Development of ACI 327R-14, Guide to Roller-Compacted Concrete Pavements

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Based on CP Tech Center/PCA Guide

Previous ACI Document ACI 325.10R State-of-the-Art Report on Roller-Compacted Concrete Pavements

Introduction and definitions

Definition

- "Roller-Compacted Concrete (RCC) is a no-slump concrete that is compacted by vibratory rollers."
- Zero slump (consistency of damp gravel)
- No forms
- No reinforcing steel
- No finishing
- Consolidated with vibratory rollers

- Concrete pavement placed in a different way!

Roller-Compacted Concrete

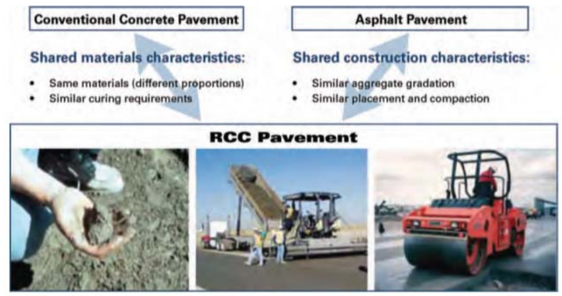


Fig. 3.2a—RCC combines aspects of conventional concrete and hot-mix asphalt paving materials and construction practices (Harrington et al. 2010).

Key Elements

Engineering Properties

- Equal or superior to conventional concrete
- Compressive strength
  - 4,000 to 10,000 psi
- Flexural strength
  - 500 to 1,000 psi
  - $f_r = C(f'c)^{1/2}$
- Modulus of Elasticity
  - 3,000,000 to 5,500,000 psi
  - $E = C_E(f'c)^{1/2}$

Basic Difference Between RCC & PCC

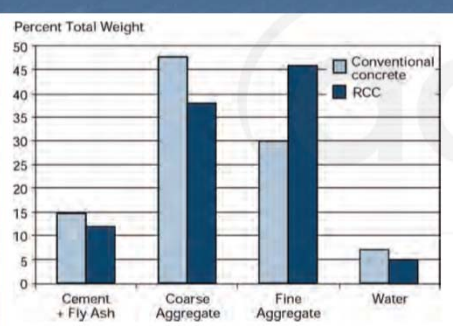


Fig. 3.3a—Typical material comparisons of conventional concrete and RCC (Harrington et al. 2010).

Basic Difference Between RCC & PCC

	Type of Pavement	
General Materials and Practices	**Conventional Concrete Pavements**	**RCC Pavements**
Mix materials proportions	• Aggregates typically account for 60 to 75 percent of the mixture by volume. • (w/cm) ratio is 0.40 to 0.45	• Aggregates compose 75 to 85 percent of RCC mixtures by volume. • (w/cm) ratio of 0.34 to 0.40 is typically lower than that used in conventional concrete mixtures
Workability	• Manipulated by the paving machine, (slump is generally about 2 in.)	• The mixture has the consistency of damp aggregates. RCC's relatively dry and stiff (zero slump) • Mixture is not fluid enough to be manipulated by traditional concrete paving machines.
Paving	• The mixture is placed ahead of a slipform paving machine, which then spreads, levels, consolidates through vibration.	• Typically the RCC mixture is placed with a conventional or heavy-duty, self-propelled asphalt paving machine • To initially consolidate the mixture to a slab of uniform thickness.

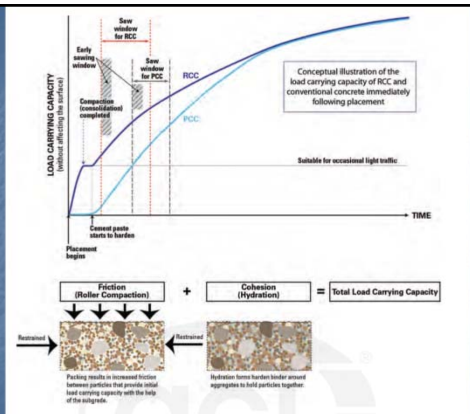


Fig. 3.3c—Load-carrying capacity of conventional concrete and RCC over the first few days (Harrington et al. 2010).

Benefits of RCCP

- Fast construction with minimum labor
- High load carrying ability
- Early strength gain
- Durable
- Low maintenance
- Light surface reduces lighting requirements
- Economical

Common Uses

- Ports, Intermodal facilities, and heavy industrial areas
- Light industrial areas
- Airport service areas
- Arterial streets
- Local streets
- Widening and shoulders
- Multilayer pavement systems for high speed uses
- Logging facilities, composting areas, and storage yards

Honda Plant – Alabama

Also used RCC for Saturn plant in Tennessee, Mercedes plant in Alabama

Port of Norfolk, Virginia

Two-lift Construction – Norfolk

Intermodal Facilities

Central Station, Detroit, MI

Burlington Northern, Denver, CO

Port Terminals

Norfolk International Terminal, VA

Port of Los Angeles, CA

Distribution Centers

18 acre distribution center in Austin, TX

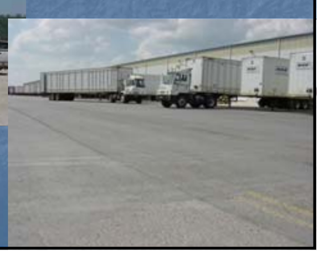
10 years after construction

Warehouse Facilities

Interior Floor Lynnterm Terminal
Port of Vancouver, BC

Warehouse, Appleton, WI

Industrial



Military Facilities

Ft Lewis, WA built in 1986

Ft. Drum, NY built in 1990

Tank Hardstands – Fort Carson, CO

Streets & Interchanges

Intersection Replacement
Calgary, AB

Residential Street Alliance, NB

Highway Shoulders

I-285 Highway
Atlanta, GA

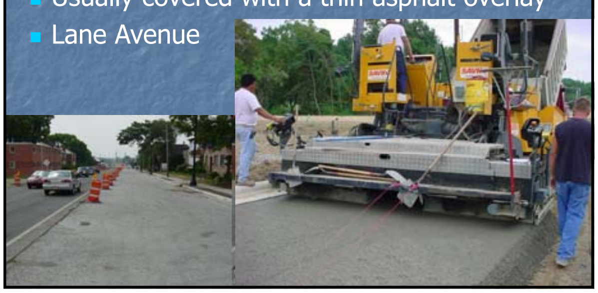
Waste Handling Facilities

5 acre composting
yard near Toronto

25 acre sludge drying
basins in Austin, TX

City Streets and Subdivisions

- Quebec and Columbus, Ohio
- Usually covered with a thin asphalt overlay
- Lane Avenue



South Carolina US 78

- Near Charleston
- 2 inches asphalt on 10 inches of RCC

Properties and Materials

RCC Materials

- Aggregates
  - Coarse – usual top size 5/8 to ¾ inch for surface finish
  - Fine
  - Combined gradation
- Cementitious materials
  - Cement
  - Fly ash
  - GGBFS
  - Silica fume – common in Quebec
- Water
- Limited use of chemical admixtures

Combined Aggregate Gradation

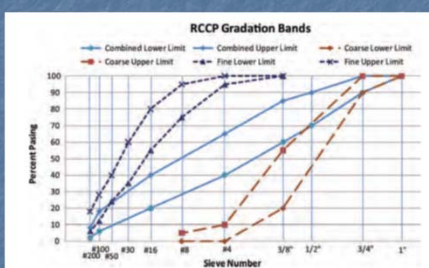


Fig. 5.2.1—Suggested combined aggregate grading with fine and coarse aggregate gradation bands (Harrington et al. 2010). (Note: 1 in. = 25 mm.)

Factors in RCC Mixture Proportioning

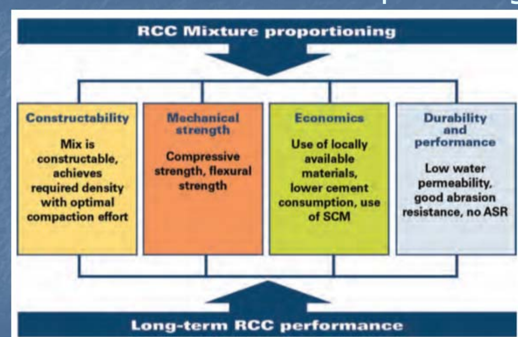


Fig. 6.1—Factors considered in RCC mixture proportioning (Harrington et al. 2010).

Mixture Proportioning Methods

- Soil compaction method (most common for pavements)
- Concrete consistency method
- Solid suspension model
- Optimal paste volume method
- Last 3 methods most common for hydraulic structures, e.g. dams

Soil Compaction Method

- Choose well-graded aggregates
- Select a mid-range cementitious content
- Develop moisture density relationship plots
- Cast samples to measure compressive strength
- Test specimens and select required cementitious content
- Calculate mixture proportions

Combined Aggregate Gradation based on 0.45 power curve

Fig. 6.3.1.1—Suggested aggregate gradation band and 0.45 power curve (Harrington et al. 2010). (Note: 1 in. = 25 mm.)

Cementitious Materials

- Typically 11 to 13 % by mass without addition of SCMs
- CM % = (Weight of cementitious materials)/(Weight of cementitous materials + oven dried aggregates)

Moisture-Density Curve (Modified Proctor)

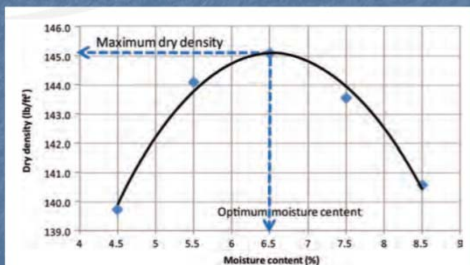


Fig. 6.3.1.3—Moisture-density curve (Harrington et al. 2010). (Note: 1 lb/ft^3 = 0.6 kg/m^3.)

Molding RCC Cylinders with Vibrating Hammer

Fig. 6.3.1.4—Molding RCC cylinders with vibrating hammer (Harrington et al. 2010).

Mixture Proportioning Example

- Parking lot facility
- Specified compressive strength 4,000 psi at 28 days
- Need 1,000 psi over required (e.g. 5,000 psi)
- Local aggregates with ¾ inch NMSA – BSG 2.70, absorption 2 %
- Fine aggregate BSG = 2.55, absorption 1 %
- Type I cement

Combined Aggregate Gradation

- Use sieve analysis of each aggregate
- Develop blend as close to 0.45 power line as possible
- In this case CA = 55 %, FA = 45 %
- Try cement content of 12 %

Test Specimens

- Test specimens at 10 %, 12 %, and 14 % cement at OMC (6.5 % water)
- Plot and find cement content at 5,000 psi
- Use 12.7 % cement

Strength versus Cementitious Content

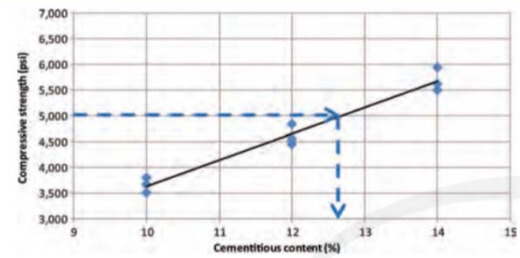
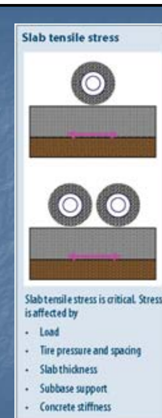


Fig. 6.3.1.5—Strength versus cementitious content plot (Harrington et al. 2010). (Note: 1 psi = 6.8 kPa.)

Structural Design

Structural Design

- Plain, unreinforced
- Undoweled
- Design is otherwise the same as for conventional concrete pavements
- Thickness range for 1 lift 4 to 10 inches
- Pavement thickness is a function of
  - Expected loads
  - Concrete strength
  - Soil characteristics



Design Procedures

- Portland Cement Association (PCA) – (Single Vehicles)
  - Industrial Pavements
  - RCC-PAVE computer program
- U.S. Army Corps of Engineers (USACE) (Single Vehicles)
- Conventional design procedures for parking lots, streets, and roads (Mixed Traffic)
  - ACI 330 tables
  - ACI 325.12R tables
  - StreetPave software

Stress Ratio

$$SR = Stress\_Ratio = \frac{Critical\_Applied\_Flexural\_Stress}{Flexural\_Strength}$$

Where:
Critical Applied Flexural Stress is the maximum tensile stress at the bottom of the concrete pavement slab, and
Flexural Strength (or modulus of rupture) is the breaking stress of a beam tested by third-point loading (ASTM C 78, AASHTO T97, CSA A23.2-8C)

Fatigue of RCC

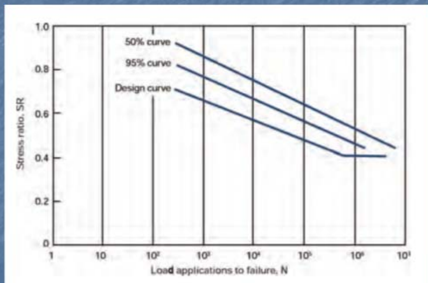


Fig. 7.4— Fatigue relationship for RCC (Portland Cement Association 1987).

Subgrade, Subbase, and Base Design

- Same requirements as for conventional concrete pavements
- Bearing capacity must be sufficient for adequate compaction of every RCC lift

Design Example 1 – Single Wheel

Fig. 7.4.1a—Straddle carrier (Harrington et al. 2010).

Design Example 1 – Single Wheel

- Load applications – 30 per day, 219,000 over 20 years
- Vehicle – maximum weight of 120,000 lb., tire 100 psi with 300 in^2 contact area
- RCC flexural strength 650 psi
- Subgrade *k*-value = 100 pci

Design Calculations

- Design stress ratio = 0.433 (interpolated from chart)
- Allowable stress σ = MOR x SR = 650 x 0.433 = 281 psi
- Maximum single wheel load P = 120,000/4 = 30,000 lb
- Allowable stress per 1,000 lb. load = σ/(P/1,000) = 281/30 = 9.37 psi/kip
- Use chart – design thickness 11 ½ inches

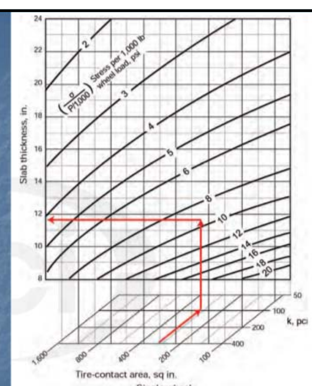


Fig. 7.4.1b—Design chart for single-wheel loads (Portland Cement Association 1987). (Note: 1 in. = 25 mm; 1 in.^{2} = 645 mm^2; 1 lb/in.^{3} = 27,680 kg/m^3; 1 psi = 6.8 kPa.)

Example 2 – Dual Wheel

Fig. 7.4.2a—Dual-wheel straddle carrier and loading dock (photos courtesy of Wayne Adaska).

Example 2 – Dual Wheel

- Vehicle – 2 steer wheels, 4 drive wheels, 60,000 lb. on each dual set
- Dual spacing s=20 inches, tire inflation pressure 120 psi
- Concrete flexural strength 700 psi, subgrade *k*-value 200 pci
- 40 channelized load applications per day, 20 year design life, total 292,000 applications

Design Calculations

- Tire contact area = 60,000/(2 x 120) = a = 250 in^2 per tire
- Design stress ratio = 0.43 (same chart as before) gives 280,000 applications
- Allowable stress σ = MOR x SR = 700 x 0.43 = 301 psi
- Use trials for different pavement thicknesses, try 15 inches
- Need radius of relative stiffness ℓ, get 49 inches from table

Design Calculations

- Use ℓ, a, and s to get F = 1,000
- Find σ = (Dual-wheel load/1,000) x 1/(slab thickness)^2 x F
- σ = 60 x ($1/15^2$) x 1,000 = 266 psi
- Since 266 < 301 psi, reduce slab thickness and iterate

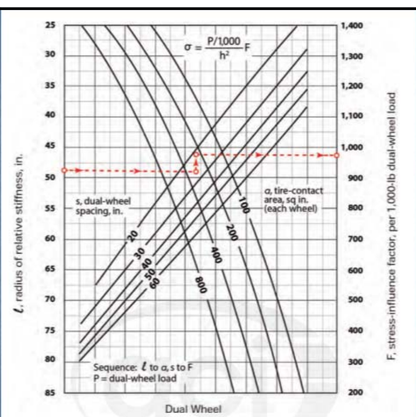


Fig. 7.4.2b—Stress-influence factor for dual-wheel loads (Portland Cement Association 1987). (Note: 1 in. = 25 mm.)

USACE Design Procedure

- Similar that for conventional pavements
- Vehicle loading converted to ESALs
- Then, converted to a pavement design index
- USACE procedure assumes 0 % load transfer
- For multi-lift pavements, can consider three bond conditions – full bond, partial bond, no bond

USACE Design Example

- Tank hardstand – 80,000 lb. tracked vehicles, 30 per day
- Subgrade *k*-value 100 pci
- RCC flexural strength 600 psi
- Parking lot classified as a Class E facility
- Cross-index Traffic Category VI (up to 90,000 lb. tracked vehicles), 40 vehicles per day, and Class E to find pavement design index = 7
- Design thickness = 8.5 inches should be satisfactory

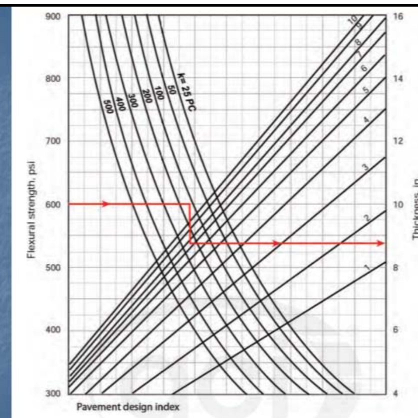


Fig. 7.5—Design curves for conventional concrete roads and streets and RCC pavement (Department of the Army and the Air Force 1992). (Note: 1 in. = 25 mm; 1 psi = 6.9 kPa.)

ACI Parking Lot Procedure

- Tables from ACI 330R-08, *Design and Construction of Concrete Parking Lots*
- Example parking lot
  - Car parking – Category A
  - Average daily truck traffic (ADTT) = 10
  - K = 100 pci
  - Concrete MOR 600 psi
- Gives RCC thickness of 5 inches

Table 7.6a—Design of concrete parking lots (ACI 330R)

Twenty-year design thickness recommendations, in. (no dowels)

		k = 500 psi/in. (CBR = 50, R = 86)				*k* = 400 psi/in. (CBR = 38, R = 80)				*k* = 300 psi/in. (CBR = 26, R = 67)			
	MOR, psi:	650	600	550	500	650	600	550	500	650	600	550	500
Traffic category*	A (ADTT = 1)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.5
	A (ADTT = 10)	4.0	4.0	4.0	4.5	4.0	4.0	4.5	4.5	4.0	4.5	4.5	4.5
	B (ADTT = 25)	4.0	4.5	4.5	5.0	4.5	4.5	5.0	5.5	4.5	4.5	5.0	5.5
	B (ADTT = 300)	5.0	5.0	5.5	5.5	5.0	5.0	5.5	5.5	5.0	5.5	5.5	6.0
	C (ADTT = 100)	5.0	5.0	5.5	5.5	5.0	5.5	5.5	6.0	5.5	5.5	6.0	6.0
	C (ADTT = 300)	5.0	5.5	5.5	6.0	5.5	5.5	6.0	6.0	5.5	6.0	6.0	6.5
	C (ADTT = 700)	5.5	5.5	6.0	6.0	5.5	5.5	6.0	6.5	5.5	6.0	6.5	6.5
	D (ADTT = 700)	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
		k = 200 psi/in. (CBR = 10, R = 48)				*k* = 100 psi/in. (CBR = 3, R = 18)				*k* = 50 psi/in. (CBR = 2, R = 5)			
	MOR, psi:	650	600	550	500	650	600	550	500	650	600	550	500
Traffic category*	A (ADTT = 1)	4.0	4.0	4.0	4.5	4.0	4.5	4.5	5.0	4.5	5.0	5.0	5.5
	A (ADTT = 10)	4.5	4.5	5.0	5.0	4.5	5.0	5.0	5.5	5.0	5.5	5.5	6.0
	B (ADTT = 25)	5.0	5.0	5.5	6.0	5.5	5.5	6.0	6.0	6.0	6.0	6.5	7.0
	B (ADTT = 300)	5.5	5.5	6.0	6.5	6.0	6.0	6.5	7.0	6.5	7.0	7.0	7.5
	C (ADTT = 100)	5.5	6.0	6.0	6.5	6.0	6.5	6.5	7.0	6.5	7.0	7.5	7.5
	C (ADTT = 300)	6.0	6.0	6.5	6.5	6.5	6.5	7.0	7.5	7.0	7.5	7.5	8.0
	C (ADTT = 700)	6.0	6.5	6.5	7.0	6.5	7.0	7.0	7.5	7.0	7.5	8.0	8.5
	D (ADTT = 700)	7.0	7.0	7.0	7.0	8.0	8.0	8.0	8.0	9.0	9.0	9.0	9.0

*ADTT = average daily truck traffic. Trucks are defined as vehicles with at least six tires; excludes panel trucks, pickup trucks, and other four-wheel vehicles. Refer to Appendix A. *k* = modulus of subgrade reaction, CBR = California Bearing Ratio, R = resistance value, MOR = modulus of rupture.

Notes: 1 in. = 25.4 mm; 1 psi = 0.00690 MPa; and 1 psi/in. = 0.27 MPa/m.

Traffic categories

1. Car parking areas and access lanes—Category A
2. Shopping center entrance and service lanes—Category B
3. *Bus parking areas, city and school buses*
   Parking area and interior lanes—Category B
   Entrance and exterior lanes—Category C
4. Truck parking areas—Category B, C, or D

Truck type	Parking area and interior lanes	Entrance and exterior lanes
Single units (bobtailed trucks)	Category B	Category C
Multiple units (tractor trailer units with one or more trailers)	Category C	Category D

Subgrade soil types and approximate support values

Type of soil	Support	*k*, psi/in.
Fine-grained soils in which silt and clay-size particles are predominate	Low	75 to 120
Sands and sand-gravel mixtures with moderate amounts of silt and clay	Medium	130 to 170
Sand and sand-gravel mixtures relatively free of plastic fines	High	180 to 220

ACI Streets and Local Roads Procedure

- ACI 325.12R *Guide for Design of Jointed Concrete Pavements for Streets and Local Roads*
- Design example
  - Collector street without curb and gutter, 50 ADTT
  - k = 100 pci
  - MOR = 650 psi
- Gives RCC thickness of 7 inches
- ACPA StreetPave program can also be used for parking lots, streets, or roads

Basic Construction Sequence

- Produced in a pugmill or central mix plant or dry batch plant
- Transported by dump trucks
- Placed with an asphalt paver
- Compacted by vibratory and pneumatic-tired rollers
- Cured with water or curing compound

Production

Fig 8.2.1.1—Tilt drum mixers (Harrington et al. 2010).

Fig 8.2.1.2—Transit mixer dumping into trucks (Harrington et al. 2010).

(a)

(b)

Fig 8.2.2.1a—(a) Continuous flow pugmill mixer; and (b) close-up view of mixing chamber (Harrington et al. 2010).

(a) (b)

Fig 8.2.2.1b—(a) Horizontal shaft mixer; and (b) close-up view of mixing chamber.

Construction

Preparation for Placement

- Simple preparation: no dowels, reinforcing, or forms
- RCC ideal for wide-open, unimpeded placement runs
- Block off fixtures (stormwater inlets, etc)
- Ensure subbase is smooth and at specified grades
- Set up stringlines
- Moisten subbase prior to RCC placement

Fig. 9.1—Subgrade preparation (Harrington et al. 2010).

Fig. 9.2—RCC uniformly loaded into dump truck.

Placing

- Layer thickness
  - 4 in. minimum
  - 8 in. maximum (10 in. with heavy-duty pavers)
- Timing sequence
  - Adjacent lanes placed within 60 minutes for "fresh joint", unless retarders used
  - Multiple lifts placed within 60 minutes for bond
- Production should match paver capacity
  - Continuous forward motion for best smoothness

Placing Equipment

- Conventional Asphalt Pavers
  - Provides some initial density (85%-92%)
  - Relatively smooth surface
  - Increased cleaning and maintenance

Placing Equipment

- Aggregate spreaders
  - Jersey spreader
  - Motor grader/dozer
  - Little initial compaction
  - Low surface smoothness
  - Poor surface texture
  - Additional surface (or diamond grinding) required for smooth ride

Fig. 9.4—Close-up view of high-density paver (Harrington et al. 2010).

Fig. 9.5—Side-by-side view of steel drum and rubber-tired rollers (Harrington et al. 2010).

Jointing

- Construction joints
- Sawed (contraction) joints
- Isolation joints
- Expansion joints
- Load transfer across joints, if any, is through aggregate interlock

Construction Joints

- Most critical area of project
- Must be constructed properly for durability
- Ensures bond/interlock, so slab acts monolithically
- Three types of construction joints:
  - "Fresh joints"
  - "Cold joints"
  - "Horizontal joints"

Fig. 9.5.1a—Fresh longitudinal joint (Harrington et al. 2010).

Fig. 9.5.1b—Finished longitudinal construction cold joint (Harrington et al. 2010).

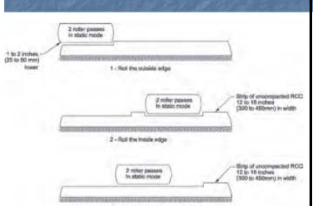


Fig. 9.5.3—Rolling the first course (Harrington et al. 2010).

Fig. 9.5.6—Sawed transverse and longitudinal joints (Harrington et al. 2010).

Fig. 9.5.6.3—Coring (left) and isolation joint (right) around a manhole (Harrington et al. 2010).

Need for Isolation Joints

Fig. 7.8.4—Distressed RCC possibly caused by expansion of the RCC slabs (Harrington et al. 2010).

Curing

- EXTREMELY IMPORTANT
- Ensures surface durability; reduces dusting
- Low moisture content in RCC; no bleed water
- Three methods:
  - Moist cure
  - Concrete curing compound
  - Asphalt emulsion

Fig. 9.5.8a—Application of curing compound (Harrington et al. 2010).

Fig. 9.5.8b—Moisture curing using sprinklers and fog spraying (Harrington et al. 2010).

Future Developments

- Three to four year revision cycle
  - Incorporate information from ACI 325.10R-95
  - Incorporate information from ACI 309.5R Compaction of Roller-Compacted Concrete
- Other improvements?
- Possible development of a specification

Thank you – Questions?