Heavily Reinforced Shearwalls and Mass Foundations Built with "Green" Concrete

BY DUSHYANT MANMOHAN AND P. KUMAR MEHTA

Fig. 1 (left): Barker Hall, a six-story, 40-year-old concrete building on the campus of the University of California at Berkeley.
Fig. 2 (below): Heavy congestion of reinforcing steel, post-tensioning ducts, and vertical compression rods in a foundation corner for the seismic retrofit of Barker Hall

The seismic retrofit of Barker Hall (Fig. 1), a six-story, 40-year-old concrete building on the University of California Campus in Berkeley, required the construction of a concrete belt foundation that is 11 ft deep by 6 ft wide (3.4 m x 1.8 m), with bonded post-tensioned (PT) tendons at the top and bottom. The four corners of the foundation were enlarged to about 8 ft (2.4 m) wide to accommodate tensioning of the tendons in three directions. The belt foundation supports the new exterior shearwalls and collector beams that strengthen the structure. The shearwalls, which are about 19-in. (480 mm) thick, are heavily reinforced and serve as the exposed facade of the building. Figure 2 shows the heavy congestion of reinforcing steel, PT ducts, vertical compression rods, and associated hardware in the foundation corner, and the unusually heavy congestion of reinforcement in the shearwalls.

With a strong commitment to promote "green" concrete for building construction, the structural designer mandated the use of high-volume fly ash (HVFA) concrete, which requires at least 50% cement replacement with fly ash by mass. Originally developed in the 1980s by Malhotra and his associates[1-3] for the construction of massive concrete structures requiring low heat of hydration, HVFA concrete is increasingly being accepted as a construction material for conventional structural applications. Its increased acceptability is due to several factors, including: better workability and superior durability of concrete, lower material cost, and a much-reduced environmental impact. HVFA concrete decreases environmental impact by using less cement, thus consuming less energy and releasing fewer greenhouse-gas emissions than conventional portland cement concrete mixtures.[4-8]

Since, for this project, the contractor did not have any previous experience with HVFA concrete, it had the following concerns, especially for the shearwalls:

- Setting time, and early-age strength gain, required before form removal;
- Impact of a more rigorous curing regimen on the construction schedule;
- Visual appearance of the finished product due to the HVFA content; and
- Adequate strength for post-tensioning.

The contractor's concerns were satisfactorily resolved after the review of the data from the trial mixture proportions from the ready-mixed concrete supplier and on-site "mock-up." This article contains a description of the materials, mixture proportions, construction practice, and properties of the HVFA concrete used for Barker Hall's foundation and shearwalls.

MATERIALS AND MIXTURE PROPORTIONS

Mixture proportions approved for placement (Table 1) included an ASTM Type I/II portland cement with 63% C_3S and a Blaine fineness of 400 m^2/g, and an ASTM Class F fly ash with 22% residue on No. 325 mesh sieve and 93% strength activity index at 28 days. The aggregates used were a dredged sand (2.6 fineness modulus) and a mixture of pea-size gravel (9 mm maximum size) and coarser rocks. Although the water content of the concrete was considerably reduced by the presence of the high volume of fly ash and well-graded aggregate mixture, both a normal water reducer (ASTM Type A) and a high-range water-reducing admixture (ASTM Type F) were used. Low dosages of these admixtures additionally reduced the content of mixing water that was necessary to obtain the specified strength. The principal differences between the foundation mixture and the wall mixture are as follows:

- To control adiabatic temperature rise, the portland cement content of the foundation concrete mixture was reduced by about 18%, as compared to the wall concrete mixture;
- To accommodate the unusually congested reinforcement, the maximum size of coarse aggregate for the wall mixture was limited to 1/2 in. (13 mm); and
- To reduce drying shrinkage for the wall mixture, a low-shrinkage aggregate (crushed limestone) was specified because the locally available siliceous gravel produced concrete mixtures with high drying shrinkage.

FIELD TRIAL MIXTURES

The specifications required that, prior to construction, the properties of the proposed mixtures be evaluated from 4 ft (1.2 m) test cubes cast on site, but the contractor was allowed to reduce the size of the test block to 3 ft (0.9 m). Information from these trial batches was valuable in achieving the final mixture proportions. Final mixtures, which have now been successfully placed at the site, possessed the desired characteristics of good workability, good finishability, required strength, low drying shrinkage, low thermal shrinkage, and freedom from cracking. The following information was obtained from the field trial batches:

Compressive strength

The compressive-strength test data in Table 2 are from the final field trial batches. Compressive strength tests were performed in accordance with ASTM C 39 on 6 x 12 in. (150 x 300 mm) cylinders cast in conjunction with the site-cast block. In addition, 3-in.-diameter (75 mm) cores were extracted from the blocks for compression tests. The forms for the blocks were removed at two days and thereafter the concrete was moist-cured for 14 days with wet burlap.

TABLE 1:
SPECIFICATION AND MIXTURE PROPORTIONS FOR BARKER HALL

	Foundation concrete	Wall concrete
Minimum strength, 28 days 56 days	4000 psi (30 MPa) 5000 psi (35 MPa)	4000 psi (30 MPa) 5000 psi (35 MPa)
Minimum slump	4 in. (100 mm)	5 in. (130 mm)
Cement, Type II	270 lb/yd^3 (160 kg/m^3)	329 lb/yd^3 (195 kg/m^3)
Fly ash, Class F	329 lb/yd^3 (195 kg/m^3)	329 lb/yd^3 (195 kg/m^3)
Water	200 lb/yd^3 (118 kg/m^3)*	200 lb/yd^3 (118 kg/m^3)†
Coarse aggregate Natural gravel, 25 mm max. size Crushed limestone, 12 mm max. size Pea gravel, 9 mm max. size	 1470 lb/yd^3 (872 kg/m^3) — 450 lb/yd^3 (267 kg/m^3)	 — 1457 lb/yd^3 (864 kg/m^3) 385 lb/yd^3 (228 kg/m^3)
Fine aggregate Dredged sand	 1431 lb/yd^3 (849 kg/m^3)	 1448 lb/yd^3 (859 kg/m^3)
water-binder ratio	0.33	0.30

*Type A admixture: 18 oz/yd^3 (410 mL/kg^3); Type F admixture: 18 to 30 oz/yd^3 (410 to 680 mL/kg^3)
†Type A admixture: 20 oz/yd^3 (447 mL/kg^3); Type F admixture: 26 to 39 oz/yd^3 (595 to 895 mL/kg^3)

TABLE 2:
Field trial mixture, compressive strength data for Barker Hall

	Foundation concrete		Wall concrete	
Age, days	Core, psi (MPa)	Cylinder, psi (MPa)	Core, psi (MPa)	Cylinder, psi (MPa)
2	—	1350 (9)	—	1980 (14)
3	—	1605 (11)	—	2435 (17)
7	—	2110 (15)	—	2965 (20)
8	2895 (20)	—	4245 (29)	—
14	3400 (23)	2950 (20)	4360 (30)	3990 (28)
28	5125 (35)	4660 (32)	5650 (39)	5610 (39)
56	5620 (39)	5670 (39)	5710 (39)	5860 (40)

TABLE 3:
Field trial mixture, modulus of elasticity values for Barker Hall

	Foundation concrete		Wall concrete	
	$\times 10^6$ psi (GPa)		$\times 10^6$ psi (GPa)	
Age, days	ACI*	Test	ACI*	Test
2	—	—	2.3 (16)	2.5 (17)
3	—	—	2.6 (18)	2.9 (20)
7	3.5 (24)	4.5 (31)	—	—
28	4.1 (28)	5.1 (35)	—	—
56	—	—	4.4 (30)	4.7 (32)

*ACI = 57,000 $\sqrt{f_c'}$ psi

TABLE 4:
Field trial mixture (foundation concrete) temperature history

Age, days	Temperature, °F (°C)	
	Block	Air
0	81 (27)	77 (25)
1	114 (46)	91 (33)
2	102 (39)	69 (21)
3	72 (22)	66 (19)
6	67 (19)	71 (22)
7	69 (21)	73 (23)

The curing protocol for the cylinders and cores was as follows:

Cylinders: All cylinders were left in the molds and field-cured in the shade for 7 days. Samples were tested at ages up to 7 days and were transported to the laboratory on the day of the test. At 7 days, all samples were transported to the laboratory, demolded, and cured in a moist cabinet at 70 °F (21 °C) until the test age.

Cores: Samples for 7- and 14-day tests were extracted from the blocks and tested. The remaining cores were extracted at 14 days, cured, and tested in a manner similar to the cylinders.

As shown in Table 2, both mixtures achieved their 28- and 56-day specified strengths. The wall mixture's compressive strength was about 2000 and 2500 psi (14 and 17 MPa) at 2 and 3 days, respectively. Comparing the core and cylinder strengths up to 14 days, the strength of the in-place concrete, as measured by the cores, was greater than the strength measured by the standard 6 x 12 in. (150 x 300 mm) cylinders. The higher core strengths reflect the better performance of HVFA concrete in a warm and humid curing environment, particularly with massive concrete elements. After 14 days, when both test cylinders and cores were cured at controlled, 100% humidity conditions, the strength differences disappeared.

Modulus of elasticity

The modulus of elasticity data are presented in Table 3. The modulus data, even at 2 and 3 days, compares favorably with conventional portland-cement concrete. All modulus values were equal to or exceeded the normally assumed ACI approximation of 57,000 $\sqrt{f_c'}$ psi. (4700 $\sqrt{f_c'}$ MPa)

Temperature of concrete

Temperature data obtained from the foundation-mixture-test block are reported in Table 4. Temperature measurements were made using a thermocouple installed in the middle of the test cube. Ambient temperatures were also measured and are reported.

PLACEMENT, FINISHING, AND CURING

Most of the concrete was batched in a ready-mix plant in Berkeley with a transit time of about 15 min. Some of the concrete was dispatched from the Oakland plant with a transit time of approximately 30 min. This article was written when the structural concrete was about 80% complete and the walls were placed up to the fifth floor on all four elevations.

The slump of the concrete placed ranged from 5 to 7 in. (125 to 180 mm) for the foundation mixture and 4 to 6 in. (100 to 150 mm) for the wall. An observation made by the field technician while performing the slump tests, in particular for the wall mixture, was that the concrete continued to slump (or flow) with time. Thus, the original 5 in. (125 mm) slump would, a few minutes later, become 6 in. (150 mm). To our field inspectors, it was obvious that HVFA concrete does not behave in the same manner as conventional portland-cement concrete. The workability of HVFA concrete with a 5 in. (125 mm) slump may be equivalent to a 7 in. (180 mm) slump conventional concrete. However, due to the very low water content, the HVFA concrete does not segregate or bleed. Figure 3 shows the flowing characteristic of HVFA concrete. The concrete mixture in Figure 3 had a slump of 4 in. (100 mm).

The contractor was very pleased with how easily HVFA concrete could be pumped and consolidated. With the exception of the foundation corners, which were vibrated externally, consolidation of the walls and foundations was accomplished with conventional internal vibrators. There was no need to finish the foundation concrete and, as expected, there was very little bleed water.

The foundations were moist-cured with wet burlap on the surface and forms in place on the corners for 14 days. Most of the walls were cured by leaving the forms in place for 14 days (Fig. 4) and curing the top of the wall with water. If it was necessary to remove the wall forms early, the wall was cured with wet burlap for 14 days.

PROPERTIES OF HVFA CONCRETE

Surface finish

Finishes obtained on the foundation corner walls are shown in Fig. 5. There was minimal evidence of bug holes and no observable honeycombing on any of the finished surfaces. The concrete did not show any cracks 6 months after placement.

Finishes obtained on the shearwalls are typical of concrete (Fig. 4 and 5) with some segregation when the supplied material did not meet slump criteria, and to which no additional water could be added on site to

Fig. 3: Workers placing the easily-flowing HVFA concrete into the belt foundation

Fig. 4: New shearwalls with forms being removed after 14 days of curing

Fig. 5: Close-up of corner foundation with post-tensioning ducts. Notice the smooth finish on the exterior surface

TABLE 5:
Field slump and compressive strength results for foundation concrete

Slump in. (mm)	7-day strength psi (MPa)	28-day strength psi (MPa)	56-day strength psi (MPa)
7 (180)	2020 (14)	4040 (28)	5045 (35)
7 (180)	2195 (15)	5525 (38)	5670 (39)
5 (125)	3750 (25)	5175 (36)	5500 (38)
7 (180)	2190 (15)	4330 (30)	5020 (35)
5 (125)	2920 (20)	4440 (30)	5280 (36)
5 (125)	2905 (20)	4185 (29)	5255 (36)
7 (180)	2695 (19)	4330 (30)	5500 (38)
8 (200)	2430 (17)	4090 (28)	5490 (38)
4 (100)	1990 (14)	4100 (28)	5240 (36)

improve workability. If the contractor could have adjusted the workability by retempering the concrete with a small dose of high-range water-reducing admixture added at the site, this problem could have been resolved. The most recent survey of walls cast about 9 months ago did not reveal any cracks on any of the elevations.

Slump, compressive strength, and modulus of elasticity

The slump and compressive strength data for cylinders cast and tested as quality control during construction are presented in Tables 5 and 6 for the foundation and wall mixtures, respectively. The concrete for the two mixtures consistently achieved the minimum specified strengths of 4000 psi (28 MPa) at 28 days and 5000 psi (35 MPa) at 56 days.

Foundation temperature

A more comprehensive temperature history was obtained from the east foundation concrete. Prior to concrete placement, a thermocouple was installed in the center of the 11 x 6 ft (3.35 x 1.82 m) foundation, and temperature measurements were recorded every 3 min. In addition to the surrounding air temperature, the surface temperature of the foundation was measured about 1 in. (25 mm) below the surface. Temperature data for the foundation are included in Table 7.

The following comparisons can be made between the temperature data obtained from the foundation concrete and the test block:

- At about 24 h after placement, the temperature of the foundation had risen by 31 °F (17 °C) and a similar temperature rise was recorded for the test block.
- While the test block began to cool after 24 h, the foundation temperature continued to rise during the next 56 h to a maximum of 124 °F (51 °C) about 80 h after placement, due to the greater volume of concrete.

TABLE 6:
Field slump and compressive strength results for wall concrete

Slump in. (mm)	7-day strength psi (MPa)	28-day strength psi (MPa)	56-day strength psi (MPa)
6 (150)	2920 (20)	3770 (25)	5455 (38)
8 (200)	3380 (23)	5450 (38)	5610 (39)
9 (230)	3050 (21)	4535 (31)	5470 (38)
7 (180)	3100 (21)	4405 (30)	5390 (37)
7 (180)	3030 (21)	4690 (32)	5430 (38)
5 (125)	3030 (21)	4650 (32)	5580 (39)
7 (180)	2780 (19)	4360 (30)	5250 (36)
7 (180)	3930 (27)	4335 (30)	5560 (38)
6 (150)	3175 (22)	4760 (33)	5750 (40)
8 (200)	3665 (25)	4160 (29)	5340 (37)
6 (150)	2635 (18)	4470 (31)	5540 (38)
7 (180)	3350 (23)	4810 (33)	5750 (40)
5 (125)	4480 (31)	4940 (34)	5720 (40)
6 (150)	3410 (23)	4750 (33)	5510 (38)
3 (75)	2000 (14)	4010 (28)	5360 (37)
8 (200)	3500 (24)	5170 (36)	5810 (40)
6 (150)	4050 (28)	5180 (36)	5840 (40)
8 (200)	3220 (22)	5030 (37)	5780 (39)
7 (180)	3380 (23)	5390 (37)	5890 (41)
8 (200)	3530 (24)	5720 (39)	6110 (42)

TABLE 7:
FOUNDATION CONCRETE TEMPERATURE HISTORY

Age, days	Interior °F (°C)	Surface °F (°C)	Air °F (°C)
0	80 (27)	80 (27)	74 (23)
1	111 (44)	—	64 (18)
2	121 (49)	84 (29)	65 (18)
3	124 (51)	82 (28)	65 (18)
5	121 (49)	73 (23)	63 (17)
6	118 (48)	76 (24)	66 (19)
7	114 (46)	75 (24)	65 (18)

TABLE 8:
SHRINKAGE VALUES

Days drying	Drying shrinkage, %	
	Foundation mixture	Wall mixture
7	0.019	0.012
14	0.029	0.019
21	0.037	0.022
28	0.042	0.028

Drying shrinkage of concrete

Results of the shrinkage tests on the foundation and wall mixtures, performed in accordance with ASTM C 157, are provided in Table 8.

The test data show that both mixtures have 28-day shrinkage values that are acceptable for low-shrinkage concrete. The maximum measured 28-day shrinkage for the wall, and the foundation mixtures were 0.042% and 0.028%, respectively. A maximum shrinkage value of 0.035% is considered acceptable for low-shrinkage concrete in the San Francisco Bay area where the local aggregates tend to produce high shrinkage. These HVFA-concrete mixtures had acceptable shrinkage values because of their very low water-cementitious materials ratio.

Cores from the foundation

Four 3.75-in. (95 mm) cores were removed from the east foundation about 6 months after placement. The cores (with length/diameter ratio of 2) were tested in compression, examined petrographically, and tested for chloride ion permeability. The results are as follows:

Compressive strength and modulus: About 6 months after placement, the compressive strength of the foundation concrete was 6560 psi (45 MPa) and the modulus of elasticity was 5.3×10^6 psi (37 GPa).

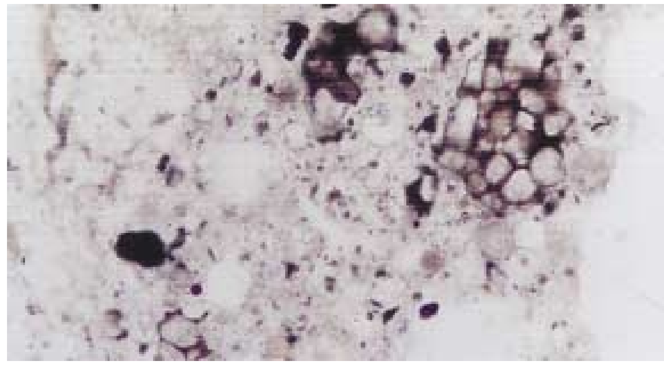

Fig. 6: Concrete microstructure of the HVFA concrete used at Barker Hall

Petrographic analysis: The petrographic analysis was performed in accordance with ASTM C 856. Figure 6 shows the typical microstructure of the concrete. The following important observations were made from this examination:

- Overall, the concrete was hard and sound, with no evidence of microcracking;
- The fly ash was well-distributed in the paste, and the paste had a uniform density, even adjacent to the aggregate particles;
- There was essentially no interstitial aggregate/paste transition zone; and
- The calcium hydroxide content of the paste was low and the crystals present were very small and randomly oriented.

Chloride permeability: The Rapid Chloride Permeability Test was performed on one core (at 6 months) in accordance with AASHTO T277/ASTM C 1202. The charge passed (1510 coulombs) classifies the concrete to a low permeability rating according to ASTM C 1202.

"GREEN" CONCRETE COMPLETES THE JOB

With a cooperative construction team, the hurdles of using "green" concrete were overcome. Mixture proportion formulation followed by field trial proved to be invaluable in developing HVFA-concrete mixtures that met the designer's criteria and expectations, and were also accepted by the contractor. Until there is more information available, requiring field trial mixtures and placing test blocks, as required at Barker Hall, is very appropriate. The concrete supplier and the placement and finishing crew all gained tremendous confidence in the ability to work with the material after placing the test blocks.

The important findings are summarized as follows:

1. The surface finish achieved with HVFA concrete is better than that achieved with conventional concrete;
2. Compressive strengths of the order of 2000 psi (14 MPa) at 2 days and 2500 psi (17 MPa) at 3 days were achieved;
3. Considering the reportedly mediocre quality of some of the aggregates used and the high fly ash content, the drying shrinkage was low; and

4. Because there is no evidence of thermal cracking on the foundations placed to date, satisfactory heat control was apparently achieved, with no special precautions such as the use of ice or cooling of aggregate and water.

The experience with HVFA concrete at Barker Hall has been very positive, and there is no reason why this type of concrete should not be used as the concrete of choice for most structural applications. So far, its use seems to be promoted as a "green" material that will help sustainability of the concrete industry.[4,5] Be that as it may, there is today, however, ever-increasing accumulated field data and experience that suggests that this material, with all of its beneficial properties, should be used on its own merit. HVFA concrete has improved workability, lower permeability, reduced propensity to crack, and achieved strengths comparable to conventional portland cement concrete when designed and executed with proper attention to curing. We believe that the day is not far away when contractors will ask for HVFA concrete to be specified for their projects.

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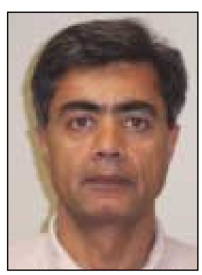

Dushyant Manmohan is a Principal of Applied Materials & Engineering, Inc. He has a Doctor of Engineering Degree in Materials Science from the University of California at Berkeley. For the past 22 years he has been involved with providing materials consulting and testing services to the construction industry.

P. Kumar Mehta, FACI, is Professor Emeritus in the Civil Engineering Department at the University of California at Berkeley. He has received several awards, including ACI's Wason Medal for Materials Research, and Construction Practice Award. He held the Roy Carlson Distinguished Professorship in Civil Engineering at Berkeley and, upon his retirement, received the Berkeley Citation, the highest campus honor, for exceptional contributions to his field and to the university.