Pavement Design of Gantry Crane Lanes for the Port of Portland

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The pavement design of gantry crane lanes for the principal container facility of the Port of Portland is described. The pavement design was required to replace deteriorated sections of portland cement concrete pavement in an area subject to heavy trafficking. Traffic included forklift trucks and regular trucks as well as gantry cranes with wheel loads of as much as 80,000 lb. Alternate portland cement concrete and asphalt concrete pavement designs were investigated, and an evaluation of construction and drainage considerations and joint sealants was made. The alternate designs were investigated using layered elastic analysis and finite element techniques. Critical responses were compared with allowable fatigue criteria to estimate design life. The favored alternate design was 22 in. of reinforced portland cement concrete. Work began in June 1985 to replace the deteriorated sections with this alternate in three out of eight container storage areas. To minimize disruption of the facility, the storage areas are being closed one at a time and the contract will take about 2 years.

Terminal 6 is the principal container facility for the Port of Portland. Berths 604 and 605 were constructed in 1973 using 20 in. of stabilized base and 2 to 3 in. of dense-graded asphalt concrete. The stabilized base is a mixture of hydraulically dredged sand, lime, cement, and pozzolan, designated LCPF.

The initial designs for Berths 604 and 605 subsequently experienced performance problems (e.g., shoving and distortion of the asphalt concrete) in the gantry crane wheel paths. In 1978 the deteriorated sections were removed and replaced with fibrous concrete. These sections also experienced early distress (e.g., cracking of the fibrous concrete slab). This pavement was removed in 1980 and replaced with 6 in. of reinforced concrete pavement placed directly on LCPF. The slab is 5 ft by 60 ft with reinforcing steel passing through the joint. By November 1984 a considerable amount of this lane had experienced distress (e.g., cracking, spalling, and subsequent distortion).

Berth 603 was constructed in 1981. This berth used 18-in.-deep reinforced concrete slabs as gantry crane lanes. As of November 1984 there were no visible problems in these travel lanes.

PURPOSE OF STUDY

To correct the problems with the 6-in. portland cement concrete (PCC) pavement lanes in Berths 604 and 605, three repair strategies were investigated:

1. A 10-in. PCC slab with top and bottom reinforcement,
2. A 16-in. PCC slab with no reinforcement, and
3. A 6-in. asphalt concrete pavement to replace the existing PCC travel lane.

This study was directed at evaluating these alternates using analytical techniques.

STUDY APPROACH

The approach used in the conduct of this study was as follows:

1. Site visit. On November 2, 1984, a visit to Terminal 6 was made to evaluate the condition of the travel lanes.
2. Collection of pavement materials data. Information on cross sections and materials properties was collected and summarized.
3. Collection of traffic data. Information on vehicle types, loading and expected traffic volumes, and performance objectives (design life) was collected.
4. Structural analysis. The three alternatives were evaluated using layered elastic and finite element techniques. Critical responses were compared with allowable fatigue criteria to estimate design life.
5. Evaluation of design details. An evaluation of such details as construction and drainage considerations and joint sealants was also made.

Each of these elements is described hereafter, followed by final recommendations for repair of the travel lanes in Berths 604 and 605.

PRELIMINARY DESIGN DATA

Performance Evaluation

On November 2, 1984, a visit to Terminal 6 was made to

1. Determine the type of pavement distress,

2. Identify possible causes of the observed distress, and
3. Identify the types of vehicles operating on the facilities.

Pavement Condition

The distress observed in the concrete travel lanes generally consisted of

1. Longitudinal cracks in the concrete slab (Figure 1), followed by transverse cracks, followed by spalling in the center crack in the lane;
2. Minor spalling of the longitudinal joint between the PCC and the asphalt concrete (AC) (Figure 2);
3. Patching of slabs with asphalt concrete (Figure 3); and
4. Patching of slabs with metal plates (Figure 4).

All of this distress was observed in Berths 604 and 605. There was no major distress noted in Berth 603.

Cause of Distress

The reinforced concrete slab apparently functioned like a beam on a uniform foundation. In places, the passage of a crane caused noticeable movement in the slab. If moisture were present, pumping of the underlining base (LCPF) was observed. On the basis of these brief observations, it appeared that

1. The slab dimension (6 in.) was insufficient to preclude initial longitudinal cracking of the mat;
2. Water entered the crack and edge joints;
3. Passage of heavy loads resulted in excessive slab deflection and pumping of water and the LCPF base material, creating a void beneath the concrete slab; and
4. General slab breakup had occurred, which had been repaired either with asphalt concrete or metal plates.

The extent of distress appeared to be greater in the following areas:

1. Where forklifts and trucks cross the concrete slab (roadway between Berths 604 and 605) and

FIGURE 1 Longitudinal cracking of slab with subsequent spalling.

FIGURE 3 AC patching of slab deterioration.

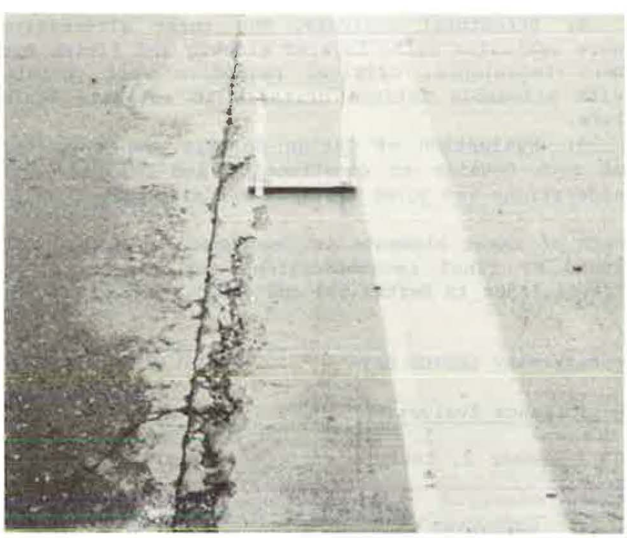

FIGURE 2 Spalling of longitudinal joint between the PCC slab and the asphalt concrete.

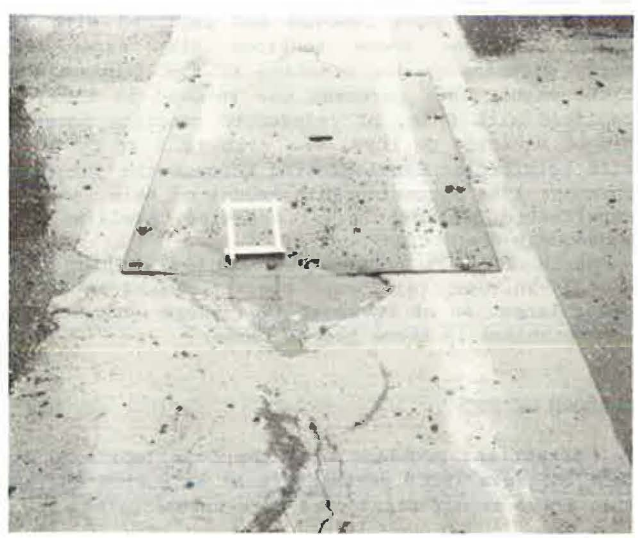

FIGURE 4 Patching of slab with metal plate.

2. Generally in one of the travel lanes, which could be related to the method of loading or unloading the trucks.

Material Properties

Performing a computer analysis using either layered elastic theory or finite element techniques requires a knowledge of certain material properties. These include the properties given in Table 1. It should be recognized that the accuracy of the analysis is directly related to the accuracy of the material properties used. Because material testing was not part of this project, all values were based on previous work at Terminal 6 or on standard literature. The values selected for use in the analysis are described next.

TABLE 1 Material Properties Needed for Design Analysis

Material	Property
Asphalt concrete surface	Elastic modulus
	Poisson's ratio
	Fatigue curves
Portland cement concrete surface	Elastic modulus
	Poisson's ratio
	Flexural strength or fatigue curve
LCPF–base	Elastic modulus
	Poisson's ratio
	Tensile strength or fatigue curve
Subgrade	Elastic modulus
	Poisson's ratio

Asphalt Concrete Surface

Two sources of literature were used to determine the needed properties of this material:

1. Properties for Oregon mixes (modulus) developed by Oregon Department of Transportation (1) and
2. Work by the Asphalt Institute (modulus, fatigue) (2,3).

For modulus, Oregon mixes have values that range from 200,000 to 400,000 psi at 25°C, depending on the mix characteristics (asphalt type and aggregate gradation). The Asphalt Institute recommends the use of the following equation:

$$E_1 = K_o/K_1{}^{q^{d_1}} \tag{1}$$

where

E_1 = asphalt concrete modulus (psi);
K_o, K_1, d_1 = regression constants equal to 3.8 x 10^6, 1.0046, and 1.45;
q = mix temperature (°F).

This results in the following values for modulus values as a function of temperature:

Temperature (°F)	Modulus (psi)
50	1,000,000
60	669,000
70	432,000
77	313,000

Because this equation yields (at 25°C) about the same modulus as tests on the Oregon cores, it was used to select moduli for the analysis. A Poisson's ratio value of 0.4 is also recommended.

The failure criterion used for fatigue is the one developed by the Asphalt Institute for use in the development of MS-1 (3). This relationship is given by

$$N = 18.4\,(C)\,(4.32 \times 10^{-3}\,\epsilon_t^{-3.29}\,E^{-0.854}) \tag{2}$$

where

N = number of load application associated with strain level ϵ_t,
C = function of voids and asphalt content ($C = 10^M$),
M = $4.84\,[V_b/(V_v + V_b)] - 0.69$,
V_b = volume of asphalt (%),
V_v = volume of air voids (%),
ϵ_t = tensile strain in the asphalt layer (in./in.), and
E = modulus (psi).

Fatigue curves for asphalt concrete as a function of modulus are shown in Figure 5.

Portland Cement Concrete

For this material a modulus of 4 x 10^6 psi with a Poisson's ratio of 0.15 is normally recommended by the Portland Cement Association and the fatigue relationship is given in Table 2 (4). No measured data were available for a modulus of rupture (strength), which can be assumed to be no greater than 800 psi.

LCPF Mixture

In previous work by Barenberg (5) a modulus of 1.5 x 10^6 psi was used for this material. Poisson's ratio would be on the order of 0.20. No flexural strength data were available for the in situ material; however, work by Yang (6) would indicate compressive strengths (f_c) to be as follows:

Layer	Initial f_c (psi)	Current f_c (psi)	Flexural Strength (psi)	Elastic Modulus (psi)
LCPF A	1,600	3,200	640	2,400,000
LCPF B	1,000	2,000	400	1,500,000
LCPF C	800	1,600	320	1,200,000

$M_r = 0.2\,f_c$ for flexural strength, and $E = 750\,f_c$ for elastic modulus. These modulus values are similar to those used by Barenberg (5) and were selected for use in this study.

Subgrade

In prior work by Yang (6), plate bearing and dutch cone penetrometer tests were performed to evaluate the condition of the sand subgrade. His data indicated that modulus of the subgrade ranged from 4,500 to 9,000 psi with an average of 6,500 psi. In design, he used a value of 5,000 psi (about the 90 percentile value). It would be expected that with traffic the sand would densify and the modulus would be increased. Therefore, for this analysis modulus values of 5,000, 10,000, and 15,000 psi were selected. Poisson's ratio was assumed to be 0.4.

Traffic Considerations

Various types of vehicles operate over these concrete travel lanes. They include

1. Several types of gantry cranes that operate directly on the concrete slab (Figures 6 and 7); these are all rubber-tired vehicles.

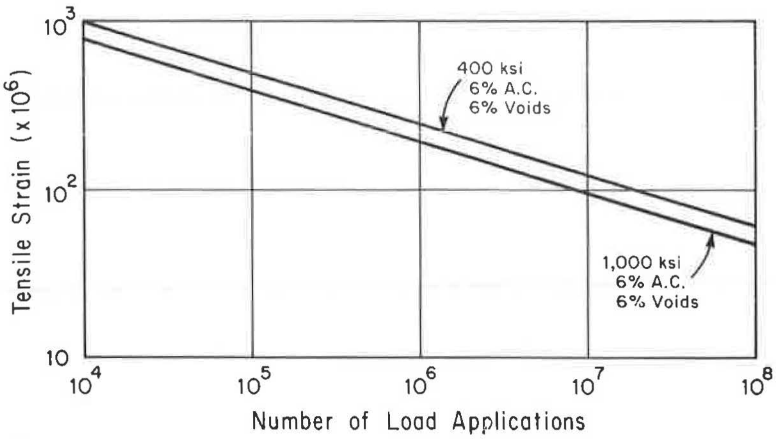

FIGURE 5 Fatigue relationship for asphalt concrete [MS-1 *(3)*].

TABLE 2 Stress Ratio and Allowable Load Repetitions, PCA[a]

Stress Ratio	Allowable Repetitions
0.51	400,000
0.55	130,000
0.60	32,000
0.65	8,000
0.70	2,000

[a]After *Thickness Design for Concrete Pavements (4)*.

FIGURE 6 Gantry cranes operating on PCC slab.

FIGURE 7 Second view of gantry crane operating on PCC slab.

FIGURE 8 Other vehicles operating in Terminal 6 area.

2. Several types of rubber-tired forklifts that operate either parallel to or at angles to the concrete travel lanes (Figure 8).
3. Fully loaded trucks that operate either parallel or at angles to the concrete slab (Figure 9).

Table 3 gives a summary of the vehicles operating in each category. Details on the vehicle gear configurations are shown in Figure 10. Table 4 gives a summary of the expected operations for the gantry cranes and for the forklifts and loaded trucks (at the crossings).

For the purposes of this analysis, each gantry crane was analyzed separately for evaluation of the travel lanes and the forklift was considered to be

FIGURE 9 Second view of other vehicles operating in Terminal 6 area.

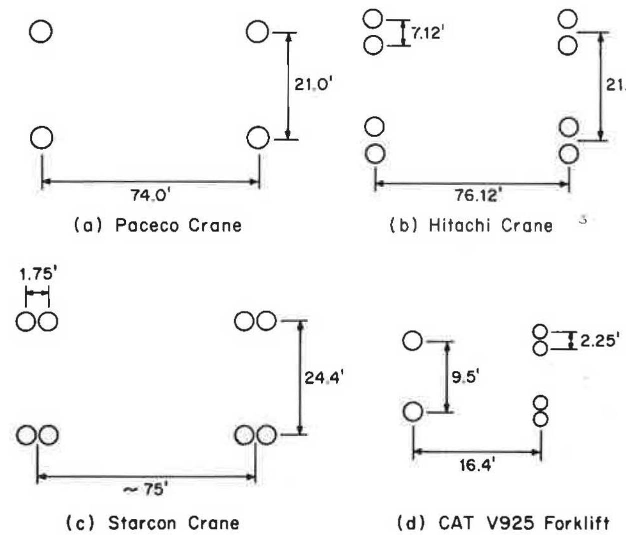

FIGURE 10 Layout of wheels for vehicles.

TABLE 3 Types of Vehicles Working Berths 604 and 605

Type	Number[a]
Gantry Lanes	
Paceco	4
Hitachi	2
Starcon	2[b]
Fork Lifts	
CAT V925	2
Taylor	2
Trucks	
Standard	N/A
5-axle truck	N/A

[a]One crane per lane per berth. This number may decrease to six cranes because of maintenance needs.
[b]Vehicle 471 started operation on 4/26/83, and vehicle 470 started operation on 3/5/83.

the design vehicle at the crossing between Berths 604 and 605. The truck was considered only in terms of a damage equivalency factor (F). [$F = (\text{Truck wheel load/Forklift wheel load})^4 = (9/55)^4 = 0.0007$.] This implied that the combined total crossings per year would be 520 (forklift) plus 53,500 x 0.0007 (truck) for a total of 557 crossings per year.

EVALUATION OF ALTERNATE DESIGNS

Approach

Each of the alternate pavement sections was analyzed using

1. Linear elastic models [ELSYM5 (7) and PCA (8)] and
2. Finite element techniques [ILLISLAB (9)].

The analyses used in both models assumed the material properties and cross sections shown in Figure 11. The loads and contact areas for each vehicle and analysis are shown in Figure 12. In the case of the

TABLE 4 Number of Passes per Area

Area	Operations[a] per Day	Passes[b]	Annual Passes
Gantry Cranes			
Lane 1	15 ops/hr x 8 hr/day = 120 ops/day	60/day	5 days/wk x 52 wk/yr x 10 passes = 15,600 passes/yr
Lane 2-4	10 ops/hr x 8 hr/day = 80 ops/day	40/day	5 days/wk x 52 wk/yr x 40 passes = 10,400 passes/yr
Crossing between Berths 604 and 605		10/day	5 days/wk x 52 wk/yr x 10 passes = 2,600 passes/yr
Fork Lifts			
Crossing between Berths 604 and 605		10/week	10 passes/wk x 52 wk/yr = 520 passes/yr
Loaded Trucks			
Crossing between Berths 604 and 605		107,000 annual passes	107,00/2 = 53,500 passes/yr on in-bound and outbound sides

[a]One operation means moving a box from a truck to the stack or from the stack to a truck.
[b]Estimate 50 percent of total operations cause a crane to pass a point at the center of each berth.

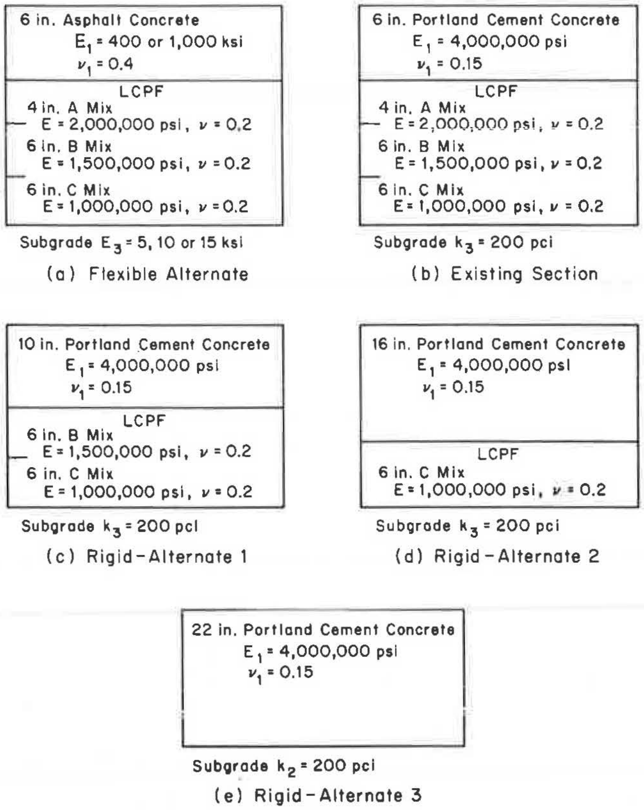

FIGURE 11 Cross sections for pavements analyzed.

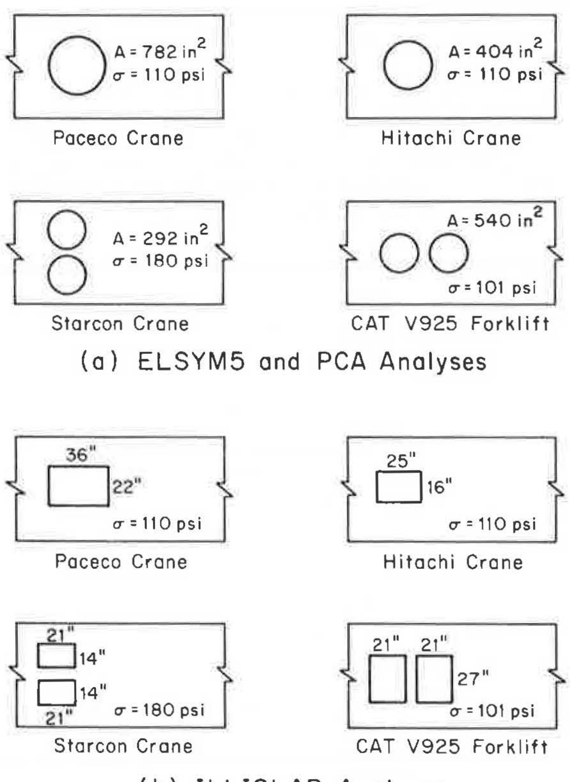

FIGURE 12 Design footprints for vehicles.

ELSYM5 and PCA models the width of the lanes was assumed to be infinite. In the case of the finite element models, the width was finite (5 ft). Both cracked and uncracked slabs were considered in the finite element analysis.

For each case, the maximum stresses at the bottom of the surface layer and the stabilized base were calculated and compared with available criteria to estimate the number of load applications to cause fatigue failure.

Results

Asphalt Section

For the asphalt section (Figure 11), ELSYM5 was used to calculate the tensile strain in the asphalt layer and the tensile stress in the LCPF for four vehicles:

1. Paceco,
2. Hitachi,
3. Starcon, and
5. Cat V925.

For each case, two asphalt concrete moduli were used corresponding to summer (4×10^5 psi) and winter (10^6 psi) temperatures. Also, the LCPF was considered in both cracked and uncracked conditions. The modulus assigned to the cracked condition (75,000 psi) was based on the assumption that the base would correspond to a high-quality crushed rock material after undergoing fatigue failure. The results of the analyses are summarized in Table 5.

Concrete Section

ELSYM5, PCA, and ILLISLAB programs were used to calculate stresses in the concrete slabs (6, 10, 16, and 22 in.) and in the stabilized base (16, 12, 6, and 0 in.). With ILLISLAB, stresses were also calculated for a cracked and an uncracked slab. The ELSYM5 results are summarized in Table 6, and those for PCA and ILLISLAB are given in Tables 7 and 8, respectively. Due to the relatively high cost of operating ILLISLAB, fewer cases were examined than with the other two analyses.

The sections were first evaluated assuming the LCPF to be uncracked where the modulus varied from 1×10^6 to 2×10^6 (for ILLISLAB an average of 1.5×10^6 psi was used). Subsequent analyses were made using a cracked LCPF base with the modulus equal to 75,000 psi.

Evaluation of Results

Critical Vehicle

Examination of Tables 5-8 shows that the Starcon crane was the critical (most damaging) vehicle according to all analyses. The tensile stresses in the PCC slab and the LCPF base were the best indicators of the critical vehicle. The ILLISLAB program is the best indicator of trends due to varying the pavement cross section and due to different vehicles, as will be discussed further. Table 8 gives some extremely high tensile stresses in all pavements due to the Starcon. These stresses were approximately 30 percent greater than those caused by the Paceco crane or Cat V925 forklift, and 2 1/2 times those caused by the Hitachi crane. The differences were not as pronounced in the results of the other analyses.

TABLE 5 Summary of Results of ELSYM5 Analyses—Flexible Alternate

PAVEMENT DESCRIPTION (See Figure for general cross-section)												
Asphalt Concrete Modulus (psi):	$1x10^6$	$1x10^6$	$1x10^6$	$4x10^5$	$4x10^5$	$4x10^5$	$1x10^6$	$1x10^6$	$1x10^6$	$4x10^5$	$4x10^5$	$4x10^5$
Base Moduli (psi) Layer A:	$2x10^6$	$2x10^6$	$2x10^6$	$2x10^6$	$2x10^6$	$2x10^6$	75,000	75,000	75,000	75,000	75,000	75,000
Layer B:	$1.5x10^6$	$1.5x10^6$	$1.5x10^6$	$1.5x10^6$	$1.5x10^6$	$1.5x10^6$	75,000	75,000	75,000	75,000	75,000	75,000
Layer C:	$1x10^6$	$1x10^6$	$1x10^6$	$1x10^6$	$1x10^6$	$1x10^6$	75,000	75,000	75,000	75,000	75,000	75,000
Subgrade Modulus (psi):	5,000	10,000	15,000	5,000	10,000	15,000	5,000	10,000	15,000	5,000	10,000	15,000
VEHICLE PARAMETER												
Paceco Crane												
Max. tensile strain in ACP (in/in)	-	-	-	-	-	-	.000251	.000229	.000217	.000204		
Max. tensile stress in base (psi)	184	163	149	215	187	170	73.6	54.1	42.9	84.3		
Max. vertical stress in s.g. (psi)	3.1	6.0	7.7	3.8	6.0	7.7	10.8	15.8	19.4	12.6		
Max. surface deflection (in x 10^{-3})	-	-	-	-	-	-	143	92	71	156		
Hitachi Crane												
Max. tensile strain in ACP (in/in)	-	-	-	-	-	-						
Max. tensile stress in base (psi)	110	93	86	121	108	100						
Max. vertical stress in s.g. (psi)				2.1	3.2	4.2						
Max. surface deflection (in x 10^{-3})												
Starcon Crane												
Max. tensile strain in ACP (in/in)	-	-	-	-	-	-	.000442	.000415	.000399	.000471		
Max. tensile stress in base (psi)	222	198	183	259	229	211	91.5	68.1	54.3	106		
Max. vertical stress in s.g. (psi)	3.8	5.8	7.4	4.6	6.9	8.9	12.5	18.5	22.6	14.7		
Max. surface deflection (in x 10^{-3})	-	-	-	-	-	-	171	109	84.5	186		
CAT V925 Forklift												
Max. tensile strain in ACP (in/in)	-						.000375	.000289	.000273	.000286		
Max. tensile stress in base (psi)	248						83.9	61	47.9	94.7		
Max. vertical stress in s.g. (psi)	4.4						11.8	16.9	20.3	13.6		
Max. surface deflection (in x 10^{-3})	-						171	107	81.3	187		

Fatigue Life Estimates

ELSYM5 analyses for the flexible alternate (Table 5) indicated that there was no tensile strain in the asphalt concrete when the base was uncracked and, therefore, no fatigue would occur. However, the tensile stress in the base is probably sufficient to lead to eventual fatigue of the base and therefore to a reduced modulus of the base. Subsequently, tensile strains would occur in the asphalt concrete but would be small enough to allow projection of a long life. The critical vehicle for this situation was the Starcon crane, which caused a tensile strain of 442 to 471 microstrain (10^{-6} in./in.) depending on the stiffness of the asphalt concrete (Table 5 with E_{SG} = 5,000 psi). Figure 5 shows that this would still allow a further 50,000 load applications of this vehicle. Hence, fatigue appeared to be a minor problem with the flexible alternate, but, due to the high compressive stresses, permanent deformation could be a problem.

Figure 13 shows the fatigue data for the portland cement concrete given in Table 2. Estimation of the number of applications of a given vehicle to cause fatigue failure is achieved by determining the stress ratio and entering the figure or chart to read the appropriate value. The stress ratio is the value of the estimated repeated tensile stress (σ) divided by the modulus of rupture (MR) of the concrete.

The modulus of rupture (MR) of the PCC was not measured for this project, neither were compressive strengths (from which MR could be estimated). However, MR values are typically 650 to 700 psi for new PCC and rarely more than 800 psi for older samples. It may be seen from the ILLISLAB analyses (Table 8) that predicted tensile stresses were in excess of 400 psi for many of the cases examined. For the existing pavement (6 in. of PCC, Columns 1-4, Table 8), if the LCPF base was assumed to be uncracked and to have a high modulus (1.5 x 10^6 psi), the edge stress due to the Starcon crane was more than 500 psi in both the PCC and the LCPF. Although the assumed modulus of the LCPF ranges from 2.4 to 1.2 x 10^6 psi, it was necessary to adopt an average value for the analysis, and that of the middle layer (1.5 x 10^6 psi) was adopted. The level of stress predicted for the LCPF should cause fatigue failure, hence alternate analyses were carried out for a reduced modulus (75,000 psi). The stresses resulting in the PCC for this situation are extremely high, indicating that when the LCPF cracks the PCC slab will deteriorate rapidly. Though the stresses appear to be unrealistically high, ILLISLAB gives a better indication than PCA or ELSYM5.

Because the predicted tensile stresses in the PCC were in excess of the possible modulus of rupture, none of the predicted stresses could be used directly to predict a fatigue life. However, the following equation should apply if fatigue failure had occurred:

$$(n_1/N_1) + (n_2/N_2) + (n_3/N_3) + (n_4/N_4) \ngtr 1.00 \quad (3)$$

where n_1, n_2, n_3, and n_4 are the actual number of load applications for vehicles 1, 2, 3, and 4, and N_1, N_2, N_3, and N_4 are the numbers of load applications to cause failure for these vehicles.

For any vehicle causing a stress ratio of less than 0.5, the fatigue life is infinite. According to the ILLISLAB analyses for the existing section with an uncracked base, the stresses due to the Paceco and Hitachi cranes are both less than half of the likely MR value when the load is in the center of the slab. Therefore, on the basis of this loading position, only the Starcon crane was likely to be the cause of initial fatigue of the slab. However, it was most likely that fatigue initiated in the LCPF and that when the LCPF cracked the high stresses in the PCC caused rapid deterioration of the surface. The data given in Table 9 indicate that there are approximately 10,000 to 15,000 crane operations per year depending on the lane. For the 4 years (1980-1984) that the cranes had operated on the PCC slab, this leads to from 40,000 to 60,000 total operations per lane. The actual distribution

TABLE 6 Summary of ELSYM5 Analysis—Required Pavement Section

PAVEMENT DESCRIPTION												
PCC Thickness (in):	6	6	6	6	6	6	10	10	10	10	10	10
PCC Modulus (psi):	4x10^6	4x10^6	4x10^6	4x10^6	4x10^6	4x10^6	4x10^6	4x10^6	4x10^6	4x10^6	4x10^6	4x10^6
Base Thickness (in):	16	16	16	16	16	16	12	12	12	12	12	12
Base Modulus (psi) Layer A:	2x10^6	2x10^6	2x10^6	75,000	75,000	75,000	2x10^6	2x10^6	2x10^6	75,000	75,000	75,000
Layer B:	1.5x10^6	1.5x10^6	1.5x10^6	75,000	75,000	75,000	1.5x10^6	1.5x10^6	1.5x10^6	75,000	75,000	75,000
Layer C:	1x10^6	1x10^6	1x10^6	75,000	75,000	75,000	1x10^6	1x10^6	1x10^6	75,000	75,000	75,000
Subgrade Modulus (psi):	5,000	10,000	15,000	5,000	10,000	15,000	5,000	10,000	15,000	5,000	10,000	15,000
VEHICLE PARAMETER												
Paceco Crane												
Max. tensile stress in slab (psi)	-	-	-	1160			117	108	102	841		
Max. tensile stress in base (psi)	149	134	124	50.5			144	129	119	26		
Max. vertical stress in s.g. (psi)	2.4	3.7	4.9	7.8			2.3	3.6	4.7	-		
Max. surface deflection (in x 10^{-3})												
Hitachi Crane												
Max. tensile stress in slab (psi)	-	-	-				81	76	73			
Max. tensile stress in base (psi)	84	75	71				80	72	67			
Max. vertical stress in s.g. (psi)	1.3	2.0	2.6				1.3	2.0	2.6			
Max. surface deflection (in x 10^{-3})												
Starcon Crane												
Max. tensile stress in slab (psi)	-	-	-	1490			168	156	148	1030		
Max. tensile stress in base (psi)	182	162	150	62			176	156	144	31		
Max. vertical stress in s.g. (psi)	3.0	4.5	5.8	9.1			3.0	4.4	5.6	-		
Max. surface deflection (in x 10^{-3})												
CAT V925 Forklift												
Max. tensile stress in slab (psi)	-	-		990			138	128		757		
Max. tensile stress in base (psi)	171	153		62			166	148		34		
Max. vertical stress in s.g. (psi)	2.8	4.3		9.2			2.7	4.2		5.8		
Max. surface deflection (in x 10^{-3})												

PAVEMENT DESCRIPTION									
PCC Thickness (in):	16	16	16	16	16	16	22	22	22
PCC Modulus (in):	4x10^6	4x10^6	4x10^6	4x10^6	4x10^6	4x10^6	4x10^6	4x10^6	4x10^6
Base Thickness (in):	6	6	6	6	6	6	0	0	0
Base Modulus (psi) Layer A:	2x10^6	2x10^6	2x10^6	75,000	75,000	75,000	75,000	75,000	75,000
Layer B:	1.5x10^6	1.5x10^6	1.5x10^6	75,000	75,000	75,000	75,000	75,000	75,000
Layer C:	1x10^6	1x10^6	1x10^6	75,000	75,000	75,000	75,000	75,000	75,000
Subgrade Modulus (psi):	5,000	10,000	15,000	5,000	10,000	15,000	5,000	10,000	15,000
VEHICLE PARAMETER									
Paceco Crane									
Max. tensile stress in slab (psi)	245	223	209	478					
Max. tensile stress in base (psi)	115	104	97	10					
Max. vertical stress in s.g. (psi)	2.0	3.2	4.1	-					
Max. surface deflection (in x 10^{-3})									
Hitachi Crane									
Max. tensile stress in slab (psi)	142	130	123						
Max. tensile stress in base (psi)	64	58	54						
Max. vertical stress in s.g. (psi)	-	-	2.2						
Max. surface deflection (in x 10^{-3})									
Starcon Crane									
Max. tensile stress in slab (psi)	309	277	260	576					
Max. tensile stress in base (psi)	141	125	116	12					
Max. vertical stress in s.g. (psi)	2.6	3.8	4.9						
Max. surface deflection (in x 10^{-3})									
CAT V925 Forklift									
Max. tensile stress in slab (psi)	237	257	241	442			280	252	187
Max. tensile stress in base (psi)	173	119	92	13			-	-	-
Max. vertical stress in s.g. (psi)	2.3	3.7	4.7	3.0			1.85	2.7	6.0
Max. surface deflection (in x 10^{-3})									

of the gantry cranes for each lane is given in Table 9. Table 10 gives the results for Lane 1.

As indicated, the calculated stress for the edge condition for both the Paceco and the Starcon vehicles exceeded the allowable stress indicating the occurrence of distress; however, the rate of distress was probably accelerating because of the increased operations of the destructive Starcon vehicle. This would indicate that the analysis approach used (ILLISLAB) was reasonable in predicting distress. It should be noted that the maximum load ratings for the vehicles were used in the analyses. Information available at the time indicted that the cranes could be operating at about 70 percent of their capacity. Because pavement response is approximately linear in relation to the load, the stress for the cranes (Table 8) should probably be decreased by about 30 percent.

For the cranes, the edge loading produced stresses about 30 to 50 percent higher than for the

TABLE 7 Summary of Results from PCA Analyses

PAVEMENT DESCRIPTION													
Slab Thickness (in):		6	6	6	10	10	10	16	16	16	22	22	22
E_1 (psi):		$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$
Base Thickness (in):		16	16	16	12	12	12	6	6	6	-	-	-
E_2 (psi):		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Modulus of Subgrade Reaction (pci):		830	500	200	830	500	200	830	500	200	200	100	50
VEHICLE													
Paceco Contact Area = 1 @ 782 in² Contact Pressure = 1 @ 110 psi	σ_{max}	1088	1235	1510	427	612	716	279	301	343	204	221	238
Hitachi Contact Area = 1 @ 404 in² Contact Pressure = 1 @ 110 psi	σ_{max}	764	844	992	364	394	448	175	187	208	122	131	140
Starcon Contact Area = 2 @ 292 in² Contact Pressure = 2 @ 180 psi	σ_{max}	1305	1482	1814	668	736	862	356	363	414	247	268	288
Cat V925 Contact Area = 2 @ 540 in² Contact Pressure = 2 @ 101 psi	σ_{max}	978	1145	1468	543	611	734	287	315	367	223	244	266

center slab loading condition. However, this situation does not occur regularly and would only cause a slight increase in the onset of fatigue cracking because the location of the maximum stress created by this load condition is not at the center of the slab.

The stresses caused by the forklifts were low for the center slab loading condition but high enough to contribute significantly to fatigue for the edge loading condition. Because the forklifts cross the subject concrete pavement for all operations of the vehicle, the edge loading condition occurs for every operation. The forklifts are much more likely to be operating close to their capacity and therefore the stresses shown in Table 8 should be close to those that actually occur. This significant contribution of the forklift trucks explains the more severe deterioration noted where these vehicles cross the subject pavement and provide loading in addition to that from the cranes. Hence, these areas are the critical areas in the terminal. The number of load applications from these vehicles is low (about 500 per year). However, the dynamic effect as they cross the concrete slab and bounce on the "step" between the flexible and rigid pavements increases their effect markedly.

From the results, it is clear that the stresses calculated are reasonable. They ranked the vehicles consistently with regard to damaging potential, and they indicated the effects of changes in the pavement sections. The effects of increasing PCC slab thicknesses were also indicated. The ILLISLAB analyses show that in order to improve fatigue life compared with the existing section, it would be desirable to increase the PCC thickness to 18 to 22 in., depending on the vehicle, and not to use any stabilized base material (Tables 11 and 12). For example, the Paceco would require 18-in. PCC to ensure 100,000 load repetitions whereas the Starcon would require about 21 in. For a pavement designed for 20 years this would mean the following repetitions for Lane 1:

Vehicle	No. of Operations per Year	Percentage of Total Vehicles	Total Operations for 20 Years
Paceco	15,600	50	156,000
Hitachi	15,600	25	78,000
Starcon	15,600	25	78,000

Using Miners hypothesis (Equation 3) and a pavement thickness of 20 in., the percentage fatigue life would be

$$(156{,}000/\infty) + (78{,}000/\infty) + (78{,}000/30{,}000) = 2.6 \times 100 = 260 \text{ percent}$$

For 22 in., the percentage fatigue life consumed would be

$$(156{,}000/\infty) + (78{,}000/\infty) + (78{,}000/200{,}000) = 0.39 \times 100 = 39 \text{ percent}$$

For 20 years, then, a slab thickness of 22 in. would be required. This could be reduced if a shorter design period were used.

Evaluation of Analysis Procedures

Of the analysis procedures used, ILLISLAB is potentially the best model for PCC pavement sections. ILLISLAB enables the finite dimensions of the PCC slab to be modeled and has the ability to consider the modulus of the stabilized base and more than one wheel load in any appropriate location. This program also models friction or no friction between the PCC and the base. The PCA program will only consider the PCC slab on a subgrade, and assumes infinite dimensions laterally. ELSYM5 enables each layer in the pavement to be modeled but is constrained to assume full friction between the PCC and the base. For these reasons, ILLISLAB is preferable to the other methods for rigid pavement analyses, and it will tend to predict higher stresses. However, for this

TABLE 8 Summary of Results of ILLISLAB Analyses

VEHICLE	LOAD POSITIION	PAVEMENT DESCRIPTION / PARAMETER													
		Slab Thickness (in):	6	6	6	6	10	10	10	16	16	16	16	22	28
		E_1 (psi):	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$
		Base Thickness (in):	-	16	16	16	-	12	12	-	6	6	-	-	-
		E_2 (psi):	-	$1.5\ x10^6$	$75x10^3$	$75x10^3$	-	$1.5\ x10^6$	$75x10^3$	-	$1.5\ x10^6$	$75x10^3$	-	-	-
		Modulus of Subgrade Reaction, k (psi):	830	200	200	200	830	200	200	640	200	200	200	200	200
		Slab Condition: Cracked (C) Uncracked (UC)	UC	UC	UC	C	UC	UC	UC	UC	UC	UC	UC	UC	UC
Paceco	Center of Slab	max. tensile stress in slab (psi)	820	363	1182	1947	463	636	878	381	537	544	529	379	280
		max. tensile stress in base (psi)	-	375	70	1034	-	296	22.5	-	78	4.3	-	-	-
		max. vertical stress in subgrade (psi)	31	12	19	44	17	12		13	9.8	9.9	9.6	7.8	6.5
		max. surface deflection (in x 10^{-3})	38	61	95	219	21	62	69	21	49	49	49	39	33
	Edge of Slab	max. tensile stress in slab (psi)	1269	526	1866		850			549					
		max. tensile stress in base (psi)	-	531	98		-			-					
		max. vertical stress in subgrade (psi)	64	22	39		41			24					
		max. surface deflection (in x 10^{-3})	77	110	196		50			38					
Hitachi	Center of Slab	max. tensile stress in slab (psi)		196	661			344	479		286	291	No damaging effect		
		max. tensile stress in base (psi)		203	40			161	12		42	2.3			
		max. vertical stress in subgrade (psi)		6.2	9.9			6.3	7.1		5.0	5.0			
		max. surface deflection (in x 10^{-3})		31	50			32	37		25	25			

VEHICLE	LOAD POSITION	PAVEMENT DESCRIPTION / PAVEMENT STRUCTURES													
		Slab Thickness (in):	6	6	6	6	10	10	10	16	16	16	16	22	28
		E_1 (psi):	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$	$4x10^6$
		Base Thickness (in):	-	16	16	16	-	12	12	-	6	6	-	-	-
		E_2 (psi):	-	$1.5\ x10^6$	$75x10^3$	$75x10^3$	-	$1.5\ x10^6$	$75x10^3$	-	$1.5\ x10^6$	$75x10^3$	-	-	-
		Modulus of Subgrade Reaction, k (psi):	830	200	200	200	830	200	200	640	200	200	200	200	200
		Slab Condition: Cracked (C) Uncracked (UC)	UC	UC	UC	C	UC	UC	UC	UC	UC	UC	UC	UC	UC
Starcon	Center of Slab	max. tensile stress in slab (psi)		445	1412			779	1072		660	668	669	466	350
		max. tensile stress in base (psi)		455	79			359	264		95	51	-	-	-
		max. vertical stress in subgrade (psi)		15	23			15	17		12	12	12.1	9.6	8.0
		max. surface deflection (in x 10^{-3})		74	116			75	85		60	60	60	48	40
	Edge of Slab	max. tensile stress in slab (psi)		559	1915										
		max. tensile stress in base (psi)		564	101										
		max. vertical stress in subgrade (psi)		22	38										
		max. surface deflection (in x 10^{-3})		111	192										
CAT V925 Forklift	Center of Slab	max. tensile stress in slab (psi)		337	1052			440			506		641	457	349
		max. tensile stress in base (psi)		348	626			273			73		-	-	-
		max. vertical stress in subgrade (psi)		12	19			11			10		12.7	10.1	8.5
		max. surface deflection (in x 10^{-3})		60	93			55			49		64	51	43
	Edge of Slab	max. tensile stress in slab (psi)		528	1972										
		max. tensile stress in base (psi)		537	103										
		max. vertical stress in subgrade (psi)		27	45										
		max. surface deflection (in x 10^{-3})		133	227										

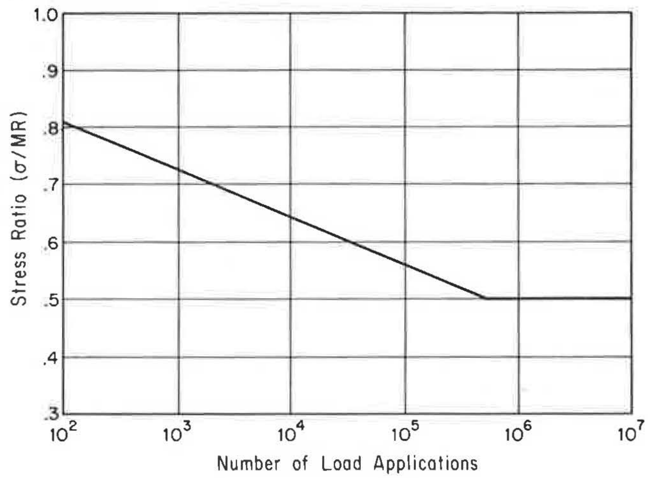

FIGURE 13 Fatigue relationship for portland cement concrete [after *Thickness Design for Concrete Pavements (4)*].

analysis it did not enable accurate modeling of the base and subgrade, which were much wider in their lateral extent than the 60 in. necessitated by the slab dimensions. Hence, stresses in all layers may be lower for this reason in addition to those discussed in the previous section.

The stresses predicted using ILLISLAB are less than those obtained previously by Barenberg. These differences are most likely due to differences in the loads and contact pressures used for each analysis.

RECOMMENDATIONS FOR DESIGN

Recommendations for the design section, special construction considerations, and drainage considerations are presented in this section.

Design Cross Sections

1. For a 20-year design life in the travel lanes, the recommended portland cement concrete thickness were as follows:

Lane	PCC Slab Thickness (in.)
1	22
2-4	22

This assumes that the PCC slab would be placed directly on compacted sand or aggregate and would require complete removal of the existing LCPF base course. Longitudinal and transverse steel should be placed in the top and bottom of the slab as shown in Figure 14. It is essential that steel be used to hold the cracks tightly together.

2. An alternate would be to use 6 in. of asphalt concrete on "sound" LCPF. The major disadvantage with this alternate would be permanent deformation in the asphalt mix or tearing of the mix during turning operations, or both. It is possible a mix could be designed to preclude rutting. This would require the use of a hard base asphalt (AR-8000) and a filler (approximately 2 percent) such as hydrated lime or portland cement. Another alternate would be the use of polymer-modified asphalt cement. In both cases laboratory mixes should be designed carefully. Normal criteria will have to be modified to ensure a stable mix. Tentative values would be Marshall stability of 3,000 lb and elastic modulus of 10^6 psi. Creep tests should be run on the final mix design over a range of temperatures to evaluate deformation resistance of the developed mix.

3. The design cross section for the asphalt alternate is shown in Figure 14. As indicated, it was recommended the existing PCC slabs be completely removed, and if the LCPF base was cracked, it too should be removed and replaced with asphalt concrete full depth. This condition most likely would occur only in areas where the PCC slab was badly deteriorated. For partly deteriorated areas, it may not be necessary to completely remove the LCPF. Surface grouting with hot asphalt or a cement grout would stabilize the base surface and minimize further erosion. Where the LCPF is intact, the asphalt concrete

TABLE 9 Distribution of Gantry Cranes Along Traffic Lanes April 1978–Present

						OPERATIONS / VEHICLE TYPE					
	TOTAL OPERATIONS		VEHICLE TYPE, %			LANE 1			LANES 2 - 4		
Year	Lane 1	Lanes 2-4	Paceco	Hitachi	Starcon*	Paceco	Hitachi	Starcon*	Paceco	Hitachi	Starcon*
1980	11,700	7,800	67	33	0	7,839	3,861	0	5,226	2,574	0
1981	15,600	10,400	67	33	0	10,452	5,148	0	6,968	3,432	0
1982	15,600	10,400	67	33	0	10,452	5,148	0	6,968	3,432	0
1983	15,600	10,400	64	32	4	9,984	4,992	624	6,656	3,328	416
1984	15,600	10,400	52	25	23	8,112	3,900	3,588	5,408	2,600	2,392
					TOTALS:	46,839	23,049	4,212	31,226	15,366	2,808

* Assumes No. 471 began operation on 10/83 and No. 470 began operation on 3/84.

TABLE 10 Results for Lane 1

Vehicle	Actual No. of Repetitions	Stress Ratio[a]	Allowable Stress[b] (psi)	Calculated Stress[c] Center	Edge
Paceco	47,000	0.58	460	363	526
Hitachi	23,000	0.61	488	196	
Starcon	4,200	0.67	536	445	559

[a]Stress ratio x MR where MR = 800 psi.
[b]From Figure 13.
[c]Maximum stress for the uncracked LCPF.

surface can be placed directly on the existing LCPF; however, it was recommended that a tack coat be applied to ensure a good bond. It would also be desirable to overcut the existing asphalt concrete surface by at least 6 in. on each side to minimize water entrance into the LCPF base.

4. It would be possible to reduce the PCC slab thickness significantly (to 18 in.) if the Starcon cranes were not used, or reduced for much of the area if they were restricted to only certain areas of the terminal.

TABLE 11 Predicted Stresses for PCC Slab on Compacted Sand—Center Load Condition

Vehicle Type	Maximum Stress (psi) 16 in.	22 in.	28 in.	Design Stress[a] (psi) 16 in.	18 in.	20 in.	22 in.	28 in.
Paceco	529	379	280	423	375	325	303	224
Hitachi	350	350	350	—	—	—	—	—
Starcon	669	466	350	535	480	420	372	280

[a]Maximum stress x 0.70 (average operating load) x 1.05 (average of center and edge) = maximum stress x 0.8.

TABLE 12 Allowable Repetitions

Vehicle Type	Stress Ratio[a] 16 in.	18 in.	20 in.	22 in.	28 in.	Repetitions 16 in.	18 in.	20 in.	22 in.	28 in.
Paceco	0.604	0.54	0.46	0.43	0.32	25,000	115,000			
Hitachi	0.5	0.5	0.5	0.5	0.5					
Starcon	0.76	0.69	0.60	0.53	0.40	350	25,000	30,000	200,000	

[a]Design stress/MR where MR = 700 psi.

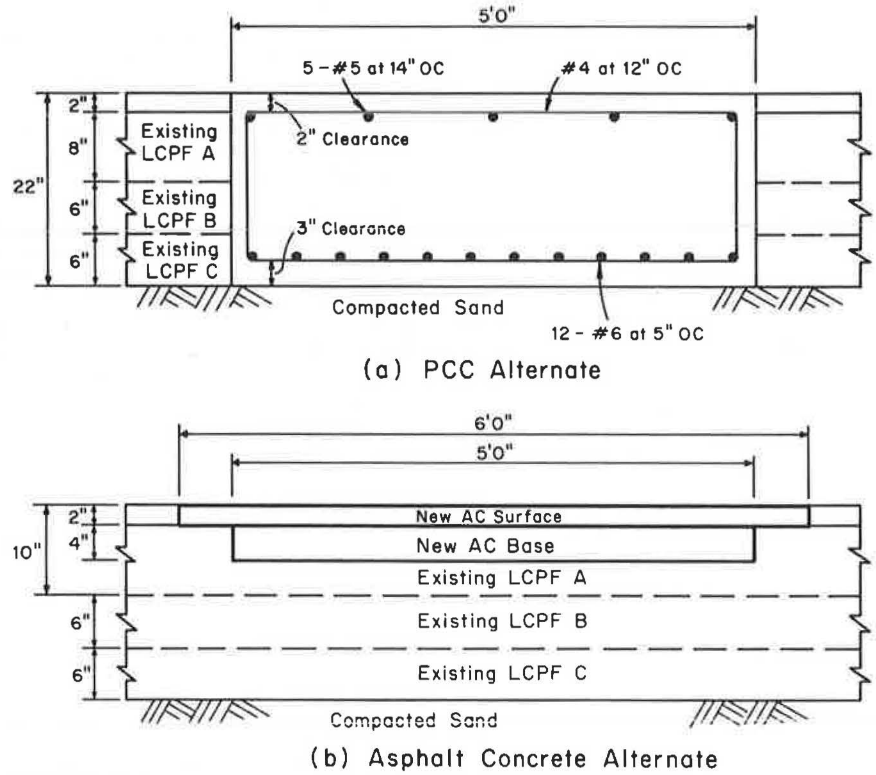

FIGURE 14 Design cross sections.

Special Construction Considerations

1. On removal of the deteriorated travel lanes, special attention should be given to the condition of the sides and the base of the excavated lanes. The sides should be vertical and somewhat rough to provide for improved load transfer for either the asphalt or portland cement concrete alternates.

2. For the asphalt alternate, the base should be firm with no loose areas. Badly cracked areas should be removed and replaced with asphalt concrete. For the portland cement concrete alternate, the LCPF should be completely removed and the PCC slab placed directly on compacted sand.

Drainage Considerations

1. For the asphalt concrete alternate, it would be expected that there would be little water entering from the surface into the base. Therefore the need for internal drainage is virtually nonexistent.

2. For the portland cement concrete alternate, water entering the joints would pass directly into the sand fill. Drainage, therefore, should not be a problem.

Final Selection

In June 1985, work began on replacing the deteriorated gantry crane lanes with a 22-in.-thick reinforced concrete section. Replacement of the lanes in Berths 604 and 605 will be done in phases, taking at least 2 years. The contract for the first phase involves repairing the lanes in three of eight container storage areas. Work in each storage area involves replacing two lanes, one on each side of the cranes. The three storage areas are being closed for work one at a time in order to minimize disruption of normal terminal operation.

Demolition of existing lanes involves sawing 16 in. deep along both edges of the lane. The purpose of sawing 16 in. is to produce smooth trench walls during excavation of the LCPF. Concrete for the new lanes will subsequently be cast directly against the saw-cut walls. Although sawing 16 in. did not cut completely through the LCPF, it was decided that the benefit gained by sawing an additional 6 in. did not justify the cost.

After demolition of the existing lanes, excavation of the underlying LCPF and compacting the sand subgrade, reinforcing steel was placed. Concrete was then placed in a continuous operation from one end of the storage area to the other, a distance of about 897 ft.

After the concrete had reached design strength, containers were moved from the next work area into the one just completed.

ACKNOWLEDGMENTS

The authors are grateful to their employers for the opportunity to participate in this project. We are indebted to Jim Lundy, who carried out some of the analyses, and to Sharon Toner and Nancy Brickman, who typed the manuscript, and to Linda Haygarth who contributed to the graphics.

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