Wiss, Janney, Elstner Associates, Inc.

TESTS ON CONCRETE CONTAINING SPECIALIZED FOAM FOR STABLE AIR INC.

WJE NO. 971264

SEPTEMBER 1997

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TABLE OF CONTENT

September 1996

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BACKGROUND

On May 8, 1997, a letter was sent from Wiss, Janney, Elstner Associates, Inc. (WJE) to Mr. David Master, President of Stable Air Inc., regarding high air content structural concrete. This work was conducted at the request of Mr. John Nanna, President of J. W. Peters and Sons, Inc. of Burlington, Wisconsin, and other PCI producer member companies. WJE reviewed the high air content concrete technology from Stable Air Inc. for producing structural quality concrete.

At that time it was discussed that our goal was to demonstrate that Stable Air concrete can maintain proper and adequate concrete strength properties and other necessary properties such as creep, modulus of elasticity, shrinkage, flexural strength and unit weight for use in precast and precast, prestressed concrete.

Based on our existing knowledge at WJE about conventional concrete and concretes with intentionally high air contents, Messrs. David Master, Stewart Jones, Byron Smith, and Louis Sweet (from Stable Air), John Nanna, and Donald Pfeifer held a conference call on April 29, 1997. During this telephone conference call, WJE presented an outline of proposed work tasks that WJE felt was appropriate. This outline is as follows:

Task No.	Task	Goal of Work
1	Literature Review	WJE review of Stable Air, Inc. concrete technology files, test reports by Stable Air and other reports supplied by Stable Air to confirm present state-of-the-art at Stable Air for producing structural quality concrete.
2	Develop Test Program	After WJE review of Stable Air literature and reports are completed, Stable Air and WJE will cooperatively develop a test program to help confirm state-of-the-art of Stable Air concretes.
3	Finalize Test Program	After WJE and Stable Air develop test program, the PCI-producer members who have an interest in this project will review test program and provide their input on tasks
4	Produce Concrete Test Specimens for Test Program	WJE will supervise the producing and fabrication of the concrete test specimens for the test program at the J.W. Peters factory in Burlington, Wisconsin. Stable Air staff will also participate in this work.
5	Undertake Test Program Laboratory Studies on J.W. Peters produced high air concretes.	The laboratory tests will be completed at the Northbrook, Illinois laboratories of WJE.
6	Prepare Final Report	A final report on the literature review and the test program will be prepared by WJE.

Technical issues relating to mixing, transporting, casting, and consolidating high air content concretes that were suggested to be incorporated in the Test Program by WJE are as follows:

- Length of mixing period
- Length of transportation period
- Casting height
- Length of vibration period
- Consolidation without vibration versus with minimal vibration of high-slump, high air content concretes

STRUCTURAL LIGHTWEIGHT CONCRETE

Structural concrete and structural lightweight concrete, as defined by ACI Committee 116 in *Cement and Concrete Terminology* are as follows:

> **Concrete, structural**—Concrete used to carry structural load or to form an integral part of a structure; concrete of a quality specified for structural use; concrete used solely for protective cover, fill, or insulation is not considered structural concrete.

> **Concrete, structural lightweight**—Structural concrete made with lightweight aggregate; the unit weight usually is in the range of 90 to 115 lb per cu ft (1440 to 1850 kg per cu m).

The usual lower-bound 28-day compressive strength for structural purposes is 2500 psi. More typical 28-day compressive strengths for precast concrete which is not prestressed is 3000 to 4000 psi, and 5000 to 6000 psi for concrete that is prestressed. The 1992 4th Edition of the PCI Design Handbook utilizes 28-day design compressive strengths of 5000 to 8000 psi in Chapter 2 "Product Information and Capability."

When structural concrete of any unit weight from 100 to 155 lb/ft^3 contains entrained air contents of 4 to 8 percent, there is an average strength reduction of about 4 to 6 percent for each 1 percent increase in air content above about 2 percent.

During the April 29, 1997 telephone conference call, Stable Air briefly discussed ACI Committee 523 reports. As a result, WJE reviewed:

ACI 523.1R-92	"Guide for Cast-in-Place Low-Density Concrete"
ACI 523.2R-96	"Guide for Precast Cellular Concrete Floor, Roof and Wall Units"
ACI 523.3R-92	"Guide for Cellular Concretes Above 50 pcf, and for Aggregate Concretes Above 50 pcf with Compressive Strengths Less than 2500 psi"

These three reports are the only current ACI Committee 523 reports in the 1997 ACI Manual of Concrete Practice—Part 5. Comments from this brief review are as follows:

ACI 523.1R-92 - Oven-dry densities are less than 50 pcf, and usual range of compressive strength is 450 to 750 psi for 40 to 50 pcf oven-dry concretes. Modulus of elasticity ranges from 0.1 to 0.16×10^6 psi for 35 to 48 pcf oven-dry concrete. Drying shrinkage ranges 1000 to 6000 x 10^{-6} in./in., which is 1.5 to 15 times that of typical concretes. This concrete type with densities less than 50 pcf (oven dry) is not structural concrete capable of being prestressed.

ACI 523.2R-96 - This Guide is for producing precast reinforced cellular concretes with 50 pcf of less oven dry densities for floor, roof, and wall units that will result in structural members of adequate load capacity, durability, appearance and overall serviceability. These units must be protected from exposure to weather, as water is readily absorbed into these materials. A minimum compressive strength is 300 psi is required. Drying shrinkage should not exceed 2000×10^{-6} in./in. These concretes are described as having high porosity.

Structural load tests on flexural units using 80 and 60 psf test loads must sustain the test load for 24 hours without the midspan deflection exceeding 1/160 of the span. Residual deflection after load removal should not exceed 1/400 of the span.

ACI 523.3R-93 - This Guide is for 50 to 120 pcf oven-dry cellular or aggregate concretes with compressive strengths less than 2500 psi. The lower densities are used for thermal and sound insulation fills for roofs, walls, and floors. The higher densities are used in cast-in-place walls, floors, and roofs and also for precast walls and floors.

The cellular concretes in this Guide contain a stable air-void system, with or without other aggregates, and commonly uses sand aggregates. The aggregated concretes in this Guide do not contain a stable air-void system, unless caused by a normal air-entraining agent. They may or may not use sand aggregates.

Typical plastic unit weight versus compressive strength for sanded cellular concretes are shown in Figure 1 from ACI 523.3R-93.

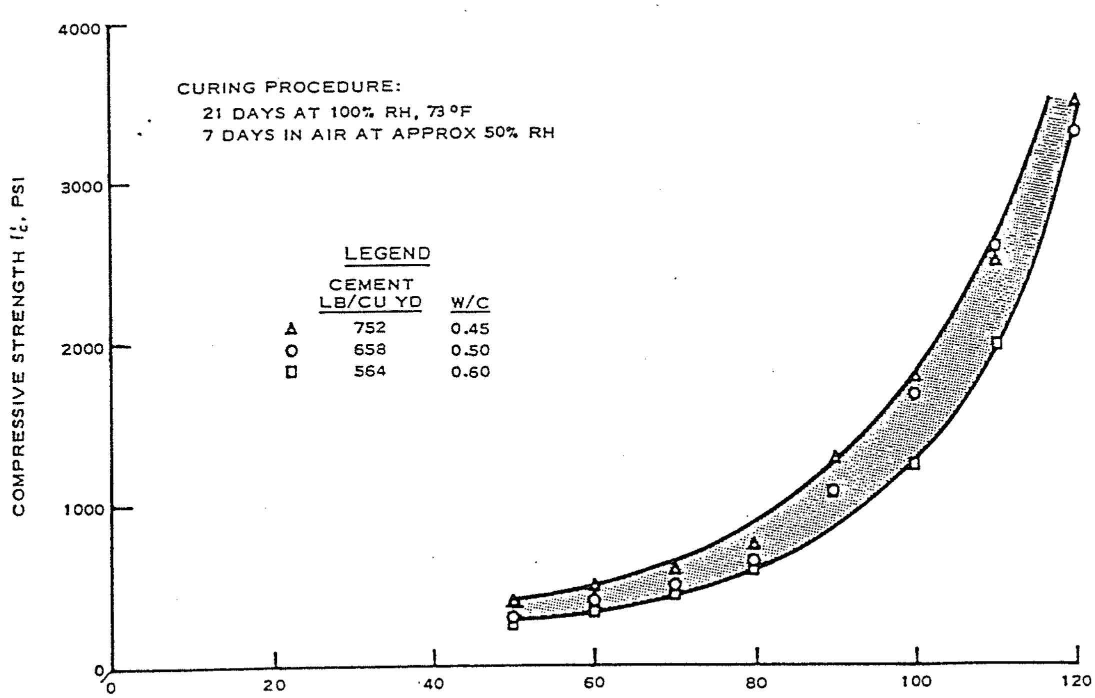

Figure 1 — Plastic weight, lb/cu ft

Typical measured modulus of elasticity for various aggregated and sanded concretes from ACI 523.3R-93 are shown in Figure 2.

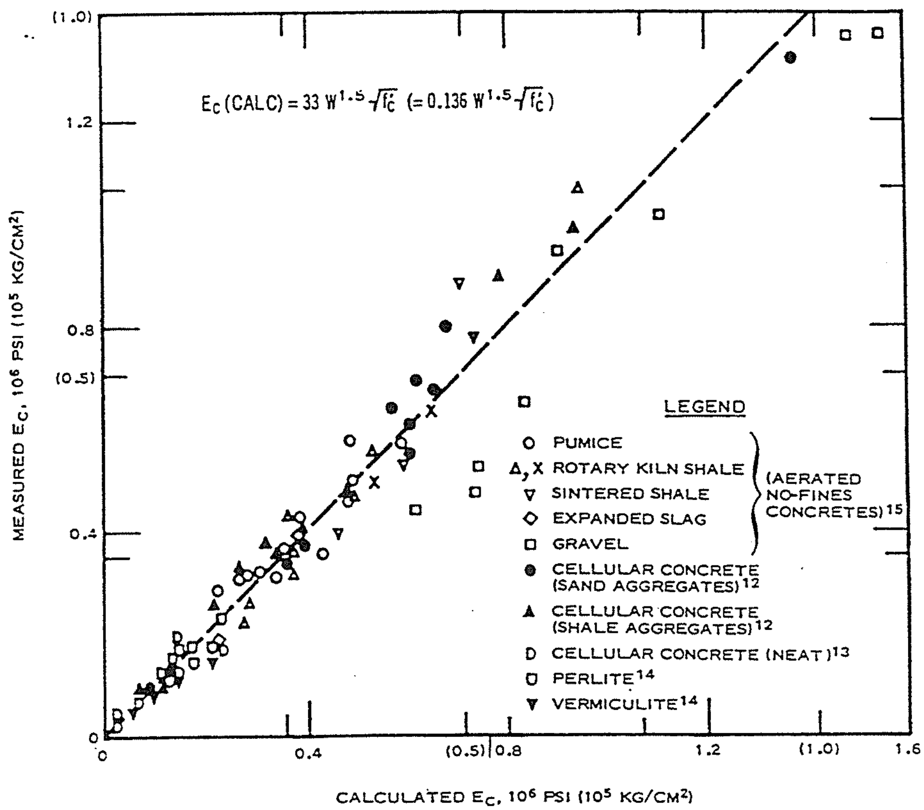

Figure 2 — Measured versus calculated modulus of elasticity

The above concretes had unit weights of 23 to 90 pcf and E_c values ranging up to 1.2 x 10^6 psi.

The 1993 Committee Report indicates that data for shear and diagonal tension strength and development of reinforcement are not available. In addition, data for creep, shrinkage, fire endurance, durability, abrasion, sound absorption, and transmission is usually not readily available.

Very little data are available for aggregated concretes with 50 to 105 pcf densities, while concretes with 105 to 130 pcf densities have been commonly tested. As noted later in this report, Donald Pfeifer from WJE has extensive experience with lightweight concretes with densities from 90 to 130 pcf and was a main contributor to the development of the ACI Committee 213 "Guide for Structural Lightweight Aggregate Concrete" in 1967.

This limited review of the 1992, 1993, and 1996 ACI 523 Committee Guides establish the general state-of-the-art of cellular and aggregated concretes with densities of 50 to 130 pcf, as well as establishing what data is lacking. Therefore, Stable Air high air concretes can be directly compared with current state-of-the-art for other similar high air content, low density concretes.

Additional data available for comparison are the numerous papers written by Donald Pfeifer based on structural lightweight aggregate concretes containing normal air contents. These published papers are as follows:

- Fiorato, A. E., Person, A., Pfeifer, D. W., "The First Large Scale Use of High Strength Lightweight Concrete in the Arctic Environment," Presented at the Second Symposium on Arctic Offshore Drilling Platforms, Houston, Texas, Apr. 11, 1984.
- Pfeifer, D. W., "Shrinkage-Compensating Concrete in Walls," ACI Klein Symposium on Expansive Cement Concrete, Publication SP-38, 1973, pp. 165-191.
- Pfeifer, D. W. and Hognestad, E., "Incremental Loading of Reinforced Lightweight Concrete Columns, ACI Symposium on Lightweight Concrete, Publication SP-29, 1971, pp. 35-45.
- Pfeifer, D. W., "Full-Size Lightweight Concrete Columns," Proceedings, ASCE, V. 97, ST2, Feb. 1971, pp. 495-508.
- Pfeifer, D. W., "Reinforced Lightweight Concrete Column," Proceedings, ASCE, V. 95, ST1, Jan. 1969, pp. 57-82.
- Pfeifer, D. W., "Fly-Ash Lightweight Concrete," PCA Research and Development Bulletin RD041.01T, Portland Cement Association, Skokie, Illinois, 1969.
- Pfeifer, D. W., "The Structural Use of Lightweight Concrete in the U.S.A.," Concrete Society (Great Britain) London and Birmingham, England, 1968.
- Pfeifer, D. W. and Hognestad, E., "Incremental Loading of Reinforced Lightweight Concrete Columns," Proceedings, 8th Congress of International Association for Bridge and Structural Engineering, New York, Sept. 1968, pp. 1055-1063.
- Pfeifer, D. W., "Sand Replacement in Structural Lightweight Concrete—Creep and Shrinkage Studies," Proceedings, ACI Journal, V. 65, Feb. 1968, pp. 131-139. Also, PCA Development Department Bulletin D128.
- Pfeifer, D. W., "Sand Replacement in Structural Lightweight Concrete—Freezing and Thawing Tests," Proceedings, ACI Journal, V. 64, November 1967, pp. 735-744. Also, PCA Development Department Bulletin D126.
- Pfeifer, D. W., "Sand Replacement in Structural Lightweight Concrete—Splitting Tensile Strength," Proceedings, ACI Journal, V. 64, July 1967, pp. 384-392. Also, PCA Development Department Bulletin D120.
- Pfeifer, D. W. and Hanson, J. A., "Sand Replacement in Structural Lightweight Concrete—Sintering Grate Aggregates" Proceedings, ACI Journal, V. 64, March 1967, pp. 121-127. Also, PCA Development Department Bulletin D115.

- Landgren, R., Hanson, J. A., and Pfeifer, D. W., "An Improved Procedure for Proportioning Mixes of Structural Lightweight Concrete," PCI Journal, V. 7, No. 2, May 1965, pp. 47-65. Also, PCA Research Department Bulletin 183.

ASTM TEST METHODS AND PRACTICES FOR EVALUATION OF STABLE AIR CONCRETE PROPERTIES

The following list of relevant ASTM Test Methods and Practices was provided to Stable Air in the May 8, 1997 letter.

C 31 - 91	Practice for Making and Curing Concrete Test Specimens in the Field
C 39 - 93a	Test Method for Compressive Strength of Cylindrical Concrete Specimens
C 78 - 94	Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading
C 138 - 92	Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete
C 143 - 90a	Test Method for Slump of Hydraulic Cement Concrete
C 157 - 93	Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
C 172 - 90	Practice for Sampling Freshly Mixed Concrete
C 173 - 94	Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
C 469 - 94	Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
C 490 - 93a	Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete
C 496 - 90	Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
C 511 - 93	Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
C 512 - 94	Test Method for Creep of Concrete in Compression
C 496 - 90	Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete
C 617 - 94	Practice for Capping Cylindrical Concrete Specimens

Thermal conductivity and transmittance tests were regarded by WJE as unnecessary since the 1967 PCA paper by Harold W. Brewer[1] and the 1993 ACI 523.3R report define these properties based on their unit weights, varying from 20 to 160 pcf, using saturated, oven-dry and normally dry conditions. Brewer reported that the conductivity of normally dried and saturated concrete with a unit weight of 120 lb/ft^3 was approximately 5 and 16 BTU.in./Hr/sq Ft/°F, respectively.

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[1]Brewer, H.W., *General Relations of Heat Flow Factors to the Unit Weight of Concrete,* Portland Cement Association Research and Development Laboratories Bulletin D114, 1967.

Supplemental freeze-thaw, salt scaling, and structural bond tests should be undertaken following the basic investigation, if the basic investigation warrants the supplemental tests. These tests were as follows:

C 234 - 91a	Test Method for Comparing Concretes on the Basis of the Bond Developed with Reinforcing Steel
C 457 - 90	Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete
C 666 - 92	Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 672 - 92	Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals

LITERATURE REVIEW AND REVIEW OF EXISTING DATA

On May 19, 1997, a letter was sent from WJE to Mr. David Masters, President of Stable Air Inc., containing a review of submitted test data on high air content, cellular concretes with and without coarse aggregates. The following documents were reviewed.

- Standard Method for Sampling and Testing Lightweight Cellular Concrete
- Review of Composite Concretes for Precast and In-Situ Applications
- Lightweight Foam and Composite Concrete
- Standard Fire-Resistant Test on a 150-mm (6-in.) Thick Lightweight Concrete Wall Panel By BHP Research, Sept. 1992
- Cellular Foamed Concretes — Notes on Fire Resistance
- Technical Report No. C101/5 - M/86 Cellular Lightweight Concrete Using Light-weight Concrete By Royal Scientific Society Building Materials Division, Sept. 1986
- Cellular Concrete
- Data from Mr. Gray

The comments from our review process follow:

Standard Method for Sampling and Testing Lightweight Cellular Concrete

- This document uses metric values, such that standard cylinder sizes of 4 x 8 or 6 x 12 in. are not used. A 3 x 6 in. cylinder size is used, a size not accepted with structural concrete in the United States.

- The 3 days of oven drying at age 25 days is not defined as to oven temperature, and a unit weight test at 28 days is not required as a companion to the 28-day compressive strength test. The oven temperature and the unit weight must be defined.

- ASTM Test Procedures and Methods should be specified when possible. This document utilizes no ASTM Procedures or Methods.

- The document does not include a unit weight measurement when allowed to air dry under controlled conditions at 23 ± 2°C and 50 ± 10 percent relative humidity. This is vital, since oven drying unit weight will never occur in structural precast concrete members placed outside.

- This document needs significant revisions, such as:
  - Vibration is not permitted.
  - Rate of load application during strength testing should follow ASTM.
  - Cylinder size needs revision.
  - Only fog-cured concrete is allowed. Heat-cured concrete is not permitted.
  - Modulus of elasticity tests are not required.
  - Density versus age at different relative humidity conditions should be considered.

Based upon review of this document we consider that it would not provide data that could be utilized within the United States Precast Concrete Industry.

Review of Composite Concretes for Precast and In-situ Applications

- This document covers concretes with densities from 25 to 100 lb/ft^3 with compressive strengths from 300 to 2600 psi.

- Four hour heat transmission fire rating data for an unspecified density can be achieved with 4 to 6 in. of cellular concrete, based on tests in Australia, Italy, New Zealand, and England.

- Data are very limited.

Lightweight Foam and Composite Concrete

- This document is limited to concretes with densities of 25 to 100 lb/ft^3 with compressive strengths from 300 to 2600 psi.

- Tensile strength can be as high as 25 percent of the compressive strength, although no data are shown.*

- Shear strength can be between 6 and 10 of the compressive strength, although no data are shown.*

- Tensile strain capacity can be as high as 1000 x 10^{-6} in./in. at rupture.*

- Shrinkage in 28 days can be as low as 600 x 10^{-6} in./in.

- Coefficient of thermal expansion is same as regular concrete, that is, 5×10^{-6} in./in./°F.
- There are no data on normal weight concrete plus stable foam addition or with lightweight aggregate concrete plus foam.
- The curing section (page 10) is unusual and the write-up regarding air-curing is questionable.
- The steam-curing write up discusses the possibility of air pressure in air bubbles causing fracture of the air bubbles during heat curing if heat is applied too soon. A 5-hr present period is discussed, and maximum temperature of 158°F is discussed.
- Autoclaving is discussed. This method has little application for structural precast. Autoclaves are too big and costs are huge.

  * Data reviewed in "Cellular Concrete" suggest that these percentages are only valid for autoclaved concretes.

Standard Fire-Resistant Test on a 150-mm (6-in.) Thick Lightweight Concrete Wall Panel by BHP Research, Sept. 1992

- The 6-in. wall panel consisted of a 4.8-in. thick core of 37 lb/ft^3 cellular concrete with a 0.6-in. thick surface skin of 94 lb/ft^3 cellular concrete. The core contained polyproplyene fibers.
- The fire test lasted 5 hours and 7 minutes and passed the Australian Standard AS 1530.4-1990.
- Temperature of the unexposed face increased from about 81°F to 163°F, far less than the average 284°F maximum allowed.
- No data on compressive strength of concrete were presented in report.
- No cracks, fissures or openings developed during the test.

Cellular Foamed Concrete — Notes on Fire Resistance

- No comment, except Table 8.1 indicates essentially the same thickness to time relationship as the typed-in. note for 70 pcf density concrete.

Technical Report No. C 101/5 - M/86 Cellular Lightweight Concrete Using Lightweight Concrete by Royal Scientific Society Building Materials Division, Sept. 1986

- This report deals with cellular concretes with dry densities of 25 to 37 lb/ft^3, composed of sand and cement mortars with a stable foam.
- Foam density was 5 lb/ft^3. Air pressure had to be maintained constant or foam density consistency was a problem.
- Natural density and 90°C oven dry densities were very similar.

- Compressive strengths at 28 days were 90 to 260 psi measured on nominal 6-in. cubes.
- Densities at 28 days ranged from 23 to 38 lb/ft^3.
- Comparison of this cellular concrete with other types of lightweight concretes, as shown in Appendix (Table 7.2), is as follows:

Approximate density, lb/ft^3	Approximate compressive strength, psi	Concrete type
25	87	Subject concrete
25	44 to 275	Polystyrene concrete
25	175 to 400	Aerated concrete
31	193	Subject concrete
31	109 to 400	Polystyrene concrete
31	230 to 580	Aerated concrete
37	96 to 260	Subject concrete
37	160 to 565	Polystyrene concrete
37	360 to 926	Aerated concrete
69	1880 to 3534	Lightweight aggregate concrete
87	>5070	Lightweight aggregate concrete

- These tests indicate very low compressive strengths at 28 days of 100 to 300 psi, far below the 2000 to 5000 psi strengths shown in Table 7.2 for 69 to 87 lb/ft^3 concretes that used an air foaming system.

Lightweight Foam and Composite Concrete

- This undated 70-page document contains references up to 1983.
- Cellular concrete projects in the United States have been few.
- Cellular concretes range in density from 12 to 120 pcf.
- Cellular concretes generally do not contain coarse aggregates, just cement, water, sand, and air.
- Lightweight coarse aggregates are sometimes used.

- Allowances must be made for unit weight changes for instability of the bubbles during the placement.

- The steam curing at atmospheric pressure discussion is highly questionable, as related to using 175 to 212°F temperatures after steam curing.

- The autoclaving discussion is probably of little value to this current study for the precast, prestressed concrete industry. The one factor of value is the warning that high curing temperatures will cause air pressure increases in the bubbles which can cause cracking and strength loss.

- Most of the strength data discussed are from autoclaved concretes, flexural, tensile and shear strengths.

- The static modulus of elasticity of 80 pcf moist-cured concrete with a compressive strength of 530 psi is stated to be 10.7×10^6 psi! The ACI 318 equation for E would predict 0.54×10^6 psi. The ACI E equation on page 38 is incorrect.

- Absorptions for cellular concretes are indicated to be very high at 32 percent by weight or 28 percent by volume, and these values appear to be independent of density.

- The thermal conductivity values on page 41 correlate well with the 1967 PCA paper by Brewer over the range of 20 to 140 pcf.

- Oven dry coefficient of thermal expansion ranges from 5.6 to 6.7×10^{-6} in./in./°F.

- Cellular concretes produced by the ordinary air curing process has very high shrinkage. These concretes also have very high re-wetting expansions of 700 to 1500×10^{-6} in./in.

- Structural concrete in the range of 80 to 120 pcf has a 28-day minimum strength requirement of 2500 psi, as per ACI 523.3R.

Mr. Gray's Data

- All of the data sheets were reviewed. These data sheets generally were limited to compressive strength data at different ages, date of casting and testing, air-drying unit weight, but no specific mix design figures or yield values.

1997 WJE LABORATORY STUDIES

June 5, 1997 Proposal

Based on the WJE review of the submitted data on high air content concrete by Stable Air, WJE suggested a series of limited tests in the WJE laboratories since the submitted data from Stable Air Inc. on 120 pcf structural concrete was so limited. Three days of mixing concrete in our laboratory, starting on June 23, 1997, was proposed. These limited laboratory studies were to deal with the following aspects:

1. Unit weight stability under varying degrees of mechanical vibration.
2. Plastic versus hardened unit weights.
3. Strength versus hardened unit weight.
4. The role of accelerators and high range water reducers in producing 120 pcf concretes.

Laboratory Work June 24 to 25, 1997

On June 23 to 25, 1997 Wiss, Janney, Elstner Associates, Inc. (WJE) worked with Messrs David Masters and Brian Smith on concretes containing Stable Air. During this period WJE was informed that the Stable Air System delivers an air-entrained foam that is then mixed into concrete. The machine used to supply the foam is shown in Figure 3. We understand that the process to obtain the foam is a highly-specialized procedure and that the stability of the air in the foam is related to bubble size, moisture content of the bubbles and the type of surfactant used in forming the foam. From research conducted by Stable Air it was indicated that the best foam was obtained at a density of approximately 67 g/L; which is equivalent to 3.35 lb for a 6 gal bucket of foam. During batching of concrete containing foam at WJE, measurements were taken to determine if the foam met this density requirement, prior to placement of the foam into the concrete, as shown in Figure 4.

Concrete mixing, procedures, and materials were similar to those used in precast concrete operations. No. 6 coarse aggregate, sand, and Type I/II cement from Mr. John Nanna of J.W. Peters were used in all concretes mixed by WJE. The coarse aggregate and sand have absorption values of 2.75 and 2.71 percent. All materials were cast using aggregates that were approximately saturated surface dry (SSD). During the unit weight and slump testing, rodding of the cylinders was not conducted.

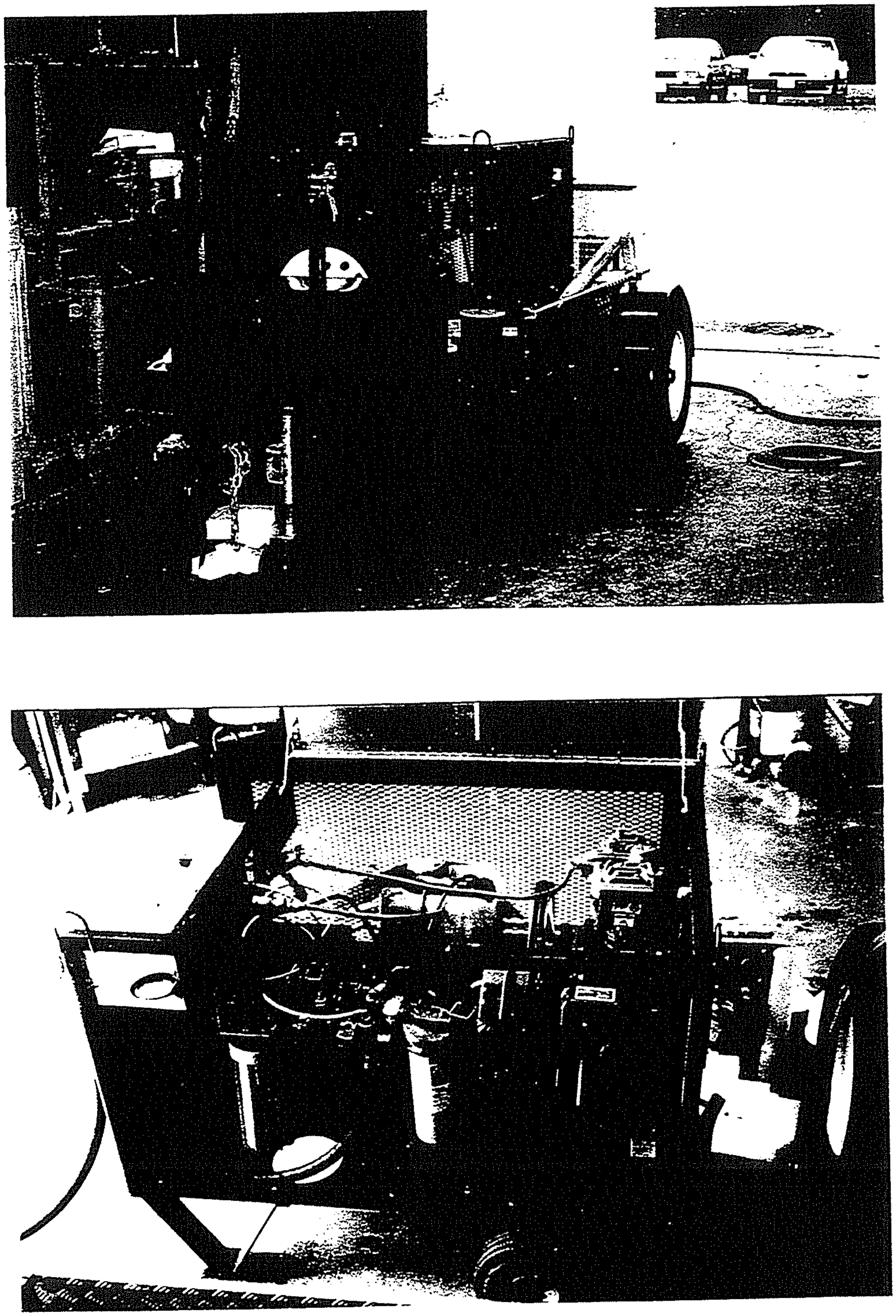

Figure 3 — Specialized foam delivery machine used in the studies

Figure 4 — Measuring foam into 6-gallon bucket

Studies were conducted to consider the effect of vibration time and heat curing on the concrete compressive strength. Additional studies considered the effect of mixing sequence on the concrete compressive strengths. The studies are outlined below.

Complete mixing details are shown in Appendix A. All concrete was mixed in a pan mixer with a single rotary blade turning in the opposite direction to the pan. In general, mixing was conducted using 3 minutes of mixing, 3 minutes of rest and 2 minutes of re-mixing. If additional foam was added, the concrete was mixed for a further 2 minutes. All mixtures had high slumps and finished readily. Figure 5 shows foam being mixed into the concrete. Notes based upon batching are shown in Table 1. Mixtures 1, 106, 2 and 3 were cast on June 24, 1997 while mixtures 4, 5, 6, and 7 were cast on June 25, 1997.

Figure 5 — Mixing foam into concrete batch using high shear mixer

TABLE 1 - NOTES FROM BATCHING OF STABLE AIR MIXTURES

Mix ID	Foam weight per 6 gal (lb)	Density of foam (g/L)	Total weight of foam added (lb)	Fresh unit weight (lb/ft^3)	Notes - All batches were approximately 345 lb
1	3.47	69.4	5.5 (approx)	113.1	Non-vibrated cylinder weight = 22.97 lb (116.9 lb/ft^3) 5-minute vibrated cylinder weight = 22.31 lb (118.2 lb/ft^3) Cast 9 cylinders - normal cure V-0: non-vibrated V-2: 2 minutes vibration V-5: 5 minutes vibration
106	3.5	70.0	7.0	105.9	Cast 3 cylinders
2	3.4	68.0	6.71	116.2	Cast 14 cylinders - heat cure to 145°F.
3	3.33	66.6	5.63	116.4	Cast 14 cylinders - burlap cure
4	3.25	65.0	5.72	117.7	Cast 14 cylinders - heat cure 6 cylinders to 110°F, burlap cure 8 cylinders
5	3.38	67.6	7.08	112.5	Cast 14 cylinders - heat cure 6 cylinders to 110°F, burlap cure 8 cylinders
6	3.30	66	5.56	116.5	Cast 14 cylinders - heat cure 6 cylinders to 110°F, burlap cure 8 cylinders
7	3.26	65.2	4.94	110.1	Contains PMT-1. Cast 14 cylinders - heat cure 6 cylinders to 110°F, burlap cure 8 cylinders

Mixtures 1, 106, 2 and 3 were cast with a coarse/fine aggregate ratio of 1.5 while Mixtures 4, 5, 6, and 7 were cast with a coarse/fine aggregate ratio of 1.0. After curing, the cylinders were demolded and placed at 50 percent relative humidity and 73°F until tested.

From Mix 1, it was found that the unit weight would only increase slightly under extended vibration. This mix exhibited an increase from 116.9 to 118.2 lb/ft^3 after 5 minutes on a vibration table. In order to compare the effects of vibration on compressive strengths and hardened unit weight, three cylinders from this mixture were not vibrated, three were vibrated on a table vibrator for 2 minutes and three were vibrated on a table vibrator for 5 minutes.

Mixture 106 was cast using a higher foam concentration than that of Mixture 1. The fresh density of this material was 105.9 lb/ft^3. Only 3 cylinders were cast from this mixture.

Mixture 2 was cast at a fresh unit weight of 116.2 lb/ft^3. Heat curing of the cylinders began 4.4 hours after casting. These were heat cured to a maximum of 145°F at a heating rate of 20°F/hr. After 11.5 hours the curing was reduced to ambient temperature.

Cylinders cast with Mixture 3 were cast at a unit weight of 116.4 lb/ft^3. Cylinders from this mixture were cured under burlap for 24 hours.

Cylinders cast with Mixture 4 were cast at a unit weight of 117.7 lb/ft^3. Six cylinders from this mixture were heat cured while 8 cylinders were burlap cured for 24 hours. Heat curing of the cylinders began 8 hours after casting. These were heat cured to a maximum of 110°F at a heating rate of 20°F/hr. After 6 hours the curing was reduced to ambient temperature.

Cylinders cast with Mixture 5 were cast at a unit weight of 112.6 lb/ft^3. Six cylinders from this mixture were heat cured while 8 cylinders were burlap cured for 24 hours. Heat curing of the cylinders began 6.5 hours after casting. These were heat cured to a maximum of 110°F at a heating rate of 20°F/hr. After 6 hours the curing was reduced to ambient temperature.

Cylinders cast with Mixture 6 were cast at a unit weight of 116.5 lb/ft^3. Six cylinders from this mixture were heat cured while 8 cylinders were burlap cured for 24 hours. Heat curing of the cylinders began 5.8 hours after casting. These were heat cured to a maximum of 110°F at a heating rate of 20°F/hr. After 6 hours the curing was reduced to ambient temperature.

Cylinders cast with Mixture 7 were cast at a unit weight of 110.1 lb/ft^3. This concrete contained an additive PMT-1 Enhance. Six cylinders from this mixture were heat cured while 8 cylinders were burlap cured for 24 hours. Heat curing of the cylinders began 5.4 hours after casting. These were heat cured to a maximum of 110°F at a heating rate of 20°F/hr. After 6 hours the curing was reduced to ambient temperature.

Even through only cylinders from Mixture 1 had been vibrated, it was found that formed surfaces all appeared good, with minimal bug-holes in the concrete surface.

At various ages, the compressive strengths of the various concretes were measured. At the same time, the strengths were determined, the weights of each cylinder were also measured to enable the approximate hardened unit weight of the concrete to be determined, as shown in Figure 6. Results from these tests are shown in Table 2.

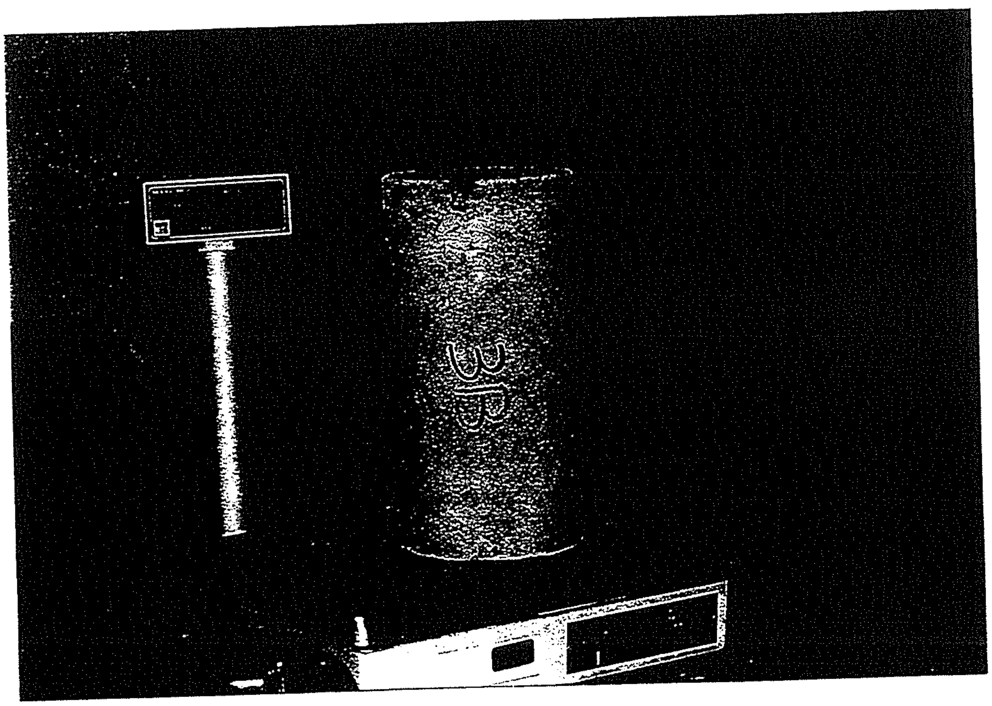

Figure 6 – Determination of hardened unit weight (119.5 lb/ft^3)

TABLE 2 — COMPRESSIVE STRENGTHS AND HARDENED UNIT WEIGHTS

Mixture	Cure	Compressive strengths (psi)				Hardened cylinder unit weight at 7 days (lb/ft^3)
		14 hrs	24 hrs	7 days	28 days	
1 — zero vibration	Normal			1185 1193		123.4 122.5
1 — 2-min. vibration	Normal			1167 1070		119.6 118.5
1 — 5-min. vibration	Normal			1061 1034		120.1 119.6
106	Heat			967 912		123.0 121.9
2	Heat	600 688 527	746 739	739 896		118.5 118.2
3	Normal		557 645	1005 1028		120.9 121.7
4	Normal		1026 1061	1361 1335	1609 1742	119.0 118.0
4	Heat		1061 1079	1273 1238	1600 1574	118.3 115.6
5	Normal		637 654	867 849		113.8 114.0
5	Heat		654 619	867 849		113.9 113.4
6	Normal		902 920	1318 1326		118.4 116.8
6	Heat		937 973	1256 1220		114.3 116.3
7	Normal		566 566	858 849		113.8 114.3
7	Heat		619 601	814 822		113.1 113.6

Figure 7 shows the average compressive strength of the cylinders after 7 days. From this figure the following conclusions were drawn.

- Extended vibration is detrimental to the development of compressive strength (Mixture 1).
- Heat curing reduced the strengths obtained after 7 days of curing (Mixtures 4, 5, 6, and 7).
- The mixing sequence plays a significant role in the development of compressive strength (Mixtures 4, 5, and 6).

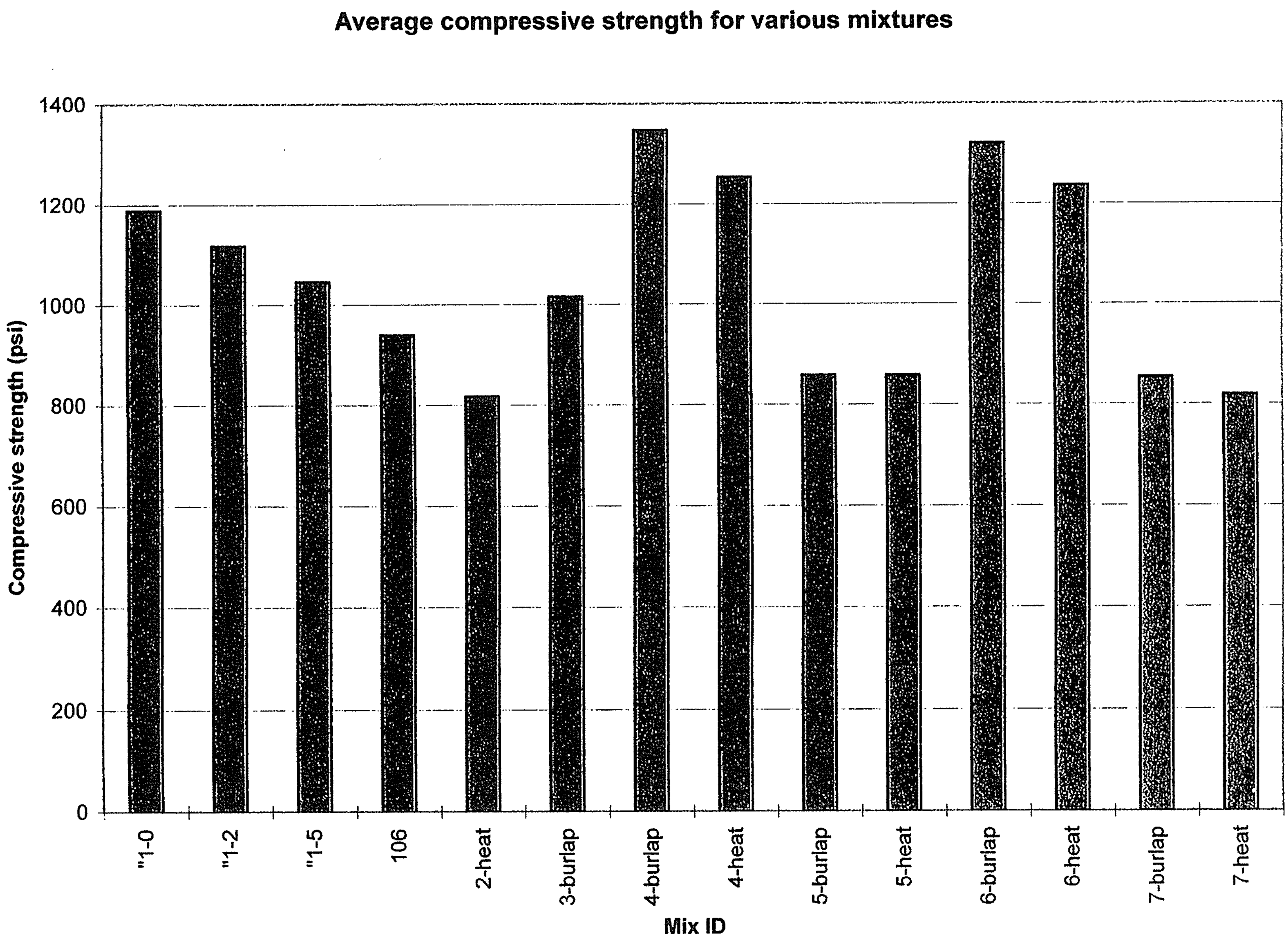

Figure 7 — Average compressive strength for various mixtures made in June 1997

After 24 hours, only Mixture 4 heat-cured and Mixture 4 burlap-cured cylinders had strengths greater than 1000 psi. The lowest strengths were obtained by mixture 7 normal cure, containing a chemical "hardener" PMT-1. For this reason, and based upon discussions by Bill Hime from WJE with the manufacturer of that material, we recommended that further studies containing the PMT-1 be discontinued at this time.

After 7 days the highest strength (1348 psi) was obtained by Mixture 4, burlap cured. We believed that additional compressive tests on the cylinders will not lead to significantly different results from those obtained after 7 days. Cylinders from Mixture 4 were evaluated after approximately 28 days of curing. These exhibited a compressive strength of approximately 1600 psi. There was no significant difference in the compressive strength of the cylinders that had been heat cured and those that were moist cured.

Figure 8 shows the fresh concrete unit weights and those determined from the hardened concrete cylinders after 7 days. All cylinders exhibited an increase in unit weight indicating that the air contents of these mixtures decreased during hardened. Figure 9 shows the compressive strength of the cylinder plotted against the hardened unit weight of the concretes

Cylinder From Coreslab

Data shown to WJE by Stable Air from tests conducted at Coreslab Structures (L.A.) Inc. of Perris, California showed concretes with compressive strengths at 24 hours in excess of 3000 psi. The 24 and 7-day strengths obtained by WJE were considerably lower than this value. It was recommended by WJE that the fundamental factors leading to the differences between our studies and those conducted by others should be determined. The studies conducted by Coreslab were run in a drum type mixer, and not a high-shear pan mixer used by WJE. For the precast industry, mixing machines, similar to our high-shear pan mixer, have been developed to ensure that constituents are thoroughly mixed. Possibly, the differences in mixing devices used in the two studies are leading to variations in the air distribution and air size in the mixture. It was later determined that the cement types used in these studies were different and that Coreslab had used a Type III cement.

WJE was sent a cylinder from Coreslab that reportedly had a unit weight of around 120 lb/ft^3 and had obtained a compressive strength greater than 3500 psi. Upon receipt of the 4 x 8 in. cylinder, WJE weighed this cylinder and determined its unit weight. The cylinder weighed 8.199 lb indicating a unit weight of 140 lb/ft^3. This weight is typical of high air-content normal-

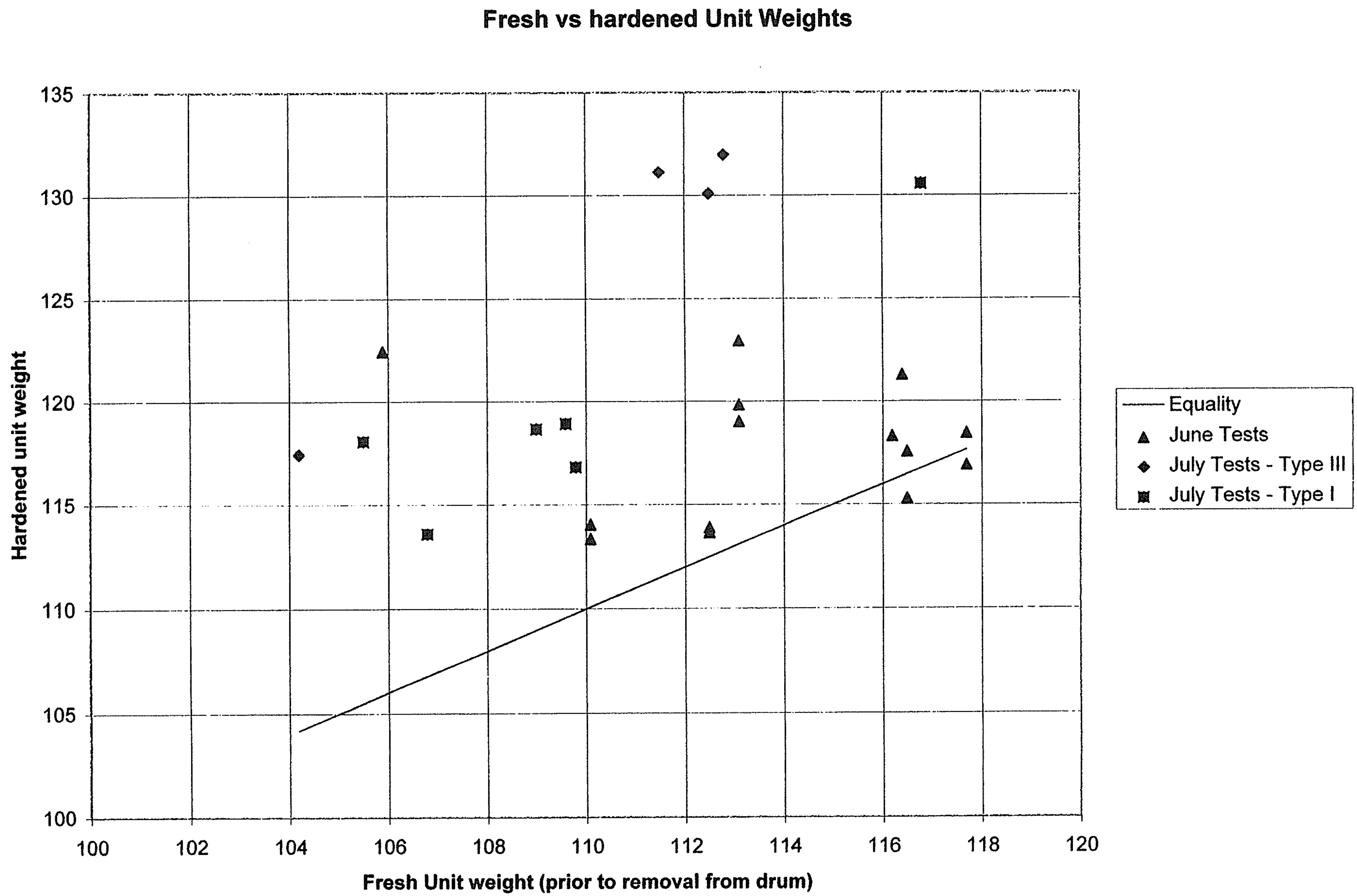

Figure 8 — Fresh and hardened unit weights determined for concretes made in June and July 1997

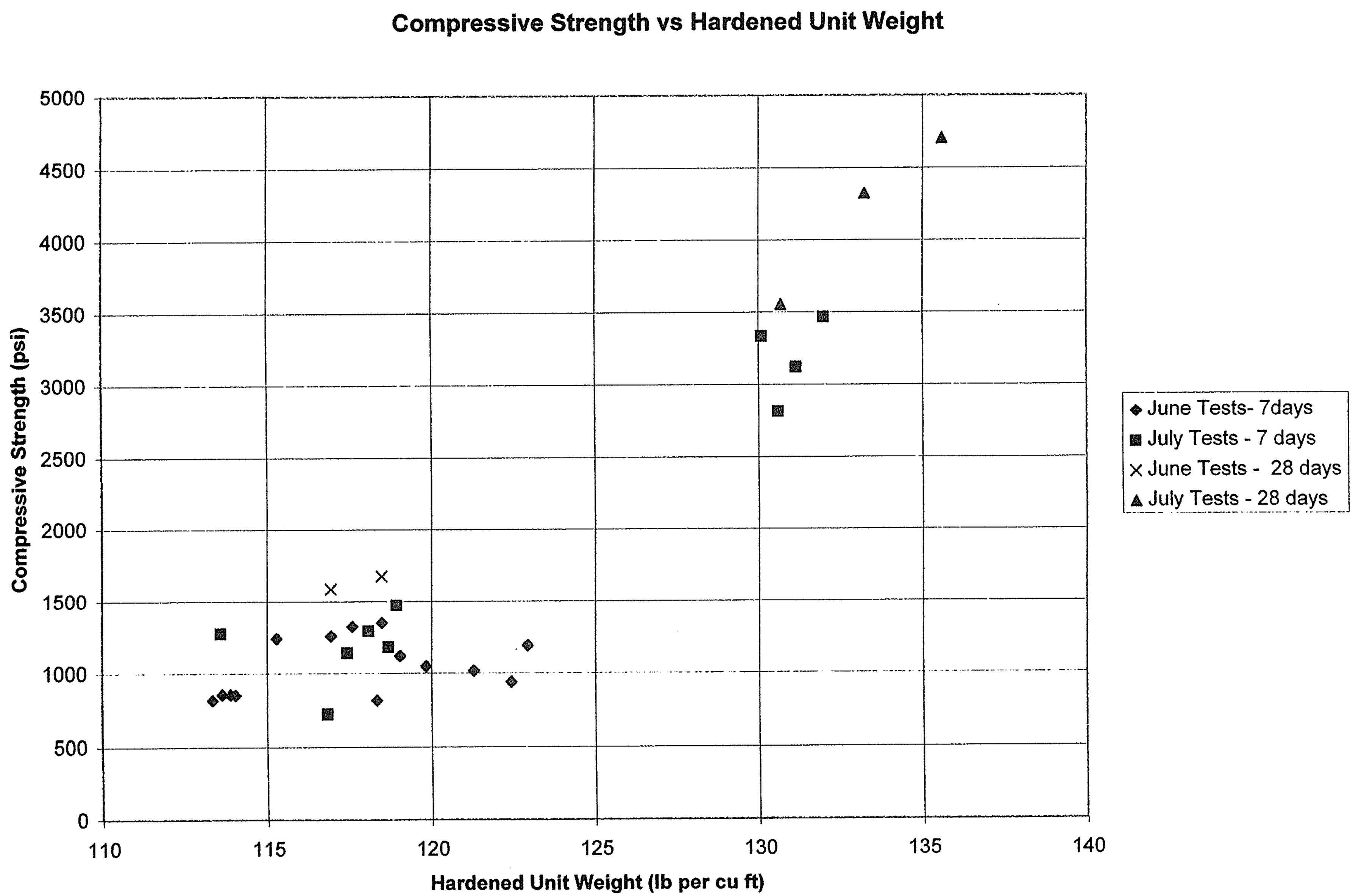

Figure 9 — Compressive strength versus hardened unit weight

weight concretes. The cylinder compressive strength was measured by WJE to be approximately 6500 psi; which would be typical of a reasonably high air-content concrete with a very low water-cement content.

July 18, 1997 Proposal

On July 18, 1997, WJE sent a proposal to Mr. David Masters regarding further testing of Stable Air. Four days of mixing concrete in the WJE laboratory was proposed, starting on July 22, 1997. Testing proposed was strength, unit weight, and modulus of elasticity, tests on these various hardened concrete and the plastic concrete. Based upon the results obtained during the prior studies, it was determined that the cylinders would not be heat cured during the additional work.

Laboratory Work July 21, to July 23, 1997

On July 21 to 23, 1997 Wiss, Janney, Elstner Associates, Inc. (WJE) worked with Mr. David Masters on concretes containing Stable Air. During previous studies WJE used a high shear pan mixer. A rotating drum mixer was used for all batches in this phase of work in late July. Most of the concretes mixed during this period contained No. 6 coarse aggregate, sand, and Type I cement from Mr. John Nanna of J.W. Peters; however, mixtures 7, 8, 9 and 10 contained Type III cement sent to WJE by Mr. Brian Smith of Stable Air.

All materials were cast using aggregates that were approximately SSD. During the unit weight and slump testing, rodding of the cylinders was not conducted. Complete mixing details are shown in Appendix B. All cylinders were cured in sealed molds at room temperature. Although the mixtures are similar in overall composition, differences exist in the exact batching procedures used for these studies. Notes based upon batching are shown in Table 3. Mixtures 1, 2, and 3 were cast on July 21, 1997; Mixtures 4, 5, and 6 on July 22, 1997 and Mixtures 7, 8, 9, and 10 on July 23, 1997. The aim of the testing on July 21, 1997 was to determine if the type of mixer played a role in the compressive strength. Other mixtures were cast to investigated the effects of mixing sequence on the unit weight of the concretes.

TABLE 3 - NOTES FROM BATCHING OF STABLE AIR MIXTURES

Mix ID	Foam weight per 6 gal (lb)	Density of foam (g/L)	Total weight of foam added (lb)	Fresh unit weight (lb/ft^3)	Notes — Batch weights were approximately 292 ln
1	3.56 3.25 3.42	71.7 65.0 68.4	4.52	109.6	Type I cement
2	3.40	68.0	5.19	106.8	Type I cement
3	3.47	69.4	4.44	105.5	Type I cement
4	3.36	67.2	4.44	109.8	Type I cement. Extended mixing and unit weight study
5	3.38	67.6	5.11	116.8	Included high-range water reducer
6	3.44	68.8	5.15	109.0	Type I cement
7	3.05	67.4	10.07	111.5	Type III cement
8	3.43	68.6	7.58	112.5	Type III cement
9	3.38	67.6	7.41	112.8	Type III cement
10	3.34	66.8	8.01	104.2	Type III cement

Mixture 1 was cast at a density of 109.6 lb/ft^3. This mixture was cast using Type I cement at a w/c of 0.25 and a coarse/fine aggregate ratio of 1.0.

Mixture 2 was similar to Mixture 1 but cast at a density of 106.8 lb/ft^3. This mixture was cast using Type I cement at a w/c of 0.26 and a coarse/fine aggregate ratio of 1.0.

Mixture 3 was similar to Mixture 2 but cast at a density of 105.5 lb/ft^3.

Mixture 4 was used to evaluate the stability of unit weight for the concrete. Unit weights obtained for the mixture at different periods are shown below:

Elapsed time (minutes)	Unit weight (lb/ft^3)
During mixing	
11	113.8
16	113.7
21	111.5
26	109.8
Dump concrete into barrow	
31	111.9
42	112.8
50	113.1
60	113.2
81	113.8

During the mixing process the unit weight of the concrete was observed to decrease from 113.8 lb/ft^3 to 109.8 lb/ft^3. Immediately after removal of the concrete from the mixer the unit weight increased from 109.8 to 111.9 lb/ft^3; possibly indicating that air bubbles were collapsing during the discharge process. When the concrete was allowed to stand the unit weight increased from 111.9 to 113.8 lb/ft^3.

Mixture 5 was cast at a density of 116.8 lb/ft^3, 30 minutes after the cement and water were added to the mixer. This concrete contained the high range water-reducer, Rheobuild 1000. This mixture was cast using Type I cement at a w/c of 0.26 and a coarse/fine aggregate ratio of 1.5. After 35 minutes the mixture exhibited a unit weight of 127.2 lb/ft^3 and after 46 minutes exhibited a unit weight of 129.8 lb/ft^3. The rapid changes in unit weight indicate that the stability of the air bubbles may be influenced by the particular high-range water-reducer. The interaction of air-entraining and water-reducing admixtures is well known in the concrete industry and care should be taken to ensure that the Stable Air system is compatible with commonly used admixtures.

Mixture 6 was cast at a density of 109.0 lb/ft^3, 13 minutes after the cement and water were added to the mixer. This mixture was cast using Type I cement at a w/c of 0.26 and a coarse/fine aggregate ratio of 1.5. After 27 minutes the unit weight of the concrete was 116.3 lb/ft^3 and after 40 minutes the unit weight of the concrete was 116.4 lb/ft^3. This indicates that once discharged the Stable Air system may have good unit weight stability for this particular mixture.

Mixture 7 was placed into the barrow at a density of 111.5 lb/ft^3, 18 minutes after the cement and water were added to the mixer. This mixture was made using a Type III cement at a w/c of 0.26 and a coarse/fine aggregate ratio of 1.5. After 26 minutes the unit weight of the concrete was 123.4 lb/ft^3. This mixture suffered from a significant slump loss from 10 in. after 23 minutes to only 1 in. after 34 minutes. This unforseen slump loss was investigated in Mixtures 8, 9, and 10 and in additional foam/cement studies discussed later in this report.

Mixture 8 was cast at a density of 112.5 lb/ft^3, 17 minutes after the cement and water were added to the mixer. This mixture was cast using Type III cement at a w/c of 0.26 and a coarse/fine aggregate ratio of 1.5. After 23 minutes the unit weight of the concrete was 130.8 lb/ft^3. This mixture suffered from a significant slump loss from 4 in. after 21 minutes to only 1 in. after 25 minutes.

After 12 minutes the unit weight of Mixture 9 was 112.8 lb/ft^3; however, after 16 minutes the unit weight was 132.4 lb/ft^3. This mixture was cast using Type III cement at a w/c of 0.26 and a coarse/fine aggregate ratio of 1.5. Again, rapid slump loss was observed with this concrete.

Mixture 10 was cast at a density of 104.2 lb/ft^3, 15 minutes after the cement and water were added to the mixer. This mixture was cast using Type III cement at a w/c of 0.275 and a coarse/fine aggregate ratio of 1.5. After 19 minutes the unit weight of the concrete was 118.0 lb/ft^3. This mixture also suffered from a significant rapid slump loss.

Mixtures 7 to 10 all had rapid slump losses; presumably resulting from interactions between the cement type/chemistry and the foam. Cement/foam interactions were believed to cause this unusual rapid slump loss and air loss and these aspects are discussed later in this report.

The compressive strengths of the various concretes were measured. At the same time, the strengths were determined, the weights of each cylinder were also measured to enable the approximate hardened unit weight of the concrete to be determined. Results from these tests are shown in Table 4.

TABLE 4 — COMPRESSIVE STRENGTH AND UNIT WEIGHT

Mixture	Cure	Compressive strengths (psi) Unit weights (lb/ft^3)		
		19-24 hours	7 days	30 days
1	Normal	1175, 118.3 1185, 119.4	1512, 117.2 1433, 119.6	
2	Normal	848, 114.2 840, 114.5	1291, 114.8 1256, 113.0	
3	Normal	972, 118.8 955, 119.5	1203, 116.9 1380, 117.4	
4	Normal	318, 116.4 341, 118.2	548, 113.0 902, 117.3	
5	Normal	1804, 128.9 1892, 128.1	2273, 125.7 3360, 132.3	
6	Normal	318,119.5 1397, 119.4	999, 116.7 1362, 120.7	
7	Normal	2174, 128.5 2263, 128.6	2883, 129.7 3360, 132.6	4704, 134.7 4704, 136.5 5430*, 136.7
8	Normal	2387, 130.2 2670, 130.8	3343, 130.6 3767, 133.4	3820, 131.5 3289, 129.9 4687, 134.1 5023*, 132.8
9	Normal	2829, 131.0 2759, 130.5	3166, 130.6 3767, 133.4	4492, 132.1 4156, 134.4 4439, 133.0 5041*, 132.8
10	Normal	787, 117.6 755, 116.6	1203, 118.1 1079, 1079	
*Tests conducted after modulus tests and 3 days of air drying.				

From the strength evaluations of Mixtures 1, 2 and 3 and comparison with data from the June studies it was determined that the mixer played a minimal role in the strength development of the concretes.

The four mixtures containing the Type III cement exhibited significant bug-holes and generally had poor consolidation caused by the rapid changes in slump loss and placement difficulties. These mixtures generally had higher compressive strengths and higher unit weights than the other concretes.

Concretes that were permitted to air dry prior to testing exhibited approximately 10 percent higher strength than the concretes that were not permitted to air dry.

Figure 8 shows the fresh concrete unit weights and those determined from the hardened concrete cylinders after 7 days. All cylinders exhibited an increase in unit weight indicating that the air contents of these mixtures decreased. Unit weight increases were higher for those mixtures containing the Type III cements; probably due to the rapid slump losses and cement/foam interactions observed shortly after mixing.

Figure 9 shows the compressive strengths plotted against the hardened unit weight of the concretes. Data from the June and July tests are comparable. As may be expected, a strong relationship exists between the unit weight and the compressive strength of the concretes. For concretes with hardened unit weights of around 115 to 120 lb/ft^3, compressive strengths at 7 days of 1100 to 1500 were measured. For mixtures with hardened unit weights of around 130 lb/ft^3, compressive strengths at 7 days of 3000 psi were measured.

Elastic Modulus of Hardened Concrete

The elastic modulus is an important design parameter as it is used in predicting deflections and prestress losses. In the design standard ACI-318, it is common to assume that the compressive strength is related to the square root of the compressive strength ($57000\sqrt{f'_c}$). ACI Committee 209 and 523 present a similar equation that relates the elastic modulus to the unit weight of the concrete and square root of the compressive strength ($33\sqrt{w^3 f'_c}$).

Elastic modulus results were determined for concretes from Mixtures 7, 8, and 9 according to ASTM C 469 *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete In Compression,* approximately 30 days after casting. Values obtained are shown in Table 5.

TABLE 5 — MEASURED ELASTIC MODULUS, COMPRESSIVE STRENGTH AND UNIT WEIGHT

Mixture	Unit weight lb/ft³	Compressive strength (psi)	Elastic modulus (x 10^6 psi)
7	134.7 136.7	4704 5430*	3.58 3.69*
8	131.5 132.8	3820 5023*	3.19 3.40*
9	132.1 132.8	4492 5041*	3.05 3.08*
*Tests conducted after 3 days of air drying.			

The predicted elastic modulus for these concretes using both the ACI-318 equation and the ACI-209 equation are plotted against the compressive strength in Figure 10. The ACI-318 equation over-predicts the elastic modulus while the ACI-209/523 equation fits the measured data relatively well.

Splitting Tensile Strength

The tensile strength of concrete is an important design parameter as it is used in slab design and predicting shear strengths. Tests were conducted on concretes from Mixtures 7, 8, 9 and 10 according to ASTM C 496 *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens,* approximately 30 days after casting. Values obtained are shown in Table 6 along with average compressive strengths for these mixtures.

TABLE 6 — SPLITTING TENSILE STRENGTH

Specimen ID	Unit weight (lb/ft³)	Tensile strength (psi)	Average compressive strength (psi)
7	136.4 137.5	420 469	4704
8	133.6 132.2	477 354	3932
9	130.5 135.2	447 548	4362

Tensile strengths are in the range expected for concretes with these compressive strengths.

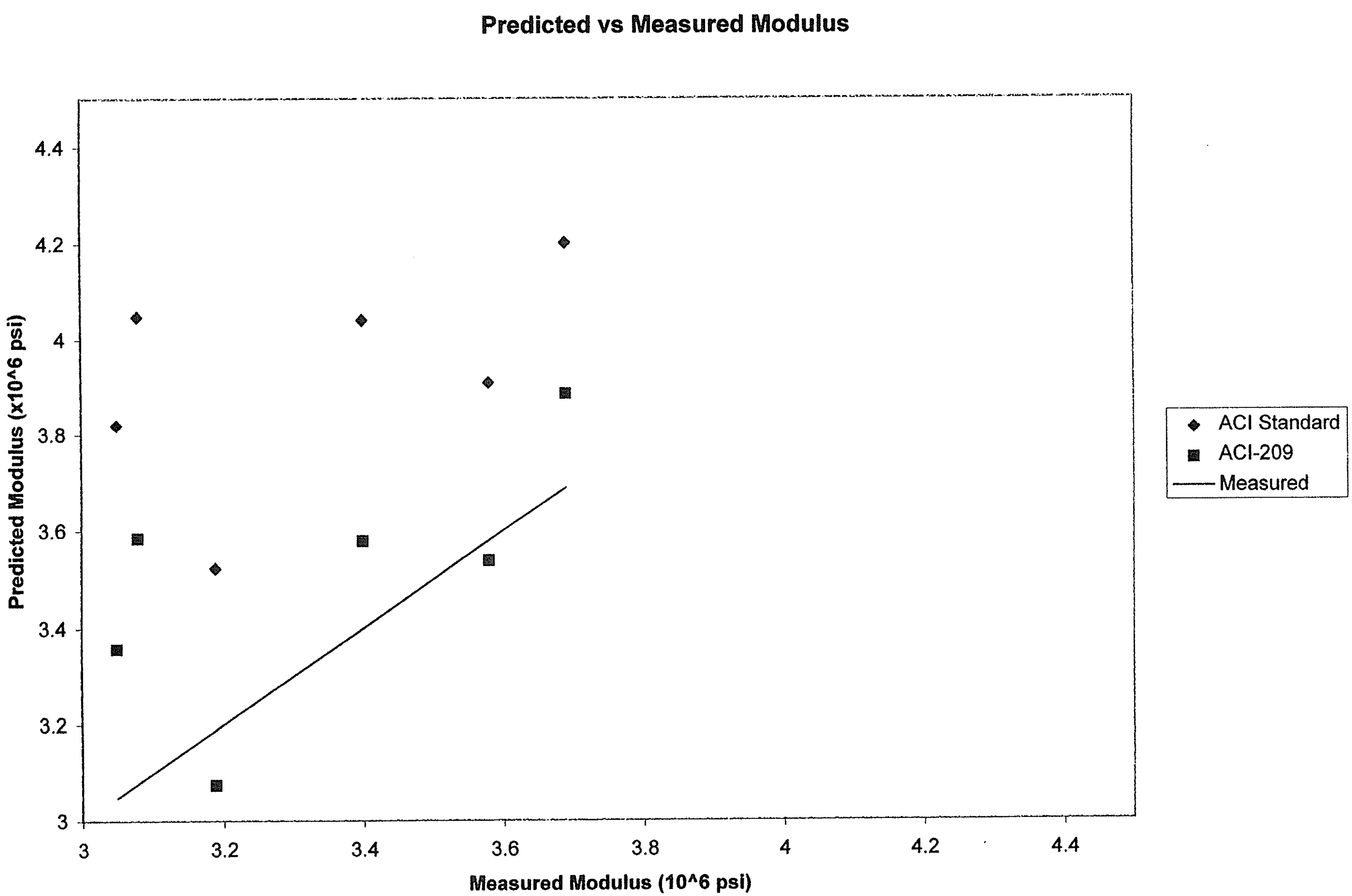

Figure 10 — Measured versus predicted elastic modulus

Moisture Absorption

Specimens from Mixtures 7, 8, and 9 that had been used for determining the tensile strength of the concrete were used to evaluate the absorption and specific gravity of the concretes. Testing was conducted according to ASTM C642 *Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete.* Results obtained are shown in Table 7.

TABLE 7 — SPECIFIC GRAVITY, ABSORPTION, AND VOIDS IN HARDENED CONCRETE

	Mixture 7	Mixture 8	Mixture 9
Absorption after immersion, percent	7.010	7.172	7.216
Absorption after immersion and boiling, percent	9.653	9.341	7.807
Bulk specific gravity (dry)	2.069	2.044	2.056
Bulk specific gravity (after immersion)	2.213	2.191	2.204
Bulk specific gravity (after immersion and boiling)	2.268	2.235	2.238
Apparent specific gravity	2.585	2.526	2.575
Volume of permeable pore space (voids), percent	19.970	19.093	20.164

Values are typical of low-weight, high air content concretes.

Foaming Studies

During the studies conducted by WJE in July, it was found that there appeared to be a considerable difference in the air stability for concretes containing the two different cements. Studies were developed by Mr. Jim Connolly and Dr. David McDonald of WJE to determine the effect of different cements in the testing.

One-hundred milliliters of deionized water (100 ml) were placed into a 500 ml graduated cylinder. To this 10 g of either the Type I or Type III cement was added. After 1 minute, 1 ml of the Stable Air surfactant was added to the cylinder. The top of the graduated cylinder was then sealed with plastic and after 2 minutes the cylinder vigorously shaken 20 times. After shaking the amount of foam was observed. The foam reached a level of 350 ml for the J.W. Peters Type I cement and only reached 230 ml for the California Type III cement.

It was readily observed that the cements affected the formation of foam to a different degree. The foam obtained when the Type I cement was used was finer and more stable than that obtained from the Type III cement. Although the differences in bubble formation may be due to the cement type, we believe that the alkali concentrations of the cements may also play a vital role in the stability of the air bubble. Further studies on the role of the cement chemistry on the bubble formation are suggested.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

As requested by Stable Air, WJE conducted a literature review on lightweight structural concretes. At that time our goal was to demonstrate that Stable Air concrete can maintain proper and adequate concrete strength properties and other necessary properties such as creep, modulus of elasticity, shrinkage, flexural strength and unit weight for use in precast and precast, prestressed concrete.

Technical issues included the effects of:

- Length of mixing period
- Length of transportation period
- Casting height
- Length of vibration period
- Consolidation without vibration versus with minimal vibration of high-slump, high air content concretes

Review of the 1992, 1993, and 1996 ACI 523 Committee Guides establish the general state-of-the-art of cellular and aggregated concretes with densities of 50 to 130 pcf, as well as establishing what data are lacking. It was concluded that Stable Air high air concretes can be directly compared with current state-of-the-art for other similar high air content, low density concretes.

Based upon the literature review, WJE conducted two laboratory investigations, initiating in June and July 1997, respectively.

WJE conducted tests using a foam with a density of approximately 67 g/L that was added to the concrete mixer in various sequences. The June studies used concrete mixing, procedures, and materials were similar to those used in precast concrete operations.

Studies were conducted to consider the effect of vibration time and heat curing on the concrete compressive strength. Additional studies considered the effect of mixing sequence on the concrete compressive strengths. All concrete was mixed in a pan mixer with a single rotary blade turning in the opposite direction to the pan. Concretes with coarse/fine aggregate ratios of 1.0 and 1.5 were evaluated at w/c ratios of 0.25 to 0.275. All tests used a Type I cement.

Even though only cylinders containing the Type I cement had generally not been vibrated, the formed surfaces of cast cylinders all appeared good. Findings included:

- The unit weight of mixtures containing the Type I cement only increased slightly under extended vibration.
- Heat curing minimally reduced the compressive strength development of the cylinders after 7 days of curing.
- The mixing sequence played a significant role in the development of compressive strength.

All cylinders exhibited an increase in density during the curing process; indicating that the air contents of these mixtures decreased.

During the July studies, a rotating drum mixer was used for all batches. Several of the concrete made during this period contained a Type III cement.

During a study that used the high-range water-reducer, Rheobuild 1000, rapid slump losses were observed, indicating that the stability of the air bubbles may be influenced by the particular high-range water-reducer. Other mixtures exhibited relatively good unit-weight stability.

All mixtures containing the Type III cement had rapid slump losses; presumably resulting from interactions between the cement type/chemistry and the foam. Further studies on the role of the cement chemistry on the bubble formation are suggested.

The mixer played a minimal role in the strength development of the concretes.

A strong relationship was found to exist between the unit weight and the compressive strength of the concretes. The elastic modulus was reasonably well predicted from the compressive strength and unit weight of the concrete. Tensile strengths are in the range expected for concretes with these compressive strengths. Moisture absorption and volume of permeable voids values were typical of low-weight, high air content concretes.

APPENDIX A - MIX DATA

CONCRETES CAST 6/24/97 TO 6/25/97

June 24, 1997 - Mixture 1

	Added to mixer (lb)
Cement	99.3
Water	26.8
Coarse aggregate	131.9
Sand	87.69
Total	345.7

Mix 1 was cast on June 24, 1997. The total batch weight was approximately 345 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
9:28 a.m.	0	Add coarse aggregate and cement to mixer
9:28 a.m.	0	Add water and 3.47 lb (6 gal) of foam. Foam density = 69.4 g/L
9:31 a.m.	3	Add sand and mix for 3 minutes, stand for 3 minutes
9:36 a.m.	8	Mix for a further 2 minutes. Unit weight - (40.51 - 7.83) x 4 = 130.7 lb/ft^3.
9:37 a.m.	9	Add approximately 3.5 gal foam. It was found that the foam was not mixing completely into batch and tended to "float" on top of the mix.
9:40 a.m.	12	Unit weight (36.10 - 7.83) x 4 = 113.1 lb/ft^3. Place mix into two 6 in. cylinders. One not vibrated - weight = (22.03 - 0.64) lb. Density = 116.9 lb/ft^3 One vibrated for 5 minutes - weight = (22.95- 0.64) lb. Density = 118.2 lb/ft^3 Slump = 8.5 in. Placed concrete into 9 cylinders; three vibrated for 5 minutes, three vibrated for 2 minutes, three not vibrated.
2:30 p.m.	302	Time of set testing - approximately 600 psi.

June 24, 1997 - Mixture 106

	Added to mixer (lb)
Cement	99.3
Water	26.8
Coarse aggregate	131.9
Sand	87.69
Total	345.7

Mix 106 was cast on June 24, 1997. The total batch weight was approximately 345 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
10:39 a.m.	0	Add coarse aggregate, cement. water and (6 + 1.5 gal) foam. 6 gal of foam weight = 3.5 lb. Foam density = 70.0 g/L
10:40 a.m.	1	Add sand, mix for 3 minutes, stand for 3 minutes, mix for 2 minutes.
10:49 a.m.	9	Slump = 5 in., Unit weight = (39.25 - 7.83) = 125.7 lb/ft^3
10:52 a.m.	12	Add 2.7 lb foam, mix for 2 minutes. Unit weight = (34.29 - 7.83) x 4 = 105.9 lb/ft^3. Cast 3 cylinders.

June 24, 1997 - Mixture 2

	Added to mixer (lb)
Cement	99.3
Water	26.8
Coarse aggregate (J.W. Peters)	131.9
Sand	87.69
Total	345.7

Mix 2 was cast on June 24, 1997. The total batch weight was approximately 345 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
11:09 a.m.	0	Add coarse, cement, water and 6 gal of foam. 6 gal foam weight = (6.18 - 2.84) = 3.34 lb. Foam density = 68. 0 g/L
11:13 a.m.	4	Add sand and foam (4.26 - 2.82) lb. Mix for 3 minutes, stand for 3 minutes, mix for 2 minutes
11:20 a.m.	11	Unit weight = 38.58 - 7.83 = 123 lb/ft^3.
11:22 a.m.	13	Add foam (2.13 + 0.75 - 0.95) = 1.93 lb. Mix 2 minutes
11:24 a.m.	15	Unit weight (2.93 + 33.94 - 7.83) x 4 = 116.2. Slump = 8 in.
11:25 a.m.	16	Cast 14 cylinders.
3:25 p.m.	265	Start heat cure
10:45 p.m. or p.m.	690	Stop heat cure

June 24, 1997 - Mixture 3

	Added to mixer (lb)
Cement	99.3
Water	26.8
Coarse aggregate (J.W. Peters)	131.9
Sand	87.69

Mix 3 was cast on June 24, 1997. The total batch weight was approximately 345 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
1:25 p.m.	0	Add coarse, cement, water and 6 gal of foam. 6 gal foam weight = (6.11 - 2.82) = 3.29 lb Foam density = 66.6 g/L Add sand, mix for 3 minutes, stand for 3 minutes
1:31 p.m.	6	Add foam (4.16 - 2.80) = 1.36 lb. Mix 2 minutes
1:34 p.m.	9	Unit weight = (39.15 - 7.83) x 4 = 125.2 lb/ft^3
1:35 p.m.	10	Add foam (3.84 - 3.22) = 0.62 lb. Mix 2 minutes
1:38 p.m.	13	Unit weight = (37.62 - 7.83) x 4 = 119 lb/ft^3
1:40 p.m.	15	Add foam (3.52 - 3.16) = 0.36 lb. Mix 2 minutes
1:42 p.m.	17	Unit weight = 36.94 - 7.83 x 4 = 116.4 lb/ft^3 Cast 14 cylinders for normal cure Slump = 8.25 in.

June 25, 1997 - Mixture 4

	Added to mixer (lb)
Cement	99.3
Water	26.8
Coarse aggregate	109
Sand	109

Mix 4 was cast on June 25, 1997. The total batch weight was approximately 345 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
11:38 a.m.	0	Add coarse aggregate, cement, water
11:39 a.m.	1	Add foam 6.03 - 2.83 = 3.20 lb. Foam density = 65.0 g/L
11:40 a.m.	2	Add sand
11:42 a.m.	4	stop mixing
11:44 a.m.	6	Add foam (4.01 - 2.82) = 1.19 lb
11:47 a.m.	9	Unit wt (40.17 - 7.83) x 4 = 129.4 lb/ft^3
11:50 a.m.	12	Add foam (4.15 - 2.82) = 1.33 lb. Unit wt = (37.26 - 7.83) x 4 = 117.7 lb/ft^3. Cast 14 cylinders
8:00 p.m.	500	Heat 6 cylinders in curing chamber. Burlap cure 8 other cylinders

June 25, 1997 - Mixture 5

	Added to mixer (lb)
Cement	99.3
Water	26.8
Coarse aggregate	109
Sand	109

Mix 5 was cast on June 25, 1997. The total batch weight was approximately 345 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
1:34 p.m.	0	Add coarse aggregate, water and 79.3 lb cement.
1:36 p.m.	2	Add foam (6.16 - 2.92) = 3.24 lb. Foam density = 67.6 g/L Add 20 lb cement
1:37 p.m.	3	Add sand
1:40 p.m.	6	Add foam (4.53 - 2.91) = 1.62 lb
1:44 p.m.	10	unit weight = (41.84 - 7.83) x 4 = 136.1 lb/ft^3
1:45 p.m.	11	Add foam (5.19 - 2.97) = 2.22 lb
1:47 p.m.	13	Unit wt = (35.97 - 7.83) x 4 = 112.6 lb/ft^3. Slump = 8.25 in. Cast 14 cylinders.
8:00 p.m.	390	Heat cure 6 cylinders, burlap cure 8 cylinders.

June 25, 1997 - Mixture 6

	Added to mixer (lb)
Cement	99.3
Water	26.8
Coarse aggregate	109
Sand	109

Mix 6 was cast on June 25, 1997. The total batch weight was approximately 345 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
2:06 p.m.	-1	Add aggregate, sand and cement
2:07 p.m.	0	Add water
2:08 p.m.	1	Add foam (6.08 - 3.00) = 3.08 lb. Foam density = 61.0 g/L
2:09 p.m.	2	Add foam (4.48 - 2.85) = 1.63 lb
2:14 p.m.	7	Unit weight = (38.61 - 7.83) x 4 = 123.1 lb/ft^3
2:16 p.m.	9	Add foam (3.73 - 2.88) = 6.85 lb
2:18 p.m.	11	Unit weight (36.96 - 7.83) x 4 = 116.5 lb/ft^3 Slump = 8.75 in. Cast 14 cylinders.
8:00 p.m.	350	Heat cure 6 cylinders, burlap cure 8 cylinder

June 25, 1997 - Mixture 7

	Added to mixer (lb)
Cement	99.3
Water	26.8
Coarse aggregate	109
Sand	109
PMT-1 Enhance	300 ml

Mix 7 was cast on June 25, 1997. The total batch weight was approximately 345 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
2:36 p.m.	-1	Add coarse aggregate, sand and cement
2:37 p.m.	0	Add water with PMT-1 mixed into the mixing bucket
2:38 p.m.	1	Add foam (6.04 - 2.97) = 3.07 lb Foam density = 61.4 g/L
2:39 p.m.	2	Add foam (4.65 - 2.78) = 1.87 lb
2:46 p.m.	10	Unit weight (35.37 - 7.83) x 4 = 110.1 Slump = 9 in. Cast 14 cylinders
8:00 p.m.	324	Heat cure 6 cylinders and burlap cure 8 cylinders

APPENDIX B - MIX DATA

CONCRETE CAST 7/21/97 TO 7/24/97

July 21, 1997 - Mixture 1

	Added to mixer (lb)
Cement - Type I	82.6
Water	20.6
Coarse aggregate	94.5
Sand	94.5
Total	292.2

Mix 1 was cast on July 21, 1997. The total batch weight was approximately 292.2 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
2:22 p.m.	0	Add coarse aggregate and water to mixer and approximately 1/2 of the cement
2:24 p.m.	2	Add approximately 3 gal of foam (6 gal weight = 3.56 lb) Foam density = 71.7 g/L
2:25 p.m.	3	Add remaining cement
2:26 p.m.	4	Add sand
2:27 p.m.	5	Add (1.02 + 0.63) = 2.65 lb foam (6 gal weight = 3.25 lb) Foam density = 65.0 g/L
2:29 p.m.	7	Add (0.27 + 0.71) = 0.98 lb foam (6 gal weight = 3.42 lb) Foam density = 68.4 g/L
2:32 p.m.	10	Unit weight = (38.34 - 7.89) x 4 = 121.8 lb/ft^3
2:34 p.m.	12	Add (0.09 + 0.77) = 0.89 lb foam
2:36 p.m.	14	Unit weight = (35.26 - 7.89) x 4 = 109.6 lb/ft^3
2:40 p.m.	18	Slump = 5 in. Cast 11 6 in. cylinders

July 21, 1997 - Mixture 2

	Added to mixer (lb)
Cement - Type I	82.6
Water	21.5
Coarse aggregate	94.5
Sand	94.5
Total	293.1

Mix 2 was cast on July 21, 1997. The total batch weight was approximately 293.1 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
3:26 p.m.	0	Add coarse aggregate, water and half cement
3:28 p.m.	2	Add approximately 3.5 gal foam (3.91 - 2.10) = 1.81 lb
3:29 p.m.	3	Add remaining cement
3:30 p.m.	4	Add 6 gal foam (6.09 - 3.03) = 3.06 lb Foam density = 68.0 g/L
3:31 p.m.	5	Add sand
3:34 p.m.	8	Add foam (2.61 - 2.29) = 0.32 lb
3:36 p.m.	10	Unit weight = (34.60 - 7.89) x 4 = 106.8 lb/ft^3
3:44 p.m.	18	Slump = 7.5 in. Cast 11 cylinders

July 21, 1997 - Mixture 3

	Added to mixer (lb)
Cement - Type I	82.6
Water	21.5
Coarse aggregate	113.4
Sand	75.6
Total	293.1

Mix 3 was cast on July 21, 1997. The total batch weight was approximately 293.1 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
3:57 p.m.	0	Add coarse aggregate, water and 1/2 cement
4:00 p.m.	3	Add (3.84 - 2.12) = 1.72 lb foam
4:01 p.m.	4	Add remaining cement
4:03 p.m.	6	Add (6.16 - 3.71) = 2.45 lb foam Foam density = 69.4 g/L
4:05 p.m	8	Add sand
4:07 p.m	10	Add (2.57 - 2.30) = 0.27 lb foam
4:09 p.m.	12	Wt = (34.27 - 7.89) x 4 = 105.5 lb/ft^3
4:11 p.m.	14	Slump = 7.5 in. Cast 11 cylinders

July 22, 1997 - Mixture 4

	Added to mixer (lb)
Cement - Type I	82.6
Water	21.5
Coarse aggregate	113.4
Sand	75.6
Total	293.1

Mix 4 was cast on July 22, 1997. The total batch weight was approximately 293.1 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
1:30 p.m.	0	Mix coarse aggregate, water and approximately 1/2 cement
1:31 p.m.	1	Add (3.68 - 2.21) = 1.47 lb foam.
1:32 p.m.	2	Add remaining cement
1:34 p.m.	4	Add (6.05 - 3.39) = 2.66 lb foam Foam density = 67.2 g/L
1:36 p.m.	6	Add sand
1:39 p.m.	9	Add (2.55 - 2.24) = 0.31 lb foam
1:41 p.m.	11	Unit weight = (36.34 - 7.89) x 4 = 113.8 lb/ft^3
1:46 p.m.	16	Unit weight = (36.31 - 7.89) x 4 = 113.7 lb/ft^3
1:51 p.m.	21	Unit weight = (35.68 - 7.89) x 4 = 111.5 lb/ft^3
1:56 p.m.	26	Unit weight = (35.34 - 7.89) x 4 = 109.8 lb/ft^3
2:00 p.m.	30	Dump concrete to barrow
2:01 p.m.	31	Unit weight = (35.88 - 7.89) x 4 = 111.9 lb/ft^3 Cast cylinders 4A, 4B, and 4C Weight 4B = (23.97 - 1.41) = 22.56 lb (114.8 lb/ft^3)
2:07 p.m.	37	Slump = 7.5 in.
2:12 p.m.	42	Unit weight = (36.09 - 7.89) x 4 = 112.8 lb/ft^3
2:20 p.m.	50	Unit weight = (36.17 - 7.89) x 4 = 113.1 lb/ft^3
2:30 p.m.	60	Unit weight = (36.20 - 7.89) x 4 = 113.2 lb/ft^3
1:41 p.m.	81	Unit weight = (36.34 - 7.89) x 4 = 113.8 lb/ft^3 Cast cylinders

July 22, 1997 - Mixture 5

	Added to mixer (lb)
Cement - Type I	82.6
Water	21.4
Coarse aggregate	113.4
Sand	75.6
Rheobuild 1000	200 ml
Total	293.1

Mix 5 was cast on July 22, 1997. The total batch weight was approximately 293.1 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
2:39 p.m.	0	Add coarse aggregate, water cement and Rheobuild 1000 (cement balled)
2:42 p.m.	3	Add (3.87 - 2.09) = 1.64 lb foam 6.07 - 2.69 = 3.38 lb per 6 gal Foam density = 67.6 g/L
2:45 p.m.	6	Add (3.85 - 2.23) = 1.62 lb foam
2:48 p.m.	9	Add sand
2:50 p.m.	11	Add (2.97 - 2.39) = 0.58 lb foam Unit weight = (42.25 - 7.89) x 4 = 137.4 lb/ft^3
2:54 p.m.	15	Add (3.00 - 2.45) = 0.55 lb foam
2:57 p.m.	18	Unit weight = (39.21 - 7.89) x 4 = 125.3 lb/ft^3
2:59 p.m.	20	Add (0.54 - 0.34) = 0.20 foam
3:02 p.m.	23	Unit weight = (39.81 - 7.89) x 4 = 127.6 lb/ft^3
3:04 p.m.	25	Add foam (3.19 - 2.67) = 0.52 lb
3:09 p.m.	30	Unit weight = (37.09 - 7.89) x 4 = 116.8 lb/ft^3 Dump concrete to barrow. Slump = 7 in. Cast 5A, 5B, 5C: Cylinder weight = (26.08 - 1.36) = 24.72 Unit weight = 126.1 lb/ft^3
3:14 p.m.	35	Unit weight = (39.70 - 7.89) x 4 = 127.2 lb/ft^3
3:25 p.m.	46	Unit weight = (40.33 - 7.89) x 4 = 129.8 lb/ft^3

July 22, 1997 - Mixture 6

	Added to mixer (lb)
Cement - Type I	82.6
Water	21.4
Coarse aggregate	113.4
Sand	75.6
Total	293.1

Mix 6 was cast on July 22, 1997. The total batch weight was approximately 293.1 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
3:33 p.m.	-2	Add coarse aggregate, sand and cement to mixer
3:35 p.m.	0	Add water
3:37 p.m.	2	Add foam (6.13 - 3.09) = 3.04 6 gal weight = 6.13 - 2.69 = 3.44 lb Foam density = 68.8 g/L Add foam (4.23 - 2.12) = 2.11 lb
3:42 p.m.	7	Unit weight = (35.30 - 7.89) x 4 = 109.6 lb/ft^3
3:48 p.m.	13	Unit weight = (35.15 - 7.89) x 4 = 109.0 lb/ft^3 Cast cylinders 6A, 6B, and 6C Dump to barrow
4:00 p.m.	25	Slump = 8 in.
4:02 p.m.	27	Unit weight = (36.97 - 7.89) x 4 = 116.3 lb/ft^3
4:15 p.m.	40	Unit weight = (37.00 - 7.89) x 4 = 116.4 lb/ft^3

July 23, 1997 - Mixture 7

	Added to mixer (lb)
Cement - Type III	82.6
Water	21.4
Coarse aggregate	113.4
Sand	75.6
Total	293

Mix 7 was cast on July 23, 1997. The total batch weight was approximately 293 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
10:47 a.m.	0	Add coarse aggregate, water and half cement
10:49 a.m.	2	Add foam (4.05 - 2.10) = 1/95 lb
10:51 a.m.	4	Add remaining cement
10:53 a.m.	6	Add foam (6.06 - 3.01) = 3.05 lb 6 gal weight = (6.06 - 2.69) = 3.37 Foam density = 67.4 lb/ft^3
10:55 a.m.	8	Add sand
10:58 a.m.	11	Add foam (4.06 - 2.16) = 2.44 lb
10:59 a.m.	12	Add foam (3.32 - 2.21) = 1.11 lb
11:03 a.m.	16	Unit weight = (41.66 - 7.89) x 4 = 135.1 lb/ft^3
11:03 a.m.	16	Add foam 3.83 - 2.31 = 1.52 lb
11:05 a.m.	18	Unit weight = (35.77 - 7.89) x 4 = 111.5 lb/ft^3 Dump to barrow
11:10 a.m.	23	Slump = 10 in.
11:13 a.m.	26	Weight = (38.75 - 7.89) x 4 = 123.4 lb/ft^3
11:21 a.m.	34	Mixture experienced very rapid slump loss

July 23, 1997 - Mixture 8

	Added to mixer (lb)
Cement - Type III	82.6
Water	21.4
Coarse aggregate	113.4
Sand	75.6
Total	293

Mix 8 was cast on July 23, 1997. The total batch weight was approximately 293 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
11:25 a.m.	0	Add coarse aggregate, water and half cement
11:27 a.m.	2	Add foam (6.12 - 3.00) = 3.12 lb 6 gal weight = (6.12 - 2.69) = 3.43 lb Foam density = 68.6 g/L
11:29 a.m.	4	Add remaining cement
11:31 a.m.	6	Add foam (6.03 - 3.11) = 2.92 lb
11:34 a.m.	9	Add sand
11:37 a.m.	12	Add foam (3.81 - 2.27) = 1.54 lb
11:42 a.m.	17	Weight (36.01 - 7.89) x 4 = 112.5 lb/ft^3
11:46 a.m.	21	Slump = 4 in. Cast cylinders
11:48 a.m.	23	Weight (40.56 - 7.89) x 4 = 130.8 lb/ft^3
11:50 a.m.	25	Rapid slump loss

July 23, 1997 - Mixture 9

	Added to mixer (lb)
Cement - Type III	82.6
Water	21.4
Coarse aggregate	113.4
Sand	75.6
Total	293

Mix 9 was cast on July 23, 1997. Care was taken to prevent balling of the mixtures. The total batch weight was approximately 293 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
1:24 - 1:26 p.m.	0	Add coarse aggregate, sand, water and half cement No balling of mixture
1:27 p.m.	1	Add foam (6.07 - 3.16) = 2.91 lb 6 gal weight = (6.07 - 2.69) = 3.38 lb Foam density = 67.6 g/L
1:30 p.m.	4	Add approximately 1/4 of cement
1:31 p.m.	5	Add foam (3.96 - 2.14) = 1.82 lb
1:32 p.m.	6	Add approximately 1/8 of cement
1:33 p.m.	7	Add foam (3.89 - 2.55) = 1.34 lb
1:35 p.m.	9	Add remaining cement
1:37 p.m.	11	Add foam (3.89 - 2.55) = 1.34 lb
1:38 p.m.	12	Weight (36.10 - 7.89) x 4 = 112.8 lb/ft^3
1:42 p.m.	16	Slump = 6.5 in. Weight = (40.99 - 7.89) x 4 = 132.4 lb/ft^3
1:44 p.m.	18	Cylinders 9A weight = (26.48 - 0.66) = 25.82 lb Density = 131.5 lb/ft^3

July 23, 1997 - Mixture 10

	Added to mixer (lb)
Cement - Type III	82.6
Water	22.7
Coarse aggregate	113.4
Sand	75.6
Total	294.3

Mix 10 was cast on July 23, 1997. The total batch weight was approximately 294.3 lb. The mixing sequence and data obtained for the mix are as follows:

Time	Elapsed (minutes)	Operation
3:11 p.m.	-2	Add coarse aggregate, sand and water
3:13 p.m.	0	Add approximately 1/2 cement preventing balling
3:15 p.m.	2	Add foam (6.03 - 3.05) = 2.98 lb 6 gal weight = (6.03 - 2.69) = 3.34 lb Foam density = 66.8 g/L
3:16 p.m.	3	Add remaining 1/4 cement
3:17 p.m.	4	Add foam (6.05 - 3.14) = 2.91 lb
3:18 p.m.	5	Add remaining cement
3:20 p.m.	8	Add foam 3.94 - 2.17 = 1.77 lb
3:23 p.m.	11	Weight = (34.00 - 7.89) x 4 = 104.4 lb/ft^3
3:25 p.m.	13	Add foam (2.72 - 2.37) = 0.35 lb
3:27 p.m.	15	Weight = (33.93 - 7.89) x 4 = 104.2 lb/ft^3
3:28 p.m.	16	Dump mixture to barrow
3:30 p.m.	18	Slump = 8 in.
3:31 p.m.	19	Unit weight = (37.39 - 7.89) x 4 = 118.0 lb/ft^3
3:32 p.m.	20	Cylinder weight = (24.68 - 0.66)= 20.02 lb Density = 122.3 lb/ft^3