# Center for By-Products Utilization

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**ABSTRACT**

This study was carried out to investigate the effects of temperature and fly ash addition on concrete strength and abrasion resistance under simulated hot weather conditions. Test data were collected at four levels of fly as content (0.10, 20 and 30 percent cement replacement), three levels of temperature (73, 95 and 100°F) with varying relative humidity (20-80%) depending upon age and temperature during the curing. Two different types of concretes A and B with their respective design strengths of 2500 psi and 4500 psi were tested for compressive strength. Concrete A was used for abrasion resistance tests.

The results revealed that fly ash inclusion was more effective concrete A as compared to concrete B. The optimum fly as content varied between 10 to 20 percent depending upon age and type of con-
crete. The resistance to abrasion increased with increasing fly ash content at 70°F. However, the abrasion resistance at higher temperatures was adversely affected by inclusion of fly ash.

**INTRODUCTION**

Recent advances in concrete technology have indicated that inclusion of fly ash is not only desirable for economic reasons, but also highly effective in modifying concrete properties to meet requirements in various applications. The use of fly ash as an admixture is required for production of very dense and durable concretes. More recently, attempts have been made to improve properties of high strength concretes through addition of fly ash. The use of fly ash in high strength concrete mixes reduces the early heat of hydration and thus helps reduce the adverse effects of rapid hydration reaction resulting from the use of rich mixes. Although initial gain in strength due to inclusion of fly ash is lower, the long-term strength and durability are generally higher than the plain concrete.

Researchers have shown that fly ash concrete is greatly sensitive to curing conditions. Therefore, maintenance of optimum temperature and moisture during curing is essential for production of durable fly ash concrete. Improper curing, which results from high temperature and low humidities as found in hot weather conditions, causes a substantial reduction in strength, resistance to abrasion, resistance to deicing salt scaling, resistance to weathering, and an increase in permeability and cracks. A limited number of investigations have been conducted so far regarding concrete performance in hot weather conditions.

## RESEARCH SIGNIFICANCE

This investigation was undertaken to evaluate the addition of fly ash and temperature on concrete strength and resistance to abrasion under above normal temperature and low relative humidity conditions. An attempt was made to obtain data under varying temperature and relative humidity conditions, as generally observed in hot climates. The data obtained in this investigation would be of use in determining the performance of fly ash concrete structures under hot climates.

**PREVIOUS STUDIES**

Davis et al. {1} were the first in the U.S. to publish comprehensive data on the effects of temperature and fly ash on concrete properties. They concluded that inclusion of fly ash in concrete resulted in reduced compressive strength at early ages but substantially higher compressive strength at later ages at a during temperature of 70°F. When curing temperature was further increased to 100°F, compressive strength of fly as concrete was found to be significantly higher compared to concrete containing portland cement even at the age of 28 days. Lovewell and Washa (2) suggested that in order to achieve equal compressive strength at early ages, between 3 and 28 days, mixes made with fly ash should have a total weight of cement and fly ash in excess of the weight of cement used in a comparable portland cement concrete mix.

Several studies have revealed that the addition of fly ash in concrete is more effective in improving compressive strengths in lean mixes compared to rich (2.3). Berry and Malhotra (4) analyzed test data reported by a large number of studies on fly ash utilization in concrete. They concluded that inclusion of fly ash caused improvement in several properties of concrete including durability and strength. As study by Lane and Best (5) substantiated that fly ash affected compressive strength of concrete to a greater degree as compared with modulus of elasticity. Lohitia et al. (6) conducted an investigation optimize the amount of fly ash in concrete. Based on the results, they concluded that replacement of 15% cement by fly ash showed the best results with respect to strength, elasticity and creep.

A large number of studies have been directed toward studying temperature effects on concrete properties (7,8,9,10,11,12,13). In general, high temperatures during curing were found to have adverse effects on concrete strength and durability. Cebeci (14) investigated the combined influence of temperature and relative humidity of the curing medium on concrete properties. The analysis of data showed that relative humidity was the most important parameter affecting development of concrete strength. The compressive strength of concrete kept at low humidity was found to be 30 to 40 percent lower compared to concrete cured in water. A study by Barrow et al. (15) revealed that strength gain in fly ash concrete was highly sensitive to curing conditions relative to that of plain concrete.

Most of the early studies indicated that abrasion resistance of concrete increased with compressive strength up to a certain limit, beyond which the resistance was affected little by the strength (16,17, 18,19). Liu (19) developed an underwater test method to evaluate the relative resistance of concrete surfaces to abrasion of waterborne particles. The variables considered were: aggregate type, water-cement ratio, and treatment of the concrete surfaces. The results showed that abrasion resistance of concrete increased with a decrease in the water-cement ratio and an increase in compression strength. He recommended that concrete of the lowest practical water-cement ratio and the hardest available aggregates should be used for construction and repair of hydraulic structures.

In another study, Liu (20) compared the abrasion resistance of concrete containing 25% fly ash by volume and the concrete with no fly ash using the underwater test method. Average compressive strengths of the concretes with fly ash and no fly ash cured for 90 days were about 7200 psi and 6900 psi, respectively. No significant difference in resistance to abrasion of the two concretes was observed for test duration up to 36 hours. However, the performance of the fly ash concrete was adversely affected when the test period was further increased. The fly ash concrete lost about 25 percent more mass, due to abrasion, compared to plain concrete.

Barrow et al (15) investigated durability of concrete, including abrasion resistance as influenced by inclusion of fly ash in the range of 0-35% by volume basis. Their results showed that the concrete containing either Class C or Class F fly ash had equivalent abrasion resistance to that of concrete with no fly ash given equal strengths. More recently Tikalsky et al (21) evaluated strength and durability of concrete containing fly ash. In this investigation, concrete specimens containing 0-35% fly ash (Class C and F) by weight were manufactured. Abrasion resistance of the test specimens was determined by measuring the depth of wear caused by a rotating dressing wheel. The data show that concrete containing Class C fly ash exhibited superior abrasion resistance to that of either plain portland cement concrete or concrete containing Class F fly ash. This was attributed to the fact that for equal strength and workability, the reduction in water requirement in the Class C fly ash mix decreased the amount of bleeding water and permeability, which in turn improved the surface hardness.

Ukita et al. (22) determined properties of concrete including abrasion resistance of concrete. Their results showed that for 15% replacement of cement by fly ash, the abrasion resistance increased with the fineness of fly ash. The abrasion resistance of the test specimens with beneficiated by ash containing the finest particles was higher than the reference concrete.

## EXPERIMENTAL PROGRAM

Portland cement concretes were proportioned to have 28 day strengths of 2500 and 4500 psi. Fly ash concretes were proportioned to have cement replacements of 10, 20, and 30%. Experiments were designed to evaluate the compressive strength and abrasion resistance of all concretes as a function of fly ash addition and temperature condition. Test temperature and humidity was maintained to simulate hot weather conditions at three different temperature levels of 73$^{\circ}$F, 95$^{\circ}$F and 120$^{\circ}$F. Four series of tests were conducted as follows: In the first series, tests were designed to study compressive strength of concretes as a function of fly ash content and temperature and relative humidity conditions in which the concretes were made and cured. The second series of tests were planned to evaluate the abrasion resistance of concrete as a function of fly ash addition and the above mentioned ambient conditions. The third series of tests were designed to study the strength characteristics of concretes containing 30% fly ash replacement at the three temperature levels. However, in this series, the concretes were proportioned to have a constant workability equivalent to 1 in. kelly ball reading at both strength levels. A fourth series of tests was also conducted using concrete proportions recommended by Lovewell and Washa (2), in which the fly as concretes were proportioned to have a higher amount of cementitious material compared to the respective portland cement concretes.

## Materials

ASTM Type I portland cement obtained from the same source was used in all the series of tests. Thy physical properties and chemical analysis of the cement were determined using the appropriate ASTM standard methods, and are given in Table 1. Physical and chemical properties of the fly ash, determined in accordance with ASTM test methods, are shown in Table 2. The coarse and fine aggregates were air dried 3/4 in Madison gravel and Ottawa sand. The physical properties of the aggregates are shown in Table 3. The coarse aggregate was a combination of two different size fractions; two parts of 3.8 to 3/4 in. and one part of No. 4 to 3/8 in.

## Mixture Design

A trial batch method of mixture design was utilized in this investigation. Four trial batches were designed and mixed, and compressive strength specimens were made and tested at various ages. The trial mixture proportions are given in Table 5. From the results, mix design curves were plotted as shown in Fig. 1. From the above curves, two concrete mixture proportions were selected to have 28 day compressive strengths of 2500 (concrete A) and 4500 psi (concrete B). The design mixture proportions are given in Table 6.

In the first and second series, fly ash concrete mixtures were proportioned to have fly ash at a cement replacement by weight of 10, 20, and 30%. At each strength level, the proportion of the rest of the ingredients were kept constant.

The third series of concrete mixture were made with fly ash at 30% cement replacement by weight, at both strength levels. The water content of these mixtures was reduced appropriately in order to obtain workability equivalent to 1 in Kelly ball measurement.

The fourth series of mixtures were proportioned according to the method recommended by Lovewell and Washa (2) as mentioned earlier. These, too, were proportioned at both of the strength levels.

Preparation and Casting of Test Specimens

All the concrete ingredients were kept in rooms at the three temperature levels (73, 95 and 120°F) for at least 24 hours prior to mixing the concretes. All the associated equipment was also kept at the above three temperatures. The aggregates were mixed dry for two minutes and then half of the required water was added. Wet mixing was conducted for 45 seconds and then fly ash, cement and the remaining water was added and mixing was continued for two minutes and 15 seconds. The resulting mixture was used to cast samples for the test conditions. The properties of the fresh concretes are given in Table 7.

For the compression tests, cylindrical specimens of 6 x 12 inch were made in cast iron molds. Disc samples (2-1/2 inch diameter x 1 inch thick) were cast for abrasion testing.

Curing of Test Specimens

All the test samples for the 73°F designation were kept in a room at about 73°F and 55% relative humidity for the first three weeks of storage. Beyond this, the room was maintained at 73°F and 20% relative humidity until all specimens were tested. The specimens for the 95°F designation were kept in a hot room about 95°F and 50% relative humidity. For the 120°F and 55% relative humidity for the first two weeks, and later at about 120°F and 25% relative humidity until testing was completed.

## TEST OF SPECIMENS

All the cylindrical specimens were tested in compression according to the relevant ASTM test methods. Three specimens were tested for each experimental condition.

Dory's abrasion testing machine was employed to test the disc samples. Each sample was placed in one of the two barrels of the machines and was held down on a rotating disc at 30 rpm by means of a 2.2 lb. weight. The rotating disc was continually fed with standard fine graded Ottawa sand from the hoppers at a uniform rate. After 2000 revolutions, the loss of weight for each set of specimens was determined.

## RESULTS AND DISCUSSION

### Compressive Strength

The compressive strength data is shown in Table 8. The relative between compressive strength and age are presented in Figures 2 through 4. The relation between compressive strength and percent of fly ash inclusion in the concretes is shown in Figure 5.

The results showed that compressive strength increased with age. The rate of increase was, however, different for each group. The rate of increase was generally higher for specimens made and cured at 95 and 120$^{o}$F as compared to those at 73$^{o}$F. No general trend between compressive strength and addition of fly ash could be established. For concrete A. at 28 days, the maximum compressive strength (2630 psi) was obtained for 20 percent optimum fly ash at 120°F. Whereas for the concrete B at 28 days, the maximum compressive strength 4820 psi was observed at 10% fly ash (Figure 5) at 75°F. While comparing the fly ash proportion in concrete A, addition of fly ash at 10 percent did not cause significant decrease in the 90 day strength at 120°F. Thus, 10 percent fly ash can be taken as optimum replacement with respect to 90 day compressive strength for hot weather conditions. At 90 days, the maximum compressive strength of (5310 psi) was again obtained at fly ash inclusion of 10 percent for concrete B at 73°F.

Analysis of test data at an age of 28 days revealed that inclusion of fly ash in concrete A was more beneficial than in concrete B. This appears to be due to the rapid rate of hydration of concrete B at the high temperatures leading to microcracks in the system and consequently the potential benefits of fly ash addition could not be derived.

Compressive strength of concrete A with increasing fly ash content ($A_0$, $A_{10}$, $A_{20}$, $A_{30}$) decreased as temperature was increased from 73 to 120°F at 90 days of age.

Several factors, especially temperature and humidity (moisture) for a given mix proportion, influence the concrete properties {12,14}. High temperature and low humidity (moisture) are known to have adverse effect on concrete properties. The effects of low humidity are more harmful than the high temperature effects in strength development of concrete during curing. Below 80% relative humidity, the rate of hydration reaction becomes low and becomes negligible below 30% relative humidity {15}. In light of these, the data reported above can be explained. Probably the hydration reaction of the concretes ($A_0$, $A_{10}$, $A_{20}$, $A_{30}$) was reduced by inclusion of fly ash in early ages, and at later ages the strength development was suppressed by the undesirable curing conditions especially low humidity.

In the second series of tests, abrasion resistance for concrete A was determined at three levels of temperature (73, 95 and 120°F), and four levels of fly ash content (0, 10, 20, and 30%). The abrasion test data are presented in Tale 10.
The test data showed that abrasion resistance of concrete increased with an increase in fly ash content at 73°F. At 95°F, abrasion resistance of concrete A increased with fly ash content up to 10%, and beyond this the performance of the concrete deteriorated. When the temperature was further increased to 120°F, an increase in fly ash caused substantial reduction in abrasion of the concrete.

Abrasion resistance of concrete is known to depend upon factors such as water-cement ratio, compressive strength, surface finish and curing conditions. Development of strength in fly ash concrete is more sensitive to curing condition than a comparable portland cement. In this investigation, conditions, such as high temperature and low humidity, were used to simulate hot climates. Due to inadequate curing of the concrete under the hot weather conditions, abrasion resistance decreased with an increase in fly ash, especially at high temperatures.

In the third series of tests, the concretes $A_{EX}$ and $B_{EX}$, each containing 30 percent fly ash, were tested at the three test temperatures (73, 95 and 120$^{o}$F). It was decided to study this series after the mixing of concretes in the first series, where the workability of concrete $B_{30}$ reduced to 1-inch Kelly ball reading at 120$^{o}$F. This was contrary to the general trend of increase in workability with increasing fly ash content at the three temperature levels. Since the water content was reduced in the $A_{EX}$, $B_{EX}$ concretes to obtain the same workability (Table 7), the strengths of these concrete were higher than respective $A_{30}$, $B_{30}$ concretes. The data on the concrete $A_{EX}$ showed that the compressive strength increased as the temperature was increased from 73 to 120$^{o}$F at ages up to 28 days. The same result was obtained for the concrete $B_{EX}$ increased from 73 to 95$^{o}$F. However, the 90 day strength of the concretes $A_{EX}$ and $B_{EX}$ decreased substantially as the temperature was increased from 73 to 120$^{o}$F. This was probably due to undesirable effects of temperature and relative humidity maintained during curing which resulted in decreased rates of hydration reaction, especially at later ages fared better in adverse ambient conditions.

The fourth series of tests were made on the concrete $A_{LW}$. The concrete mix for the $A_{LW}$ was based on the fly ash replacement as suggested by Lovewell and Washa {1}. Thirty percent fly ash replacement was used in the mix design. The results showed that, in general, compressive strength of concrete increased with increasing temperature and age within the experimental range. Hence, it appears that the concretes proportioned according to the method suggested by Lovewell and Washa {1} would perform well in adverse hot weather conditions.

**CONCLUSIONS**

Based on the data analysis, the following main conclusions were drawn for performance of the concretes under hot weather conditions.

1. In general, the fly ash replacement was more effective in the concrete A with lower strength than the concrete B with high strength.

2. The maximum 28 day compressive strength was obtained for concrete A with optimum fly ash of 20 percent at temperature of 120°F. Whereas the concrete B attained the maximum 28 day compressive strength for the optimum fly ash of 10 percent at temperature of 73°F. At 120°F, both A and B concretes exhibited optimum 90 day strength at 10% fly ash level.

3. Generally, for not weather concreting, the optimum fly ash replacement for concrete appears to vary in the range of 10-20%.

4. Abrasion resistance of the concretes ($A_o$, $A_{10}$, $A_{20}$ and $A_{30}$) increased with increasing fly ash content at 70°F within the

experimental range. However, the concrete performance deteriorated as fly ash content was increased at higher temperatures, especially at 120°F.

5. The fly ash concretes $A_{EX}$ and $B_{EX}$, at 7 days, showed equal or greater strength than that of the concrete $A_{30}$ and $B_{30}$ respectively as temperature was increased from 73 to 120°F. The concrete $A_{EX}$ exhibited better performance at all test temperatures (73, 95 and 120°F) and ages 7, 28, and 90 days) compared to the concrete $A_{30}$. Similar results were also obtained from the concrete $B_{EX}$ compared to $B_{30}$.

6. The fly ash concrete ($A_{LW}$), designed as per recommendation of Lovewell and Washa {1}, generally showed increasing compressive strength with age and temperature in the tested range.

7. Under the adverse hot weather conditions, concretes proportioned in accordance with the method suggested by Lovewell and Washa {2} appears to perform well.

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**Table 1 - Physical Properties and Chemical Composition of Cement**

| | |
|---|---|
| <u>Physical Tests</u> | |
| Baline fineness, $cm^2/gm$ | 3345 |
| Normal consistency, % | 24.5 |
| Setting time, hrs. | |
| -Initial | 3.0 |
| -Final | 6.25 |
| Autoclave expansion, % | 0.094 |
| Tensile strength, psi | |
| - 3 day | 310 |
| - 7 day | 400 |
| -28 day | 525 |
| -90 day | 475 |
| Compressive strength, psi | |
| - 3 day | 1900 |
| - 7 day | 2955 |
| -28 day | 4965 |
| -90 day | 6365 |
| Chemical composition, % | |
| Silicon dioxide ($SiO_2$) | 21.30 |
| Calcium oxide (CaO) | 63.71 |
| Aluminum oxide ($A1_2O_3$) | 4.79 |
| Ferric oxide ($Fe_2O_3$) | 2.35 |
| Sulphur trioxide ($SO_3$) | 2.40 |
| Loss on ignition (LOI) | 0.90 |
| Insoluble residue | 0.20 |
| Bogue potential compounds, % | |
| -$C_3S$ | 55.17 |
| -$C_2S$ | 19.47 |
| -$C_3A$ | 8.72 |
| -$C_4AF$ | 7.15 |

**Table 2 - Physical Properties and Chemical Composition of Fly Ash**

| | |
|---|---|
| Physical Tests | |
| Fineness | |
| -Mean particle diameter, microns | 6.87 |
| Specific gravity | 2.47 |
| Autoclave expansion, % | 0.01 |
| Drying shrinkage of mortar bars | |
| Mix data | |
| -Portland cement, gm | 500 |
| -Fly ash, gm | 125 |
| -Graded Ottawa sand, gm | 1250 |
| -Water, gm | 270 |
| -Flow (consistency), % | 112.5 |
| Change of drying shrinkage of mortar bars at 28 days, % | |
| Pozzolanic activity index with lime | |
| Mix data | |
| -Fly ash, gm | 350 |
| -Lime, gm | 175 |
| -Ottawa sand, gm | 1575 |
| -Water, gm | 350 |
| -Flow (consistency), % | 112.5 |
| Activity index | 925 psi |
| Chemical Analysis, % | |
| Silicon dioxide ($SiO_2$) | 41.5 |
| Aluminum oxide ($A1_2O_3$) | 27.0 |
| Ferric oxide ($Fe_2O_3$) | 24.2 |
| Calcium oxide (CaO) | 2.2 |
| Magnesium oxide (MgO) | 0.9 |
| Sulphur trioxide ($SO_3$) | 1.0 |
| Available alkalies as $N_2O$ | 0.44 |
| Loss on ignition (LOI) | 2.5 |
| Mositure content | 0.3 |

**Table 3 - Trial Batch Concrete Mix Proportions**

| Batch No. | Net w/c Ratio by Weight | Weight of Material; lbs. per cu. yd. | | |
|---|---|---|---|---|
| | | Cement | s.s.d. Sand | s.s.d. Gravel |
| 1 | 0.434 | 722 | 888 | 2220 |
| 2 | 0.478 | 575 | 1085 | 2200 |
| 3 | 0.600 | 444 | 1211 | 2150 |
| 4 | 0.750 | 365 | 1330 | 2060 |

**Table 4 - Selected Concrete Mix Proportions**

| Design Strength at 28 days and 73°F in psi | Mix Proportions in lb./cu. ft. | | | |
|---|---|---|---|---|
| | Cement | Sand | Gravel | Net w/c ratio |
| 2500 | 13.42 | 49.25 | 76 | 0.76 |
| 4500 | 17.25 | 44.00 | 80.5 | 0.57 |

**Table 5 - Notations Used in Concrete Designations**

The concretes designated by the Letters A and B were designed for 2500 psi and 4500 psi at 28 days and 73°F respectively. The subscripts subscripts 0, 10, 20, and 30 designate percentage fly ash replacement by weight of cement. Subscript LW designates concrete designed according to procedure suggested by Lovewell and Washa [1]. Subscript Ex designates concrete designed with less water required for a link Kellyball reading.

## Table 6 - Properties of Fresh and Hardened Concretes

| Temp. | Concrete Designation | % Air | Kelly Ball in. | Weight of fresh concrete in lb/cu ft. | Weight of hardened concrete in lb/cu. ft. |
|---|---|---|---|---|---|
| 73 | $A_o$ | 1.3 | 1 | 150.0 | |
| | $A_{10}$ | 1.0 | 1 | 151.6 | |
| | $A_{20}$ | 0.8 | 1 1/2 | 150.0 | |
| | $A_{30}$ | 1.3 | 1 1/2 | 150.8 | |
| | $A_{LW}$ | 1.3 | 1 | 150.4 | |
| | $A_{EX}$ | 1.0 | 1 | 151.6 | |
| | $B_O$ | 0.6 | 1 | 152.3 | |
| | $B_{10}$ | 0.5 | 1 1/4 | 152.9 | |
| | $B_{20}$ | 0.9 | 1 | 151.9 | |
| | $B_{30}$ | 1.1 | 1 1/4 | 152.0 | |
| | $B_{EX}$ | 1.1 | 1 | 151.6 | |
| 95 | $A_o$ | 1.4 | 1 | 148.4 | 147.1 |
| | $A_{10}$ | 1.0 | 1 | 149.6 | 147.5 |
| | $A_{20}$ | 0.8 | 1 1/2 | 149.6 | 147.0 |
| | $A_{30}$ | 0.8 | 1 3/4 | 149.6 | 147.2 |
| | $A_{LW}$ | 1.4 | 1 | 149.2 | 148.5 |
| | $A_{EX}$ | 0.6 | 1 | 149.6 | 147.4 |
| | $B_O$ | 1.2 | 1 | 150.4 | 148.6 |
| | $B_{10}$ | 0.8 | 1 | 150.0 | 149.3 |
| | $B_{20}$ | 0.4 | 1 1/4 | 150.8 | 149.0 |
| | $B_{30}$ | 0.5 | 1 3/4 | 150.0 | 148.5 |
| | $B_{EX}$ | 0.4 | 1 | 151.2 | 149.5 |
| 120 | $A_o$ | 1.8 | 1 | 149.6 | 147.7 |
| | $A_{10}$ | 1.4 | 1 | 148.4 | 146.5 |
| | $A_{20}$ | 1.3 | 1 1/4 | 149.6 | 146.3 |
| | $A_{30}$ | 2.0 | 1 3/4 | 149.6 | 146.5 |
| | $A_{LW}$ | 1.4 | 3/4 | 150.4 | 147.6 |
| | $A_{EX}$ | 1.2 | 1 | 150.0 | 147.5 |
| | $B_O$ | 1.7 | 1 | 150.0 | 147.8 |
| | $B_{10}$ | 1.2 | 1 | 151.0 | 147.5 |
| | $B_{20}$ | 1.1 | 1 | 150.6 | 147.7 |
| | $B_{30}$ | | 1 | | 147.7 |

*The notations used in concrete designation are described in Table 5.

**Table 7 - Compressive Strength Data**

| Temp. | Concrete Designation | Compressive Strength psi 7-day | 28-day | 90-day |
|---|---|---|---|---|
| 73 | $A_o$ | 1805 | 2309 | 3450 |
| | $A_{10}$ | 1460 | 2580 | 2970 |
| | $A_{20}$ | 1180 | 2000 | 2665 |
| | $A_{30}$ | 1170 | 2285 | 2745 |
| | $A_{EX}$ | 1380 | 2250 | 2900 |
| | $A_{LW}$ | 1855 | 3240 | 3450 |
| | $B_O$ | 2780 | 4675 | 4830 |
| | $B_{10}$ | 2895 | 4820 | 5310 |
| | $B_{20}$ | 2475 | 3815 | 4785 |
| | $B_{30}$ | 1935 | 3125 | 3685 |
| | $B_{EX}$ | 2290 | 3765 | 4435 |
| 95 | $A_o$ | 1680 | 2400 | |
| | $A_{10}$ | 1660 | 2460 | |
| | $A_{20}$ | 1490 | 2315 | |
| | $A_{30}$ | 1315 | 2405 | |
| | $A_{EX}$ | 1360 | 2485 | |
| | $A_{LW}$ | 2280 | 3810 | |
| | $B_O$ | 3115 | 4355 | |
| | $B_{10}$ | 2555 | 3945 | |
| | $B_{20}$ | 2535 | 3950 | |
| | $B_{30}$ | 2110 | 3435 | |
| | $B_{EX}$ | 2340 | 3785 | |
| 120 | $A_o$ | 1860 | 2420 | 2795 |
| | $A_{10}$ | 1830 | 2530 | 2785 |
| | $A_{20}$ | 1470 | 2630 | 2450 |
| | $A_{30}$ | 1615 | 2500 | 2620 |
| | $A_{EX}$ | 1770 | 2630 | 2740 |
| | $A_{LW}$ | 3325 | 3565 | 3990 |
| | $B_O$ | 2900 | 3975 | 3840 |
| | $B_{10}$ | 2760 | 3865 | 4045 |
| | $B_{20}$ | 2890 | 3875 | 3940 |
| | $B_{30}$ | 2375 | 3340 | 3685 |

*The notations used in concrete designation are described in Table 5.

**Table 9 - Abrasion Resistance of Concrete at an Age of 28 days**

| Temp. | Concrete Designation | Weight loss due to abrasion percent |
|---|---|---|
| 73 | $A_o$ | 8.9 |
| | $A_{10}$ | 7.3 |
| | $A_{20}$ | 4.4 |
| | $A_{30}$ | - |
| 95 | $A_o$ | 8.1 |
| | $A_{10}$ | 6.4 |
| | $A_{20}$ | 9.3 |
| | $A_{30}$ | 11.0 |
| 120 | $A_o$ | 7.5 |
| | $A_{10}$ | 8.8 |
| | $A_{20}$ | - |
| | $A_{30}$ | 10.0 |

*The notations for concrete designations are described in Table 5.