THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Civil Engineering

Progress Report

# EFFECT OF THE ADDITION OF FLY ASH ON THE SULFATE RESISTANCE OF CONCRETE

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## SYNOPSIS

A study was undertaken by The University of Michigan to determine the effect of the addition of fly ash on the resistance of concrete to deterioration due to sulfate action. Specimens containing a variety of cement and fly ash contents, using two different fly ashes from the Detroit Edison Company's plants, were fabricated in 1954.

Beams made from different concrete mixtures have been in three test exposures for approximately five years. One set of beams is in a solution of magnesium sulfate in the laboratory, a companion set is in a stream of "sulfur water," and a third set is exposed to a spray of raw sewage. Change in the concrete has been determined at intervals by measuring the sonic modulus of elasticity and weight of the bars.

## INTRODUCTION

Some investigators have found that the addition of fly ash to concrete reduces deterioration due to the action of sulfate waters and soils. One investigator has found regular concrete specimens to disintegrate in 18 to 24 months of exposure to strongly sulfate soils. As a result, a study was undertaken by The University of Michigan, sponsored by the Detroit Edison Company, to determine the effect of fly ash typical of that produced by Detroit Edison when used in concrete exposed to sulfate action.

In selecting mixes, it was hoped to provide sufficient variation in the fly-ash contents and cement contents to cover the range used in common practice. Limestone coarse aggregate with a good service record was used in all mixes.

The fly-ash mixes were made with air-entrained concrete only. Evidence by other investigators shows air-entrained concrete to have superior resistance to sulfate attack. For comparison, concrete without fly ash was also made, with and without entrained air.

## MIX DESIGN

The concrete mixtures were proportioned by the procedure given by the American Society for Testing Materials, "Tentative Method of Testing Air Entraining Admixtures for Concrete (ASTM Designation C 233-52T)." The only deviation was in the use of a fine aggregate slightly coarser than that specified. The fine aggregate was 41% of the absolute volume of the total aggregate in the mixes with entrained air and 45% in the mixes without purposely entrained air.

Air-entrained concrete with three cement contents were used, namely, 4, 5, and 6 sacks per cubic yard. Two fly-ash contents with each of two fly ashes were used, along with no fly-ash control, for each cement content. In addition, mixes with nominal cement contents of 5, 6, and 7 sacks per cubic yard without fly ash and without air entrainment were also made.

## MATERIALS

### 1. FLY ASH

The fly ashes used were furnished by the Detroit Edison Company from the Trenton Channel station and from the Conners Creek station. The Trenton ash was furnished in January, 1954, and the Conners Creek ash in March, 1954. Physical tests and chemical analyses of these ashes have been previously reported but are here repeated in the Appendix.

## 2. PORTLAND CEMENT

Three brands of cement available locally, namely, Huron, Peerless, and Wyandotte, were blended in equal weights to give an "anonymous" cement. This was done to reduce the effect of variations between different brands due to differences in physical and chemical characteristics. Chemical and physical tests of the cement are shown in the Appendix.

## 3. FINE AGGREGATE

Natural sand from the Killins Gravel Company, located about 3 miles west of Ann Arbor, was used in all specimens. The gradation was slightly coarse compared to that recommended in ASTM Designation C 233.

## 4. COARSE AGGREGATE

Limestone coarse aggregate from the Inland Quarry, Manistique, Michigan, was used in the concrete. This was separated into four sizes - passing 1 inch and retained on 3/4 inch, passing 3/4 inch and retained on 1/2 inch, passing 1/2 inch and retained on 3/8 inch, and passing 3/8 inch and retained on No. 4 sieve. These were then recombined using equal weights of each size of stone.

## 5. AIR-ENTRAINING ADMIXTURE

Neutralized vinsol resin in water solution was used as the air-entraining admixture. This was prepared from commercial powdered NVX, manufactured by the Hercules Powder Company.

# FABRICATION OF SPECIMENS

American Society for Testing Materials methods were generally followed in the fabrication of the test specimens. The fine aggregate was air-dried before use by spreading in a thin layer on the laboratory floor. The coarse aggregate was dry as received. The use of dry aggregate aided in accurate determination of the water content of the mixes.

The concrete was mixed in a Blystone mixer having rotating paddles on a horizontal shaft. The mixer was "buttered" each day before using with a mixture of cement, sand, and water to coat the paddles and tub. The dry concrete materials were weighed on an 800-lb-capacity Toledo scale and placed in the mixer in the following sequence: stone, sand, fly ash, and cement. The water was weighed on a 250-lb Buffalo scale. Most of the water was introduced before starting the mixer in order to reduce dusting of the dry materials. Simultaneously with starting the mixer, the vinsol resin solution was added. The mixing continued for 2 minutes during which time additional water was added to adjust the slump. Following the 2-minute mixing, the mixer was stopped and the concrete allowed to rest for 3 minutes. A 1-minute final mix followed the rest period. Occasionally small additions of water were made at the start of the final period. Water not used was weighed back so that the exact amount actually put in the batch could be determined.

Following mixing, the concrete was dumped into a moistened flat pan and slump and air tests were conducted simultaneously. These were followed by a weight-per-cubic-foot determination, using a 1/2-foot calibrated measure. An Acme pressure air meter was used for the air content.

The batch contained nominally 2.2 cubic feet of concrete, sufficient to make 6 test cylinders, 6 x 12 inches, and 6 beams, 3 x 4 x 16 inches. This furnished 2 cylinders for each age of 7, 28, and 90 days for determination of the compressive strength of the concrete, and 2 beams for each of 3 conditions of exposure to sulfate attack. Waxed cardboard molds with metal bottoms were used for casting the cylinders. Immediately after filling, they were covered with steel plates to prevent evaporation from the fresh concrete. The beams were cast in steel molds which were covered with wet burlap after the concrete had taken its initial set.

The mixing was restricted to two batches per day by the number of steel beam molds available. A random sequence of making batches was followed with the one limitation that the corresponding mixes of Trenton and Conners Creek fly ashes were made on the same day.

The beams were removed from the molds the day after making concrete, and together with the cylinders were placed in the moist fog room for curing.

## COMPRESSION-TESTING OF CONCRETE CYLINDERS

When the concrete cylinders reached their designated ages for testing, namely, 7, 28, or 90 days, they were removed from the moist fog room, stripped of the cardboard molds and capped with Hydrostone capping plaster on each end. Caps were cast against hardened, polished 1/2-inch-thick special steel-bearing plates. After allowing sufficient time for the capping plaster to harden, the cylinders were broken in a Riehle 300,000-lb testing machine.

## DISCUSSION OF TEST RESULTS

### 1. COMPRESSIVE STRENGTH RESULTS

Table I gives the mix data and the compressive-strength test results for 7, 28, and 90 days. The compressive strengths of the concrete made in this study are in good agreement with the strengths obtained in the previous studies of Trenton Channel and Conners Creek ashes in air-entrained concrete. This is somewhat surprising since the mixes in this study generally have a higher water-cement ratio than comparable mixes in the previous work. The increased water was required by the relative increase in the amount of sand. Up to twice the weight of sand per cubic yard of concrete was required by using angular instead of pebble coarse aggregate by the ASTM proportioning procedures. The additional sand required additional water to lubricate the fresh concrete, but in general a smaller slump was utilized than in the previous studies of Trenton and Conners Creek ashes.

The reason for the low compressive strength of the 7-sack non-air-entrained concrete in relation to the corresponding 6-sack concrete is not apparent.

### 2. LABORATORY TESTING OF SULFATE RESISTANCE

Two beams from each mix were used in the laboratory tests of the sulfate resistance of the concrete. When the concrete had reached an age of 88 or 89 days, the beams were removed from the moist fog room and were immersed in water so that they would be in the saturated condition that would be typical throughout the remainder of the testing sequence.

At 90 days, the beams were weighed and the sonic modulus of elasticity was determined in accordance with ASTM Designation C 215. The beams were then immersed in a 10% magnesium sulfate solution. Seven days after being placed in the solution and at intervals thereafter, the beams were removed from the solution, washed with fresh water to remove possible accumulation of salt, reweighed, and the sonic modulus was determined again.

The concentration of the magnesium sulfate solution was checked weekly by means of a hydrometer and corrected whenever necessary.

After 55 months in the magnesium sulfate solution, the beams have generally increased in sonic modulus, indicating internal strength gain, but at the same time have lost weight due to surface disintegration, as indicated in Table II.

Weight losses are fairly small in 55 months for all the specimens not containing fly ash—either air-entrained or otherwise. In almost all cases, specimens containing fly ash show greater surface disintegration. The trend

## TABLE I

## CONCRETE MIX DATA AND COMPRESSIVE-STRENGTH TEST RESULTS

| Nominal Cement Content, sk/cyd | Batch No. | Date Made, 1954 | Fly Ash, lb/cyd, and Source | Actual Cement Content, sk/cyd | Material Proportions, lb/cyd: Sand | Stone | Net Water | W/C, gal/sk | Wt Fresh Concrete, lb/cu ft | Pressure Air Content, per cent | Slump, in. | Vinsol Resin, lb/cyd | Compressive Strength, psi: 7 days | 28 days | 90 days |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 127 | 10- 4 | 0 | 4.00 | 1330 | 1959 | 238 | 7.13 | 145.7 | 4.5 | 2.25 | 0.044 | 1820, 1960 } 1890 | 2790, 2670 } 2730 | 3445, 3500 } 3470 |
| | 115 | 9-22 | 150 Trenton | 4.02 | 1268 | 1867 | 229 | 6.88 | 145.9 | 4.6 | 2.25 | 0.135 | 2615, 2630 } 2620 | 4010, 4170 } 4090 | 4630, 4610 } 4620 |
| | 116 | 9-22 | 150 Conners Ck | 4.01 | 1269 | 1869 | 240 | 7.21 | 146.2 | 4.4 | 2.5 | 0.578 | 2315, 2315 } 2315 | 3355, 3885 } 3620 | 3835, 4490 } 4165 |
| | 124 | 9-30 | 250 Trenton | 4.02 | 1217 | 1791 | 254 | 7.62 | 145.9 | 4.1 | 2.5 | 0.245 | 1855, 1835 } 1845 | 3040, 3055 } 3045 | 3800, 4790 } 4295 |
| | 123 | 9-30 | 250 Conners Ck | 4.01 | 1205 | 1774 | 261 | 7.84 | 144.5 | 4.9 | 2.75 | 0.982 | 2050, 2175 } 2110 | 3215, 3250 } 3230 | 4965, 4840 } 4900 |
| 5 | 117 | 9-23 | 0 | 5.11 | 1295 | 1905 | 223 | 5.36 | 148.5 | 4.1 | 1.25 | 0.054 | 2895, 2810 } 2850 | 3885, 3780 } 3830 | 4470, 4100 } 4285 |
| | 131 | 10- 7 | 150 Trenton | 5.04 | 1215 | 1788 | 255 | 6.11 | 145.8 | 4.4 | 3.0 | 0.147 | 2915, 2670 } 2790 | 3995, 3535 } 3765 | 4910, 5090 } 5000 |
| | 132 | 10- 7 | 150 Conners Ck | 5.03 | 1207 | 1778 | 267 | 6.42 | 145.4 | 4.5 | 3.5 | 0.565 | 2970, 2950 } 2960 | 3890, 3605 } 3750 | 5070, 5300 } 5185 |
| | 122 | 9-27 | 250 Trenton | 4.99 | 1171 | 1724 | 274 | 6.59 | 144.8 | 4.4 | 3.25 | 0.245 | 2455, 2490 } 2470 | 3655, 3655 } 3655 | 4450, 4435 } 4440 |
| | 121 | 9-27 | 250 Conners Ck | 4.99 | 1151 | 1695 | 288 | 6.90 | 143.4 | 5.4 | 4.25 | 0.982 | 2580, 2490 } 2535 | 3355, 3410 } 3380 | 4910, 4490 } 4700 |
| 6 | 118 | 9-23 | 0 | 6.09 | 1265 | 1862 | 249 | 4.99 | 149.2 | 3.9 | 3.0 | 0.065 | 3585, 3480 } 3530 | 4260, 4575 } 4415 | 5285, 5210 } 5245 |
| | 119 | 9-24 | 100 Trenton | 6.08 | 1216 | 1791 | 250 | 5.00 | 148.2 | 4.1 | 3.0 | 0.123 | 3620, 3375 } 3495 | 4755, 4505 } 4630 | 5550, 5620 } 5585 |
| | 120 | 9-24 | 100 Conners Ck | 5.92 | 1206 | 1776 | 265 | 5.29 | 143.8 | 6.2 | 3.0 | 0.540 | 3285, 3005 } 3145 | 3815, 4045 } 3930 | 4700, 5070 } 4885 |
| | 130 | 10- 6 | 200 Trenton | 6.06 | 1129 | 1662 | 286 | 5.72 | 144.6 | 4.0 | 3.75 | 0.196 | 2755, 2985 } 2870 | 3920, 4010 } 3965 | 5320, 4840 } 5080 |
| | 129 | 10- 6 | 200 Conners Ck | 6.00 | 1120 | 1650 | 302 | 6.04 | 143.0 | 5.1 | 4.5 | 0.786 | 2650, 2880 } 2765 | 3780, 3995 } 3885 | 5670, 5495 } 5580 |
| 5 | 128 | 10- 4 | 0 | 4.81 | 1519 | 1900 | 268 | 6.42 | 149.4 | 1.4 | 2.5 | Non-Air-Entrained | 2405, 2175 } 2290 | 3375, 3215 } 3295 | 4450, 3835 } 4140 |
| 6 | 126 | 10- 1 | 0 | 5.89 | 1458 | 1823 | 254 | 5.09 | 150.3 | 1.9 | 2.0 | Non-Air-Entrained | 3975, 3695 } 3835 | 4560, 4435 } 4495 | 5300, 5440 } 5370 |
| 7 | 125 | 10- 1 | 0 | 6.83 | 1421 | 1775 | 274 | 4.71 | 150.4 | 1.8 | 3.0 | Non-Air-Entrained | 3390, 3500 } 3445 | 4435, 3850 } 4140 | 5370, 5175 } 5270 |

TABLE II

CHANGE IN SONIC MODULUS AND WEIGHT OF BEAMS AFTER 55 MONTHS IN LABORATORY MAGNESIUM SULFATE SOLUTION

| Cement Content, sk/cyd | Fly-Ash Content, lb/cyd, and Source | Loss in Weight, per cent | Increase in Sonic Modulus of Elasticity, per cent |
|---|---|---|---|
| | 0 | 2.8 | 17.5 |
| | | 2.3 | (-1.2) |
| | 150 - Trenton | 5.3 | 2.7 |
| | | 5.3 | 5.8 |
| 4 | 150 - Conners Creek | 7.0 | 0.9 |
| | | 8.7 | 2.7 |
| | 250 - Trenton | 12.2 | 1.9 |
| | | 14.6 | (-0.8) |
| | 250 - Conners Creek | 5.2 | 6.7 |
| | | 8.8 | 2.6 |
| | 0 | 4.7 | 4.8 |
| | | 5.7 | 6.9 |
| | 150 - Trenton | 5.2 | 9.8 |
| | | 4.0 | 5.4 |
| 5 | 150 - Conners Creek | 6.9 | 12.4 |
| | | 6.1 | 6.9 |
| | 250 - Trenton | 9.4 | 8.0 |
| | | 8.0 | 5.7 |
| | 250 - Conners Creek | 7.5 | 10.6 |
| | | 6.7 | 7.3 |
| | 0 | 2.5 | 5.6 |
| | | 2.9 | 4.9 |
| | 100 - Trenton | 4.5 | (-0.6) |
| | | 4.9 | 0.2 |
| 6 | 100 - Conners Creek | 1.3 | 9.3 |
| | | 0.3 | 7.6 |
| | 200 - Trenton | 5.9 | 7.3 |
| | | 5.4 | 8.7 |
| | 200 - Conners Creek | 5.1 | 7.4 |
| | | 4.3 | 2.8 |
| 5 (Non-Air-Entrained) | 0 | 3.9 | 15.0 |
| | | 3.2 | 1.2 |
| 6 (Non-Air-Entrained) | 0 | 2.0 | 10.4 |
| | | 1.7 | 8.2 |
| 7 (Non-Air-Entrained) | 0 | 2.7 | 7.7 |
| | | 1.9 | 5.8 |

of these data is perplexing in two aspects and is not in accord with that of two recent investigations.[1,2]

1. Weight losses for all the concretes are far less than would be expected from such a prolonged exposure.

2. Improvement in behavior is not indicated for the specimens containing fly ash.

For instance, Ref. 1 (discussion, p. 1019) shows 5-sack concrete with a high C3A cement to have a 25% weight loss in only 9 months under similar exposure. Reference 2 shows superior performance for concrete in which some of the cement is replaced by a pozzolan when complete submersion was used. The effect of a pozzolan is more controversial if periods of drying are introduced.

It has been speculated that in the present investigation the concrete, for some reason, is inherently much more resistant to sulfate attack or that a difference in manner of handling the solution is the reason for such a disparity of results. The latter seems more plausible but is not well understood.

In other investigations, the sulfate solution, generally, was completely changed once monthly. In the present tests, the solution was renewed only once, at age of 8 months, but weekly hydrometer checks were made to insure a specific gravity of close to 1.103. Either sulfate crystals or water was added, as necessary, to adjust the specific gravity. The specimens were stored upright in two drums with covers, each containing 18 bars and requiring 18 gallons of solution to submerge the specimens. This provided a somewhat greater volume of solution than specimens. Approximately 33.9 lb of epsom salts ($MgSO_4 \cdot 7H_2O$) were required in each drum to provide the 10% concentration of $MgSO_4$. Approximately 300 lb of concrete were in each container so that the amount of salts (as $MgSO_4$) available to react is about 5% of the weight of concrete or, on the average, about 50% by weight of the portland cement in the bars. Neither actual specific gravity readings that were taken nor our knowledge of chemistry would lead us to believe that this amount of sulfate would be actually consumed and thus that entire replacement of solution at intervals would be necessary. Prolonged storage in the stagnant sulfate solution would probably cause leaching of the calcium hydroxide from the concrete, and it has been speculated that the presence of this lime may depress the number of available sulfate ions which cause destruction. In usual field exposures, sufficient solution would normally be available to carry off the leached lime and to furnish fresh sulfate ions. In this sense, the present laboratory exposure may not be realistic.

The data actually give some support to an entirely contrary viewpoint proposed by Benton,[3] who, after presenting some basic experimental background work, postulates that a pozzolan containing alumina should be less sulfate resistant when combined with a high $C_3A$ cement. Only the entirely siliceous pozzolans should improve sulfate resistance with such cement.

## 3. FIELD TESTING OF SULFATE RESISTANCE

Companion concrete beams were placed in two field exposures. In one case, the beams were placed in a running stream of sulfur water and in the other case, the beams were placed in a moist atmosphere in the grit chamber of a sewage treatment plant.

### SULFUR WATER EXPOSURE

The pool of sulfur water where the beams were immersed is spring-fed and is located in the bottom of the Sibley limestone quarry at Trenton, Michigan. They were completely immersed and freezing does not occur in the running water during the winter. The beams were laboratory-cured in excess of 90 days in the moist fog room. On January 5, 1955, they were placed in a tank of water where they remained for two days. The sonic modulus was then determined and the beams were individually weighed. The beams were then returned to the moist room until January 19, 1955, at which time they were transferred to the sulfur water pool described above.

The beams were brought to Ann Arbor on July 20, 1955, for weighing and sonic modulus determination and returned to the pool on July 22. When the beams were removed from the pool, they were covered with heavy sulfur "streamers" and required thorough cleaning. Repeat weight and sonic modulus determinations were made on January 19 and July 10, 1956; August 5, 1957; and July 31, 1959.

Table III shows the total changes in weight and sonic modulus of elasticity, expressed as per cent, that have taken place in the 54 months that the beams have been in the test exposure. It is observed from the data that all the air-entrained concrete mixes without fly ash have experienced a slight weight loss and all containing fly ash have gained weight. The pattern of behavior is so regular as to predict positive effects from the fly ash which will be more pronounced within the next few years. The non-air-entrained concretes do not yet exhibit a positive trend but are certainly no less favorable than the air-entrained at this age. Sonic modulus determinations are inconclusive since practically all specimens show increases, thus suggesting internal strength gains during the exposure period.

### SEWAGE SPRAY EXPOSURE

The beams in the sewage spray exposure are located in a gate well at the outlet from the grit chamber at the Sewage Treatment Plant of the City of Detroit, Michigan. There is considerable turbulence in this gate well, creating

TABLE III

CHANGE IN SONIC MODULUS AND WEIGHT OF BEAMS AFTER 54 MONTHS IN "SULFUR WATER" EXPOSURE

| Cement Content, sk/cyd | Fly-Ash Content, lb/cyd, and Source | Change in Weight, per cent | Increase in Sonic Modulus of Elasticity, per cent |
|---|---|---|---|
| 4 | 0 | -0.4 | 8.5 |
| | | -0.2 | 7.5 |
| | 150 - Trenton | +0.3 | 7 |
| | | +0.2 | 6 |
| | 150 - Conners Creek | +0.1 | 3.5 |
| | | +0.2 | 2.5 |
| | 250 - Trenton | +0.2 | 7.5 |
| | | +0.2 | 6.5 |
| | 250 - Conners Creek | +0.2 | 6.5 |
| | | +0.2 | 5.5 |
| 5 | 0 | -0.1 | 0.5 |
| | | -0.1 | (-0.5) |
| | 150 - Trenton | +0.5 | 4.5 |
| | | +0.4 | 6 |
| | 150 - Conners Creek | +0.3 | 7 |
| | | +0.5 | 6.5 |
| | 250 - Trenton | +0.3 | 7 |
| | | +0.2 | 5.5 |
| | 250 - Conners Creek | +0.3 | 8 |
| | | +0.5 | 6.5 |
| 6 | 0 | -0.1 | 1 |
| | | -0.4 | 1 |
| | 100 - Trenton | +0.2 | 0 |
| | | +0.1 | 1.5 |
| | 100 - Conners Creek | +0.6 | 7.5 |
| | | +0.6 | 6.5 |
| | 200 - Trenton | +0.4 | 3 |
| | | +0.4 | 4.5 |
| | 200 - Conners Creek | +0.7 | 4 |
| | | +0.7 | 2.5 |
| 5 (Non-Air-Entrained) | 0 | -0.1 | 4.5 |
| | | 0.0 | 6 |
| 6 (Non-Air-Entrained) | 0 | +0.1 | 5.5 |
| | | +0.1 | 4.5 |
| 7 (Non-Air-Entrained) | 0 | +0.2 | 9 |
| | | 0.0 | 9 |

a very moist atmosphere. The space is enclosed so that there is no danger of freezing the beams.

As in the case of the specimens in the sulfur water exposure, the beams were cured in the laboratory moist room in excess of 90 days. On January 6, 1955, they were weighed and the sonic modulus was determined. They were returned to the moist room until January 10, 1955, at which time they were transported to Detroit and placed in the test exposure.

On July 19, 1955, the beams were returned to Ann Arbor for reweighing and sonic modulus tests. They were returned to the test exposure the following day. The bars were observed to be quite dry at this examination since the summer heat reduced the moisture content of the air considerably. Tests on the bars were repeated on January 17 and July 2, 1956; August 7, 1957; and July 31, 1959.

The total change in weight and in sonic modulus of elasticity after 54 months' exposure, expressed as per cent, is shown in Table IV. As in the case of the sulfur water exposure, there is some tendency for the air-entrained concrete without fly ash to show a greater weight loss than that containing fly ash. Several more years of exposure may be necessary to confirm this trend positively. Again, the weight loss results from the non-air-entrained concrete without fly ash are inconclusive. All specimens show increase in sonic modulus.

## SUMMARY

Reported herein are three series of sulfate resistance tests of concrete containing fly ash from the Detroit Edison Company, one laboratory exposure and two field exposures. The laboratory exposure, terminated after 55 months, tended to show no benefit to sulfate resistance by incorporating fly ash in the concrete. However, it should be emphasized that the laboratory exposure may have induced quite opposite effects from those that would normally be experienced in field concrete. A standard laboratory procedure was not available at the time these tests were started. Constant agitation and frequent changes of the solution would be suggested as alternative procedures if future laboratory determinations were to be conducted.

Not unexpectedly, sulfate deterioration in the two field exposures has been slow, and only faint trends are discernible at 4-1/2 years. Weight-loss changes of the specimens indicate that the air-entrained concrete containing fly ash possesses superior resistance. It seems possible that at least another five years of exposure in the field will be required to demonstrate positive trends, particularly to distinguish preferable fly ash or cement contents.

Custody of the raw data from the field exposures is being transferred to the Edison Company, which may continue making periodic measurements of the field-exposure specimens.

## REFERENCES


1. E. C. Higginson and O. J. Glantz, "The Significance of Tests for Sulfate Resistance of Concrete," Proceedings, ASTM, 53, 1002-1020 (1953).

2. M. Polivka and E. H. Brown, "Influence of Various Factors on Sulfate Resistance of Concretes Containing Pozzolan," Proceedings, ASTM, 58, 1077-1100 (1958).

3. J. Benton, "Cement-Pozzolan Reactions," Highway Research Board Bulletin, No. 239, pp. 56-65, 1959.

TABLE IV

CHANGE IN SONIC MODULUS AND WEIGHT OF BEAMS AFTER
54 MONTHS EXPOSURE IN SEWAGE PLANT

| Cement Content, sk/cyd | Fly-Ash Content, lb/cyd, and Source | Change in Weight, per cent | Increase in Sonic Modulus of Elasticity, per cent |
|---|---|---|---|
| | 0 | -0.3 | 9 |
| | | -1.1 | 3.5 |
| | 150 - Trenton | -0.2 | 6 |
| | | -0.4 | 6 |
| 4 | 150 - Conners Creek | -0.8 | 5.5 |
| | | -0.4 | 2.5 |
| | 250 - Trenton | +0.1 | 6.5 |
| | | -0.7 | 2 |
| | 250 - Conners Creek | -0.2 | 9 |
| | | -0.5 | 5 |
| | 0 | -1.0 | 5.5 |
| | | -0.8 | 4.5 |
| | 150 - Trenton | 0.0 | 7.5 |
| | | -0.1 | 7 |
| 5 | 150 - Conners Creek | +0.2 | 10 |
| | | 0.0 | 5.5 |
| | 250 - Trenton | -0.7 | 11.5 |
| | | -0.5* | 5.5 |
| | 250 - Conners Creek | +0.4 | 10.5 |
| | | -0.1 | 8.5 |
| | 0 | -0.6 | 5.5 |
| | | -0.6 | 6.5 |
| | 100 - Trenton | -0.4 | 4.5 |
| | | -0.5 | 4 |
| 6 | 100 - Conners Creek | -0.1 | 7.5 |
| | | -0.3 | 6.5 |
| | 200 - Trenton | +0.5 | 9 |
| | | -0.3 | 7 |
| | 200 - Conners Creek | +0.2 | 7 |
| | | +0.1 | 5.5 |
| 5 (Non-Air-Entrained) | 0 | 0.0 | 11 |
| | | -1.9* | 8.5 |
| 6 (Non-Air-Entrained) | 0 | -0.6 | 7.5 |
| | | -1.0 | 6 |
| 7 (Non-Air-Entrained) | 0 | -0.3 | 13 |
| | | -0.5 | 7.5 |

* Corner broken off in handling.

# APPENDIX

## PROPERTIES OF FLY ASH

| Physical Properties | Trenton Channel 54C-159 | Conners Creek 54C-295 |
|---|---|---|
| Specific surface, air permeability test, sq cm/gram | 2960 | 3476 |
| Compressive Strength, 25% by weight of cement, sand replacement, machine mixing, 73°F cure, per cent of control | | |
| 7 days | 143 | 147 |
| 28 days | 142 | 143 |
| 90 days | 155 | 145 |
| Water requirement, per cent of control | 100 | 102 |
| Drying shrinkage, 28 days, per cent | 0.09 | 0.09 |
| Autoclave expansion, per cent | 0.02 | (-)0.01 |
| Specific gravity | 2.42 | 2.47 |
| **Chemical Properties, per cent** | | |
| Silicon dioxide, $SiO_2$ | 46.0 | 40.7 |
| Aluminum oxide, $Al_2O_3$ | 27.7 | 21.9 |
| Ferric oxide, $Fe_2O_3$ | 17.0 | 21.9 |
| Calcium oxide, CaO | 2.6 | 1.7 |
| Magnesium oxide, MgO | 0.9 | 0.9 |
| Sulfur trioxide, $SO_3$ | 0.7 | 0.7 |
| Loss on ignition | 2.9 | 9.9 |
| Moisture | 0.2 | 0.3 |

PROPERTIES OF CEMENT (54C-158)

Physical Properties

| | | |
|---|---|---|
| Specific surface, air permeability test, sq cm/gram | | 3133 |
| Autoclave expansion, per cent | | 0.08 |
| Normal consistency, per cent | | 24.8 |
| Time of set, Gillmore | | |
| Initial | | 4:00 |
| Final | | 6:00 |

| Compressive strength, psi | Hand Mix | Machine Mix | |
|---|---|---|---|
| 7 days | 3129 | 3283 | 2950 |
| 28 days | 4463 | 4650 | 4271 |
| 90 days | 5050 | 5379 | 4438 |

| | |
|---|---|
| Tensile strength, psi | |
| 7 days | 358 |
| 28 days | 462 |
| Air in mortar, per cent | 12.0 |

| Chemical Properties | Per cent by Weight |
|---|---|
| Silicon dioxide, $SiO_2$ | 21.0 |
| Aluminum oxide, $Al_2O_3$ | 5.9 |
| Ferric oxide, $Fe_2O_3$ | 3.0 |
| Calcium oxide, CaO | 61.9 |
| Magnesium oxide, MgO | 2.3 |
| Sulfur trioxide, $SO_3$ | 2.2 |
| Loss on ignition | 1.5 |
| Sodium oxide, $Na_2O$ | 0.49 |
| Potassium oxide, $K_2O$ | 0.68 |
| Tricalcium silicate, $3CaO.SiO_2$ | 42 |
| Dicalcium silicate, $2CaO.SiO_2$ | 29 |
| Tricalcium aluminate, $3CaO.Al_2O_3$ | 11 |
| Tetracalcium aluminoferrite, $4CaO.Al_2O_3.Fe_2O_3$ | 9 |
| Total alkali expressed as $Na_2O$ | 0.94 |