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Sensitivity Analysis of Heavy Pavement Design for a Container Terminal Area, Case Study: Port of Gaza, Palestine

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Abstract: This study focuses on the sensitivity analysis of various design parameters for heavy-duty pavement for container terminal areas using Airport Pavement Structural Design System (APSDS) to yield an optimal design solution. APSDS is based on layered elastic theory, which was introduced into airfield design practice with the release of the computer program LEDFAA (Layered Elastic Design, Federal Aviation Administration). In this study, the pavement structure was found very sensitive to design parameters, where 15-60 mm more in base thickness was increased the design life twice. A reduction of base thickness was 27% by changing the handling system from rubber tyred gantry crane system to straddle carrier system and a reduction of 42-76% of base thickness by changing the interface condition at the bottom of base layer from smooth to rough. Other effects of design parameters such as lateral wandering distribution, container weight frequency, variation of elastic modulus for concrete block pavers and sub-grade are discussed. Also various construction materials were used and several combinations of base and sub-base materials were analysed to be able to select the most economical pavement structures.

Key words: Heavy-duty pavement, mechanical approach, APSDS, container terminal, Gaza Port

INTRODUCTION

Mechanistic pavement design programs such as APSDS are used to calculate elastic strains at subgrade level and at the underside of asphalt and stabilized layers. Pavement life is then calculated using empirical equations that relate these strains to load repetitions that cause unacceptable rutting of the surface or cracking of the asphalt and stabilized layers (Wardle, 1999).

Many types of pavement are available for port use; those that will have to stand up to the hard conditions are in general expensive. All requirements should be considered before deciding the optimum pavement for a particular situation.

More economical surfacing will be the result if different paving specifications are used for terminal areas with different duties. This however may result in a lack of flexibility in operations when there is a change in duty or give rise to failure if there is poor control of the more damaging plant, which must be restricted to areas with heavy duty paving.

In today's economic climate, the cost of constructing a new cargo handling facility is often beyond the financial resources of even the most successful terminal operator. Infrastructure costs form a large portion of any new development and the major cost in any rehabilitation of a handling facility. There is a wide range of construction methods used in paving, each of which has a different level of serviceability and different maintenance levels.

Regrettably many terminal operators consider their handling equipment in isolation to the pavement upon which it is to operate. Consequently, investment is often higher than it need to be. Therefore, it is advisable to select cargo handling equipment and surfacing materials together.

The designers have difficulty finding a study on the sensitivity of design parameters for heavy pavements. Therefore, this paper focuses on the sensitivity of design parameters to yield an optimum structure for container terminal areas, where the container terminal area at Port of Gaza was taken as a case study.

MATERIALS AND METHODS

Port location: The Gaza strip is a coastal area along the eastern Mediterranean Sea, 40 km long and 12 km wide. The port is situated 4 km south of Gaza City and 3 km north of the mouth of Wadi Gaza as shown in Fig. 1. The layout of Port of Gaza is shown in Fig. 2.

Container terminal area loads: The container terminal will be used for handling and stacking containers. Containers

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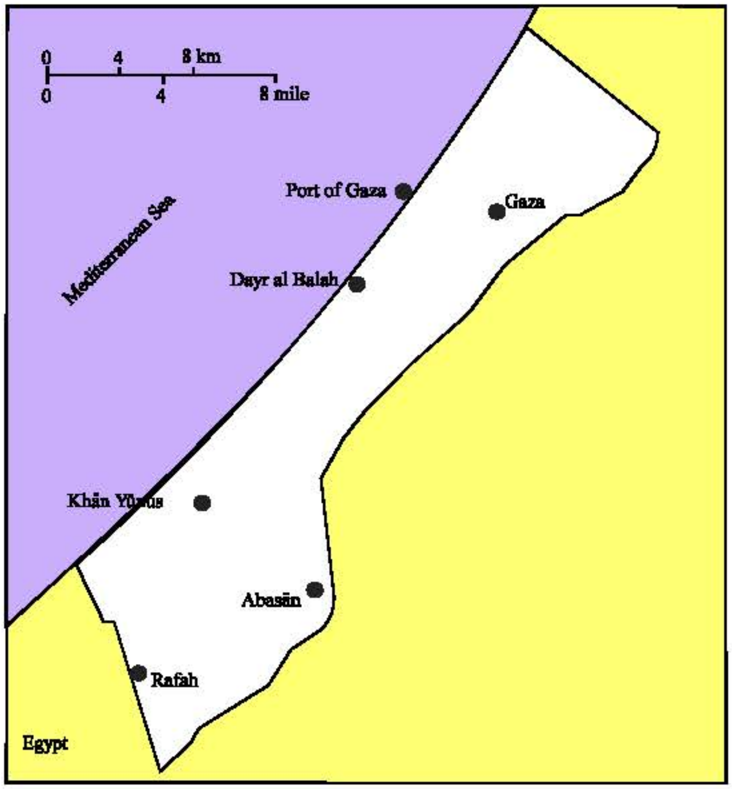

Fig. 1: Location of port of Gaza

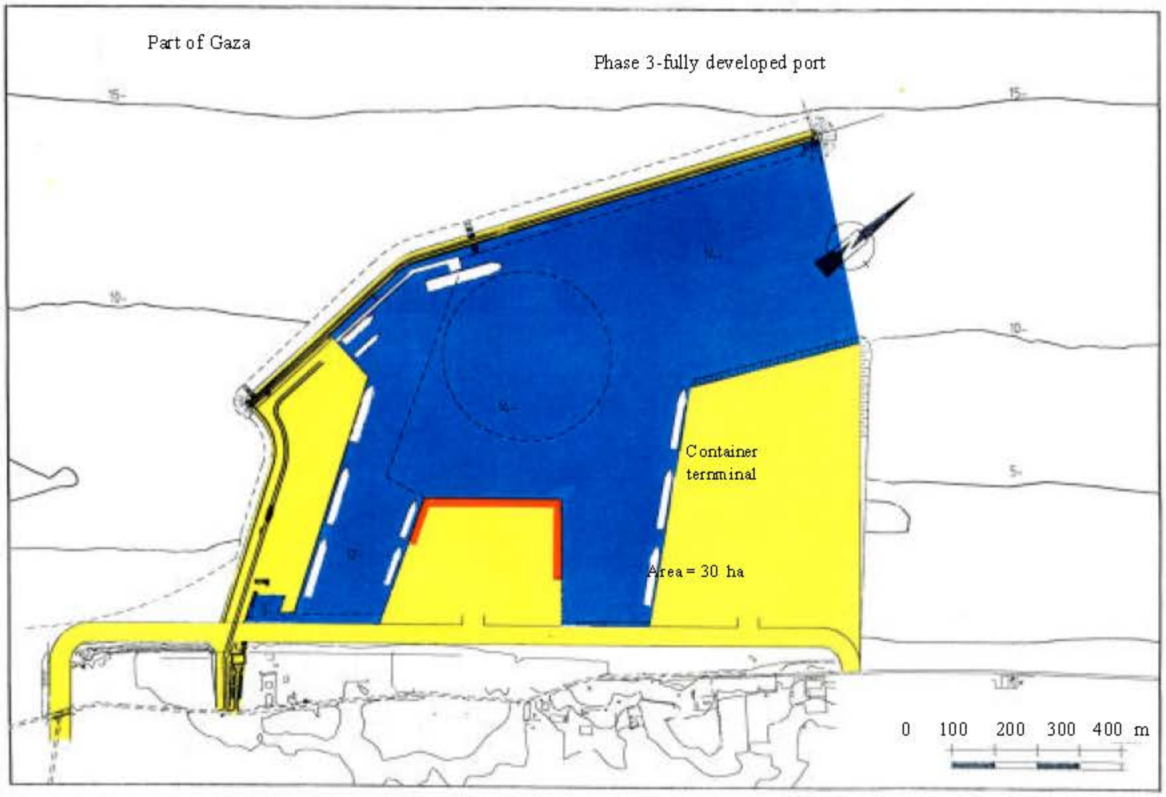

Fig. 2: Port of Gaza layout (Grabowsky and Poort, 1994)

will be transported from the quay to the stacking area and visa versa by In-Terminal Trailers (ITT). At the stacking area, the containers will be on- and off-loaded by Rubber Tyred Gantry Cranes (RTG). Empty containers will be handled at the empties stack area by Front Lift Trucks (FLT).

For design purpose, the number of ground slots and stacking height of the most common largest block will be representative for the design of RTG's runways. These container blocks are laid out in a row of 36 TEU (Twenty-foot Equivalent Units) bays, 6-wide and 4-high, with a total capacity of 864 TEU's. It was assumed that a stacking block will operate at an average capacity of 70% occupancy, reducing the capacity of the largest stack to about 605 TEU's. As the containers will be a mix of about 75% 20-feet and 25% 40-feet the operational capacity of a stacking block will be 485 containers. Assuming an average dwell time of the containers in a stacking block of 7 days and 300 operational days per year results in a through-put of about 20,750 containers through the largest stacking block per year and 415,000 over a design life of 20 years. As all containers will be handled minimal twice (in and out), the total will be 830,000 (Abdultayef, 2000).

The number of unladen RTG movements over the same spot on the runway will be about 100,000 to 200,000 times. In a stationary situation it will handle about 23,000 containers at the same spot.

The containers shall be transported to and from the stacking blocks by ITT. The ITT's shall travel the complete length of these blocks either loaded or unloaded. To bring and collect a container takes on unladen and laden movement of an ITT or 415,000 unladen movements and 415,000 laden movements with varying weights.

At the quay, the same ITT will collect and bring the containers. A possible total number of movements about 3 millions is forecasted (1.5 million laden and 1.5 million unladen movements). Based on a berth capacity of two vessels at the same time, the number of laden and unladen movements over the same location of the pavement will be about 750,000. Table 1 and 2 show summary of design input for 20 and 30 years, respectively.

APSDS method: APSDS is based on layered elastic theory, Mechanistic, which was introduced into airfield design practice with the release of the computer program LEDFAA (Layered Elastic Design, Federal Aviation Administration).

APSDS was developed to avoid the coverage concept by computing strain distribution at all points across the pavement for a given depth and relates this to pavement life using a full-scale test data. Sub-grade strains or deformation develops at the pavement surface are computed for all points across the pavement in order to capture all damage contributions from all wheels in all their wandering positions. APSDS computes the tensile strains at the undersides of relevant layers. Strains are computed using the layered elastic program CIRCLY (Wardle, 1999). The strains are converted to damage using the following relationship:

Table 1: Summary of design inputs per terminal for 20 years design life

	Load repetitions	
Equipment	Laden	Unladen
RTG	23,000	200,000
FLT	55,000	55,000
ITT loading	415,000	415,000
ITT at quay	750,000	750,000

Table 2: Summary of design inputs per terminal for 30 years design life

	Load repetitions	
Equipment	Laden	Unladen
RTG	34,500	250,000
FLT	81,000	81,000
ITT loading	622,500	622,500
ITT at quay	1,650,000	1,650,000

$$N = \left(\frac{k}{\varepsilon}\right)^{b} \tag{1}$$

where N is the predicted life (repetitions of ε); k is a material constant; b is the damage exponent of the material and ϵ is the load-induced strain.

The cumulative damage factor, CDF, is given by summing the damage factors over all the loading in the traffic spectrum using Miner's hypothesis (Shackel, 1991). The Miner's hypothesis states that each stress repetition is responsible for a certain amount of fatigue damage. It is assumed that there is a linear rate of fatigue damage irrespective of the order of load application and that fatigue failure occurs when the sum of the damage increments at each level of stress accumulates to unity. The law can be expressed in the following form:

$$\text{CDF} = \sum_{i=1}^{n} \frac{n_i}{N_i} = 1 \tag{2}$$

where n_i is the number of repetitions of a given damage indicator and N_i is allowable repetitions of a given damage indicator.

The pavement is presumed to have reached its design life when CDF reaches 1.0.

The method incorporates: (1) the design repetitions of each plant at their various operating weights; (2) the wander of the plant and (3) the material performance properties used in the design model. More theoretical background is available in MINCAD System (1999).

RESULTS AND DISCUSSION

In the sensitivity analysis, the effects of the following parameters on the required pavement structure were carried out:

The effect of lateral wander distribution on pavements: The lateral wander significantly affects the required pavement thickness. The container terminal using RTG's, with Cemented-Bound Material (CBM) for various standard deviations of lateral wanders, was investigated (Fig. 3).

In general, the pavement thickness decreases with increasing the standard deviation of lateral wandering distribution. As shown in Fig. 3, around 4% of capital cost per square metre saved from option calculated with no lateral distribution (0 mm) and 300 mm and around 425% with 3000 mm wandering. But with increasing the lateral wandering, the lane width will increase and somewhere is the optimum. The optimum base thickness at 300 mm wandering and the lane width was 1.50 m (Fig. 3).

By considering the optimum lateral wander in the design, around 5% saving in the construction cost is obtained. Therefore, the optimum lateral wander distribution was investigated for each terminal as follows: A standard deviation of 300 mm for RTG runways; 600 mm for ITT loading area; 1000 mm for ITT loading at the quay; and 1000 mm FLT maneuvering areas.

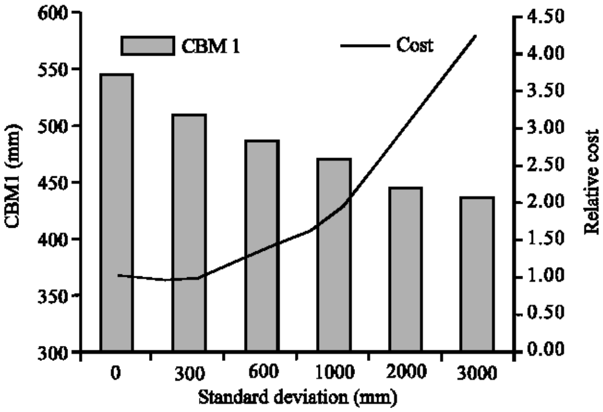

Fig. 3: CBM1 base thickness and the relative cost of RTG runways vs. the lateral wandering distribution

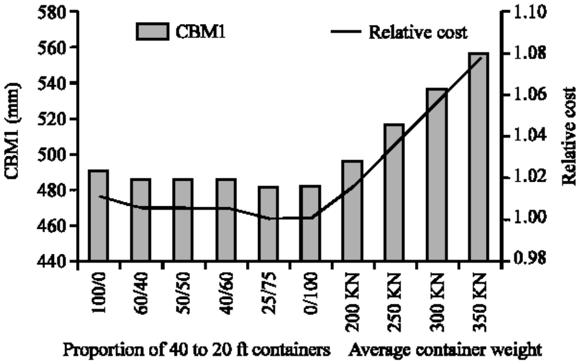

Fig. 4: The effect of container weight frequency and average container weight on the base thickness

The effect of container weight frequency on pavements: The container weight leading to the greatest value of the damage is the critical weight container and all subsequent wheel load calculations should be based upon this load. When the containers being handled comprise 100% 40ft containers, the critical load is commonly 220 kN and when 20 ft containers are being handled, the critical load is 200 kN. The number of repetitions to be used in design can be calculated accurately using a load value weighted system. Figure 4 shows the effect of container weight frequency and average container weight on the base thickness.

As shown in Fig. 4, there is no much difference in the base thickness when the container weight distribution is used. Around 3.6% of the total cost per square metre saved when 25/75 ft containers weight distribution are compared with an average weight of 250 kN and 1.6, 5.8 and 7.6% saving when container weight of 200, 300 and 350 kN were used, respectively. Therefore, it is inefficient to design container yards on the assumption that all containers are loaded to their rated maximum capacity. Rather, it is more appropriate to design the pavement to resist a spectrum of wheel loads obtained by combing the load distribution with the operating characteristics of the design handling equipment.

The effect of design life on pavements: Design life of port pavements is linked to the very concept of port development. It determines the number of operations, which the pavement is expected to withstand while in service. The design life of permanent pavements is set between 15 and 25 years. The evaluation of the design life shall take into account the possibility, ease and economic feasibility of repairs, the probability and possibility of changes in the circumstances and conditions of the project's foreseen use as a consequence of operations or port traffic variations.

Two areas were studied with two handling systems (FLT and RTG), where CBM was used. The CBM has a design life more than 25 years. Therefore, five different design lives (20, 25, 30, 35 and 40 years) were considered to calculate the base thickness.

Few millimeters more of base thickness will increase the design life of the structure twice as shown in Fig. 5 and 6. At the end of the design life, the structure will not fail immediately. Therefore, maintenance activities take place to improve the conditions of the structure to

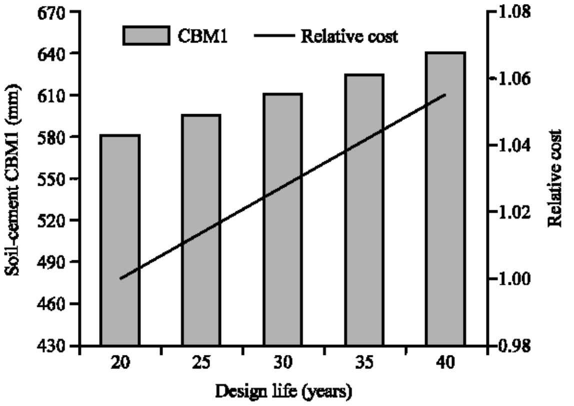

Fig. 5: The design life of the structure vs. the base thickness and the relative cost for FLT

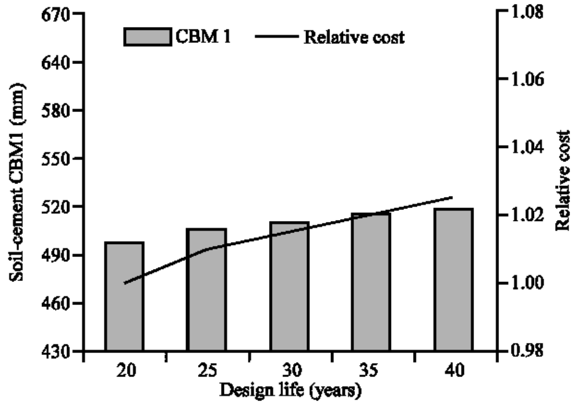

Fig. 6: The design life of the structure vs. the base thickness and the relative cost for RTG's runways

extend their life for about 10 years more. However, this case can be correct with some kind of surfacing material such as asphalt, where a resurfacing able to increase the design life and to decease the stresses on the sub-layers. But with a concrete block pavement, it needs to remove blocks and the bedding sand and to add thin layer of base materials, while it requires much more and very expensive work for the CBM bases.

As a result, few millimeters greater than the target base thickness (15-60 mm) requires a slightly higher investment but reduces to a great extent future maintenance activities, especially in case of rigid and concrete block pavements.

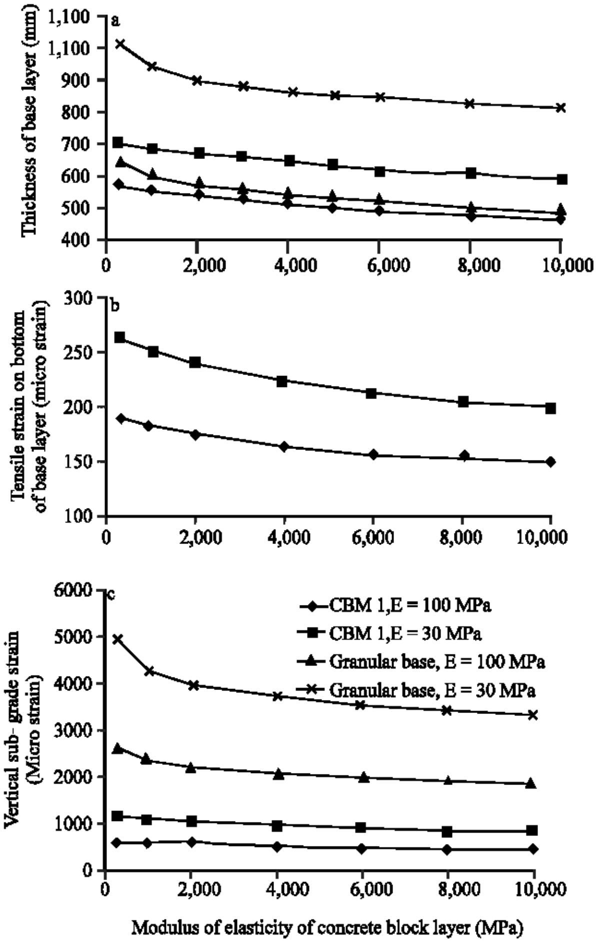

Fig. 7: Influence of modulus of elasticity of concrete block layer on: a) thickness of base layer, b) tensile strain on bottom of base layer and c) vertical strain on top of subgrade

The effect of variation of elastic modulus of concrete block pavers and subgrade on pavements: It was assumed that concrete Block Pavements (CBP) will be constructed with use of 100 mm concrete blocks for RTG's runways. The value of the effective modulus of elasticity for the concrete block layer, suggested by Shackel (1991), Hodson and Emery (1996) and Estado (1994), are within the range of 300-10,000 MPa.

The effect of variation of the modulus of concrete block layer on the pavement behaviour was studied. The subgrade modulus was assumed at five levels 30, 50, 70, 100 and 150 Mpa. Firstly, thicknesses of granular and cement stabilized base courses were calculated with varying subgrade modulus. Secondly, it was assumed that the thickness of the base course is equal to 505 mm, the modulus of the subgrade is equal to 100 MPa and the strains within the pavements, under 0.90 MPa wheel pressure acting on 364 mm circular area, were calculated. The results of the sensitivity analysis of the modulus of the subgrade and the concrete block layer on variation are presented in Fig. 7.

Table 3: The effect of increasing the modulus of CBP and subgrade on pavement

	Effect of increase modulus of CBP (300 - 4,000 Mpa)		Effect of increase modulus of CBP (4,000 - 10,000 Mpa)		Effect of increase subgrade modulus (30 - 100 Mpa)	
Analyzed value	CBM1	Type 1	CBM1	Type 1	CBM1	Type 1
Decrease of thickness of base (%)	12	20	10	11	27	60
Decrease of vertical strain on the top of subgrade (%)	17	27	14	12	63	81
Decrease of tensile strain on the bottom of CBM1 (%)	15	-	11	-	37	-

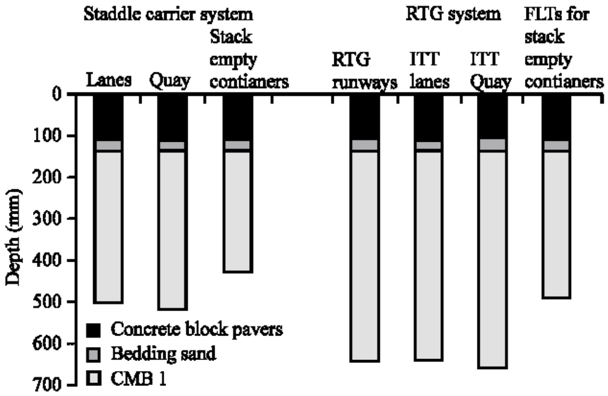

Fig. 8: The pavement structures using straddle carrier and RTG systems

The results of the analysis indicated that the CBP with cement stabilized base is less sensitive to changes of the modulus of concrete block layer and to changes of the modulus of subgrade than the CBP with granular base.

It should be noted that the variations in the modulus of the CBP from 4,000 to 10,000 MPa have less effects on both types of pavements than the change of the subgrade modulus from 30 to 100 MPa. The effect of variations in the modulus of the CBP from 300 to 4,000 MPa is more significant, especially in case of granular bases Type 1 (Table 3).

Vertical strains acting on the subgrade are high in case of granular bases Type 1 and may cause rutting in the subgrade. Therefore, the conclusion can be drawn that the effective modulus of elasticity of CBP was 4000 MPa and the granular unbound bases shall be limited (Fig. 7). Cemented-Bound Bases (CBM) provide greater resistance to rutting and can be economically attractive, as lower quality aggregate can be effectively improved with cement.

The effect of changing the handling system for the container terminal on pavements: A check was carried out using a straddle carrier system, instead of RTG system, with 100 mm pavers and CBM1, as a pavement structure. The results show that a reduction of the base thickness of 27% for both maneuvering lanes (ITT's Loading area) and quay area (ITT at quay) is required as shown in Fig. 8. However, for the stacking empty containers, a reduction of about 18% is needed.

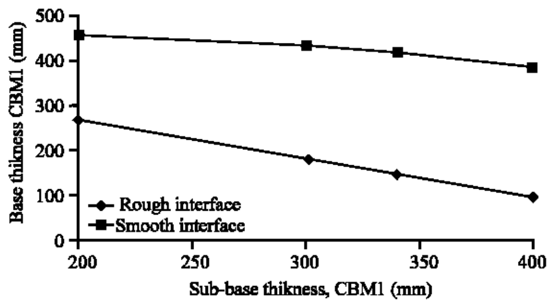

Fig. 9: The effect of changing the interface condition on the pavement structure

The effect of changing the condition for the interface at the bottom of base layer on pavements: The effect of changing the interface condition, from rough interface to smooth, at the bottom of the base layer was investigated for the RTG runways as shown in Fig. 9.

As a result of changing the condition for the interface, from rough to smooth condition between the base and sub-base layer, the base layer (CBM3) dominating the design and increases the base thickness by a factor range from 1.70 to 4.10. However, in case of rough interface, the sub-base layer (CBM1) dominating the design in all design calculations.

From an economical point of view, an increasing of the sub-base layer till 400 mm, gives a cheaper pavement structure than the case of increasing the base-layer thickness.

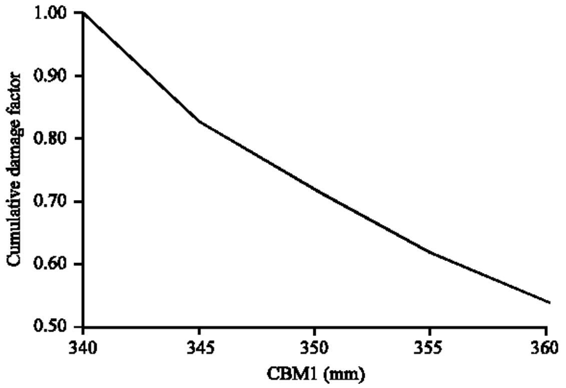

Fig. 10: The effect of the cumulative damage factor on the life consumed of the pavement

The effect of the cumulative damage factor on the life consumed of the pavement: The cumulative damage factor is defined as the number of repetitions of a given response parameter divided by the allowable repetitions of the response parameter that would cause the failure. When the cumulative damage factor reaches 1.0, the pavement structure reached its design life. If the cumulative damage is less than 1.0, the pavement has excess capacity and the cumulative damage represents the proportion of the life consumed. Figure 10 represents the effect of increasing the sub-base thickness on the life consumed for RTG runways with 100 mm pavers thick and 150 mm CBM3 base thick. Also, Figure 10 shows that by increasing the sub-base thickness by 3%, the life consumed of the pavement reached to 54%, which represent a safety factor for the structure.

The stresses and displacements on the unbound granular materials: It is difficult to find the performance criteria for the unbound granular materials in the ASDS design methods. Therefore, calculations were made, for the stacking fully containers area, to have an overview for what will happen in the pavement structure when reached its design life. The analyses were made for a top layer with gravel bed of 400 mm thick and unbound granular base (Type 1) of 360 mm.

Fig. 11 shows the displacements and the stresses at different depths (0, 400, 760, 1000 and 2000 mm). Results showed that rutting of about 12-mm at the surface, 4-mm at the bottom of the surface layer and 3-mm at the top of the subgrade. These stresses are high at the surface, where the contact area is too small with high load and negligible at the top of the subgrade. Therefore, special care should be addressed for the selection of the surfacing materials to resist these high stresses.

Economic analysis: The economical comparison was made for pavement structures at seven traffic loads under

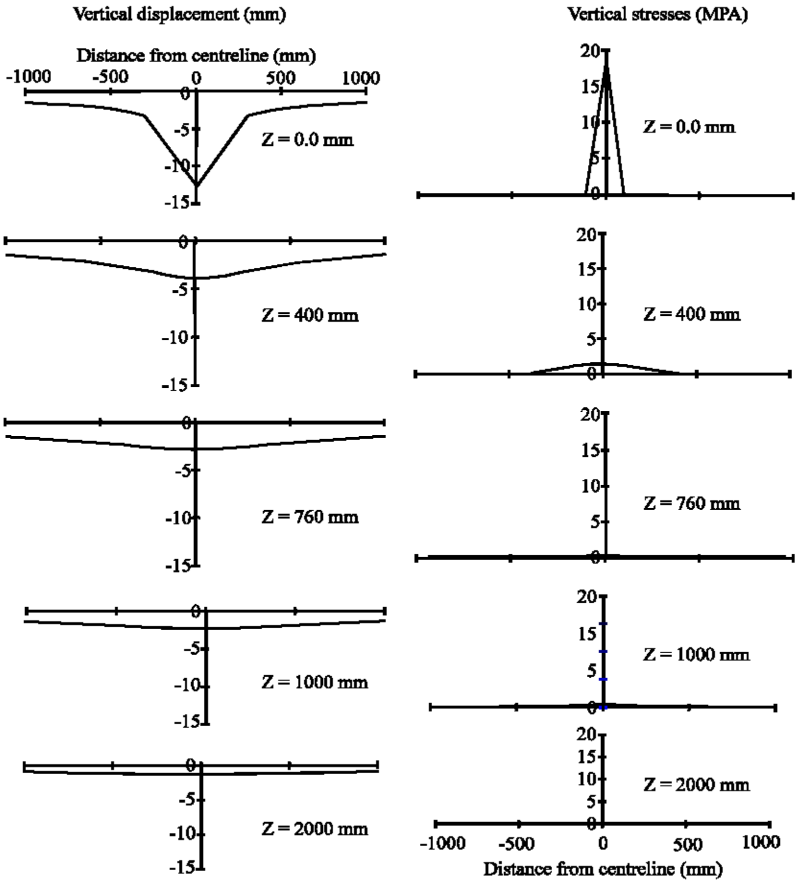

Fig. 11: The vertical displacements and stresses for gravel bed and granular base layer for the stacking fully container area

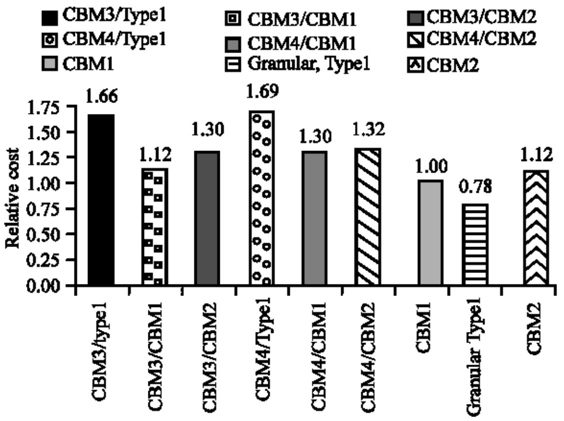

Fig. 12: An economical comparison between the various base materials with soil-cement base, CBM1

typical subgrade condition. The economical data refer to initial construction cost, as well as to the expected maintenance cost and using up-to-date practical unit prices.

A single strength value for the subgrade was chosen for the analysis, which based on the laboratory results. This CBR value is 10%, which is the design value of many typical Palestinian sub-grades.

The most economic base material is the unbound granular (Type 1). Figure 12 represents a comparison between base materials with CBM1 from the economical point of view. Furthermore, the followings are summary of the economical analysis for various materials:

- A stabilised base (CBM1 or CBM2) was found to be an economical alternative to lean concrete (CBM3 or CBM4);
- The concrete block pavement provides an attractive alternative to the rigid concrete pavement. The use of concrete block pavements instead of the rigid, provides also an economical advantage, as expressed by the substantial saving in cost;
- The concrete block pavement also provides an attractive alternative to the asphalt pavement at a wide range of traffic and loading conditions. The economical advantages are also manifested when the maintenance costs are taken into account for both cases 80 and 100 mm pavers thick. However, the initial costs of concrete block pavements were calculated to be from 16 to 33% higher than for conventional asphalt pavements;
- A base layer thickness of 150 mm is a minimum to be applied for fine-grained materials (sand fill, CBM1), whereas for coarser grained material (Type 1 aggregate, CBM3, CBM4) a minimum thickness of 200 mm is to be preferred and
- It was found that changes in block thickness of pavers have a bigger effect on pavement performance than corresponding alterations in the thickness of the base. However, having regard to the relative costs of the blocks and base, it is often more economical to vary the base thickness rather than to increase the block thickness.

CONCLUSIONS

The use of a layered elastic base (mechanistic) method provided the pavement engineer with powerful tools for studying a wide range of particular pavement materials and sub-grades.

The sensitivity analysis show that: a few millimetres more than the target base thickness will increase the design life of the pavement structure; a reduction of 27% in base thickness in the driving lanes when straddle carriers system were used instead of RTG system and a reduction of 18% for the stacking empty containers is possible; the life expectation of the pavement is increased to about 50% when the base thickness is increased by 3% and the base thickness increases by a factor range from 1.70 to 4.10 when a smooth interface, between base and sub-base layer, is considered in the calculations.

In general, paver blocks are more applicable for those areas where high wheel loads and static loads are expected.

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