quality due to working surfaces for earlier uses of the site.

Underlying the fill is a very soft to soft silty clay known locally as bay mud. These deposits are weak and highly compressive and contain various amounts of organic matter. Ground movement as a result of consolidation settlement of the underlying bay muds or as a result of seismic activity, therefore, was anticipated.

Various solutions were presented to determine the most cost-effective pavement. Two forms of surfacing materials were proposed: concrete-block pavers and roller-compacted concrete. The fact that high contact stresses generated by the container-stacking operation would cause indentation of an asphaltic concrete surface was considered. Various base layers consisting of cement-treated base courses of varying strengths, asphaltic base courses, and aggregate base courses also were considered. Various options for subbases included aggregate subbase and cement-stabilized subgrade.

Design methods developed by Nigel Nixon and Partners were used to obtain design solutions. The designs were calculated to provide a pavement capable of remaining serviceable for 15 years as an RTG grounded area. The failure mechanism considered was substantial cracking as a result of excessive, horizontal tensile strain at the bottom of the bound course, leading to full-depth cracking and a rapid breakup of the pavement. Surface deformations of up to 25 mm (1 in.) were anticipated.

An alternative considered was a pavement that would remain serviceable under much more surface deformation. This would be achieved by using a thinner bound layer that does not become subject to significant tensile strains. The failure mechanism would become settlement as a result of excessive vertical compressive strain at the top of the subgrade. Settlements of 76 mm (3 in.) or more were anticipated, and maintenance would be recommended for all rutting exceeding 51 mm (2 in.) in depth. Vehicle passes can iron out ruts to a certain extent; therefore, settlement depths are not predictable. However, surface materials would fail in these areas.

After various design options were considered, it was recommended that if the Port of Oakland is prepared to accept the noted deformations on its pavements, the high-deformation proposals should be adopted for the grounded area and chassis access lane. Low-deformation proposals, however, were recommended for the RTG runways. This would be achieved by incorporating a bound base layer under the sand bedding course. To achieve a full load spread throughout this material, an 8-ft-wide thickening was recommended.

Concrete-block pavers were recommended for surfacing material because of their ability to perform satisfactorily under the high point loads generated in the facility. The pavers also are able to perform satisfactorily even when high deformations occur. If it becomes necessary to conduct releveling maintenance, it is relatively easy to lift and relay the pavers to the required levels.

The port accepted the recommendation to use concrete-block pavers, but was willing to permit the high-deformation design for the entire area.

Port of Seattle

Nigel Nixon and Partners undertook a study into the current, standard pavement specification for the Port of Seattle. The study particularly focused on the appropriateness of the standard pavement section to the extension work being done at Terminal 5. This expansion will include up to a further 36.5 ha (90 acres) of land, along with rearrangement of the current Burlington Northern sidings. It is proposed to construct a new intermodal loading yard (ILY) consisting of six storage tracks and one through track. The area to the east of the site is a no-longer-operating refuse and industrial landfill. A large portion of the rail sidings and pavement will be constructed across the landfill. The work will include excavation of a significant depth of refuse, followed by construction of a methane collection system and low permeability cap, on which the pavement construction and rail tracks will sit.

The ground at the Port of Seattle consists of fill materials overlying native sands. The majority of the area contains medium-dense, silty, sandy hydraulic fills placed at or since the turn of the century. These fill materials will provide a range of CBR values between 7 and 10 percent. In other sections of the port, the fill material consists of slag, which is a result of the local steel industry. This material provides a significantly higher CBR value, in the range of 20 to 30 percent. In the landfill area, fill is made up of refuse, woodwaste fill, slag fill, and granular backfill. In these areas, the subgrade CBR may be 2 percent or lower. The loading regime within the landfill would be considerably changed, and long-term settlement is estimated to be between 50 mm (2 in.) and 300 mm (1 ft). To further complicate matters, two large-diameter pipes run under the ILY, one of which is on piles. RTGs will operate over the ILY and their concrete runway beams will be on piled supports. The pavement to be constructed in this area, therefore, must be able to handle the anticipated settlements and must be easy to relevel when settlements become unacceptable.

The majority of the ports container-handling operations—lifting and stacking of containers—are performed using front-lift trucks. These trucks typically have dual wheels on the front axle, with a maximum load of up to 28,850 kg (58,989 lb) per tire. The rear wheels have corresponding loads of 5,900 kg (13,007 lb) when laden and increase to 11,340 kg (25,000 lb) when the front-lift truck is not laden. The RTGs that operate within the port have significantly higher wheel loads, but operate on concrete runway beams. The majority of container movements around the port are undertaken by trucks operating at or less than the maximum legal axle loads for highway systems. For movements within the terminal and around the port, overloading of these vehicles must be assumed. The pavements are subject to static loading from container stacking and parking of chassis.

A number of flexible and rigid alternative pavements were investigated. Pavements studied included full-depth asphaltic concrete on 200-mm (8-in.) layer of asphalt concrete on an aggregate base and concrete-block pavers on bound and unbound bases. For each pavement the benefit of using geo-synthetics such as geo-textiles and two and three dimensional geo-grids was studied. The rigid pavements considered were roller-compacted concrete and Portland cement concrete with various ranges of reinforcement systems. A number of designs were produced for comparison purposes, and budget costs were applied to determine the most cost-effective pavement, both in terms of initial costs and life-cycle costs. Port of Seattle representatives believe the port's pavements have 10-year design life, and under these conditions the 200-mm (8-in.) asphalt concrete on a 300-mm (12-in.) aggregate base proved to be the most economical solution for general pavement areas on both cost counts. The solution for the ILY has not been selected.

The maintenance of minimal fails in the ILY is essential for the safe operation of trains. The complex situation of ground-bearing pavement and rails laid adjacent to piles that support runway beams and culverts requires special attention. In this area it is essential that the rail lines and pavement can be lifted and relaid easily if settlements become a problem. In these areas the preferred paving is likely to be concrete pavers due to their aptitude for this procedure.

Port of Kingston, Jamaica

Nigel Nixon and Partners prepared pavement designs, construction drawings, and specifications for an extension to the Gordon Cay Terminal in the Port of Kingston, Jamaica. The principal requirement of the Port Authority of Jamaica for the design of the terminal pavement was flexibility of use. The Port Authority currently uses straddle-carriers for the transfer of containers from quayside to storage to truck/train and vice versa. Because many of the straddle-carriers are at or near the end of their useful lives, the Port Authority wants to have the option of replacing some straddle-carriers and supplementing their use with top lifts.

The area to be developed is a barrier island that is sea bound on the three sides that separate the main harbor from the open sea. It has been used for many years as a spoil area for dredged materials taken from harbor-improvement works. The ground consists comprise sands and silty sand overlying a layer of organic material at depth. CBR values for the sand range from 5 to 15 percent, with the majority of values at about 10 percent. Because of the layer of organic material, differential settlements were expected, which made a flexible pavement the preferred solution.

Because the availability of local construction materials was limited, various design techniques were used to model the available materials and to produce various design solutions. Two forms of surfacing material were proposed: concrete-block pavers and asphaltic concrete. The base layers proposed were cement-stabilized marl and river shingle, both of which are available locally.

The pavement was designed to have a useful life of 20 years. An alternative whereby the pavement would be constructed with a thin asphaltic concrete surface, with the option to overlay it with concrete pavers in 5 to 10 years when the surfacing would have deteriorated, was presented.

A life-cycle cost analysis was produced for the various paving solutions, taking into account such items as maintenance costs and salvage value of materials. This demonstrated that the most cost-effective paving solution was the concrete-block option, due chiefly to reduced maintenance costs.

Concrete-block pavers were selected as the surfacing material because their low life-cycle costs and their ability to perform under the high contact stresses induced by container corner castings and from the heavy wheel loads associated with top-lift container-handling equipment. The concrete-block pavers are expected to perform satisfactorily if, as expected, differential settlement occurs. They also can be lifted so that the base can be releveled with minimal disruption to terminal operations.

CONCLUSION

Selection of a pavement for a new terminal depends on many factors that must be fully investigated. Cognizance of the effects of operations and equipment is necessary to ensure that most cost-effective overall scheme is adopted. In addition, a balance between the initial cost in providing the pavement and the maintenance cost over the facility's life is needed.

Sophisticated design methods gained through experience with heavy-duty port pavements since the advent of containerization and its associated handling facilities, now enable the designer to assess critical loading cases and analyze pavement construction to ensure that the required design life is achieved.

Modern materials can be incorporated into pavement construction to assist in load spreading and to reduce deformation so that maintenance costs are reduced.

The use of concrete-block pavers for heavy-duty paved areas has spread throughout the world in the past 25 years. This type of surfacing has been recognized as providing a viable alternative to concrete and asphaltic concrete because it is less prone to physical damage, chemical spillage, and indentation and because it exhibits great flexibility where deformations occur. Use of concrete-block pavers in Europe is widespread and gaining popularity in the United States, where life-cycle cost analysis demonstrates its advantage over traditional materials.

The behavior of a pavement under repeated loading from high axle-load vehicles is well understood. Design methods and modern materials have been developed to the extent that the intermodal terminal of the future will represent a synergy between facility and pavement at a higher level than ever before.