FINAL TECHNICAL REPORT
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Project Title: **DEMONSTRATION OF CFB ASH AS A CEMENT SUSTITUTE IN CONCRETE PIER FOUNDATIONS FOR A PHOTO-VOLTAIC POWER SYSTEM AT SIUC**

ICCI Project Number: DEV03-6
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ABSTRACT

A large volume application for fly ashes in cement concrete applications has been demonstrated at Southern Illinois University. Using 23% F-fly ash and CFB fly ash in conventional concrete, 48 foundation piers for supporting a photo-voltaic array have been implemented. The fly ash cement concrete mix implemented has demonstrated strength properties that are comparable to that of conventional concrete. Synergy between F-fly ash and CFB fly ash is indicated for the achieved results that compare favorably to conventional concrete. Very low swelling has been measured for samples made from the implemented mix. This successful demonstration holds a significant promise for several other similar applications.

EXECUTIVE SUMMARY

In March 2004, Southern Illinois University at Carbondale's physical plant services office (PSO) contacted the principal investigator (PI) regarding the installation of photo-voltaic (PV) arrays as part of an Illinois Department of Commerce and Economic Opportunity grant. PSO desired implementation of these PV arrays on coal combustion byproduct (CCB) based foundation piers. Illinois Clean Coal Institute awarded this grant to develop a suitable mix for this application and demonstrate it in the said piers.

The PV project involved installing a 28.2 KW photovoltaic (solar electric) power system at the Carbondale campus. This photovoltaic system would contain 176 PV modules, supported on 48 foundation piers of 1-foot diameter. The piers were arranged in four rows of 12 piers each. The piers were installed 3-feet below-grade and two rows of piers each projected 2.5-feet and 1-foot above-grade.

Upon project initiation, three candidate mixes were identified based on past experience. The traditional approach to using fly ash as a cement substitute involves up to 25% replacement of cement with fly ash. However, this only represents 3-5% fly ash in the concrete mix. To increase the utilization of coal combustion products in concrete applications, the approach utilized here involved replacement of up to 64% fine aggregate in the concrete with CFB ash and F-ash from a cyclone boiler burning bituminous Illinois coal. This represents a total of 23% fly ash in concrete. The CFB ash used in this study was obtained from the SIU power plant, where this project is implemented. The F-ash was obtained from Southern Illinois Power Cooperative's Lake of Egypt power plant.

Samples were prepared in the laboratory for the three candidate mixes and an equivalent concrete mix (control mix). The selected mix contained 10% by weight of F-fly ash and 13% by weight of CFB fly ash. This mix significantly outperformed the conventional concrete control mix achieving a compressive strength of 5,155 psi compared to 2,437 psi after 28 days of curing. The corresponding splitting tensile strengths were 402 psi and 239 psi. It is to be noted however that the control mix contained 15% entrained air compared to 1.5% entrained air for the selected mix. Also, the selected mix registered a moderately low 3.3% swelling.

Approximately 10 yd^3 of the CCBs based concrete mix was prepared at the conventional ready-mix plant and transported to the implementation site where the 48 foundation piers were installed successfully in four phases over a period of 3 weeks. Sonotube forms for the piers were used during implementation. As a QA/QC procedure, 18-20 6-inch x 12-inch cylindrical samples were prepared side-by-side during the pier implementations. The 7 and 14-day strength results for these samples indicate that the samples far exceeded both the design and control mix compressive and tensile strengths. The inter-group variability for the four groups of piers was also fairly low. A small anomalous decline in strength after 28 days curing time was recorded for two sets of samples. This behavior is currently under investigation outside the scope of this report. Overall, the data indicates that the field implementation of the piers was very successful with the achieved strength values exceeding the design expectations.

INTRODUCTION AND BACKGROUND

In March 2004, Southern Illinois University at Carbondale's (SIUC) physical plant services office (PSO) contacted the principal investigators (PI) regarding the installation of photo-voltaic (PV) arrays as part of an Illinois Department of Commerce and Economic Opportunity (DCEO) grant. PSO desired implementation of these PV arrays on coal combustion byproduct (CCB) based foundation piers. The PI approached Illinois Clean Coal Institute (ICCI) and was awarded this project to develop a suitable mix for this application and demonstrate it in the said foundation piers.

The PV project involved installing a 28.2 KW photovoltaic (solar electric) power system at the Carbondale campus. This photovoltaic system would contain 176 PV modules, mounted on 22 racks of 8 modules each. The racks would be arranged in 2 rows of 11 each. Each row would be aligned along the east-west direction and the rows would be stacked in the north-south direction. Each rack would hold the modules so that their normals pointed due south and 30 degrees below vertical.

Each rack would have four feet and adjacent racks feet would share a cylindrical concrete foundation pier so that there would be a total of 48 piers in 4 rows of 12 each. The array would be installed on a hillside with an approximate 10 degree incline to the north. Due to the slope, the front (southern) row of piers on each sub-array would be taller above-grade than the back row. The back row above-grade height would be approximately 1-foot to avoid damage from mower blades. This set the front row piers at an above-grade height of approximately 2.5 feet. Estimating a worst-case frost depth of 2 feet, each pier would be installed to 3 feet below grade. This made the front row piers 5.5-feet tall and the back row piers 4-feet tall. Each pier would be formed using sonotubes to have a 1-foot diameter for upper surface area requirements. Thus the total volume of concrete required would be approximately 4.3 ft^3 (0.16 yd^3) per front pier and 3.1 ft^3 (0.12 yd^3) per back pier. The total volume of concrete for 48 piers would be 179 ft^3 (6.63 yd^3). Each pier would be reinforced with an internal steel rebar cage.

The attached drawings show the east elevation of the concrete pier foundations and side and rear elevations of the PV array racks (Figure 1 - a, b, c). The pier elevation shows only one of each type of pier; there would be a total of 24 of each type.

EXPERIMENTAL PROCEDURES

During the mix design phase of this project, the concrete mix was prepared in an electrically driven counter-current pan mixer of 0.6 ft^3 capacity. The coarse aggregate was added to the mixer along with about 30% of the total required water. This was followed by addition of fine aggregate, circulating fluidized bed (CFB) fly ash, 30% of the required water, F-fly ash, another 30% of the required water and cement in that order. This was followed by addition of the aeration chemical diluted with 10% of the total required water. The aeration agent as well as all the water was added slowly to ensure uniform distribution of these in the mix. After about 5 minutes of mixing time, a sample of the mix was extracted and tested for slump. If the slump was less than 4-5 inches, additional water was added till this desired slump was achieved. Subsequently, measurements of entrained air were made in an aeration meter. The CFB ash used in these experiments was pre-hydrated using 25% water by weight. From each batch of mix, nine 4 x 8-inch cylindrical samples were prepared in plastic molds, coated with 10W30 motor oil to facilitate demolding, using three lifts and using the standard rodding procedure. The prepared samples were leveled at the top and covered with lids to prevent drying at the surface. After 24 hours, the samples were demolded and put under water for curing. The water temperature was maintained constant at 70^{o}F.

Eighteen samples of each mix including the control mix were prepared in 8 batches of mixes. The dimensions of a few samples from each batch were accurately measured using a vernier caliper immediately following their demolding after 24 hours. After the appropriate curing time had passed, samples were tested for compressive and split tensile strength with 3 and 2 repetitions respectively. After each test curing period, the dimensions of the measured samples were recorded to calculate the volumetric swelling. The strength testing was conducted on an M&L testing machine with a maximum capacity of 450,000 lbs.

Prior to the full scale field implementation, one trial pier was poured at the site using a laboratory concrete mixer. During the implementation phase of the piers, measured amounts of pre-hydrated CFB ash and F-ash was delivered to Illini ready mix plant. The ashes were loaded in a concrete truck and other ingredients were added on top along with the aeration agent. Sufficient water was added to the mix to achieve a slump value of approximately 2-inches. The super plasticizer and additional water was added on site to achieve a slump of 4-5 inches just before pouring the mix in the sonotube forms. During implementation, the slump of the mix had a tendency to reduce with time. This is possibly a result of further hydration of CFB ash as well as the reduced effectiveness of the super plasticizer with time. Hence, small amounts of additional water were added as and when required to maintain a slump between 4 and 5 inches. This implementation was conducted in four phases of 12 foundation piers in each phase. In the last phase additional four piers were poured for test purposes. Two of these piers will support a sign describing the project. The other two piers will be used for destructive testing after 180 days of curing time as indicated in the proposal. Though it was not a part of the scope of work in this project, freeze-thaw testing on beam samples has also been initiated. The PI will report the results from these tests to ICCI project management at a later date.

As a field QA/QC procedure, 18-20 6-inch by 12-inch cylindrical samples were prepared during each of the four phases of implementation. The samples were demolded after 24 hours and cured under water prior to compressive and indirect tensile testing after 7, 14 and 28 days of curing time.

RESULTS AND DISCUSSION

This project was initiated on March 1, 2004. Upon project initiation, the project team identified three candidate mixes based on past experience in this area. The traditional approach to using fly ash as a cement substitute involves up to 25% replacement of cement with fly ash. However, this only represents 3-5% fly ash in the concrete mix. To increase the utilization of coal combustion products in concrete applications, the approach utilized here involved replacement of up to 64% fine aggregate in the concrete with CFB ash and F-ash from a cyclone boiler burning bituminous Illinois coal. This represents a total of 23% fly ash in concrete. The CFB ash used in this study was obtained from the SIU power plant, where this project is implemented. The F-ash was obtained from Southern Illinois Power Cooperative's (SIPC) Lake of Egypt power plant.

Samples were prepared in the laboratory for the three candidate mixes and an equivalent concrete mix (control mix). The mix compositions are shown in Table 1. The details of sample preparation are provided in Table 2.

Table 1. Proposed mixes for SIU's PV-array foundation piers.

Mix	Cement (%)	Fine Aggregate (%)			Coarse Aggregate (%)	Total (%)	Fine Aggregate Replacement (%)
		Sand	F-Ash	CFB Ash			
Control	16	36	-	-	48	100	-
Mix 1	16	24	-	12	48	100	33
Mix 2	16	13	10	13	48	100	64
Mix 3	16	14	-	22	48	100	64

Table 2. Laboratory sample preparation for mix selection.

Mix	Volume (ft^3)	Plasti-cizer (gm)	Slump (inches)	Water/ Cement Ratio	Entrain-ment Agent (gm)	Air Entrain-ment (%)
Control - Batch 1	0.6	-	5	0.44	7.56	15
Control - Batch 2	0.6	-	5	0.43	7.56	14
Mix 1- Batch 1	0.6	-	4	0.64	7.56	1.7
Mix 1- Batch 2	0.6	-	5	0.64	7.56	1.0
Mix 2 - Batch 1	0.6	-	4.5	0.73	9.46	1.6
Mix 2 - Batch 2	0.6	-	4.5	0.73	9.46	1.25
Mix 3 - Batch 1	0.6	-	4.5	0.66	9.46	1.2
Mix 3 - Batch 2	0.6	-	5	0.68	9.46	1.3

These samples were tested for 7 and 14 day strengths and were also monitored for swelling, which can be a concern while using CFB ash in such applications. At the end of 7 days of curing, Mix 1 and Mix 2 exhibited higher compressive strength (1613 psi and 1186 psi) than conventional concrete control mix (987 psi). Mix 1 was characterized by 12% CFB ash in the mix while Mix 2 had 13% CFB ash and 10% F-ash in the mix. Interestingly, at the end of 14 days of curing, the control mix gained strength faster than Mix 1 reaching about the same strength at 1700 psi. Mix 2 however registered an even larger strength gain reaching 1900 psi at the end of 14 days. This behavior is explained by the presence of F-ash in Mix 2 which is known to add long term strength.

Based on the 14-day results available at that time, Mix 2 was selected for implementation. The 28-day strength data on the laboratory samples validated the selection of Mix 2 for implementation. After 28 days of curing, Mix 1 and the control mix gained strength at the same rate reaching a compressive strength of 2500 psi. Mix 2, which was the selected mix, registered a drastic gain in compressive strength reaching 5155 psi. In order to compare the strengths of the control mix with the other mixes, it must be noted that the control mix achieved a very high level of air entrainment (15%), whereas, the other mixes had only 1.5% air. An acceptably low 28-day swelling of 3.3% was measured for the selected mix. The summary laboratory mix design results are presented in Table 3.

After appropriate field work was conducted by SIU physical plant, 2.5-4.5 yd^3 of the selected mix was prepared with the cooperation of Illini Ready Mix Inc., Carbondale, for each of the four phases of implementation.

As a field QA/QC procedure, 18-20 6-inch by 12-inch cylindrical samples were also prepared during each of the four phases of implementation. The 7-day and 14-day strength results for the field implementation samples indicate that these samples far exceeded both the design and control mix compressive strengths both after 7 and 14 days of curing. The tensile strength of the field implementation samples was also higher than that for the design and control mix after 7 and 14 days of curing. The inter-group variability for the four groups of piers was also fairly low. The average 7-day compressive and tensile strength for the field implementation samples was 1793 psi and 176 psi. This compares with 987 and 169 and 1186 and 163 psi for the compressive and tensile strengths for the control and design mixes respectively. The average 14-day compressive and tensile strength for the field implementation samples was 2859 psi and 273 psi. This compares with 1622 and 215 and 1891 and 257 psi for the compressive and tensile strengths for the control and design mixes respectively.

The compressive strength results after 28 days of curing present a few anomalies. On an average the 28-day strength of the QA/QC samples exceeded the compressive strength of the laboratory control mix but not of the laboratory designed mix. Note that the QA/QC samples had achieved strength which was significantly higher than the control or the designed mix after 7 and 14 days of curing. The most significant anomaly that appeared is the decline in strength after 28 days of strength compared to the strength after 14-days of curing time. This was observed in particular for the Phase 3 and Phase 4 samples.

Table 3. Summary results from laboratory testing of deigned mixes. (Reported compression data is an average of 3 samples and split tension data is an average of 2 samples.)

Sample	7-day			14-day			28-day			
	Comp-ressive Strength (psi)	Elastic Modulus (psi)	Split Tensile Strength (psi)	Comp-ressive Strength (psi)	Elastic Modulus (psi)	Split Tensile Strength (psi)	Comp-ressive Strength (psi)	Elastic Modulus (psi)	Split Tensile Strength (psi)	Swelling (%)
Control	1096	184,663	168.6	1622	359,048	214.6	2437	-	239.3	0.50
Mix 1	1613	254,708	159.6	1774	294,615	239.9	2505	-	244.1	3.16
Mix 2	1186	159,946	162.7	1891	242,307	257.2	5155	-	402.4	3.30
Mix 3	1096	109,123	124.2	1576	198,071	152.1	1350	-	136.0	2.15

Swelling is offered as a possible explanation for this behavior. However it is unclear why this was an issue for only the Phase 3 and 4 samples. There is a possibility that the excess water used during these to phases to maintain better workability of the mix might have a role to play. The investigators are trying to research this issue further outside the scope of this report. Samples have been set aside for conducting strength measurements after 180 days of curing to ensure the integrity of the implemented piers. The compiled test data for the field QA/QC samples is presented in Table 4.

Table 4. Field implementation sample results.

Sample Set	7-day		14-day		28-day	
	Comp-ression (psi)	Split Tension (psi)	Comp-ression (psi)	Split Tension (psi)	Comp-ression (psi)	Split Tension (psi)
Control	987	169	1622	215	2437	239
Design	1186	163	1891	257	5155	402
Phase 1	1525	129	-	-	3086	283
Phase 2	1902	140	2406	292	2814	358
Phase 3	-	-	3012	217	2335	221
Phase 4	1952	258	3158	311	2486	416

The laboratory counter-current pan mixer used in sample preparation is shown in Figure 2. The prepared samples in molds are shown in Figure 3. A picture of tested samples is shown in Figure 4. Figure 5-9 show the various steps involved in implementation of these piers with the deployed PV array on the CCBs based concrete foundation piers shown in Figure 10.

Though it not a part of the scope of work in this project, freeze-thaw testing on beam samples has also been initiated. The PI will inform ICCI project management the results from these tests.

CONCLUSIONS AND RECOMMENDATIONS

All the available data indicates that the field implementation of the piers was very successful with the achieved strength values exceeding the design expectations.

There are however a few unanswered questions that need to be addressed in a follow-up study. These questions include long-term durability characteristics, swelling and shrinkage characteristics, abrasion resistance, adhesion characteristics and color of the resultant mix.

ACKNOWLEDGEMENT

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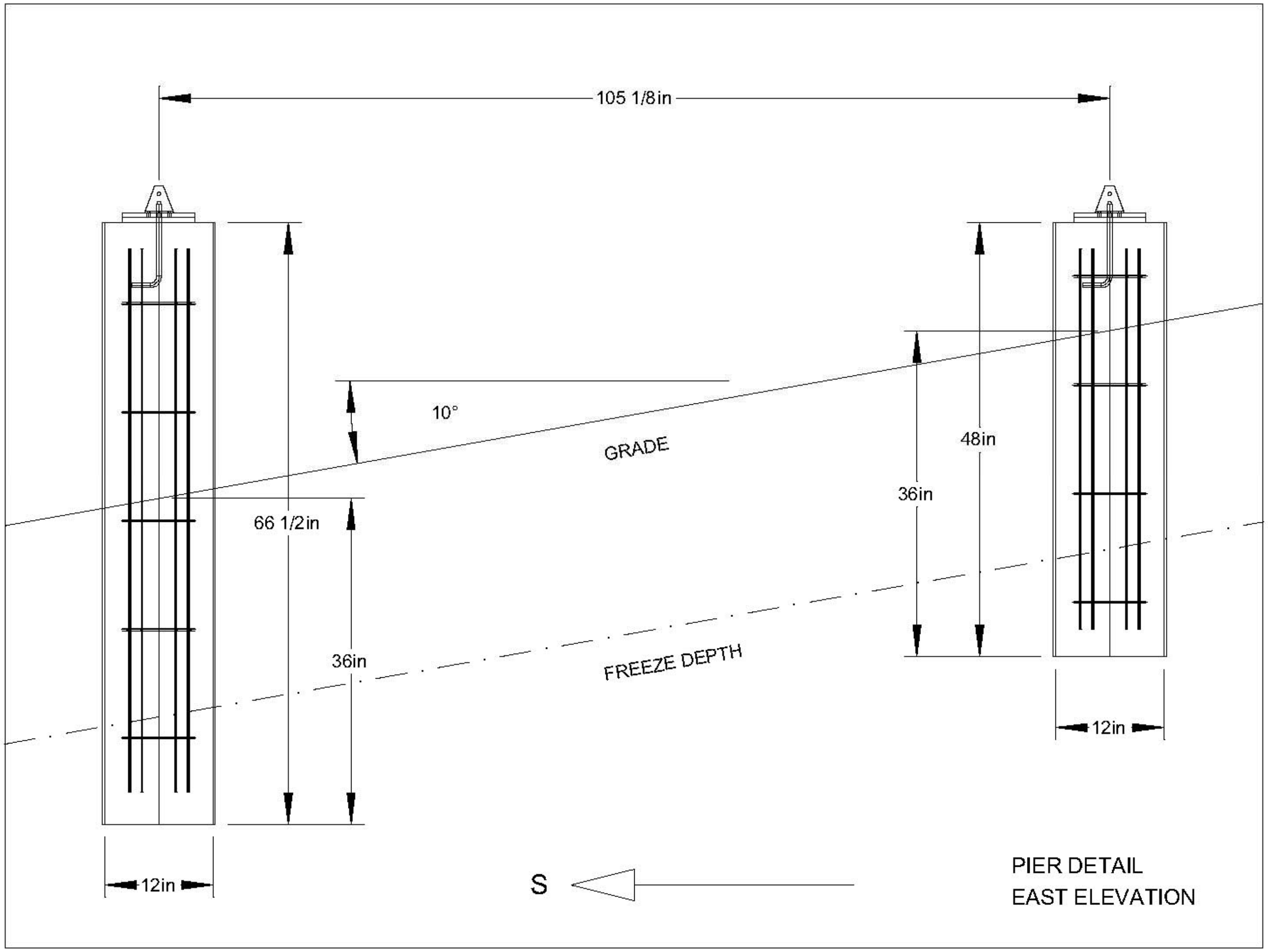

Figure 1 (a) East elevation of PV-array foundation piers.

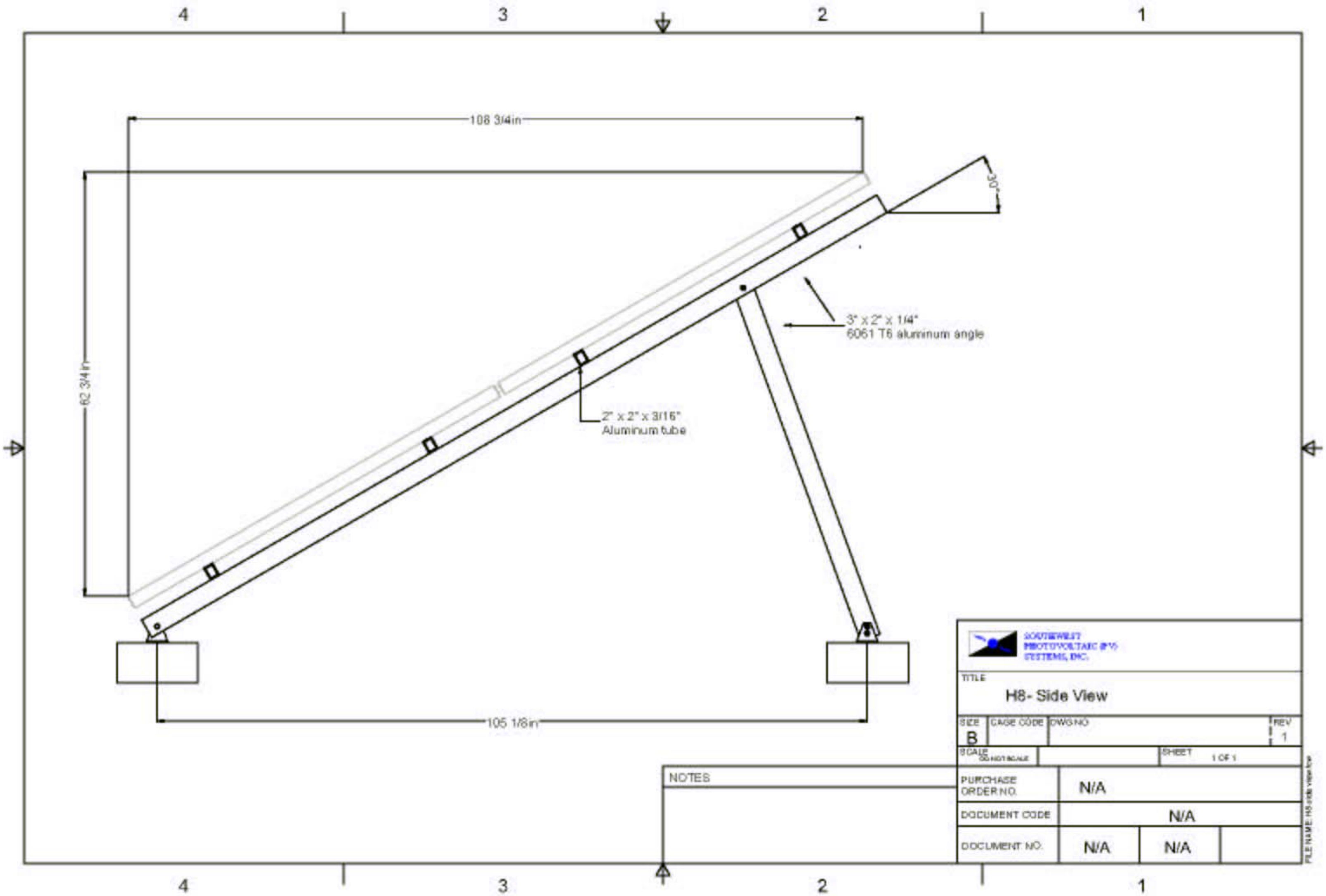

Figure 1 (b) Side view of PV-array foundation piers.

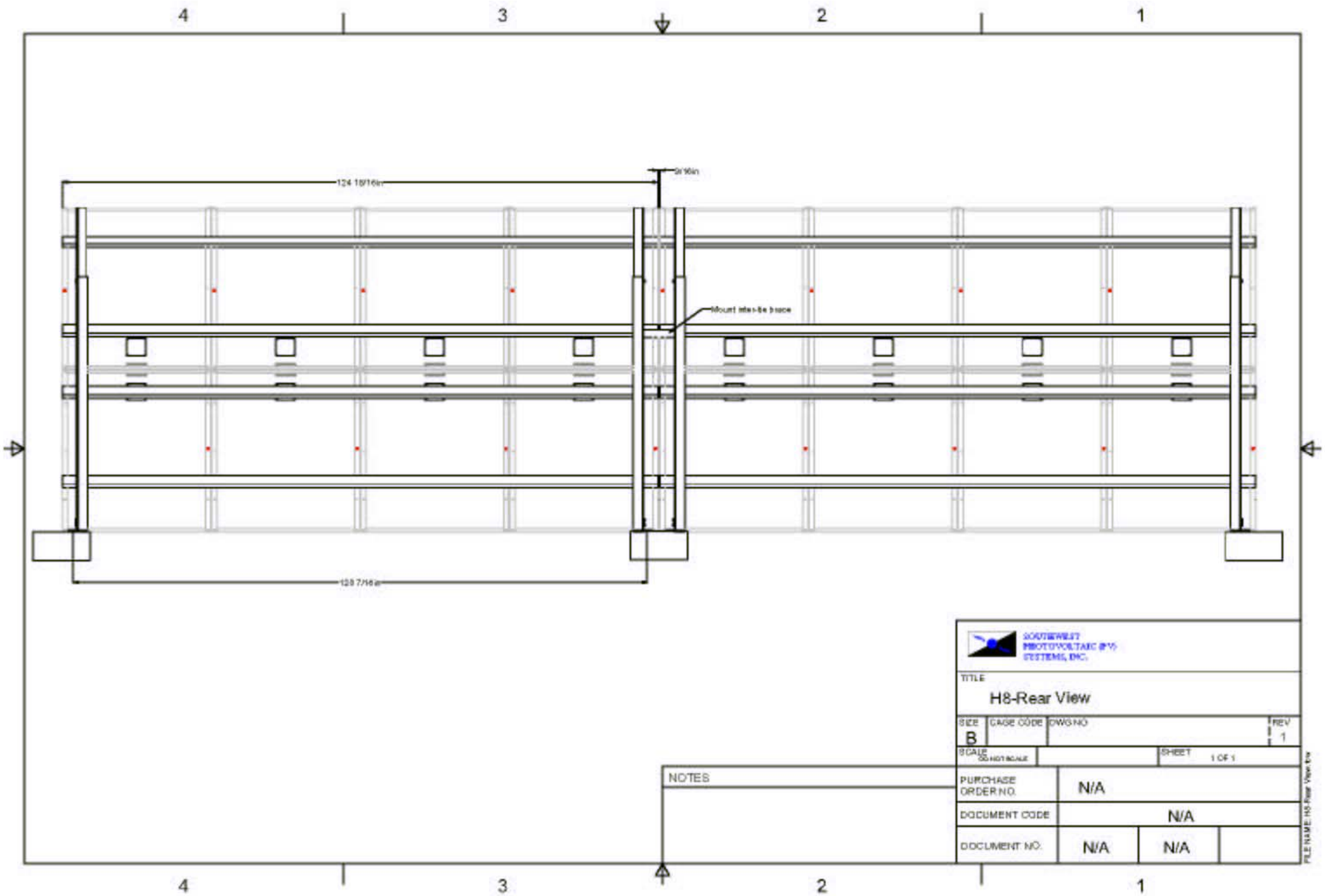

Figure 1 (c) Rear view of PV-array foundation piers.

Figure 2. Counter-current pan mixer used for laboratory sample preparation.

Figure 3. 4-inch x 8-inch laboratory samples in molds.

Figure 4. 6-inch x 12-inch laboratory samples tested for compressive strength and indirect tensile strength.

Figure 5. CCBs based foundation pier being poured.

Figure 6. CCBs based foundation pier being poured with the steel rebar ready for insertion.

Figure 7. CCBs based foundation pier being finished after being poured.

Figure 8. A row of twelve CCBs based foundation piers a few days after implementation. Forms for the second row of piers are ready and visible in the background.

Figure 9. CCBs based foundation pier after 7-days curing time. Anchor bolt is visible on top.

Figure 10. Photo-voltaic array deployment on CCBs based concrete foundation piers.