ANNEX 2: LEVEL 1 THERMAL STUDY MASS GRADIENT ANALYSIS PROCEDURE AND EXAMPLE

A2-1. Procedure

a. General. This Annex summarizes each step in a Level 1 thermal study mass gradient analysis of a mass concrete sheetware (MCS) and provides an example of how this procedure was applied for a modest-size MCS. Although alternative approaches can be used, this method is in common use for this level MCS thermal analysis. Surface gradient thermal analysis is seldom conducted at this level of analysis.

b. Input properties and parameters.

(1) Step 1: Determine ambient conditions. Simple analyses conducted for a Level 1 analysis are typically based on average monthly temperature data.

(2) Step 2: Determine material properties. Laboratory test results on material properties are seldom available for this level of thermal analysis. Material properties are generally estimated from published data in sources such as American Concrete Institute (ACI) documents, technical publications, and engineering handbooks. Often known information such as compressive strength and aggregate type is used to predict other material properties from published data. The minimum properties required are the coefficient of thermal expansion (C_{th}), the adiabatic temperature rise (ΔT_{ad}), and the tensile strain capacity (ϵ_{tc}).

(3) Step 3: Determine construction parameters. Concrete placement temperature is the essential construction parameter needed for this level of thermal analysis. A first approximation is to assume that concrete placement temperatures (T_p) directly parallel the average monthly temperature. A more accurate method is to modify the average monthly temperature based upon production time period and extent of production or to use actual placement temperature data from similar projects.

c. Temperature analysis.

(1) Step 4: Mass gradient temperature analysis. For Level 1 mass gradient analysis, no elaborate “model” is used to develop temperature history. The long-term temperature change is simply calculated as the peak concrete temperature minus the ultimate stable concrete temperature.

(a) Determine peak temperature. This is the sum of the concrete placement temperature and the adiabatic temperature rise.

(b) Determine ultimate stable temperature. Large structures cool to a stable temperature equal to the average ambient temperature. However, smaller concrete structures cool to a stable annual temperature cycle, since there is insufficient mass to provide complete insulation of the interior. ACI 207.1R provides a figure relating temperature variation with depth to determine this internal temperature cycle. It is assumed that the concrete temperature cycles about the average annual temperature.

(c) Determine long-term temperature change. The sum of the placing temperature plus adiabatic temperature rise provides a quick peak temperature of the MCS. Then subtracting the ultimate stable temperature provides the long-term temperature change used for strain and cracking evaluation.

d. Cracking analysis.

(1) Step 5: Mass gradient cracking analysis. Using long-term temperature change and ACI formulas, mass gradient strain is approximated. These strains are compared to estimates of tensile strain capacity to determine if and when cracking may occur.

(a) Determine mass gradient restraint conditions. The structure restraint factor (K_R) and the foundation restraint factor (K_f)(in ACI 207.2R termed "Multiplier for foundation rigidity") are determined as described in Appendix A, and in ACI 207.2R.

(b) Determine mass gradient thermal strain. The total induced strain is the product of the long-term temperature change, the coefficient of thermal expansion and restraint factors. Use Equation A-4 (Appendix A).

$$\text{Total strain} = (C_{th})\,(dT)\,(K_R)\,(K_f) \qquad \text{(A-4bis)}$$

where

Total strain = induced strain (millionths)

C_{th} = coefficient of thermal expansion

dT = temperature differential

K_R = structure restraint factor

K_f = foundation restraint factor

Cracking strain is computed by subtracting tensile strain capacity from the total strain. The remainder is the strain that must be accomodated in cracks at some spacing and width across the MCS.

(c) Estimate mass gradient cracking. Foundation conditions (restraint) control the spacing of cracks and the crack width. If the foundation is stiffer, tightly spaced cracks of small width can be expected. If the foundation is relatively soft (low restraint), widely spaced and wider cracks can be anticipated. Multiply the MSC length by the cracking strain to determine the total width of cracking to be accomodated in the MCS. Estimate a crack width based on foundation conditions and divide the total width of cracking by the assumed crack width to determine the total number of cracks.

e. *Conclusions and recommendations.* These typically include expected maximum temperatures for starting placement in different seasons, expected transverse and longitudinal cracking without temperature or other controls, recommended concrete placement temperature limitations, anticipated concrete precooling measures, need for adjustment in concrete properties, joint spacing, and sensitivity of the thermal analysis to changes in parameters.

A2-2. Example

a. *Introduction.* This example, based on a thermal study for the Cache Creek Detention Basin Weir, illustrates one way to estimate concrete placing temperature based on ambient air temperatures and material processing schemes and schedules. The study evaluates mass gradient cracking only. The Cache Creek Detention Basin in California is a roller-compacted concrete (RCC) overflow weir section in a levee system. The structure is 8 m (15 ft) high, 3.6 m (12 ft) wide at the top, has 0.8 to 1 slopes upstream and downstream, and is 530 m (1,740 ft) long. Compacted sands and silts were placed against the full height of the upstream face. The purpose of the study was to determine the adequacy of contraction joints spaced at 30-m (100-ft) intervals and, if necessary, provide recommendations for alternate configurations. Also addressed is the adequacy of a maximum placing temperature of 29 deg C (85 deg F) for the RCC. The following paragraphs provide explanation on the selection criteria and determination of the parameters used to summarize thermal study.

b. *Input properties and parameters.*

(1) Step 1: Determine ambient conditions. Data were provided from climatological data summaries for Woodland, CA, prepared by the National Oceanic and Atmospheric Administration (NOAA), shown in Table A2-1. The average annual temperature used was 16.1 deg (61 deg F), and monthly mean and average monthly maximum and minimum temperatures were used for other computations.

(2) Step 2: Determine material properties.

(a) Coefficient of thermal expansion. Coefficient of thermal expansion was estimated using handbook data (Fintel 1985) for the sandstone and

Table A2-1
NOAA Temperature Data, Woodland, CA

Month	Monthly avg. max. - deg C (deg F)	Monthly avg. min. - deg C (deg F)	Monthly avg. -deg C (deg F)
Jan	11.7 (53)	2.8 (37)	7.2 (45)
Feb	15.5 (60)	4.4 (40)	10.0 (50)
Mar	18.9 (66)	5.5 (42)	12.2 (54)
Apr	23.3 (74)	7.2 (45)	15.0 (59)
May	27.8 (82)	10.0 (50)	18.9 (66)
Jun	32.2 (90)	12.8 (55)	22.8 (73)
Jul	35.5 (96)	13.9 (57)	25.0 (77)
Aug	34.4 (94)	13.3 (56)	23.9 (75)
Sep	32.2 (90)	12.2 (54)	22.2 (72)
Oct	26.1 (79)	9.4 (49)	17.8 (64)
Nov	18.3 (65)	5.5 (42)	11.7 (53)
Dec	12.2 (54)	2.8 (37)	7.8 (46)
Annual	-	-	16.1 (61)

meta-sandstone aggregate concrete planned for the project:

C_{th} = 9.9 millionths/deg C (5.5 millionths/deg F)

(b) Adiabatic temperature rise. The study was performed using an RCC mixture with a Type I/II cement content of 119 kg/m^3 (200 lb/cy) and a Class F pozzolan content of 39 kg/m^3 (66 lb/cy). ACI 207.1R suggests that pozzolan can be assumed to have a heat generating capacity about one-half that of cement. Using ACI 207.1R adiabatic temperature rise curves and an equivalent cement content of 138 kg/m^3 (233 lb/cy), this mixture should produce an adiabatic temperature rise of about 22.2 deg C (40 deg F). From ACI 207.1R:

Δt_{ad} for 223 kg/m^3 (376 lb/cy) cement at 28 days = 36.1 deg C (65 deg F)

Δt_{ad} for 138 kg/m^3 (233 lb/cy) equiv. cement at 28 days = (36.1 deg C)(138)/(223) = 22.2 deg C (40 deg F)

(c) Tensile strain capacity. ACI 207.5R suggests that values of tensile strain capacity ranging from 50 to 200 millionths are achievable for early age, slow-load testing. Lean RCC mixes typically range from 60 to 90 millionths. Since the cement content of 119 kg/m^3 (200 lb/cy) is higher than most lean RCC mixes and the coarse aggregate is crushed, a value of 80 millionths was selected.

(3) Step 3: Determine construction parameters. RCC placing temperature was calculated using the average annual temperature modified by rule-of-thumb temperature effects during construction, as shown in Table A2-2. In Table A2-2, the placing temperature is the composite temperature of the aggregate source, (assumed to be the average annual temperature), plus the added heat during aggregate production, plus the added heat during RCC production. Stockpile aggregate temperatures are the base temperature, plus the ambient addition, plus crushing and production energy. Similarly, RCC production temperatures are the stockpile temperature plus ambient additions and mixer energy additions. The ambient temperature additions are calculated as 0.67, an empirical correction factor, times the differential temperature of the aggregates and the air. The complete thermal study is summarized in Table A2-3. A May placing temperature was used for following calculations:

T_p = 18.9 deg C (66 deg F)

c. Temperature analysis.

(1) Step 4: Mass gradient temperature analysis.

(a) Determine peak temperature. This is the sum of the initial RCC placement temperature and the adiabatic temperature rise:

$T_p + \Delta T_{ad}$ = 18.9 + 22.2 = 41.1 deg C (106 deg F)

(b) Determine ultimate stable temperature. Since the weir is a relatively thin MCS, it is expected to develop a stable temperature cycle, rather than a single stable temperature as in larger MCS's. The temperatures below were determined using the methodology in ACI 207.1R ("Temperature variation with depth"). Typical distance from the RCC surface to the interior was determined to be 4.6 m (15 ft). From ACI 207.1R figure:

$$\frac{\text{Temp change through concrete}}{\text{Temp range at surface}} = 0.24$$

Temp range at surface = 24.8 - 7.3 = 17.5 deg C (31.5 deg F)

Temp change in concrete interior = (0.24)(17.5 deg C) = 4.2 deg C (7.6 deg F)

Temp range in concrete interior = 16.2 ± 4.2 deg C (61.1 ± 7.6 deg F)

T_{min} = minimum interior concrete temp. = 16.2 - 4.2 = 12 deg C (53.5 deg F)

(c) Determine long-term temperature change. This value is simply the peak RCC placement temperature less the stable minimum temperature. Assuming a May placement:

$\Delta T = T_p + T_{ad} - T_{min}$ = 41.1-11.9 = 29.2 deg C (53 deg F)

d. *Cracking analysis.*

(1) Step 5: Mass gradient cracking analysis.

(a) Determine mass gradient restraint conditions. Geometric restraint is conservatively set at K_R=1.0, since the structure has a low profile. Foundation restraint is set at K_f= 0.65, since the base is not rock but rather compacted structural backfill.

$K_R = 1.0$ $K_f = 0.65$

(b) Determine mass gradient thermal strain. The total induced strain in the mass RCC is the product of the long-term temperature change, the coefficient of thermal expansion and restraint factors:

Total induced strain = $(C_{th})(\Delta T)(K_R)(K_f)$
= (9.9 millionths/deg C)(29.2 deg F)(1.0)(0.65)
= 189 millionths

(c) Estimate mass gradient cracking. The strain that results in cracking of the structure is the total induced strain less the tensile strain capacity (ϵ_{sc}) of the material. The total crack width in the length of the structure is the cracking strain multiplied by the length of the structure. The estimated number of cracks are based on the assumed crack widths. Typical crack widths range from 0.002 to 5 mm(0.01 to 0.2 in.). The larger crack widths are typical of structures founded on flexible or yielding foundations. Since such a foundation exists here, a typical crack width of 4 mm (0.15 in.) was assumed:

Cracking strain = total induced strain - ϵ_{sc}
= 189 - 80 = 109 millionths

Total crack width = (weir length)(cracking strain) = (530 m)(1,000 mm/m)(109 millionths) = 58 mm (2.3 in.)

Assumed crack widths = 4 mm (0.15 in.)

Estimated cracks = 58 mm/4 mm = 15 cracks

Estimated crack spacing = 530 m/15 cracks
= 35 m (116 ft)

Since contraction joints will be installed at 30-m (100-ft) spacing, additional cracking is not expected. Occasional center cracks can be expected where conditions and restraint factors vary from those assumed.

e. *Conclusions and recommendations*.

(1) Conclusions. Based on calculations similar to that shown above, on previous temperature analysis figures, and experience, the following conclusions were provided:

(a) May placement schedule. RCC placement temperatures should be 19.4 to 21.1 deg C (67 to

70 deg F) if aggregates are produced the preceding month. If aggregate processing is performed earlier, lower placement temperatures may result. Crack spacing in an unjointed structure is calculated to be 35 m (116 ft). The 30-m (100-ft) contraction joint interval easily accommodates this volume change with joint widths of approximately 3 mm (0.13 in.).

(b) June placement schedule. RCC placement temperatures should be 22.2 to 23.9 deg C (72 to 75 deg F) if aggregates are produced the preceding month. If aggregate processing is performed earlier, lower placement temperatures may result. Crack spacing in an unjointed structure is calculated to be 29 m (97 ft). The 30-m (100-ft) contraction joint interval just accommodates this volume change with joint widths of approximately 4 mm (0.15 in.).

(c) July and August placement schedules. RCC placement temperatures should be 23.9 to 26.7 deg C (75 to 80 deg F) if aggregates are produced the preceding month. If aggregate processing is performed earlier, lower placement temperatures may result. Crack spacing in an unjointed structure is calculated to be 26 m (87 ft). The 30-m (100-ft) contraction joint interval is not quite adequate to accommodate this volume change at a fixed joint width of 4 mm (0.15 in.). Joint widths will increase or additional cracking will occur.

(d) Since the anticipated period for RCC construction is during the late spring or summer months, the 29.4-deg C (85-deg F) placement temperature limitation specified could be a factor if unusually hot weather should occur. Under normal weather conditions, uncontrolled placing temperatures should range from 19.4 to 24.4 deg C (67 to 76 deg F) from May through August. In the event that abnormal weather causes average daily ambient temperature in excess of 29.4 deg C (85 deg F), RCC temperatures could exceed 29.4 deg C (85 deg F). Aggregate stockpile cooling and possible use of batch water chillers would be the most expedient solutions to this problem.

(e) The current joint spacing of 30 m (100 ft) is adequate for RCC placements during May and June. Later placements in July and August will result in occasional centerline cracking of monoliths, possibly in as many as three or four monoliths. Lesser cracking is very probable since material properties were conservatively estimated.

(f) Several material properties were applied conservatively. Small reductions of adiabatic temperature rise and coefficient of thermal expansion and small increases in tensile strain capacity could improve thermal cracking performance. If each of these properties were individually changed 10 percent, summer crack spacing would be around 30 m (100 ft). If these changes were cumulative, crack spacing would be over 40 m (130 ft).

(2) Recommendations.

(a) Maintain current 29.4-deg C (85-deg F) maximum placement temperature limitation. Consider allowing minor temperature violations so long as the time weighted average of the RCC placement temperature is maintained below 26.7 deg C (80 deg F).

(b) Maintain current contraction joint spacing of 30 m (100 ft). The current contraction joint configuration of 30-m (100-ft) joint intervals is sufficient to accommodate the total anticipated axial contractions due to cement induced temperature fluctuations during May and June placements. Some transverse cracking will occur during the July and August placement schedule, however the extent of cracking should not be of concern considering the upstream backfill and the frequency of use.

f. Field performance compared to predicted performance. During construction, RCC placement temperature was maintained at about 29.4 deg C (85 deg F), and transverse contraction joints were spaced at 30-m (100-ft) intervals. All the contraction joints opened properly during the first few months after construction, with no intermediate cracking. Crack widths varied from 1.5 to 6 mm (0.06 to 0.25 in.).

Table A2-2
Cache Creek Weir Placing Temperature Computation

	Temperature (deg C)				
Factor	May	Jun	Jul	Aug	Comments
Avg. annual temperature(deg C)	16.1	16.1	16.1	16.1	Base temperature, from NOAA data
Previous month temperature	15.0	18.9	22.6	24.8	From NOAA data
Added ambient temperature	-1.1	2.8	6.5	8.7	(0.67)(Annual temp. - prev. month temp.)
Aggregate subtotal temperature	15.4	18.0	20.5	21.9	Avg. annual temp. + added amb. temp.
Added processing temperature	+1.1	+1.1	+1.1	+1.1	Processing and crushing energy
Aggregate stockpile temperature	16.5	19.1	21.6	23.0	N/A
Current ambient temperature	18.9	22.6	24.8	23.9	From NOAA data
Added ambient temperature	+1.7	+2.3	+2.1	+0.6	(0.67)(Curr. Temp.-agg. stock. temp.)
Added mixer energy	+1.1	+1.1	+1.1	+1.1	N/A
Placement temperature	19.3	22.6	24.8	24.8	Agg. stockpile temp. + added effects
	Temperature (deg F)				
Avg. annual temperature (deg F)	61.1	61.1	61.1	61.1	Base temperature, from NOAA data
Previous month temperature	59.0	66.1	72.7	76.6	From NOAA data
Added ambient temperature	-1.4	3.3	7.8	10.4	(0.67)(Annual temp. - prev. month temp.)
Aggregate subtotal temperature	59.7	64.5	68.9	71.5	Avg. annual temp. + added amb. temp.
Added processing temperature	+2.0	+2.0	+2.0	+2.0	Processing and crushing energy
Aggregate stockpile temperature	61.7	66.5	70.9	73.5	N/A
Current ambient temperature	66.1	72.7	76.6	75.1	From NOAA data
Added ambient temperature	+3.0	+4.2	+3.8	+1.1	(0.67)(Curr. Temp.-Agg. Stock. Temp.)
Added mixer energy	+2.0	+2.0	+2.0	+2.0	N/A
Placement temperature	66.7	72.7	76.7	76.6	Agg. stockpile temp. + added effects

Table A2-3
Cache Creek Weir Thermal Analysis Summary

Temperature (deg C)			
Parameter	Spring (May)	Late Spring (Jun)	Summer (Jul-Aug)
Temperatures			
RCC placement temperature (deg C)	19.4	22.8	25.0
Adiabatic temperature rise (deg C)	22.2	22.2	22.2
Peak internal temperature (deg C) (Place temp. + adiabatic temp.)	41.7	45.0	47.2
Minimum temperature (deg C) (Based on annual temp. cycle)	12.2	12.2	12.2
Differential temperature (deg C) (Peak temp. - min. temp.)	29.4	32.8	35.0
Strain development			
Induced strain (millionths) (C_{th}=9.9 millionths/deg C, K_f=0.65, K_R=1.0)	189	211	225
Strain capacity (millionths)	80	80	80
Excess strain (millionths)	109	131	145
Crack distribution (length of weir = 530 m) (crack width = 4mm)			
Axis length contraction (mm)	51	76	76
Number of cracks (Contraction/crack width)	15	18	20
Avg. crack spacing (m) (Weir length/number of cracks)	35	29	26
Temperature (deg F)			
Temperatures			
RCC placement temperature (deg F)	67	73	77
Adiabatic temperature rise (deg F)	40	40	40
Peak internal temperature (deg F) (Place temp. + adiabatic temp.)	107	113	117
Minimum temperature (deg F) (Based on annual temp. cycle)	54	54	54
Differential temperature (deg F) (Peak temp. - min. temp.)	53	59	63
Strain development			
Induced strain (millionths) (C_{th}=5.5 millionths, K_f=0.65, K_R=1.0)	189	211	225
Strain capacity (millionths)	80	80	80
Excess strain (millionths)	109	131	145
Crack distribution (length of weir=1,740 ft.) (crack width=0.15 in.)			
Axis length contraction (in.)	2	3	3
Number of cracks (Contraction/crack width)	15	18	20
Avg. crack spacing (ft) (Weir length/number of cracks)	114	95	86