Monolith Foundation: Built to Last a "1000 Years"

by P. Kumar Mehta and Wilbert S. Langley

A yellow, ready-mixed concrete truck arrives at the construction site. Amidst sounds from a Balinese gong and Sanskrit chants from a fire ceremony, saffron-robed monks and a host of onlookers welcome the truck. The same ceremonial reception greets every one of the 54 truckloads of concrete that, by day's end, deposit approximately 380 m^3 (500 yd^3) of concrete into the formwork. This is the unusual setting under which an unusual structure — the first of the two slabs of the raft foundation for the first all-stone Hindu Temple in America — is being built. The unreinforced concrete monoliths, each 36 m (117 ft) long, 17 m (56 ft) wide, and 0.61 m (2 ft) thick, are required to remain crack-free during their specified 1000 years service life.

Fig. 1 — Carved granite pillar components for the temple.

Approximately 4000 km (2500 mi) to the west of the U.S. mainland, on the tranquil island of Kaua'i in the middle of the Pacific Ocean, a magnificent temple made of hand-carved granite stone is under construction (Fig. 1). Exquisitely carved beams and segments of columns from India will be imported and assembled in Kaua'i to build this temple. As the structure is being erected on a bed of soft clay, the architect specified a concrete foundation that will support 2000 tons (1814 tons (metric)) of stonework without any significant settling and without cracking; otherwise, the granite roof beams would separate from the columns and fall.

Originally, the structural design was based on a monolith raft foundation, 36 x 17 x 1 m (117 x 56 x 3 ft) in size; however, due to the inability of the local ready-mixed concrete company to supply 612 m^3 (810 yd^3) of concrete in 1 day, it was decided to install a foundation composed of two independent, parallel monolith slabs, each 36 x 17 x 0.61 m (117 x 56 x 2 ft) in size.

The foundation's soil consists of soft clay for which the depth has not been well defined due to limited soil-investigation equipment on the island. The owners, in consultation with the materials consultants, decided to surcharge the foundation rather than import drilling equipment. To control potential settlement cracking during construction of the foundation, the soil was heavily compacted, and a base course of 1 m (3.28 ft) thick, well-compacted gravel was added in the excavated clay underneath the concrete foundation. The completed foundation will have an additional 2.5 m (8.2 ft) of soil to eliminate residual settlement.

In addition to careful attention to the selection of materials and proportions for the concrete mixture, thermal cracking during construction was controlled by constructing the slabs with 1-week intervals between the two castings, discussed as follows.

Preliminary investigation

Most of the concrete structures built during this century are not expected to last for 100 years because portland cement concrete cracks and deteriorates due to a number of interrelated causes such as thermal contraction, drying shrinkage, exposure to cycles of freezing and thawing, corrosion of embedded steel, alkali-aggregate reaction, and sulfate attack. In contrast, some of the Roman structures built approximately 2000 years ago are still in good condition. Therefore, to build long-lasting concrete structures in the future, it is prudent to begin with a basic knowledge of the methods and materials that were used in the construction of ancient structures that have endured for centuries.

The Pantheon in Rome, built by the emperor Hadrian in 128 A.D., is a circular building of concrete with 6.1 m (20 ft) thick walls and a dome measuring 43.3 m (142 ft) in diameter that rises to a height of 21.6 m (71 ft) above its base. According to the *Encyclopedia Britannica*,[1] the exact method of construction is unknown; however, two factors have contributed to the success of the building that stands today entirely in its original form, namely: the excellent quality of the mortar in the concrete mixture, and the careful selection and grading of the aggregate material. Similarly, in regard to the Roman aqueducts, Malinowski[2] credits the construction methods as well as the high quality of a well-compacted, nonshrinking concrete for excellent durability of crack-free canal linings that were installed without any construction joints. According to Lea,[3] both the Greeks and the Romans were aware that certain volcanic materials (later known as pozzolans), when finely ground and mixed with lime and sand, yielded a mortar that was not only cementitious but also water resistant. There is evidence that Greeks and Romans also used crushed potshards and tiles as artificial pozzolans.

In comparison with the portland cement concrete structures of today that crack within a few months of completion, why has the ancient lime-pozzolan concrete remained crack-free after 2000 years of service? To build a long-lasting concrete structure, it is important to find an answer to this question.

Ancient concrete mixtures were generally characterized by low cementitious material content, low water content (consolidation was achieved by tamping), a very slow rate of strength development, and almost no shrinkage strains from cooling and drying. Driven by the perception that high-speed construction translates to financial gains, the portland cement concrete mixtures of today usually contain a high cement content of very reactive and finely ground cement that hydrates fast and develops not only high strength and a high modulus of elasticity, but also a high heat of hydration at very early ages. Early-age cracking in modern portland cement concrete is mainly attributable to shrinkage strain from cooling and drying. Under the restraining conditions in hardened concrete, the shrinkage strains induce a tensile stress, and the material cracks when this tensile stress exceeds its tensile strength. If the elastic modulus happens to be low and the stress relief due to creep is high, however, the potential for cracking is reduced.

In modern construction practice, it is assumed that concrete will crack due to its high early strength, high modulus of elasticity, and low creep capacity. The crack widths are limited by the use of steel reinforcement, but the substitution of a few wide cracks by numerous immeasurable minor cracks adversely affects the overall impermeability of concrete, which is the key to premature structural deterioration from corrosion of the reinforcement, freezing and thawing cycles, and alkali-aggregate reaction. Construction joints are provided to control cracking, but they are a perpetual source of leakage and also cause long-term durability problems.

One obvious solution is to go back to the types of concrete mixtures used in the past, which are known to have undergone little or no shrinkage. But how can this be accomplished with modern concrete-making materials and construction schedules? This was the challenge that would guide the selection of materials, mixture proportions, and construction practice for the Kaua'i Temple concrete foundation. In fact, the decision not to use any reinforcing steel and construction joints in either of the two concrete slabs of rather large size (36 x 17 x 0.61 m (117 x 56 x 2 ft)) could be justified only on the assumption that the tensile stresses from the thermal and drying shrinkage effects would be negligible.

Table 1 — Properties of portland cement

Parameter	Value, %
C_3S	62
C_2S	14
C_4AF	10
C_3A	7
Blaine fineness	400 m^2/kg

Table 2 — Properties of Class F fly ash

Parameter	Value
Residue on No. 325 sieve	25 %
Relative density	2.17
Loss on ignition	< 1 %
Water requirement	96 %
Strength-activity index (with portland cement)	83 %

Concrete-making materials

In Kaua'i, the choices for concrete-making materials were limited by the fact that only one ready-mixed concrete plant was able to furnish 500 yd^3 (380 m^3) of concrete in an 8- to 10-hour period. Properties of the cement, which meets ASTM C 150, are shown in Table 1.

Crushed basalt was used as the coarse aggregate, and sand with a fineness modulus of 2.83, made from crushed calcareous stone, was used as the fine aggregate. To reduce the cement paste content of the concrete mixture, two coarse-aggregate fractions, ASTM No. 57 (1 in. [25 mm] MSA) and ASTM No. 8 (3/8 in. [10 mm] MSA) were blended in a 60 to 40% ratio by mass, respectively. Air-entraining and water-reducing admixtures, both normal and high range, were used to achieve the desired workability of fresh concrete at low cement and water contents. The admixtures were necessary due to the rough texture of both the sand and the coarse aggregate.

To achieve the desired finishing characteristics and workability for the proper consolidation of fresh concrete by vibration, a minimum cement content of about 300 kg/m^3 (500 lb/yd^3) is generally needed, regardless of the strength requirements. Even at such a low cement content with normal portland cement, the temperature increase in concrete due to heat of hydration would be too high to prevent thermal-shrinkage cracking unless special cooling methods were used. A relatively inexpensive approach is to replace a portion of the portland cement with a natural or by-product pozzolanic material such as fly ash.

The control of thermal cracking in massive concrete members was the primary objective behind the development of high-volume fly ash (HVFA) concrete technology about 10 years ago by Malhotra.[4] The replacement of up to 60%

Table 3 — Trial mixture proportions and properties of concrete

Parameter	Concrete mixture proportions	
	Lab trial mixture	Field trial mixture
Portland cement	90 kg/m^3 (150 lb/yd^3)	106 kg/m^3 (180 lb/yd^3)
Class F fly ash	159 kg/m^3 (270 lb/yd^3)	142 kg/m^3 (240 lb/yd^3)
Water	103 kg/m^3 (175 lb/yd^3)	100 kg/m^3 (270 lb/yd^3)
Fine aggregate	935 kg/m^3 (1585 lb/yd^3)	944 kg/m^3 (1600 lb/yd^3)
Coarse aggregate	1130 kg/m^3 (1915 lb/yd^3)	1121 kg/m^3 (1900 lb/yd^3)
Normal water-reducing admixture	770 mL/m^3 (20 oz/yd^3)	770 mL/m^3 (20 oz/yd^3)
HRWRA	2320 mL/m^3 (60 oz/yd^3)	3480 mL/m^3 (90 oz/yd^3)
Air-entraining admixture	116 mL/m^3 (3 oz/yd^3)	116 mL/m^3 (3 oz/yd^3)
Slump	75 mm (3 in.)	150 mm (6 in.)
Air content	4.5%	3.5%
Adiabatic temperature rise	10 C (18 F)	12 C (21 F)
Compressive strength		
3 days	—	5.5 MPa (800 psi)
7 days	6.2 MPa (900 psi)	9.6 MPa (1250 psi)
28 days	12.4 MPa (1795 psi)	15.9 MPa (2300 psi)
90 days	16.5 MPa (2400 psi)	24.1 MPa (3500 psi)

portland cement by ASTM Class F fly ash, in accordance with the HVFA concrete technology, provided the basis for the development of trial-batch mixtures investigated for the construction of the Kaua'i Temple foundation; no commercially available sources of such materials are found in Kaua'i or neighboring islands. Consequently, Class F fly ash, meeting ASTM C 618, had to be imported in super sacks from a U.S. west coast coal-fired power plant at a cost of approximately \$200 per ton. Important properties of the material are outlined in Table 2.

Development of mixture proportions

The objective of mixture proportioning was to develop a concrete mixture that would have negligible thermal shrinkage and drying shrinkage, while possessing the workability characteristics acceptable to the contractor and strength characteristics acceptable to the structural designer. An air-entrained concrete (4% to 5% total air) with 100 to 150 mm (4 to 6 in.) slump was preferred by the contractor for ease of placement with truck chutes and for proper consolidation with immersion vibrators. The original design required a 20 MPa (3000 psi) 28-day compressive strength, but the structural engineer accepted the design strength at 90 days instead of 28 days because no structural loading was expected before 90 days.

For the production of an essentially nonshrinking concrete, certain maximum limits on the total binder content (cement plus fly ash) and the total water content were assumed in the development of the laboratory trial mixtures. The limits selected were 250 kg/m^3 (425 lb/yd^3) for the total binder content and 110 kg/m^3 (186 lb/yd^3) for the total water content. To reduce the potential for thermal cracking, an arbitrary value of 15 C (27 F) was chosen for the maximum permissible temperature rise in the concrete. From experience, it was expected that the binder would consist of at least 50% fly ash by mass; however, the exact ratio of fly ash to portland cement in the binder would have to be determined from the workability, strength, and the adiabatic temperature-rise characteristics of the trial mixtures.

After several laboratory trials, a concrete mixture was found in the left-hand column of Table 3 that seemed to satisfy the workability and adiabatic temperature-rise criteria but was somewhat deficient in meeting the 90-day strength requirement. Subsequently, for the mock-up mixture used in the field trial, the ratio of cement to fly ash was slightly raised, and the water content was slightly lowered with an increased dosage of the high-range water-reducing admixture (HRWRA). This concrete mixture (right-hand column, Table 3) met all the specified requirements and was used for the construction of slabs.

Construction and curing

For the success of the project, three items were singled out for special attention by the authors: enthusiastic support from the key personnel involved in construction; strict vigilance of the quality and uniformity of ready-mixed concrete at the time of placement; and extraordinary precautions for proper curing. In Kaua'i, fly ash had never been used in concrete, nor had anyone ever heard of concrete mixtures with such a low cement content and water content. Therefore, to put the ready-mixed concrete plant operator and the construction supervisors at ease, educational meetings were held at which the challenging goal of making a crack-free concrete structure was presented, and the technology to achieve it was thoroughly explained.

Any apprehensions regarding the handling characteristic of high-volume fly-ash (HVFA) concrete were subsequently dismissed when the crew responsible for transportation, placement, and consolidation of concrete for the 3.75 m^3 (5 yd^3) mock-up slab witnessed the effortless flowability of the material, without segregation. The field trial also taught an important lesson to the truck drivers, namely, that it was possible to recover the slump lost during transit by adding a small amount of the high-range water reducer rather than adding water, which is a common practice.

In August, the weather in Kaua'i remains generally warm; surprisingly, the ambient temperature varies within a narrow range from 21C (70 F) in the early morning to 30 C (86 F) in the afternoon. For making 760 m^3 (1000 yd^3) of concrete needed for both slabs, the same mixture proportions were used as for the field trial mixture (Table 3), except that only 2/3 of the dosage—2320 mL/m^3 (60 oz/yd^3)—of a naphthalene-based, high-range water reducer was added at the batch plant. The balance 1/3—1160 mL/m^3 (30 oz/yd^3) — was saved for slump adjustment at the job site, where the admixture supplier installed a special dispenser for this purpose.

The lower slab was installed on August 21, 1999. When the first truck arrived at the construction site around 7 a.m., a sample of concrete was taken for testing the quality and adjustment of slump. The air content was 7%, the temperature was 26 C (79 F), and, as expected, the slump had reduced from the original 150 mm (6 in.) at the batch plant to 75 mm (3 in.) during the 45 min. transit time. Approximately 1 L/m^3 (26 oz/yd^3) of the high-range water-reducer was added to restore the slump back to 150 mm (6 in.) before the concrete was placed. Because the construction manager had continuous telephone linkage with the ready-mixed concrete plant operator, the high air content and other necessary mixture adjustments were brought under control quickly by slight changes in the dosage of the concrete admixtures.

The quality and uniformity of the concrete from the first five truckloads were closely monitored; after which, every third truckload was tested. The responsibility for the slump adjustment was shared between the construction foreman and the admixture suppliers' field representative who was present at the job site; the transit mixer truck drivers were strictly forbidden to add any water to the concrete. From every 100 m^3 (130 yd^3) of concrete, twelve cylinders were cast for testing the compressive strength at 3, 7, 28, and 90 days. The test results are shown in Table 4.

Proper concrete curing procedures were absolutely essential to prevent development of stress due to the thermal and drying shrinkage. Given the no-bleeding characteristic of concrete containing a high volume of fly ash, low unit-water content, and the warm and windy climate under which the concrete was placed, it was also necessary to avoid plastic shrinkage due to rapid loss of moisture from the surface. Immediately after each screeding operation, a thin film of a monomer was sprayed on the concrete surface, which was then covered by a thick visqueen sheet (Fig. 2).

Tests on the concrete mixture showed that the material set in approximately 8 h and developed about 2 MPa (300 psi) strength in 16 h. The slab was, therefore, left undisturbed overnight. The mandatory moist-curing period started from the following morning when it was considered safe to walk on the slab without causing any damage.

Studies have shown that water curing of concrete, especially the HVFA concrete, is essential for the development of optimum strength and for the control of both thermal shrinkage and drying shrinkage. Water curing helps to cool the warm concrete at a relatively faster rate during the first week of casting when the material has a low elastic modulus and a high creep. Excessive labor cost is often cited as the reason why water curing is not preferred in comparison to membrane curing; however, this problem can be resolved with simple innovations, described as follows.

Fig. 2 — Application of burlap and moisture.

Table 4 — Average compressive strength of concrete cylinders, MPa (psi)

Test age	Lower slab	Upper slab
3 days	6.0 (870)	7.3 (1065)
7 days	9.0 (1300)	10.9 (1580)
28 days	14.8 (2145)	17.5 (2540)
90 days	23.1 (3350)	27.6 (4000)

Note: The data show the average strengths of 6 x 12 in. (150 x 300 mm) cylinders made from typical samples of field concrete with approximately 6 in. (150 mm) slump and 4.5% air content. The cylinders were cast at the job site from fresh concrete discharged from the mixer trucks. Some of the specimens were tested at 3 days; others were left undisturbed in the molds for 7 days at the field temperature that varied from 21 to 30 C (70 to 85 F). Thereafter, the test specimens were demolded and taken to the laboratory for moist curing, and tested under standard ASTM conditions.

On the morning of August 22, the visqueen sheets covering the slab were momentarily removed so the workers could place an 8 to 10 mm (.31 to .39 in.) thick, water-soaked layer of burlap directly on top of the concrete. Then the visqueen covering was restored to prevent quick drying of the burlap (Fig. 3). Due to the heat of hydration, the temperature of the concrete rose by 13 C (23 F) within 24 h of casting. As a result of direct exposure to the sun, in spite of occasional rain showers, some dry patches appeared in the burlap. By frequent inspections during the daytime and by promptly rewetting the dried spots of burlap, an uninterrupted water curing was ensured.

During the next 6 days, the concrete temperature in the slab dropped at the rate of about 1.7 C (3.0 F) per day. Therefore, on the morning of August 28, the concrete temperature

Table 5 — Temperature history, C (F)

Date	Lower slab	Upper slab
Aug. 21	27 (80)	—
Aug. 22	40 (104)	—
Aug. 28	30 (86)	27 (81)
Aug. 29	—	40 (104)
Aug. 31	38 (100)	—
Sept. 4	35 (95)	32 (90)
Sept. 10	34 (94)	30 (86)
Sept. 25	30 (87)	27 (81)

in the lower slab was down to almost 30 C (86 F), when the construction crew was ready to cast the upper slab. Moreover, as a consequence of continuous wet and warm curing for a week, the concrete in the lower slab had reached 9 MPa (1300 psi) compressive strength, which was adequate to withstand the traffic loads for the new placement. Table 5 shows the dates and temperature readings for the lower and upper slabs.

Without dismantling the first slab formwork, additional formwork was built for placement of the upper slab exactly on top of the lower slab. The two slabs were separated by a "slipsheet" consisting of two layers of heavy-duty visqueen. This eliminated moisture transfer to the lower slab and restrain to any movement from future volume changes in the upper slab. The quality control, casting, and curing procedures for the second slab, fabricated on August 28, were essentially the same as for the first slab. To reduce the drying shrinkage, moist curing continued for 2 weeks, and thereafter, the protective surface cover of burlap and visqueen was left in place for several additional weeks.

Fig. 3 — Burlap covered with visqueen sheet to prevent drying.

Assessing the results

At the time of this article, more than 9 months has passed since the installation of the large, unreinforced concrete monoliths that comprise the raft foundation for the stone temple in Kaua'i. The slabs look beautiful; careful examination of the exposed surface has shown no evidence of any cracking. In addition to the highly motivated team of individuals directly involved in the construction, the authors believe that the following two factors associated with warm-weather construction should not be overlooked when assessing the success of the project.

First, by limiting the cement content to 106 kg/m^3 (180 lb/yd^3) it was possible to restrict the autogenous temperature rise in concrete in the first 24 h to 13 C (23 F). Secondly, the use of relatively high quantities of fly ash significantly reduced the rate of strength gain and stiffness. During the period for 6 days after concrete placement, when the concrete was still less stiff (with an average compressive strength below 10 MPa [1450 psi]), the midslab temperature dropped at an average rate of 1.5 C (2.7 F) per day. After 2 weeks of casting, when the concrete had become stronger and stiffer, the slabs cooled down at a very slow rate of 0.24 C (0.43 F) per day. This interplay between the concrete strength or stiffness and the slow cooling rate in the Kaua'i weather was believed to be an important factor in preventing thermal cracking. Also, subsequent to the placement of the upper slab, the temperature of the lower slab started to rise again. A peak temperature rise of 8 C (14 F) was reached in 4 days before it started to drop again.

From the strength data in Table 4, the average compressive strength of the concrete mixture increased from 10 MPa (1450 psi) at 7 days to about 16 MPa (2320 psi) at 28 days—a 60% increase. Moreover, between 28 and 90 days the average strength increased from 16 to 25.4 MPa (2320 to 3685 psi), which corresponds to a further 60% increase. There is nothing unusual about the characteristics of the portland cement and the fly ash used. The explanation lies in the combination of low water content and warm curing temperatures at which the hydration reactions of both cement and fly ash are greatly accelerated. Consequently, in spite of the low cement content (106 kg/m^3 [180 lb/yd^3]), the 1-day strength of the concrete mixture was adequate for minor construction activity at the job site, the 7-day strength was adequate for formwork removal, and the 90-day strength was 25% greater than the specified design strength. The temple construction is not expected to begin before 1 year, when the concrete strength in the foundation is expected to be twice as much as the design strength. This observation is highly significant for sustainable development of the concrete industry during the 21st century, because a large amount of construction activity is projected to occur in the warm regions of the world (Asia, Africa, and South America).

The UN Intergovernmental Plan on Climate Change has concluded that our world is becoming stormier due to global warming caused by the unprecedented increase of carbon dioxide emissions.[5] The world production of portland cement is responsible for more than 1 billion tons, or approximately 7% of the total carbon dioxide loading of the environment. The use of high volumes of fly ash or slag as a cement-replacement material in concrete has shown a way by which the housing and infrastructure needs of industrially developing countries can be successfully met without increasing the production capacity of the portland cement industry.[6] If built with conventional technology, the Kaua'i temple foundation project would have used approximately 230 tons (209 tons [metric]) of portland cement and 75 tons (68 tons [metric]) of reinforcing steel. Instead, by using only 80 tons (73 tons [metric]) of cement and no reinforcing steel, this project saved the carbon dioxide loading of the environment by 225 tons (204 tons [metric]). (Both portland cement and steel productions account for one tonne of carbon dioxide per tonne for either of the materials). This may appear to be insignificant, but it certainly sets a trend that is worthy of emulation by the concrete construction industry for building sustainable and durable structures in the future.

Conclusion

Many in the concrete construction industry still suffer from an old myth that fly ash is a cheap substitute for portland cement. This simply is not true with modern fly ashes if one pays proper attention to materials, mixture proportions, and the curing of concrete. Without fly ash, the workability and durability of concrete in the structure described in this article could not have been achieved. If fly ash was a cheap substitute or only a supplement to cement, why would someone pay three times as much for it to replace cement? This indeed is the most convincing argument that materials like fly ash and slag are complementary to portland cement, because without them, it would not be possible to build durable and sustainable concrete structures.

The maximum permissible content of fly ash in blended portland-pozzolan cement is 40% by mass, according to ASTM, and even less according to other standards. (For example, it is 25% according to the Indian Standard Specification.) In practice, the fly-ash content seldom exceeds 20% whether it is marketed as portland-pozzolan cement or is incorporated directly into concrete as a cement admixture in a ready-mixed concrete plant. Such prescriptive limits, like the maximum permissible fly ash content in blended cements and the minimum required portland cement content in codes of recommended practice, are archaic and relics of the past. They ought to be scrapped and replaced with performance-oriented standards that are flexible enough to allow the use of larger amounts of industrial by-products in concrete, particularly under warm environmental conditions. HVFA or high-volume slag concrete mixtures exhibit a slow rate of strength development, but when necessary, this can be accelerated to acceptable values by the use of high-range water reducers or other methods.

Finally, the technology of building an unreinforced structure with HVFA concrete is described here; however, for a variety of reasons, many of the concrete structure will have to be reinforced with steel even when the concrete mixture is designed for little or no tensile stress from thermal and drying shrinkage effects. Langley[7] has discussed case histories showing the application of the HVFA concrete technology for making reinforced concrete columns, beams, and foundations. Obviously, reinforced concrete structures are not expected to endure for 1000 years; however, their durability would be considerably enhanced if they can remain free from cracking for a long time during the service life.

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Selected for reader interest by the editors.

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