Roller-Compacted Concrete Pavement Design Practices for Intermodal Freight Terminals at the Port of Tacoma

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Recent intermodal yard paving projects at the Port of Tacoma, Washington, are described. These projects have used a relatively new paving process known as roller-compacted concrete (RCC). RCC pavement offers a substantial cost savings over conventional portland cement concrete and asphaltic concrete pavements when used in heavy wheel load applications, such as side pick container-handling equipment and gantry-type container cranes. Besides the significant economic advantage, RCC pavement can be placed at extremely rapid rates, enabling speedy completion of tightly scheduled projects. Major items addressed include a brief history of RCC, design considerations, feasibility and economic evaluations, pavement design methods and design details, construction methods, quality control, and pavement durability and maintenance.

The Port of Tacoma became the sixth largest container-handling port in North America during 1985 because of the addition of major world-class shippers such as Sea-Land Service, Inc., and Maersk Lines. Two major factors that attracted these shippers to Tacoma were the excellent rail connections from two major railroad companies (Burlington Northern and Union Pacific) and the "on-dock" location of the intermodal transfer facilities, which eliminates over-the-road draying of containers.

To accommodate the large intermodal container volume forecast by Sea-Land, a completely new 17-acre intermodal rail yard (Figure 1) was constructed adjacent to Sea-Land's new 76-acre container terminal. This site has been named the South Intermodal Rail Yard and has storage capacity on four tracks for 91 conventional 95-ft flatcars or 30 double-stack 270-ft container cars.

The existing North Intermodal Rail Yard was expanded to almost triple its original storage capacity to accommodate the new Maersk unit train traffic as well as that from existing shippers. This 10-acre yard now has storage capacity on three tracks for 70 conventional 95-ft rail cars or 24 double-stack container cars.

Both intermodal yards have been constructed with roller-compacted concrete (RCC) pavement. This is a new pavement concept for yard pavements in the United States, and the decision to use this type of pavement in lieu of conventional portland cement concrete or asphaltic concrete was made only after lengthy deliberation of the economic and scheduling factors that affected each project. Both the Northwest Region of the Portland Cement Association (PCA) and the Canadian Portland Cement Association (CPCA) were extremely helpful in providing technical information pertaining to the design and construction methods used for RCC pavement.

Presented hereafter is a brief history of RCC paving, which demonstrated the feasibility of its use to Port of Tacoma and Sverdrup & Parcel engineers, and a discussion of design and construction procedures used on the two projects.

HISTORY OF RCC PAVING

RCC pavement is an outgrowth of the traditional cement-treated aggregate base, which has long been used by highway departments as a base course for asphaltic concrete wearing surfaces. The primary differences in RCC are that the cement content of 10 to 14 percent is high compared with approximately 5 percent in the cement-treated base and that the top surface is directly exposed to operating equipment.

As early as 1972, the British Columbia National Harbours Board constructed an 8 percent modified cement-treated base overlaid with a 2-in. asphaltic concrete wearing surface at the Port of Vancouver. This early paving work has been performing with minimum maintenance for 13 years and is generally given credit for pioneering the use of and interest in RCC pavements throughout British Columbia (1).

The major user and leader in the development of RCC pavement to date has been the British Columbia forest products industry and the Canadian Portland Cement Association. Primary uses are for dry-land log sort yards that typically use log-handling equipment with axle loads of 250,000 lb. The first project using RCC as a finished pavement was constructed on a Vancouver Island, British Columbia, log sort yard in 1976.

The use of RCC in the United States has been primarily associated with Army Corps of Engineers dam construction. The material has been found to be an economical substitute for earth fill on many recent projects. The Corps of Engineers was also responsible for promoting the use of RCC pavement on two demonstration projects in 1984. A 20,000-yd^2 (10-in.-thick) tactical equipment facility parking area at Fort Hood, Texas, was the first project in the United States to use RCC paving methods, and a subsequent 1,800-yd^2 (8-in.-thick) tank road at Fort Lewis, Washington, is providing valuable information to be used in future Corps of Engineers designs.

Before the Port of Tacoma projects, this author knows of only one other RCC paving project in the United States. This involved construction of an 18-in.-thick RCC pavement at Burlington Northern Railroad's intermodal hub facility in Houston, Texas.

FIGURE 1 South Intermodal Rail Yard.

The RCC on this project was spread with a bulldozer and motor grader, in lieu of a standard asphalt paving machine, and surface tolerances and appearance have been reported to be less than satisfactory.

In comparison with the projects previously mentioned, the Port of Tacoma's South Intermodal Rail Yard involved 52,000 yd^2 of RCC pavement area and the placing of approximately 25,000 yd^3 of loose RCC mix; and the North Intermodal Rail Yard totaled 29,000 yd^2 of pavement area and approximately 14,000 yd^3 of loose RCC mix.

PORT OF TACOMA DESIGN CONSIDERATIONS

Before evaluating the feasibility of one type of pavement against another, several design criteria and operational characteristics had to be established by the port and its consulting engineers. The major parameters affecting design of the intermodal freight terminal pavement are summarized as follows:

1. Type of container-handling equipment
   - Side pick loaders or rubber-tired bridge cranes, or both, for the South Intermodal Yard
   - Straddle carriers, side pick loaders, and rubber-tired gantry cranes for the North Intermodal Yard
2. Typical yard section to accommodate operational characteristics of selected machinery
   - North Yard, see Figure 2
   - South Yard, see Figure 3
3. Wheel loads
   - Side pick loader: 118,000 lb at 105 psi
   - Rubber-tired gantry cranes: 54,000 lb at 100 psi
   - Straddle carrier: 20,000 lb at 131 psi
4. Subgrade value
   - Soils testing indicated an average California bearing ratio (CBR) of 25 for existing sandy fill (in place approximately 30 years)
   - Asphaltic concrete design: CBR = 20 maximum
   - Concrete design: K = 300 psi per inch
5. Concrete pavement strength: 28-day flexural strength = 650 psi minimum
6. Drainage
   - Closed pipe drainage
   - Constant elevation drainage swaile
   - Catch basin location in aisleway

FEASIBILITY AND ECONOMIC EVALUATIONS

One of the primary reasons for including RCC pavement as a bid alternate for the South Intermodal Rail Yard was the Portland Cement Association's (PCA) favorable reports on the speed at which RCC could be placed and its relative insensitivity to placement during winter temperatures in the Pacific Northwest. These two factors became increasingly important after months of facility planning at a preferred site had to be abandoned because of an Indian land claims dispute. An "eleventh hour" change in sites and previous completion commitments necessitated that construction of the entire intermodal rail yard (demolition, earthwork, trackwork, drainage, paving, buildings, electrical, and mechanical work) be accomplished in only 90 calendar days in the middle of winter.

From previously constructed projects, it was apparent that RCC pavement could be constructed in 8 1/2-in. compacted lifts that would greatly reduce the time required for multiple lifts associated with the placement of asphaltic concrete. Preliminary estimates of RCC placement rates provided by the PCA were in the range of 1,500 yd^3 truck measure per day.

The finished surface tolerances and appearance of the RCC pavement were not of primary concern in evaluating the use of RCC in this yard facility. It was believed that a 3/8-in.-in-10-ft surface smoothness was adequate for the type of traffic using the facility. Because RCC, as it is most commonly specified, is a nonreinforced pavement with no control joints, the user should be prepared to accept a large amount of uncontrolled shrinkage cracking. Although the cracking is unsightly, and undoubtedly allows water to enter the subgrade, the high degree of aggregate interlock across the cracks apparently prevents differential settlement and structural failures. Inspection of Crown-Zellerbach's Fraser Mills Plant in Coquitlam, British Columbia, showed an RCC pavement with practically no maintenance for 8 years and extensive cracking patterns; yet no signs of structural pavement failure were noted.

The most obvious reason for considering the use of RCC for heavily loaded industrial pavements was its past history of considerably lower costs than equivalent sections of asphalt or portland cement concrete. This cost savings is primarily achieved through the elimination of side forms and joint details, the use of rapid batching cycles, and the economies attained from placing thicker lifts of pavement. Preliminary estimates indicated that a savings of 20 to 30 percent could be achieved in pavement costs. Tables 1-3 give bid comparisons from

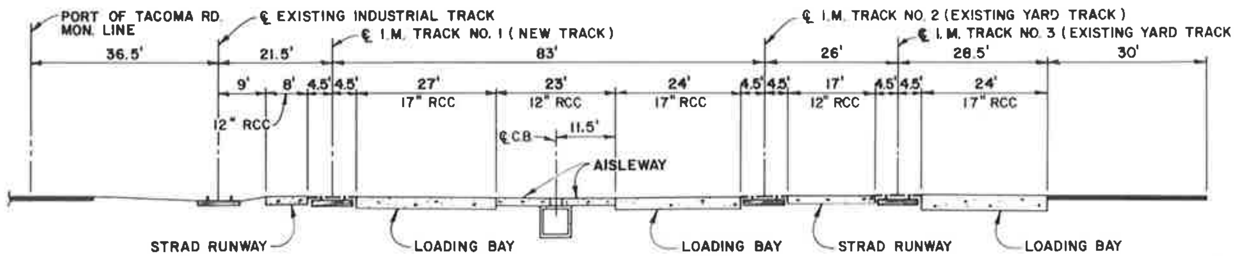

FIGURE 2 Typical yard section—North Intermodal Rail Yard.

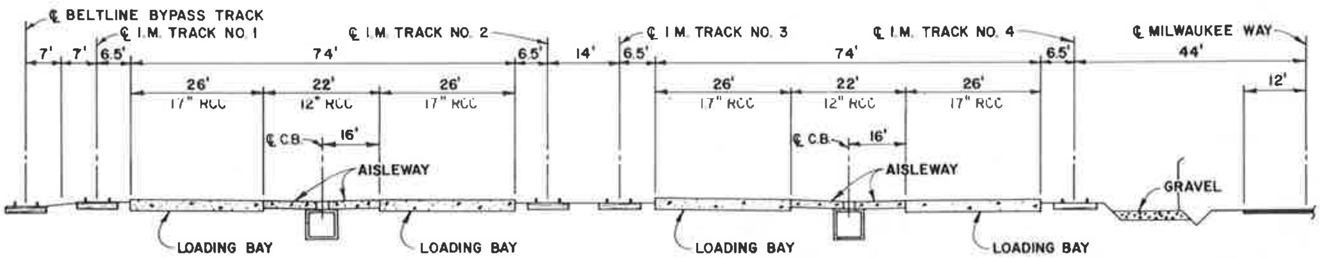

FIGURE 3 Typical yard section—South Intermodal Rail Yard.

TABLE 1 Cost Comparisons for South Intermodal Rail Yard—Total Contract Bid[a]

Contractor	RCC ($)	PCC ($)	PCC and ACP ($)
M.A. Segale	1,764,500	2,295,000	2,135,000
Kiewit Pacific	2,173,500	2,275,000	2,292,500
Woodworth Co.	2,359,083	2,358,083	2,055,580
Intertec	2,560,138	2,606,107	2,570,180

[a]Exclusive of 7.8 percent sales tax and rail materials furnished by Port of Tacoma. RCC less than ACP by 14 percent. RCC less than PCC by 22 percent.

TABLE 2 Cost Comparisons for South Intermodal Rail Yard—Low Bidder Paving Costs

Item	RCC ($)	PCC ($)	PCC and ACP ($)
Gravel base	25,000	25,000	25,000
Base course	160,000[a]	40,000	120,000
Crushed surface	15,000	15,000	45,000
ACP	50,000	50,000	510,000
RCC or PCC	954,000	1,500,000	760,000
Total	1,204,00	1,630,000	1,460,000

[a]Includes $120,000 change order for 4-in. thick base course working surface. RCC less than ACP by 18 percent. RCC less than PCC by 26 percent.

TABLE 3 Comparison of Unit Bid Prices—Extra Work

	South Yard			North Yard	
Bidder No.	RCC ($/yd^3)	PCC ($/yd^3)	ACP ($/ton)	RCC ($/yd^3)	ACP ($/yd^3)
1	42	60	30	44	62
2	44	90	25	48	60
3	47	60	33	53	40
4	61	54	25	49	60

Note: All cubic yard prices are for in-place measure.

the recently completed Port of Tacoma projects that substantiate the cost saving claims.

PAVEMENT DESIGN METHODS

The most widely accepted method for designing RCC pavement, at present, is a thickness selection based on PCA literature for thickness designs of regular unreinforced portland cement concrete pavements (2-4).

The usual parameters for pavement thickness selection, such as magnitude and frequency of loads, contact area, subgrade support strength, and flexural strength of the concrete, also apply to RCC design. In intermodal rail yards the design vehicle wheel loads are extremely large and random, so standard tables for truck wheel loads cannot be used. The PCA has, however, developed two procedures for concrete thickness design for heavy industrial wheel loads. The Port of Tacoma intermodal yards used both design procedures and then compared results to establish the actual thickness of RCC pavement to be specified.

Method 1 is from a PCA draft titled "Thickness Design of Concrete Pavements Carrying Heavy Industrial Vehicles" (2). Method 2 is based on adapting heavy container stacker wheel loads to the PCA's computer program for airport pavement design (3). Method 1 was used to obtain direct slab thicknesses for varying wheel loads and subgrade values. In Method 2, the computer program prints out maximum concrete stresses for selected wheel loads, subgrade values, and concrete thicknesses. By comparing stress ratios of the actual stress divided by the modulus of rupture, the designer is able to select the proper thickness for a frequency of loading. When the stress ratio is not more than 0.50, the concrete will withstand unlimited load repetitions at the design loading (4). Design thicknesses calculated from these design procedures, assuming a modulus of rupture at 650 psi, are

	54K Wheel (in.)	118K Wheel (in.)
Method 1, K = 300	13	17.3
Method 2, K = 300	11.5	18. 5

Final thicknesses of 12 in. for aisleways and general yard area, and 17 in. for the heavy lift loading bays were selected. This reduction in thickness was justified because the majority of the heavy lifts do not occur with a maximum rated machine lift.

The asphaltic concrete bid alternates were designed on the basis of Asphalt Institute Publication MISC-75-5, A Guide for the Design of Full-Depth Asphalt Pavements for Heavy Wheel Loads, assuming a maximum CBR of 20. Figure 4 shows equivalent pavement sections for the two design wheel loads.

MIX DESIGN

RCC mix designs were based on experience obtained by the Corps of Engineers' Fort Lewis demonstration project and by the Canadian Portland Cement Association's experience in British Columbia projects.

The basis for mix design follows principles used in cement-treated based construction (i.e., water content of the mix is selected on the basis of the optimum percentage of moisture for maximum compacted density). Hydration of the portland cement is a secondary effect of the presence of the water. General practice in Canada has been to use 12 to 14 percent cement content in the upper half of the design section and a 7 to 8 percent cement content in the lower half (1). Due mainly to the desire to produce a homogeneous concrete section similar to regular portland cement concrete pavement, a cement content of 13 percent by weight was selected for this project. On the basis of information obtained from the Fort Lewis RCC demonstration project, it was believed that flexural strengths of 700 psi could be attained with this amount of cement. Contract bid documents specified a 28-day flexural strength of 700 psi in lieu of the pavement design value of 650 psi because of the port's desire to use the pavement immediately after wet curing was completed.

The aggregate selected for the mix was a 5/8-in.-minus crushed rock conforming to the Washington State Department of Transportation's Class B asphalt

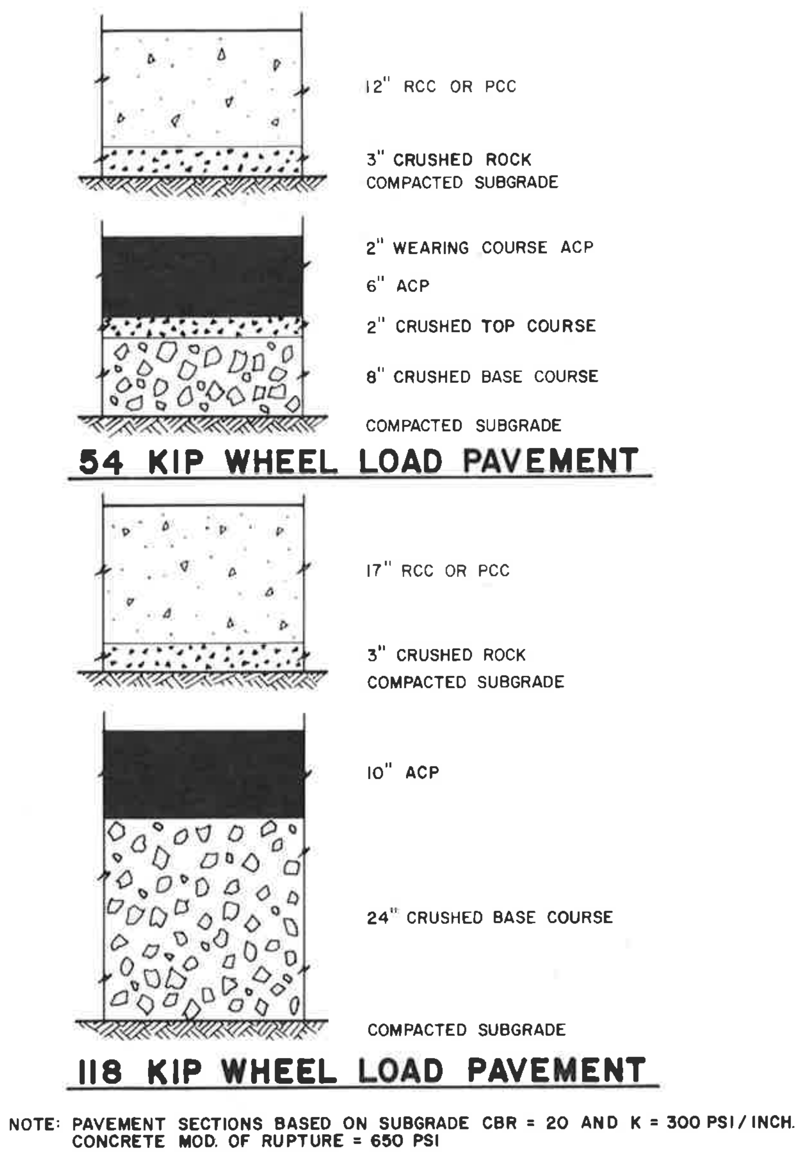

FIGURE 4 Equivalent pavement sections.

concrete aggregate. Observations of previously constructed projects showed a marked improvement in surface tightness of the compacted mix and much less aggregate segregation compared with regular concrete aggregate mixes. The Canadian paving projects also have had good results with 7/8-in.-minus crushed rock. The following table gives the specifications for the RCC aggregate used in both Port of Tacoma intermodal yards.

Sieve Size	Percentage Passing
5/8 in.	100
1/2 in.	90-100
3/8 in.	75-90
1/4 in.	55-75
No. 10	32-48
No. 40	11-24
No. 80	6-15
No. 200	3-7

Many people knowledgeable in RCC mixes believe that 5 to 10 percent passing the No. 200 sieve makes for a better finished surface, and, indeed, the Port of Tacoma aggregate always tested above 5 percent.

The amount of cementitious material was specified at 450 lb per cubic yard of portland cement Type II and 100 lb per cubic yard of fly ash Class F. The substitution of fly ash for cement provides an economic benefit and reduces some of the shrinkage problems, but according to CPCA recommendations, fly ash should be limited to 20 percent of the total cementitious content until further field testing can be carried out.

The contractor was required to submit a trial RCC mix based on the specified cement content and aggregate gradations. The mix design used on the South Intermodal Rail Yard is given in the following tables. Batch weights per cubic yard were

Cement	450 lb
Fly ash	100
Aggregate (5/8"-3/8")	850
Aggregate (3/8"-#4)	850
Aggregate (#4-0)	1,360
Aggregate (blend sand)	340
Moisture	6.5%
Unit weight	154.3 lb/ft^3

Average trial mix compressive strengths were

Day	psi
3	1,810
7	3,840
14	4,940
28	6,050

Average trial mix flexural strengths were

Day	psi
3	525
7	615
14	735
28	770

No air entrainment was specified for the design mix. Because entrained air is part of the paste in a normal concrete mix, and there is little cement paste in an RCC mix, it is questionable that an air-entraining agent will do anything at all.

DESIGN DETAILS

When designing a project with a new concept like RCC pavement, there are always lessons to be learned and details that can be improved on. The following discussion is intended to aid designers of future intermodal terminal projects.

The pavement width of 74 ft between tracks is considered the bare minimum for side pick loading machines. This was dictated by property boundaries and required track storage at both Port of Tacoma projects. A clear pavement width of 90 ft is desirable because this would allow yard hostlers with chassis to make U-turns within the space between tracks.

Loading bay widths of 26 ft, for making heavy container lifts, are adequate for lifting containers or prestaged piggy-back trailers onto the rail cars. However, when removing containers from rail cars, the side pick loaders will back up far enough to completely clear the cab of the empty yard truck, and in many instances the heavy wheel loads are on the aisleway pavement section. A more functional loading bay width of 30 ft is recommended. Although the aisleway pavement section is intended for truck and empty lifting machines, it is a certainty that fully loaded machines will use it to cross over to another cut of rail cars for last minute destination changes of containers. This may warrant a deep RCC pavement section throughout the working area of the yard.

The location of the drainage catch basin has an impact on the cost of RCC paving. Catch basins located midway between working tracks always require extra labor and time to pave around. If this center aisle location is desirable, a constant drainage swaile elevation between catch basins and a constant paving cross slope will definitely minimize the extra costs. Although not looked on with great favor by railroad maintenance personnel, a constant pavement cross slope draining to the railroad ballast, with water being picked up by an underdrain system, would greatly simplify the RCC paving operation.

The layout of RCC paving to eliminate tapers and verge areas is important to cutting costs. The South Intermodal Rail Yard had many hard-to-access areas, and in many locations RCC was placed by front-end loader, hand raked to grade, and then rolled. This procedure gave satisfactory results but was expensive.

The free edge of the RCC pavement adjacent to the loading tracks tends to slope at approximately 45 degrees but remained quite straight. The 6-ft 6-in. distance from centerline of track to the breakpoint of the pavement edge at the South Yard is a maximum that should be used for side pick loaders. Observation has shown that a distance of 6 ft 0 in. is preferred. When designing for straddle carriers, such as those used in the North Yard, a distance of 4 ft 6 in. from centerline of track to the edge of the RCC pavement is recommended.

RCC pavement is placed without reinforcing and without control joints. Observations of projects in which sawn joints were used in an attempt to control shrinkage cracks indicated that this was a futile attempt. The sawed joint acted like the free end of a slab and caused another crack to form within 1 ft of the sawn joint. An even more severe case of cracking occurred where control joints were sawn across each other at a 90-degree intersection. It is therefore recommended that no attempt be made to control cracking with sawn joints.

A working surface of 3 in. of crushed rock base was found to be a must on these projects. The paver and hauling trucks will cause subgrade rutting in sandy soils without this protection, and the working surface made paving possible even in marginal weather.

The volume compaction of loose RCC to that of maximum density was quite close to 20 percent. A single lift of 10 1/2 in. compacted to 8 1/2 in. was found to be the maximum depth that could be placed with the vibrating screed paving machine and still maintain surface tolerances of 3/8 in. per 10 ft.

CONSTRUCTION METHODS

The construction procedures used in building an RCC pavement are similar to those for standard flexible pavement construction. There are, however, certain techniques that vary from those used in asphaltic concrete paving and that can be used to assure a successful pavement.

The Tacoma intermodal yard pavements were both mixed with a continuous flow twin-shaft pugmill mixing plant (Figure 5). The mixing plant for the South Yard had a capacity of well in excess of 400 yd³ per hour and was equipped with separate cement and fly ash silos that batched into a single belt from vane feeders. The aggregate feed was from four separate bins that blended to specification. Premix concrete batch plants have been used on Canadian projects, but a production rate greater than 200 yd³ per hour is considered necessary to achieve a desirable laydown rate from the paving machine. Mix-in-place construction does not provide adequate quality control or uniformity and should not be used.

FIGURE 5 RCC batch plant.

The use of a standard track-mounted asphalt paving machine with the mix delivered by dump trucks has been the most successful method for laying down the RCC mix, which is basically no-slump concrete. Most paving machines are equipped with only vibrating screeds, but the use of a tamping bar type of machine would greatly enhance the finished surface tolerances of the pavement. By using the 5/8-in.-minus crushed aggregate, segregation of the mix was minimized both in the hauling and the placing operations. It is recommended that a conveyer storage hopper be used for transferring RCC mix to the dump trucks, but the South Yard pavement mix was dumped from the conveyor to a paved area, then loaded into the trucks with a front-end loader without noticeable signs of segregation. The concrete should be placed within 30 min after mixing.

Where space and plant capacity allow it, the most preferred method of placement is to work two pavers in a staggered configuration as shown in Figure 6. The longitudinal joint between pavers is knit together with a common roller pass and becomes nonexistent after compaction. The time delay involved in backing up the paving machine to place the second lane or lift is greatly reduced by using two machines. The maximum lane width used in the South Yard was 13 to 14 ft because the paver had trouble pulling anything wider with the depths being placed. An uncompacted pavement depth of 10 1/2 in. also appeared to be the maximum permissible to attain surface uniformity when rolled.

FIGURE 6 RCC paving operation.

Compaction should follow immediately after placement of the mix. Initial compaction was done with four passes of a vibratory steel-wheeled roller weighing a minimum of 10 tons. Intermediate rolling of the surface lift was done with two passes of a pneumatic-tired roller to tighten the surface texture, and final rolling was accomplished with two passes of a nonvibratory steel-wheeled roller. Maximum density of 98 percent was achieved with this rollering sequence; however, small ridges from the rubber-tired roller still remained after final rolling. An increase in the number of final rolling passes to 6 or 8 would minimize the ridge condition and tighten the finished surface considerably. A comparison of finished surfaces at the North and South Intermodal Yards indicates that the heavier 15-ton roller (Figure 7) used in the South Yard gave a tighter finished texture than the 10-ton steel-wheeled roller used in the North Yard.

Compaction of free edges is improved when rolling of the outer 18 to 24 in. is delayed for 15-30 min. All rolling was specified to be completed 45 min after placement. Many procedures were tried to compact the slope that results at a free edge, but none

FIGURE 7 15-ton vibratory roller.

FIGURE 8 Free pavement edge at trackside loading bay.

FIGURE 9 Dual tamping bar paver.

were more successful than hand tamping with an asphalt rake. A view of the finished free edge is shown in Figure 8.

When multiple-lift RCC pavement is being placed, it is absolutely essential that the delay in placement of the upper lifts be kept to a minimum of 3 to 4 hr. If temperature and humidity cause drying of the base layer surface, fine water sprays should be used to keep the surface damp. All vertical lifts must be completed in the same day, and under no circumstances should the lower layers remain exposed overnight. Longitudinal and transverse cold joints occurring at the end of a day's paving operation must be cut or bladed vertical, and the joint is thoroughly sprayed with water just before the next day's fresh mix is placed. Sloping "wedge" joints must be avoided because they cause dramatic separation of the cold joint with continued use.

Moisture content of the mix must be monitored extremely carefully because 0.5 to 1.0 percent too much water will cause a wave to be pushed in front of the breakdown roller. It is also imperative that vibration be stopped with changing roller direction or a dip will develop that reflects through to the finished surface.

The finished RCC was moist cured with water for 7 days. The South Yard contractor elected to use a fog-spray sprinkler truck for the entire curing period, whereas irrigation sprinkler piping was used on the North Yard. Curing should commence as soon as practical on the same day as placement.

RCC paving for the final 5,000 yd^3 of mix on the North Yard was performed with a paving machine entirely new to North America. The paver, manufactured by West Germany's ABG International, features double tamping bars and a vibrating screed that provides an initial compaction of 95 percent behind the screed. The machine provides excellent surface tolerances even at depths of from 6 to 12 in. and was able to pull a 27-ft lane width in one pass. The waviness associated with compacting free edges was completely eliminated with this type of paver. Rolling time to achieve maximum density was also greatly reduced. Figure 9 shows the paver in operation at the North Intermodal Yard.

QUALITY CONTROL

Quality control for the RCC pavements was performed in three separate phases. These phases involved preparation of a trial mix design before production, plant reports and monitoring of the mix during construction, and testing of sawn beam and core samples at completion of the construction.

The contractor was responsible for providing a trial mix design using the specified aggregate size and amounts of cementitious materials. Laboratory testing showed that the trial mix was capable of attaining the desired flexural strength in 14 days (Table 3), and the optimum moisture was determined to be 6.5 percent. Contractor-submitted plant reports provided a daily record of the materials used, stockpile moisture, and aggregate gradation.

The Port of Tacoma arranged for nuclear densometer testing during pavement construction to verify maximum field densities and moisture content. This information was made available to the contractor so that moisture or compaction adjustments could be made. Field measured dry densities ranged from 138.4 to 143.5 pcf.

Following construction, the port arranged for testing of sawn beams and core samples by the Corps of Engineers. Results of these tests at the South Intermodal Yard show average compressive strengths for seven cores to be 5,220 psi at 45 days, and tests of two beams 17 in. thick gave flexural strengths of 740 and 775 psi, respectively, at 45 days.

Because of the lack of a standard field sampling technique that is representative of the actual RCC pavement, it was decided not to sample and test the fresh RCC mix. Some agencies and laboratories have used vibrating tables or pneumatic tamping devices to approximate field conditions, but these methods and the resulting beam samples are fairly cumbersome to use.

PAVEMENT DURABILITY AND MAINTENANCE

From observations of heavily loaded RCC pavements in British Columbia, it is apparent that the pavement structure will remain quite serviceable with little or no maintenance. In areas where aggregate is not nearly as wear resistant as are Tacoma vicinity aggregates, good results have been achieved with 1- to 1 1/2-in.-thick asphalt concrete overlays.

The South Intermodal Yard has operated for only 4 months at the time of this writing (Figure 10), and overall durability appears quite good at present.

FIGURE 10 Typical yard operation.

There has been minor surface wear in a few isolated areas where it appears that moisture content was not sufficient to achieve a tight-knit surface texture, but structural adequacy has not been affected. There has also been some minor wear at longitudinal cold joints, but in general these joints appear quite good.

The North Intermodal Yard had been in service for 3 months and is being used by straddle carriers that run continually in the same path, straddling the railroad tracks. Surface wear in many areas of the strad runways has been noted. The wear consists of a crumbling of the surface cement matrix to expose larger pieces of aggregate, which are in turn ground loose by the tires. The port has used a rubberized coal tar pitch emulsion seal coat to stop the raveling in the worst areas, and the results have proven to be excellent so far.

As previously mentioned, RCC pavement will experience numerous shrinkage cracks. The spacing of cracks was initially 100 to 120 ft, and most recent observation shows cracking at about 40 to 60 ft. Again, these cracks have an extremely high degree of aggregate interlock across them and do not cause a problem to the structural behavior of the pavement. The Port of Tacoma has, however, made it a policy to seal all major shrinkage cracks with a surface coating of AR-4000 paving asphalt in an effort to minimize the amount of water that enters the subgrade.

The RCC pavement has the same durable characteristics against oil and fuel spillage that slump concrete exhibits. Also, the Corp of Engineers has tested sawn beams from the South Yard for freeze-thaw durability, and preliminary results show a DFE factor in excess of 70 percent at 300 cycles, which is an excellent rating.

In terms of overall performance, the RCC pavement at the Port of Tacoma is functioning well to date. Surface wear will be the primary factor to monitor in the future, and much more work is needed in determining suitable and cost-effective initial surface sealers and curing agents, or long-term surface treatments, if required.

CONCLUSIONS

RCC pavement at the Port of Tacoma has proven to be the most economical heavy-duty pavement for its intermodal freight terminals. First cost savings of 15 to 25 percent can be expected if RCC is specified as a pavement alternative for projects requiring wheel loadings of 50,000 to 120,000 lb.

Equipment for production and construction of RCC is readily available, and extremely high production rates are possible to ensure minimum construction time on tightly scheduled projects.

More work is needed in standardizing thickness design procedures, field sampling techniques, and laboratory test procedures. RCC pavement is in an early stage of development, and it is important to monitor the performance and associated maintenance costs to better identify its long-term durability and economic benefit.

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