Journal of the National Academy of Forensic Engineers®

NATIONAL ACADEMY OF FORENSIC ENGINEERS

http://www.nafe.org
ISSN: 2379-3252

Vol. 32 No. 2 December 2015

Development of a Computer Model to Predict Curling of Poured Concrete Slabs on Grade

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Abstract

This paper addresses the causative factors associated with curling of concrete slabs poured on grade. The study was initiated when the owner of a newly constructed warehouse brought legal action against the designer/contractor for excessive concrete slab curling. Subsequent to settling with the owner, the designer/contractor brought legal action against the subcontractors who prepared the subgrade and placed the concrete. A computer model was developed by the defendant's expert to evaluate the effect selected parameters have on curling of the concrete slab on grade. The parametric study was used to evaluate the most probable causes of the curling, which led to settlement of the case.

Keywords

Forensic engineering, construction defect, curling of concrete slab on grade, foundation modulus, concrete shrinkage

Introduction

This case involves curling of a 7-inch unreinforced concrete slab on grade (SOG) at a newly constructed warehouse facility. Subsequent to settling with the owner of the warehouse for excessive slab curling, the designer/contractor proceeded to bring legal action against the subcontractors who prepared the subgrade and constructed the concrete slab.

The concrete subcontractor entered into a contract with the designer/contractor to form, place, and finish 388,000 square feet of 7-inch unreinforced SOG, excluding weather protection, concrete material, and concrete pumping. The designer/contractor was responsible for the concrete design mix and selection of the slab thickness and joint spacing. The slab covered an area 970 feet by 400 feet and was poured in sections as noted in **Figure 1A, 1B** and **1C**.

After placing the concrete slab, it was saw cut into 15-foot by 13-foot sections, providing control joints. Subsequent to the slab installation, the ends of the slab began to curl, resulting in voids between the subgrade and underside of the slab. Numerous elevation measurements were conducted with differential curling — ranging from approximately .25 inch up to 1 inch (see **Figure 2A** and **2B**). These differentials were detrimental to the equipment operating in the warehouse.

Factors Affecting Slab Curling

All SOG concrete slabs curl due to the inherent nature of concrete shrinkage during the curing process. It is noted that *"Evaporation of moisture from the upper surface of slabs is what causes drying shrinkage. Curling is caused by the difference in drying shrinkage between the top and bottom of the slab* [1,2,3]."

The primary factor associated with slab curling is the shrinkage gradient that develops through the slab thickness during the curing process. Placement of concrete on a dry subgrade provides two surfaces for excess water to be reduced, thus providing a lesser shrinkage gradient. Placement of concrete on a moist subgrade will increase the tendency of the slab to curl because the top surface will shrink more than the bottom, resulting in a slab with a concave shape. A similar condition will occur if the slab is poured on a vapor barrier.

Factors affecting shrinkage[1,2,3] are the water/cement ratio (higher water content results in greater shrinkage), temperature of concrete at discharge point, high concrete slump (higher slump indicates higher water content), excessive haul time in transit mixer, too long of a waiting period at the job site, too many revolutions at mixing speed, use of cement having relatively high shrinkage characteristics, use of aggregates with potential of high shrinkage, and use of additives that produce high

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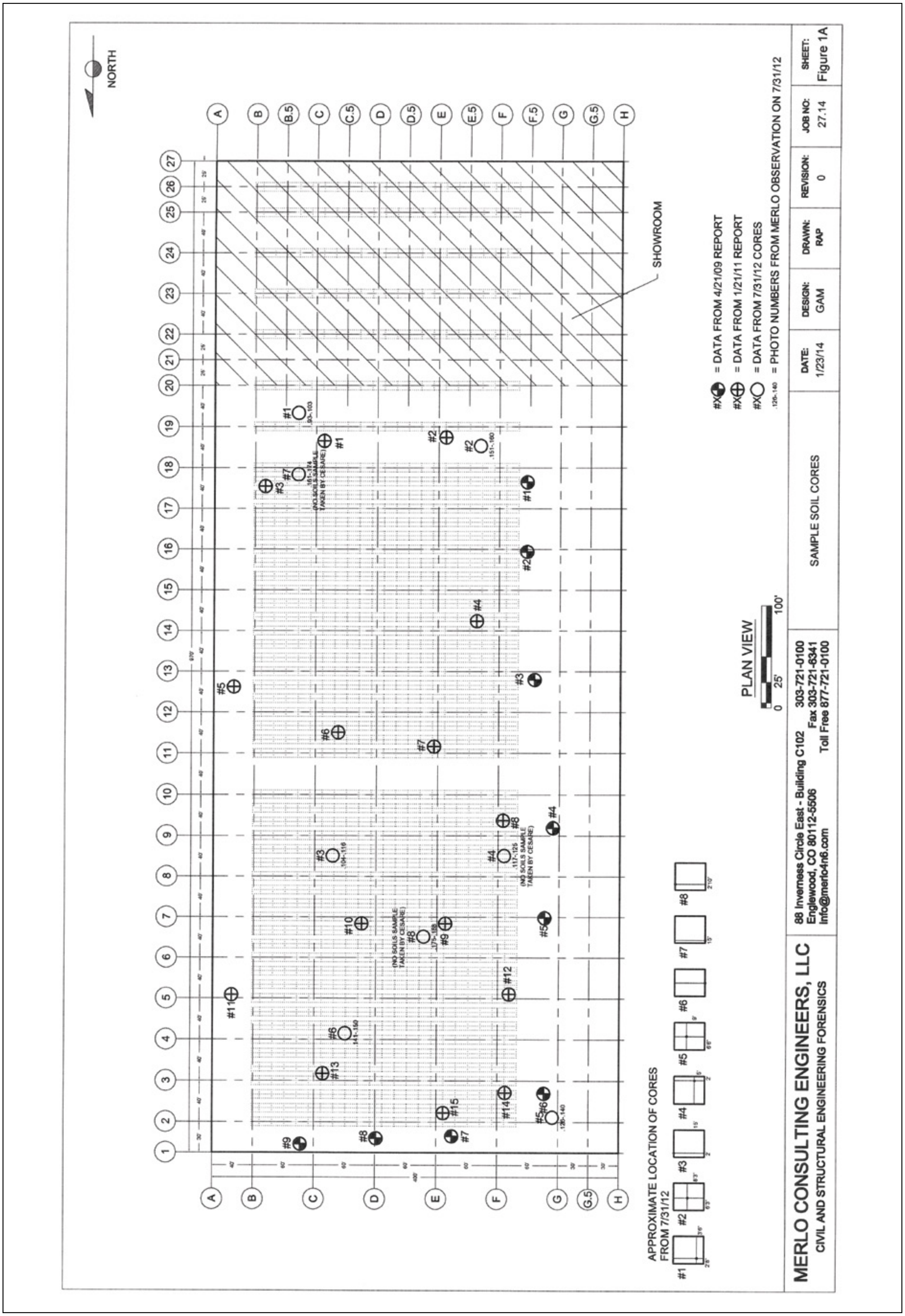

Figure 1A
Soil sample core locations.

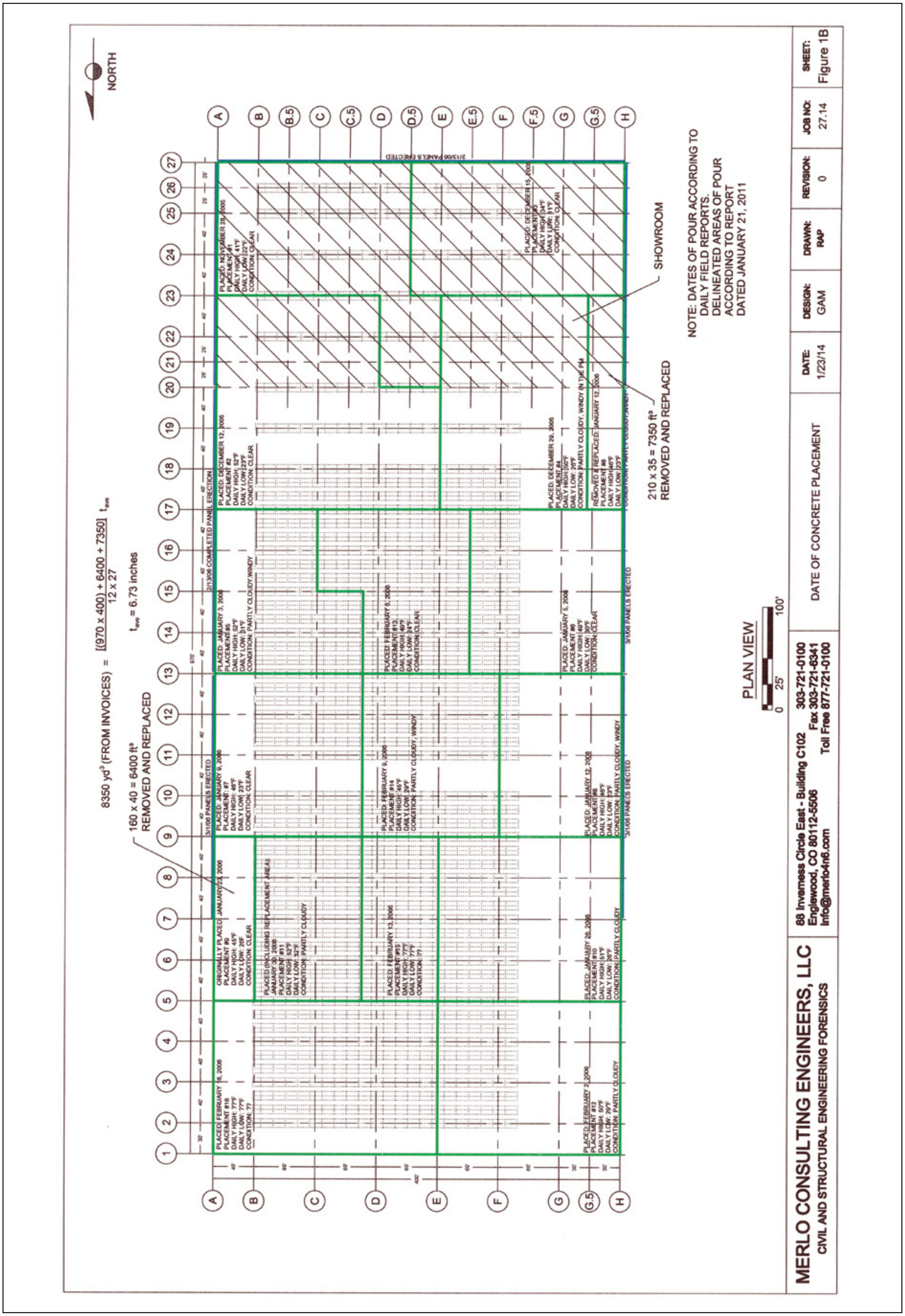

Figure 1B
Sequences of slab placement.

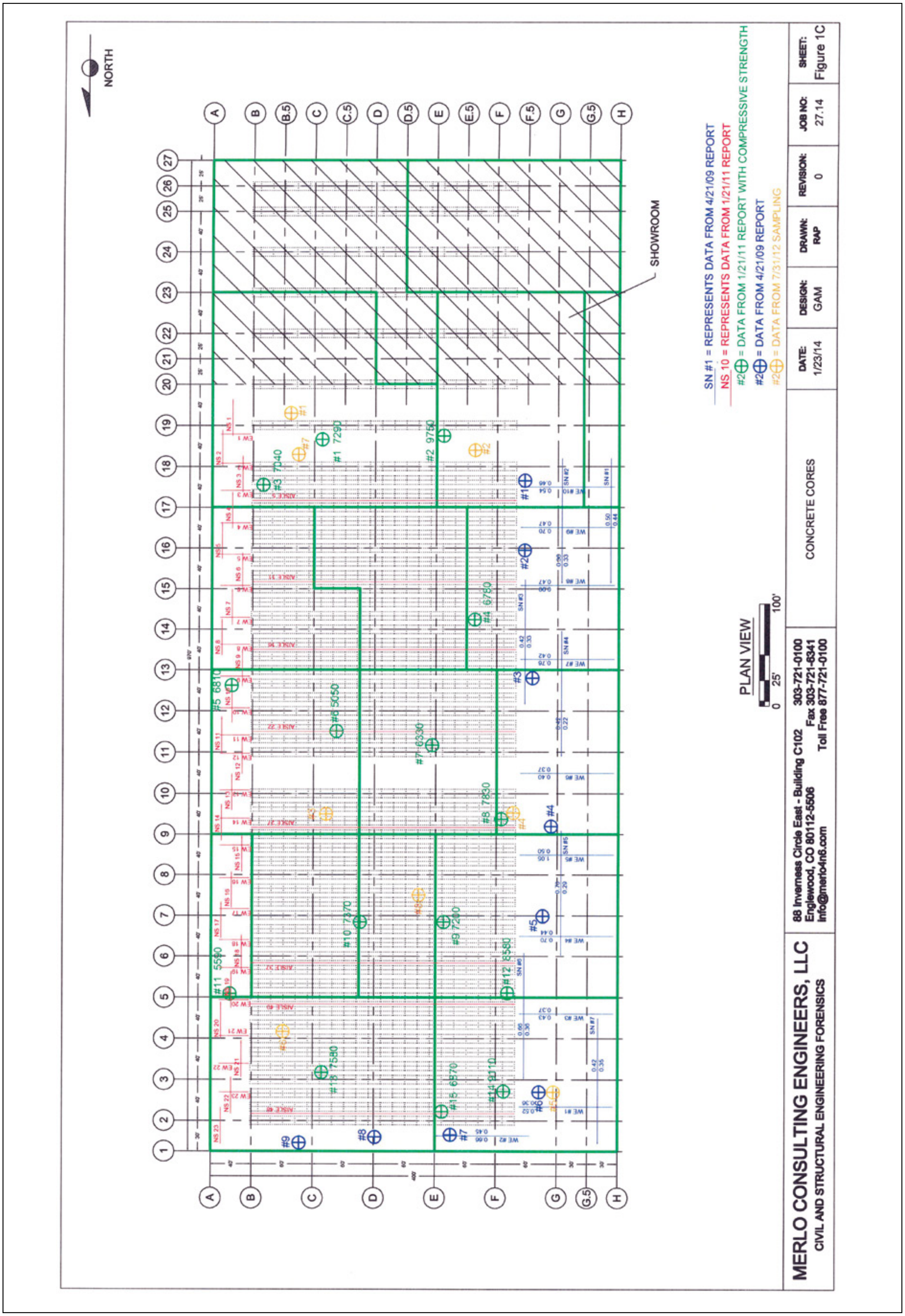

Figure 1C
Location of core samples.

Summary of Pour/Weather Data

Aisle Number	Location	Date Poured	Pour Area	Weather Data			Historical Data Period 7 Days after Pour					Elevation Differences		Estimated Concrete Shrinkage Gradient, in/in (subgrade 100pci)	
				High	Low	Condition	High	Low	High	Average	Gust	Max. Diff., inches	Average Diff., inches	Maximum	Average
5	B to E	12/12/05	#02	52 F	23 F	Clear	46 F	5 F	5 F	2 mph	11 mph	0.50	0.27	0.0007	0.00041
5	E to F.5	12/29/05	#04	50 F	26 F	Partly Cloudy, Windy in the pm	58 F	19 F	5 mph	2 mph	11 mph	0.30	0.27	0.00046	0.00041
11	A to C	1/3/06	#05	52 F	31 F	Partly Cloudy	63 F	21 F	16 mph	4 mph	27 mph	0.40	0.175	0.00058	0.00029
11	E5 to F.5	1/5/06	#06	49 F	30 F	Clear	49 F	20 F	23 mph	9 mph	37 mph	0.40	0.275	0.00058	0.00042
11	C to E.5	2/6/06	#13	49 F	24 F	Clear	60 F	22 F	25 mph	9 mph	36 mph	0.40	0.28	0.00058	0.00044
16	B to C.75	1/3/06	#05	52 F	31 F	Partly Cloudy,	63 F	21 F	16 mph	4 mph	27 mph	0.35	0.24	0.00052	0.00038
16	E.5 to F.5	1/5/06	#06	49 F	30 F	Clear	49 F	20 F	23 F	9 mph	37 mph	0.35	0.30	0.00052	0.00045
16	C.75 to E.5	2/6/06	#13	49 F	24 F	Clear	60 F	22 F	25 mph	9 mph	36 mph	0.35	0.25	0.00052	0.00039
22	B to C.75	1/9/06	#07	46 F	23 F	Clear	41 F	18 F	22 mph	10 mph	37 mph	0.40	0.36	0.00058	0.00053
22	F to F.5	1/12/06	#08	46 F	23 F	Partly Cloudy, Windy	39 F	27 F	11 mph	2 mph	18 mph	0.40	0.40	0.00058	0.00058
22	C.75 to F	2/9/06	#14	45 F	29 F	Partly Cloudy, Windy	58 F	21 F	8 mph	2 mph	14 mph	0.40	0.275	0.00058	0.00029
27	B to C.75	1/9/06	#07	46 F	23 F	Clear	41 F	18 F	22 mph	10 mph	37 mph	0.70	0.46	0.00094	0.00065
27	F to F.5	1/12/06	#08	46 F	23 F	Partly Cloudy, Windy	39 F	27 F	11 mph	2 mph	18 mph	0.40	0.40	0.00058	0.00058
27	C.75 to F	2/9/06	#14	45 F	29 F	Partly Cloudy, Windy	58 F	21 F	8 mph	2 mph	14 mph	0.50	0.37	0.0007	0.00054
37	E to F.5	1/26/06	#10	51 F	26 F	Partly Cloudy	53 F	24 F	19 mph	6 mph	41 mph	0.40	0.33	0.00058	0.00049
37	B to C.75	1/30/06	#11	52 F	32 F	Partly Cloudy	53 F	24 F	19 mph	6 mph	41 mph	0.70	0.36	0.00094	0.00053
37	C.75 to E	2/13/06	#15	?	?	?	?	?	?	?	?	0.40	0.24	0.00058	0.00038
40	E to F.5	2/2/06	#12	50 F	29 F	Partly Cloudy	58 F	15 F	7 mph	3 mph	16 mph	0.60	0.35	0.00083	0.00051
40	B to E	2/16/06	#16	?	?	?	?	?	?	?	?	0.30	0.25	0.00046	0.00039
48	E to F.5	2/2/06	#12	50 F	29 F	Partly Cloudy	58 F	15 F	7 mph	3 mph	16 mph	0.25	0.25	0.00039	0.00039
48	B to E	2/16/06	#16	?	?	?	?	?	?	?	?	0.60	0.34	0.00083	0.0005

Figure 2A
Weather conditions during slab placement.

Summary of Pour/Weather Data

Sample #	Location	Date Poured	Pour Area	Weather Data			Historical Data Period 7 Days after Pour					Elevation Difference		Estimated Concrete Shrinkage Gradient, in/in (subgrade 100pci)	
				High	Low	Condition	High	Low	High	Average	Gust	Maximum Difference,in.	Average Difference,in.	Maximum	Average
sn1	15 to 17 & G.5	1/5/06	#06	49 F	30 F	Clear	49 F	20 F	23 mph	9 mph	37 mph	0.50	0.44	0.00068	0.00061
sn1	17 to 17.5 & G.5	1/12/06	#08	46 F	23 F	Partly Cloudy Windy	39 F	27 F	11 mph	2 mph	18 mph	0.46	0.45	0.00064	0.00062
sn2	17 to 17.5 & G	12/29/05	#04	50 F	26F	Partly Cloudy Windy	58 F	19 F	5 mph	2 mph	11 mph	0.22	0.19	0.00032	0.00029
sn2	15 to 17 & G	1/5/06	#06	49 F	30 F	Clear	49 F	20 F	23 mph	9 mph	37 mph	0.36	0.33	0.00052	0.0005
sn3	13 to 15 & F.5	1/5/06	#06	49 F	30 F	Clear	49 F	20 F	23 mph	9 mph	37 mph	0.32	0.28	0.00046	0.00042
sn3	12 to 13 & F.5	1/12/06	#08	46 F	23 F	Partly Cloudy Windy	39 F	27 F	11 mph	2 mph	18 mph	0.42	0.33	0.00058	0.00048
sn4	13 to 14 & G	1/5/06	#06	49 F	30 F	Clear	49 F	20 F	23 mph	9 mph	37 mph				
sn4	11 to 13 & G	1/12/06	#08	46 F	23 F	Partly Cloudy Windy	39 F	27 F	11 mph	2 mph	18 mph	0.42	0.22	0.00058	0.00034
sn5	6 to 9 & G.5	1/26/06	#10	51 F	26 F	Partly Cloudy	53 F	24 F	19 mph	6 mph	41 mph	0.70	0.29	0.00092	0.00043
sn6	5 to 6 & F.5	1/26/06	#10	51 F	26 F	Partly Cloudy	53 F	24 F	19 mph	6 mph	41 mph				
sn6	3 to 5 & F.5	2/2/06	#12	50 F	29 F	Partly Cloudy	60 F	22 F	25 mph	9 mph	36 mph	0.66	0.36	0.00086	0.00052
sn7	1.5 to 4.5 & G.5	2/2/06	#12	50 F	29 F	Partly Cloudy	60 F	22 F	25 mph	9 mph	36 mph	0.42	0.35	0.00058	0.0005
we1	2/3 & F.5 to H	2/2/06	#12	50 F	29 F	Partly Cloudy	60 F	22 F	25 mph	9 mph	36 mph	0.52	0.36	0.0007	0.00052
we2	1/2 & E to F.5	2/2/06	#12	50 F	29 F	Partly Cloudy	60 F	22 F	25 mph	9 mph	36 mph	0.66	0.45	0.00086	0.00062
we3	4/5 & F.5 to H	2/2/06	#12	50 F	29 F	Partly Cloudy	60 F	22 F	25 mph	9 mph	36 mph	0.43	0.37	0.0006	0.00053
we4	6/7 & F.5 to H	1/26/06	#10	51 F	26 F	Partly Cloudy	53 F	24 F	19 mph	6 mph	41 mph	0.70	0.44	0.00092	0.00061
we5	8/9 & F.5 to H	1/26/06	#10	51 F	26 F	Partly Cloudy	53 F	24 F	19 mph	6 mph	41 mph	1.05	0.50	0.0013	0.00068
we6	11/12 & F.5 to H	1/12/06	#08	46 F	23 F	Partly Cloudy Windy	39 F	27 F	11 mph	2 mph	18 mph	0.40	0.37	0.00056	0.00053
we7	13/14 & F.5 to H	1/5/06	#06	49 F	30 F	Clear	49 F	20 F	23 mph	9 mph	37 mph	0.76	0.42	0.00097	0.00058
we8	15 & F.5 to H	1/5/06	#06	49 F	30 F	Clear	49 F	20 F	23 mph	9 mph	37 mph	0.90	0.47	0.0012	0.00065
we9	16/17 & F.5 to H	1/5/06	#06	49 F	30 F	Clear	49 F	20 F	23 mph	9 mph	37 mph	0.70	0.47	0.00092	0.00065
we10	17/18 & F.5 to G.5	12/29/05	#04	50 F	26F	Partly Cloudy Windy	58 F	19 F	5 mph	2 mph	11 mph	0.34	0.30	0.00048	0.00044
we10	17/18 & G.5 to H	1/12/06	#08	46 F	23 F	Partly Cloudy Windy	39 F	27 F	11 mph	2 mph	18 mph	0.54	0.46	0.00072	0.00064

Figure 2B
Weather conditions during slab placement.

shrinkage. None of these factors were under the control of the subcontractor responsible for forming, pouring, and finishing the slab. The designer/general contractor (plaintiff) was responsible for selecting the design mix, purchasing the concrete, and supervising the delivery and discharge of the concrete at the job site.

Counteracting the tendency for the edge of the slab to curl upward is the dead weight of the slab (slab thickness). Also affecting curling is the soil subgrade modulus *k* (coefficient of subgrade reaction), which can be defined as the ratio between the bearing pressure against the slab and deflection of the subgrade.

Typical units for *k* are pounds per cubic inch (pci) or psi per inch of deflection with values ranging on the order of 80 to 350 pci; the larger the *k* value, the stiffer the subgrade. Placement of a slab on a less-than-stiff subgrade will result in the curled slab "sinking" into the soil, reducing the net curling. On a stiffer subgrade, less area is required to support the dead weight of the slab, resulting in greater net curling.

Plaintiff Allegations

With the plaintiff being responsible for the factors adversely affecting concrete shrinkage, the allegations were directed at the subcontractors responsible for preparation of the subgrade and placing the concrete.

With respect to the concrete subcontractor, the allegation was directed at the slab thickness being less than specified. The allegation directed at the subcontractor responsible for the subgrade preparation and compaction was that the subgrade was prepared too stiff (450 pci vs. specified 150 pci). It should be noted that the project specifications did not require field testing of the subgrade, nor did they require measured finish slab elevations within 72 hours of completion of the pour.

Computer Model

In order to evaluate the effects slab thickness and subgrade modulus have on the net curling of the SOG, a computer model was developed using the commercially available finite element program STAAD.Pro (licensed by Bentley Architectural and Structural Software). This involved treating the SOG as a mat supported by springs representing the soil subgrade modulus. The springs were treated as compression springs — only with no resistance when subjected to uplift due to curling. The shrinkage gradient was represented by an equivalent temperature difference between the top and bottom of the slab.

In order to substantiate the validity of the model, it was first compared with the test results[4]. The test slab consisted of a 6-inch-thick concrete slab 24 feet by 13 feet with a modulus of elasticity of 3,000 ksi, subgrade modulus of 80 pci, and an equivalent shrinkage gradient of 30.5°F.

Results of the test indicated that the maximum curl at the edges was on the order of .10 inches above the original floor finish, with an unsupported length at the edge of 4 feet. Maximum deflection at the center of the slab was measured at -.02 inches. Results of the computer analysis indicated the maximum curl equaled .102 inches with an unsupported cantilever length of 4.25 feet and a maximum deflection in the middle of the slab equal to -.021 inches (see **Figure 3**). Therefore, it was concluded that the computer model was verified with the test results and could be used to analyze the SOG at the subject warehouse.

Effects of Slab Thickness and Soil Subgrade Modulus

The plaintiff alleged that the curling of the slab was the result of inadequate slab thickness and improper preparation of the subgrade. Specifications defined the slab thickness as being 7 inches founded on a subgrade modulus equal to 150 pci. The plaintiff concluded based on 31 core samples that the average slab thickness was 6.5 inches; this was less than the specified 7 inches (see **Figure 4**). Laboratory testing of the plaintiff's core samples resulted in a concrete modulus of elasticity equal to 5,000 ksi (see **Figure 5**), and the plaintiff's geotechnical expert concluded that the soil subgrade modulus equaled 450 pci.

A parametric analysis was conducted to evaluate the effects of varying the slab thickness and the soil subgrade modulus. With typical shrinkage strain for Portland cement of approximately .0004 to .0008 inches/inch, the finite element computer analysis was conducted to predict slab curling.

Using a shrinkage strain of .0006 inches/inch, and based on an evaluation of the elevation measurements (see **Figure 2A** and **2B**), the slab thickness and subgrade modulus were varied to evaluate the predicted curl. Results of the analysis, which are contained in **Figure 6A, 6B,** and **6C,** can be summarized as follows for a shrinkage strain of .0006 inches per inch (see **Figure 7**):

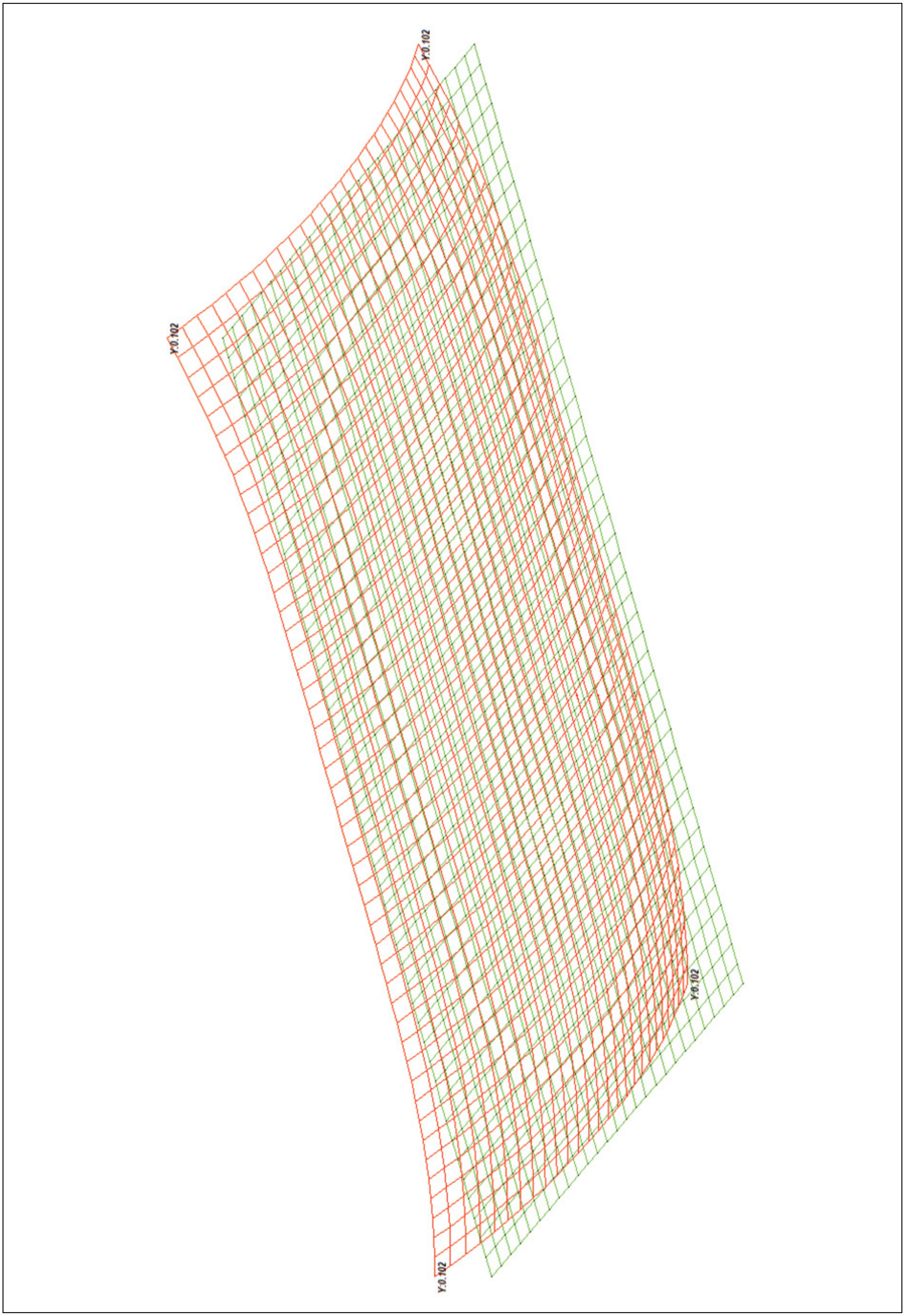

Figure 3
Computer model verification.

AVERAGE SLAB THICKNESS
MERLO CONSULTING ENGINEERS, LLC

File Name	STAT1			
File No.				
Date	August 1,2012	Jan. 21,2011 Data	1	5.125
		Jan. 21,2011 Data	2	5.000
		Jan. 21,2011 Data	3	5.875
		Jan. 21,2011 Data	4	7.750
		Jan. 21,2011 Data	5	8.500
		Jan. 21,2011 Data	6	6.500
		Jan. 21,2011 Data	7	7.000
		Jan. 21,2011 Data	8	5.375
		Jan. 21,2011 Data	9	7.000
		Jan. 21,2011 Data	10	6.000
		Jan. 21,2011 Data	11	6.500
		Jan. 21,2011 Data	12	6.000
		Jan. 21,2011 Data	13	6.000
		Jan. 21,2011 Data	14	6.500
		Jan. 21,2011 Data	15	6.750
		April 21,2009 Data	1	7.000
		April 21,2009 Data	2	7.000
		April 21,2009 Data	3	7.000
		April 21,2009 Data	4	7.000
		April 21,2009 Data	5	5.000
		April 21,2009 Data	7	6.500
		April 21,2009 Data	8	6.000
		April 21,2009 Data	9	6.500
		July 31, 2012 Measurements	1	6.500
		July 31, 2012 Measurements	2	7.000
		July 31, 2012 Measurements	3	7.000
		July 31, 2012 Measurements	4	6.375
		July 31, 2012 Measurements	5	6.500
		July 31, 2012 Measurements	6	6.625
		July 31, 2012 Measurements	7	7.000
		July 31, 2012 Measurements	8	6.625
			Average	**6.500**
			Standard Deviation	**0.75**
			68% fall within 6.5+/- .75 inches	

Figure 4
Measured slab thickness.

MERLO CONSULTING ENGINEERS LLC
File Name STAT
Title: Estimated Modulus of Elasticity
Date June 26,2012

Core Number	Compressive Strength,psi	Density,lbs/ft^3	Estimated Modulus Of Elasticity,psi
1	7290	150.7	5.21E+06
2	9750	148.6	5.90E+06
3	7040	148.4	5.01E+06
4	6780	146.2	4.80E+06
5	6810	146.2	4.81E+06
6	5050	147.9	4.22E+06
7	6330	147.4	4.70E+06
8	7830	146.7	5.19E+06
9	7200	148.4	5.06E+06
10	7370	149.0	5.15E+06
11	5590	148.5	4.46E+06
12	8580	150.9	5.67E+06
13	7580	147.5	5.15E+06
14	9110	150.5	5.82E+06
15	6870	146.1	4.83E+06
Average	**7279**	**148.2**	**5.07E+06**
Standard Deviation	**1224**	**1.60**	**5.E+05**

Figure 5
Core sample properties.

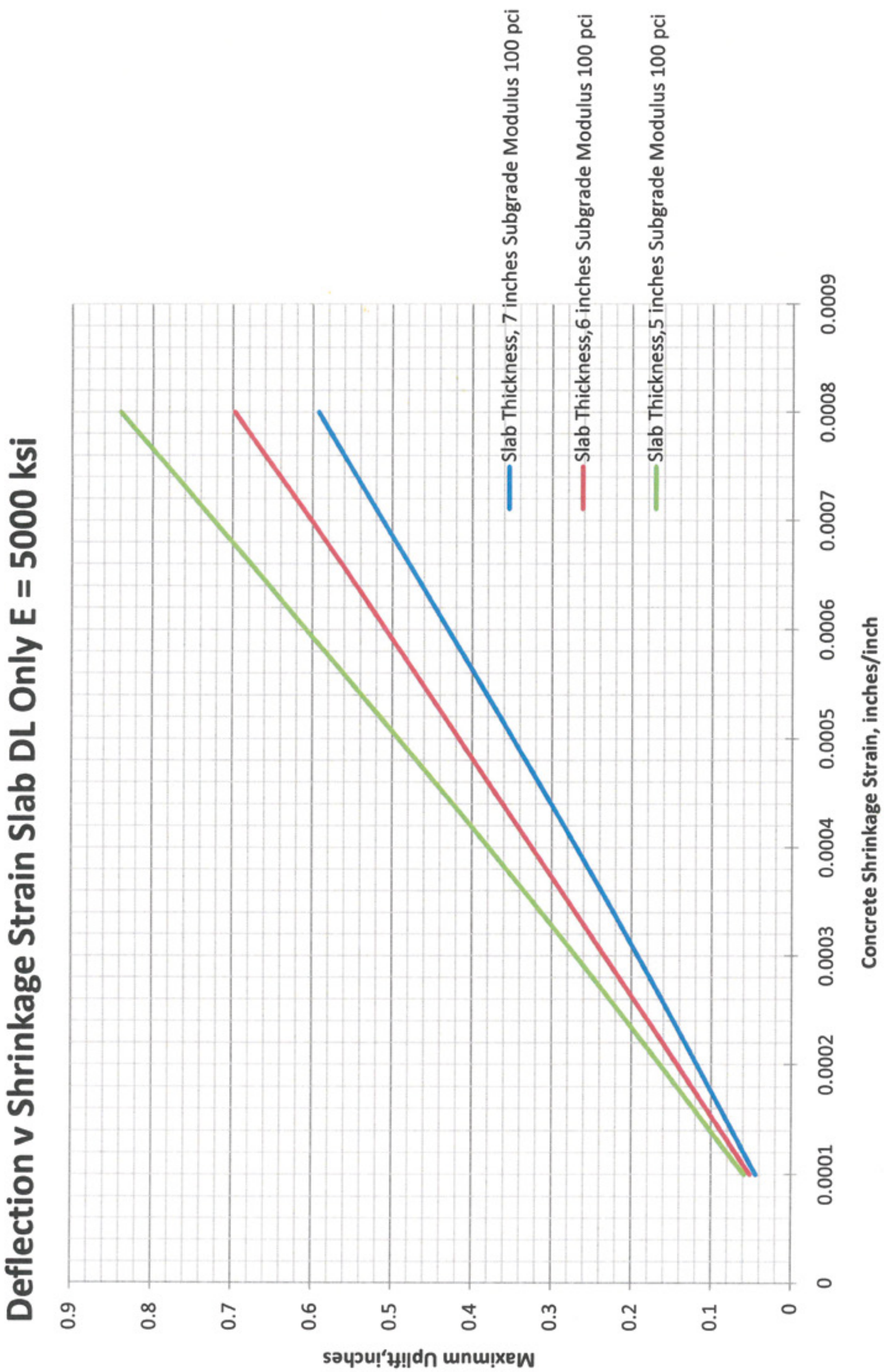

Figure 6A
Shrinkage strain vs. slab uplift for subgrade modulus 100 pci.

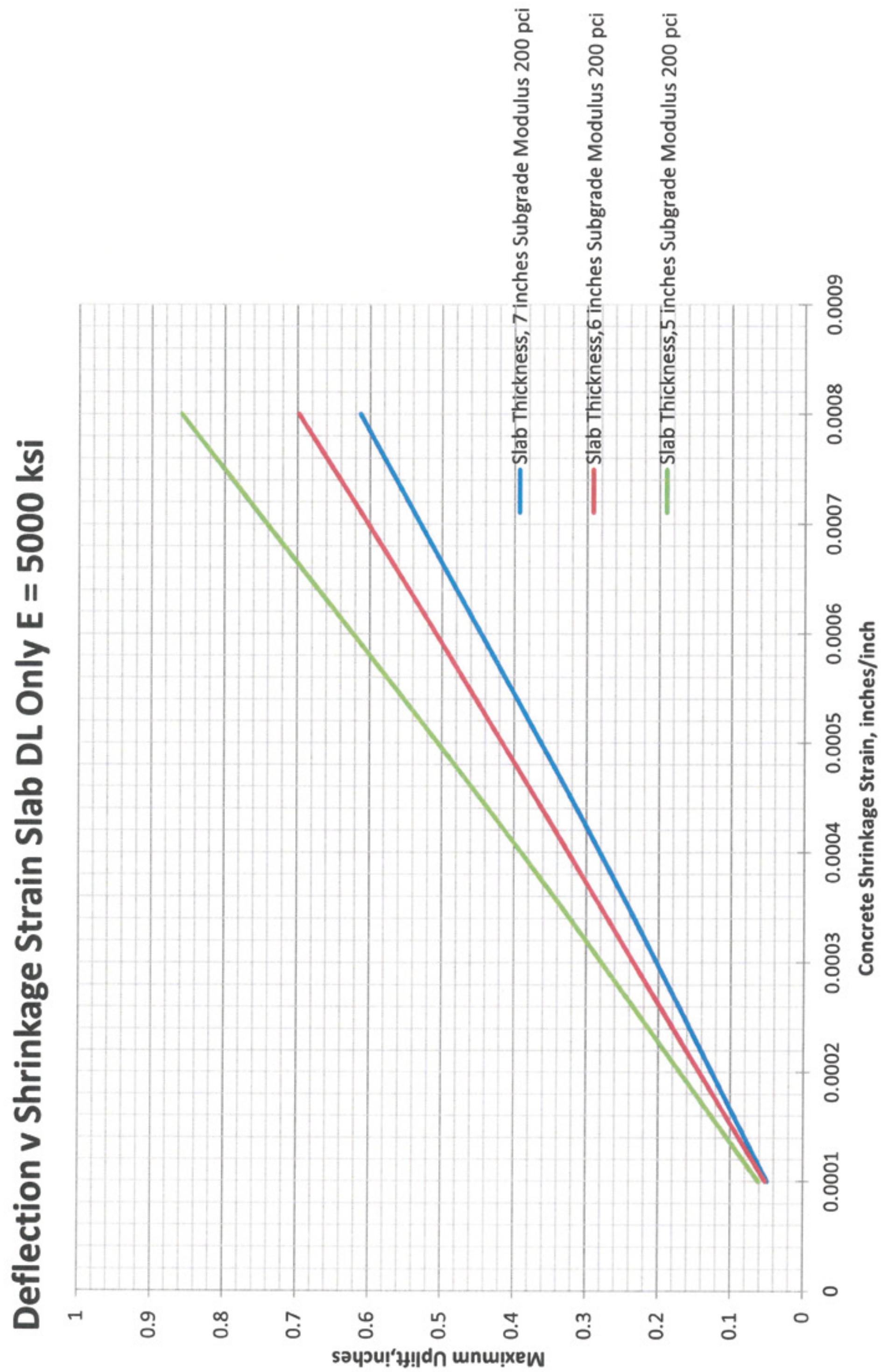

Figure 6B
Shrinkage strain vs. slab uplift for subgrade modulus 200 pci.

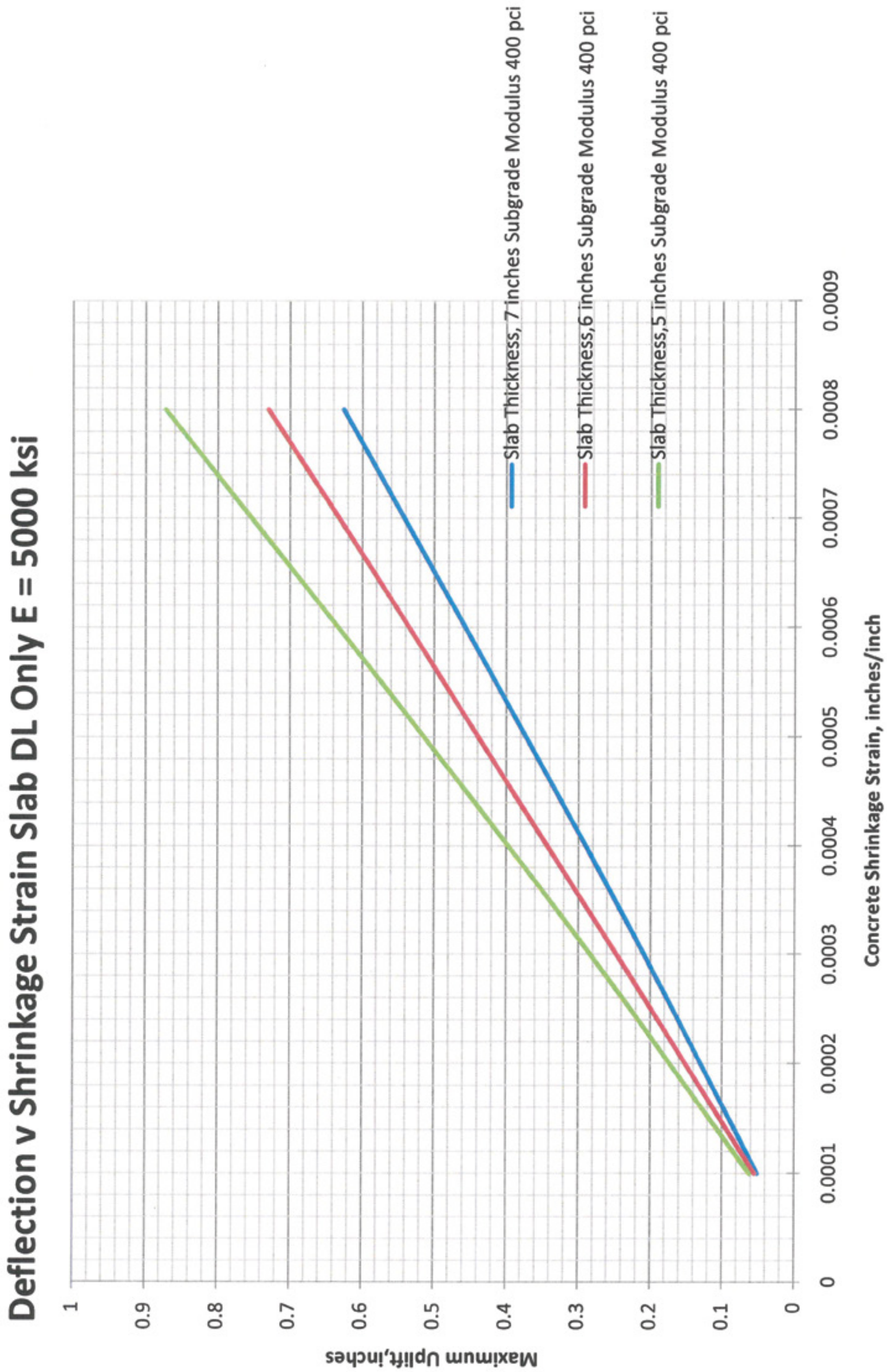

Figure 6C
Shrinkage strain vs. slab uplift for subgrade modulus 400 pci.

Subgrade Modulus, pci	Slab Thickness, inches	Maximum Curl, inches
100	7	.42
100	6	.51
100	5	.60
200	7	.44
200	6	.52
200	5	.62
400	7	.46
400	6	.54
400	5	.64

Figure 7
Shrinkage strain summarized.

As can be observed, the degree of curling is for all practical purposes independent of the subgrade modulus. However, the extent of the curling is to a minor degree dependent on the slab thickness. The plaintiff was asserting that the primary cause of the curling was attributable to the slab thickness measured as low as 5 inches in some locations (see **Figure 4**). The fallacy with this rationale is twofold.

First, the 5-inch cores do not represent the average thickness around the perimeter of the slab. It should be noted that the weight of the slab around the perimeter provides the dead weight, counteracting the effects of curl with lesser importance given to thicknesses toward the middle.

Secondly, no correlation exists between core thicknesses vs. slab curl based on the physical evidence. A comparison was made between core thicknesses and elevation differences. In several instances, areas with a 7-inch thickness exhibited greater than or equal curl as compared with areas of lesser thickness (see **Figure 1A, 1B,** and **1C**). For example, sample WE7 (with a 7-inch slab thickness) exhibited the same curl as sample WE4 with a thickness of 5 inches. The same can be stated with respect to aisle 27B to C.75 vs. aisle 27 C.75 to F.

It was the authors' opinion that the number of core samples taken were statistically inadequate to support the conclusion that slab thickness caused the curling. A review of the concrete delivery tickets indicated that a total of 8,350 cubic yards was delivered to the job site for the slab. It was calculated that the average thickness of the poured slab equaled 6.73 inches — approximately equal to the specified 7 inches.

With the slab thickness and subgrade modulus ruled out as causative factors, the cause of the slab curling remained unresolved. Clearly, the primary parameter affecting the degree of curling is the amount of shrinkage during the curing process. The subcontractor cured the concrete utilizing blankets furnished by the plaintiff. A comparison of the weather conditions vs. slab curl did not reveal any correlation (see **Figure 2A** and **2B**).

Only one factor remained as a possible consideration: the shrinkage characteristics of the mix itself. The designer/contractor should have conducted shrinkage tests of the design mix to ensure that the shrinkage was within allowable expectations. More important is the fact that the batch tickets contained evidence that calcium chloride was added to the approved mix at the request of the designer/contractor. With the slab being placed during periods of cold weather, calcium chloride was added to the mix to enhance curing and minimize freezing. The addition of the calcium chloride resulted in an increase in the heat of hydration and thus an increase in slab curling.

Conclusions

As a result of the authors' testing and analysis, the following opinions were presented:

1. Based on the range of parameters considered, neither slab thickness nor subgrade modulus were primary factors associated with the slab curling.

2. The primary cause of the curling can be attributed to one or both of the following: lack of proper evaluation of the design mix or the addition of calcium chloride to the design mix (both of which were under the control of the designer/contractor).

3. No allegations were made that the slab thickness and subgrade modulus adversely affected the structural integrity of the unreinforced slab. Repeated attempts requesting the design calculations (including the loads imparted by storage racks and warehouse equipment) proved unsuccessful.

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