DESIGN OF INDUSTRIAL PAVEMENTS

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ABSTRACT: Industrial pavements require the consideration or different treatment of several parameters that are usually less of a problem with conventional roadway or airfield pavements. The constraints of site conditions, construction time, and materials suitability coupled with potentially high contact loadings present a challenge to the designer beyond those of conventional pavements. The considerations, assumptions, and methodologies are discussed to provide the designer with some insight as to ways of handling these items under the adverse imposed conditions.

INTRODUCTION

Industrial pavement applications differ from typical roadway or airfield pavement sections in several respects. The significant differences are:

- Loadings may be similar to airfield loads but load frequencies more closely approach highway repetitions.
- Sites are often located in non-prime areas commonly having soil types or conditions unsuitable for other real estate development.
- Many industrial applications such as paper mills, power plants, containerized shipping, and unloading docks are situated near water, which tends to exacerbate poor soil conditions.

Most reference texts do not mention specific applications to the design of industrial pavements, leading one to believe that industrial applications are simply variations of highway design procedures. While this is partially true, further consideration must be given to the industrial pavement as the conditions of use vary markedly from the typical highway pavement. Similarly, the loading conditions encountered in industrial applications are more closely approximated by the loading conditions of airfield pavements; however, the traffic patterns, predictability, frequency, and

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surface contact parameters found in industrial applications impose difficulties on the design effort that are not clearly addressed in the empirical pavement design approach.

Anything less than a well drained, well designed, and properly constructed pavement section results in a compromise to performance of the pavement and results in an increased cost to the user. An intent of this writing is make the designer aware of some of the potential compromises that must be considered and offer suggestions to address the design constraints in an effective manner.

LOADING PATTERNS

The cyclic nature of these applications results in a load for a single event, for example unloading logs at a paper mill, passing the same point on the pavement perhaps several times. In unloading the logs, a wheeled loader approaches the log carrier such as a truck or rail car, imparting a single pass load of the loader only. The loader then engages the logs, lifts and backs away, imparting a single pass load of the loader plus logs. The loader then must usually make a turn, either right or left, to deliver the logs to either a storage area or secondary transport, a scale, or other measurement or classification device. This imparts at least one more single pass load to the pavement onto the previously twice-covered pavement location. The result is three passes of the loader, once unloaded and twice loaded, over the same location on the pavement for one unloading event.

Similar loading patterns prevail for most loading/unloading operations, without regard to the material or commodity moved. From these loading patterns, it can be seen that often certain sections of the pavement may get numerous load repetitions while other sections get relatively few repetitions of load. The pavement section, of course, must be designed with the presumption that any section may be loaded to its full extent and repetition.

While some loading patterns result in many turning movements such as the log example, other applications result in high repetition linear or longitudinal movements. This is true of containerized shipping facilities and intermodal transport facilities. For these uses, the orientation of the facility is usually transversely constrained into long, narrow pavement sections. This results in fewer load repetitions than a facility requiring many turning or staging movements. Load magnitudes may be similar for either type of facility.

EQUIPMENT TYPES

Equipment types vary with the application. Commonly used material handling equipment for industrial applications may include:

- Large container handlers which are special lift trucks. These devices are capable of lifting and transporting containers 40 feet long and weighing 80,000 pounds or more.
- Log stackers which are similar, specialized lift trucks. Load capacities for these devices are similar to the container handlers. Some manufacturers use the same chassis for the stackers and container handlers since the functions are similar. They are usually fitted with loading devices such as grappling forks appropriate to the use.
- Wheeled or tracked cranes. Capacities for these devices may reach 100 tons; however, when loaded, cranes have limited mobility and maneuverability thus reducing the probable load repetition of this equipment.
- Conventional forklifts. Often used in conjunction with other, larger equipment, these vehicles usually have less load carrying capacity but due to their maneuverability are used in greater quantity resulting in more load repetitions at lower wheel loads.
- Conventional bulk loaders such as front loaders are used for handling granular bulk materials. These vehicles have capacities similar to forklifts and similar mobility.

- Vehicles that transport commodity to or from the industrial site. This typically includes standard trucks and tractor-trailer combinations resulting in high frequency of standard 18-kip axles loadings in addition to the industrial equipment.

PAVEMENT TYPES

Industrial pavements utilize all common pavement section types including rigid, flexible, composite, and unsurfaced sections. Due to the limitations often imposed by site soil conditions, it is sometimes necessary to take liberties with conventional thinking in pavement design and use extraordinary sections to achieve the desired performance within budget constraints. For example, it may be necessary to use several layers of a geotextile separated by stabilized soil layers to achieve a reduction in pavement section thickness to "fit" a site. While this may seem to be more expensive than additional layer thicknesses, it might well be a last resort to allow final grade matching or to reduce overexcavation and backfilling with select materials.

Another common necessity in industrial pavement design is the use of high modulus bridging layers within a pavement section. While bridging is not usually desirable for subsurface applications due to the potential for seemingly sudden failures (the failures are not truly sudden, only the surface manifestations), it is one option available to the designer to accomodate poor subsurface conditions without selective removal and backfilling.

Unsurfaced pavement sections can be used successfully for industrial applications. There is sometimes a false economy in using an unsurfaced pavement section in that the initial cost may be low but considering the impacts of greater equipment wear, increased surface maintenance, lower productivity, and decreased safety, the unsurfaced pavement should not receive a top priority, but should be used as an option.

SUBSURFACE IMPROVEMENTS

A variety of improvements may be made to the subsurface soils. Most decisions for improvement depend on cost effectiveness, time constraints or both. In many industrial applications, the design decisions that affect the construction schedule become very critical. The downtime of an industrial facility can run into many thousands of dollars per hour, making an increase in construction time a costly option. It is often decided to use the most expedient means of improvement with less regard to initial cost than to saving construction dollars by more time consuming means or methods.

One example of expedient improvement is the use of geotextiles or geomembranes for the remediation of deficient soil conditions. These materials are used to change significant stress orientation from a vertical plane (shear) to a horizontal orientation (tension in fabric, frictional shear on soil in horizontal plane). This allows bridging of poor soil conditions. The membrane or fabric can be laid quickly to cover large areas. This process is much more expedient than selective removal of yielding materials and the placement of select backfill.

If construction time permits, selective removal of poor or yielding soils can be done to improve the subgrade section of the pavement. Due to the high loads experienced with industrial equipment, the depth of replacement of underlying soils may be comparatively large, sometimes five feet or more. This process is time consuming, both in the removal and in the proper placement of backfill. Further, the process is often made more difficult by the presence of a high groundwater level.

A third process by which improvements to the subgrade may be made is that of stabilizing existing soils with other materials to achieve an increase in the mechanical properties of the soil. This can be done with chemical injection of enhancing materials such as calcium silicates, compaction grouting, the addition of stabilizers such as cement or fly ash, or the addition of graded aggregates to modify the gradation of the materials. With the relatively thick, layered sections of the pavement, it is usually necessary to place the modification or stabilizing material in two or more lifts as in-place mixing capability is usually limited to about 12 inches.

The effect of modifying the subsurface soils is typically an effective increase in the modulus of elasticity of the material. The bridging and load attenuation characteristics of high modulus materials is usually adequate to achieve a reasonably long performance life of the pavement section, provided appropriate mechanical property assumptions or testing are used to accomplish the pavement section thickness design.

Another consideration that must be made for pavement sections placed over soft or yielding subsurface conditions is that of settlement. Improvements to the subgrade, additional fill, and the use of high unit weight pavement surfacing all contribute to an increase in overburden pressures on the existing materials. Settlement computations should be done to check the anticipated settlement of the pavement section under its static loading and to evaluate the effect the settlement might have on the pavement performance.

Providing drainage to near-surface or subsurface materials usually results in an improvement to the materials, as most granular materials are more stable in a dry condition than when wet or saturated. Supplementary drainage for industrial sites is often difficult to achieve since underdrains and ditching require positive outfalls to perform properly, and the usual adverse site conditions preclude appropriate outfalls. The relatively thick pavement sections may also reach into layers impractical to drain by conventional means.

ANALYTICAL METHODS

Empirical Methodology

Conventional empirical methods of pavement section thickness design require the relation of load to a standard 18-kip axle load for highway pavements. This process is based on the empirical relationships developed in the original AASHO Road Test done in the late 1950's and early 1960's. The general equivalence factor tables provided by AASHTO and others stop at axle loads of 40 to 48 kips depending on the axle configuration. A typical container handler or log stacker may have a single axle load greater than 200 kips. For some types of equipment with tricycle axle configurations, a single pair of tires may carry 30 to 40 kips, resulting in a high load with a small load radius.

As stated in the 1993 edition, Volume 1 of the *"AASHTO Guide for Design of Pavement Structures"* there are limitations on the use of equivalence factors. The development of the equivalence factors was based on a limited number of measured load applications (1,114,000) and limited axle load ranges of 2 to 30 kips for single axles and 24 to 48 kips for tandem axles. While extrapolation of these factors has proved successful for both increased loadings and repetitions, the parameters encountered in many industrial pavements preclude the use of these factors with a high confidence level. Computed extensions of the equivalence factors was done in the 1986 edition of Volume 2 of the *"AASHTO Guide for Design of Pavement Structures"* and are applicable up to and including axle loads of 100 kips. Again, the axle loads encountered in industrial load applications may greatly exceed this value.

The probable result of using the empirical design method to determine section thicknesses is an overestimation of required thickness. While this is conservative from a performance perspective, it may be produce impracticably thick sections wasteful in cost, time, and effort. If the empirical methodology is used and the axle loads approach about 100 kips, the *"Extension of Equivalency Factor Tables"* as given in Appendix MM of Volume 2 of the *"AASHTO Guide for Design of Pavement Structures"* should be used. For axle loads greatly exceeding 100 kips, the methodology should only be used when tempered with experienced observation of similar pavement section performance.

Layered Elastic Analysis

This method of analysis was developed in the 1940's and 1950's through analyses conducted by one of the major oil companies. The computation method is based on algorithms developed from the theory of elasticity of materials and applied to pavement section materials with the often brash assumptions of homogeneity and isotropy within the respective layers. While several groups including government agencies have expanded on the original concept by providing for additional layer capacity and additional points or coordinate geometry to observe computed results, both radially from the load and with depth, the basic approach remains fundamental to elastic theory.

In order to effectively use this method, it is convenient to use computer programs such as *ELSYM 5*, available in the public domain. The input parameters include material properties of modulus of elasticity, preferably a resilient modulus; and Poisson's ratio. The trial layer thicknesses, load application points, and result spatial observation points are also input. From the input data, the analyst receives stresses, strains, and deflections at the prescribed observation coordinates. These values are then compared to published limiting stress, strain, or deflection criteria in the development of section thicknesses. It is recognized by long observation of pavement performance that the limiting criteria in flexible pavements are transverse or radial strain at the bottom of the bituminous layers and vertical strain at the top of the critical subgrade layer. These parameters control fatigue cracking and rutting, respectively. For rigid or composite sections, the limiting criteria are usually flexural stress and strain at the bottom of the rigid layers immediately under the loads, as well as stress and strain reversals at the top of layers between loads, particularly for high wheel loads with wide spacing. The vertical strain parameter for rigid or composite sections is perhaps less critical than for flexible sections, but should be checked as this may be a more cost-effective remediation point than simply adding more bridging thickness of rigid or composite layers, particularly when fatigue criteria are important.

Some variations of the layered elastic approach include provisions for non-linearity of materials and the accounting for variable material response through the use of factors or empirically based coefficients related to load-response characteristics of unbound materials such as lateral pressure coefficients.

Finite Element Analysis and Modeling

This technique may be applied to any series of materials using similar assumptions and parameters as the elastic layer analysis. Non-linearity of materials can be simulated but results in greater model sizes and correspondingly longer computer run times. The major convenience of FEA is its ability to model very thin layers such as a geotextile, and to provide a graphic output of results to allow a better understanding of stress distributions, material response characteristics and peripheral considerations that cannot be conveniently viewed within numerical summary output achieved with other methods.

In most applications, the pavement layers are modeled as finite cubic elements with discrete mechanical properties. The cubic elements can be adjusted in size as necessary to depict critical conditions and, in some programs, the sizes may be varied at any spatial point or series of points in the model. Other modeling approaches can be used such as modeling individual layers as plate elements. This is particularly useful in analyzing rigid or composite sections as they truly act as plates under corresponding loadings and thicknesses.

The most significant detriments to the use of FEA are the cost of the required software, the computer system necessary to accomplish the modeling in reasonable timeframes, and the training of personnel to use and understand the application of the method. Although mainframe computers are usually used for large FEA programs, many are available for desktop personal computers that can conveniently handle many modeling processes, particularly if carefully pre-planned. Software may be acquired for anywhere from a few hundred dollars to many thousands of dollars depending upon the capabilities and flexibility of the software. When running FEA models on personal computers, computation times of several hours should be expected as compared to minutes or seconds with the elastic layer computation programs.

CONCLUSIONS

When designing or analyzing industrial pavements one must keep in mind the differences between these special applications and the general analysis of pavements as applied to roadways and airfields. The use of mechanistic computer modeling and the tempering of these methods with empirical observations and experienced assessment can allow the successful application of established design principles to industrial pavements. The typical design considerations of expected pavement performance, traffic and loading characteristics, subsurface soils, drainage, materials, environment, reliability, and life-cycle costing still apply to industrial pavement design with the added challenge of high loadings, increased unpredictability of traffic patterns, and a lack of available, directly applicable research information.