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# FINAL REPORT

# LOW-PERMEABILITY CONCRETES CONTAINING SLAG AND SILICA FUME

**Celik Ozyildirim, Ph.D.**
**Senior Research Scientist**



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16. Abstract

Chloride-induced corrosion causes significant deterioration in transportation structures where uncoated reinforcing steel is used. Concretes having a very low permeability are used to prevent the intrusion of chlorides into concrete to the level of the reinforcing steel. This study evaluates the strength and permeability of various combinations of silica fume and slag in concrete. It was determined that when silica fume is added in small amounts (3 to 5 percent) to concretes that have up to 47 percent slag at a water-cement ratio of 0.40 and 0.45, economical concretes with very low permeability and adequate strengths can be produced.

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## ABSTRACT

Chloride-induced corrosion causes significant deterioration in transportation structures where uncoated reinforcing steel is used. Concretes having a very low permeability are used to prevent the intrusion of chlorides into concrete to the level of the reinforcing steel. This study evaluates the strength and permeability of various combinations of silica fume and slag in concrete. It was determined that when silica fume is added in small amounts (3 to 5 percent) to concretes that have up to 47 percent slag at a water-cement ratio of 0.40 and 0.45, economical concretes with very low permeability and adequate strengths can be produced.

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# LOW-PERMEABILITY CONCRETES CONTAINING SLAG AND SILICA FUME

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## INTRODUCTION

Chloride-induced corrosion causes significant deterioration in transportation structures where uncoated reinforcing steel is used, resulting in costly repairs.[1] Protective systems are available. For example, one system widely used in repairs of bridge decks is thin-bonded concrete overlays having very high resistance to penetration by chloride ions.[2] This characteristic is generally measured by determining the chloride permeability of concretes in accordance with AASHTO T 277 or ASTM C 1202 and is termed *permeability* in this report. Over the years, latex-modified concrete (LMC) with a minimum thickness of 32 mm (1 1/4 in) has been widely used in bridge deck overlays.[3] Recently, concretes containing silica fume have been used to produce low-permeability concrete for overlays as an alternative to LMC.[4] Silica fume is a very fine siliceous material that reacts with the lime liberated during the hydration of portland cement and forms stable cementitious products. As a result, very small pores and an improved aggregate-to-paste interface are formed in concretes containing silica fume. This leads to lower permeability and an improved strength of the concrete. Silica-fume concrete (SFC) is much cheaper than LMC but still costs considerably more than the regular plain concrete and concretes containing fly ash or slag.

Because of trends noted in other research,[5] the use of combinations of slag and silica fume provides a possible means for further reduction of the cost of overlays while achieving adequate protection and acceptable strengths. Such concretes should also be cost-effective for use in structures exposed to marine environments.

## PURPOSE AND SCOPE

This study was conducted to evaluate the general range of combinations of slag and silica fume that could be expected to provide suitable strength and permeability at maximum economy. Consideration was also given to the effects of the water-cement ratio (w/c), type of cement, and curing temperatures. Two series of tests were conducted in the laboratory.

The objective of the first series was to establish the economical and practicable range of combinations of slag and silica fume that would yield concrete with satisfactory strength and low permeability using the maximum amount of slag and minimum amount of silica fume. The criteria established were that the concretes should have a compressive strength exceeding 27.6 MPa (4,000 psi) at 28 days and coulomb values of 1,000 or less at 28 days. According to AASHTO T 277, a coulomb value below 1,000 indicates very low chloride permeability. Based on the findings of the first series of tests, a second series was conducted to determine the effects of different cements, w/c's, and curing temperatures.

# METHODOLOGY

## Materials

Type II or Type III portland cement, silica fume, and slag were used as cementitious materials. The chemical and physical analyses of the portland cements are given in Table 1, and the analyses for the silica fume and slag are given in Table 2. The fine aggregate was siliceous sand, and the coarse aggregate was granite gneiss with a nominal maximum size of 25 mm (1 in). Even though a maximum aggregate size of 13 mm (1/2 in) is usually specified for thin overlays, because of geometric constraints, the selection of a 25 mm (1 in) maximum size enables a direct comparison to concretes normally specified for bridge structures or pavements and enables a wide range of applications for these experimental concretes. A commercially available air-entraining admixture and a high-range water-reducing admixture were used in all batches.

Table 1
CHEMICAL AND PHYSICAL ANALYSES OF PORTLAND CEMENTS

| Property | Type II | Type III |
|---|---|---|
| Chemical (%) | | |
| $SiO_2$ | 20.9 | 20.5 |
| $Al_2O_3$ | 4.7 | 5.1 |
| $Fe_2O_3$ | 3.7 | 2.1 |
| CaO | 63.5 | 62.8 |
| MgO | 2.8 | 3.1 |
| $SO_3$ | 2.6 | 4.0 |
| Total alkalies | 0.68 | 0.67 |
| $C_3S$ | 54.8 | 51.0 |
| $C_3A$ | 6.2 | 9.9 |
| Physical | | |
| Fineness, Blaine ($m^2/kg$) | 387 | 529 |
| 1-day compressive strength (MPa) | 15.9 | 22.1 |

1 MPa = 145 psi; 20.7 MPa = 3,000 psi.

Table 2
CHEMICAL AND PHYSICAL ANALYSES OF SILICA FUME AND SLAG

| Property | Silica Fume | Slag |
|---|---|---|
| Chemical (%) | | |
| $SiO_2$ | 93.6 | 35.5 |
| $Al_2O_3$ | 0.2 | 9.6 |
| $Fe_2O_3$ | 0.1 | 0.7 |
| CaO | 0.3 | 37.8 |
| MgO | 0.4 | 13.6 |
| $SO_3$ | — | 0.9 |
| $Na_2O$ | 0.08 | 0.07 |
| $K_2O$ | 0.92 | 0.38 |
| Physical | | |
| Fineness, Blaine ($m^2/kg$) | — | 528 |

## First Test Series

Nine batches of concrete were prepared using the mixture proportions given in Table 3. Type III cement and a w/c of 0.45 with a varying amount of a high-range water-reducing admixture were used in all the batches to attain workable concretes with a slump of 75 mm (3 in) or more. Three of the batches were controls with different cementitious materials. One had only portland cement. The second contained 50 percent portland cement and 50 percent slag by mass. The third had 93 percent portland cement and 7 percent silica fume. The remaining batches had different combinations of portland cement, slag, and silica fume.

In the mixture with portland cement only, the cement content was 375 $kg/m^3$ (635 $lb/yd^3$). In the remaining mixtures, the volume of the paste was kept equal to

Table 3
MIXTURE PROPORTIONS FOR THE FIRST TEST SERIES ($kg/m^3$)

| Batch | PC/Slag/SF | Cement | Slag | Silica Fume |
|---|---|---|---|---|
| 1 | 100/0/0 | 375 | — | — |
| 2 | 50/50/0 | 184 | 184 | — |
| 3 | 93/0/7 | 345 | — | 26 |
| 4 | 50/47/3 | 184 | 172 | 11 |
| 5 | 50/45/5 | 184 | 165 | 18 |
| 6 | 50/43/7 | 184 | 158 | 25 |
| 7 | 60/37/3 | 220 | 136 | 11 |
| 8 | 60/35/5 | 220 | 129 | 18 |
| 9 | 60/33/7 | 220 | 122 | 25 |

*Note*: The amount of coarse aggregate was 1,103 $kg/m^3$ (1,870 $lb/yd^3$) and of fine aggregate was 651 $kg/m^3$ (1,103 $lb/yd^3$). Type III cement was used, and the w/c was 0.45.
1 $kg/m^3$ = 1.69 $lb/yd^3$.

that of the control mixture to ensure that the differences in concrete behavior would relate primarily to differences in the characteristics of the cementitious materials. Thus, the volume and mass of the aggregates were constant in all the batches.

The freshly mixed concrete was tested for air content (ASTM C 231, Pressure Method), slump (ASTM C 143), and unit weight (ASTM C 138). From each batch, nine cylinders measuring 100 by 200 mm (4 by 8 in) were fabricated for tests on hardened concrete for compressive strength (AASHTO T 22 with neoprene caps) at 1, 7, and 28 days and four cylinders measuring 100 by 100 mm (4 by 4 in) were fabricated for tests of rapid chloride permeability (AASHTO T 277, ASTM C 1202) at 28 days and at 1 year. The strength specimens were moist cured until the time of test, and the permeability specimens were moist cured for 2 weeks and air dried for 2 weeks in the laboratory. Those to be tested for permeability at 1 year were then placed in the outdoor exposure area until the time of the test.

## Second Test Series

The second test series was conducted using concretes with the combinations of cementitious materials and the mixture proportions given in Table 4. This series included one set of concretes with Type II and another with Type III cement that otherwise duplicated the combinations of slag and silica fume at two w/c's.

The six batches of concrete were tested for air content, slump, and unit weight. Eighteen 100 by 200 mm (4 by 8 in) cylinders were moist cured at different temperatures and tested in compression at 7 and 28 days. Within 45 minutes after mixing, specimens in plastic molds with caps were stored in different environments at 6°C (43°F), 23°C (73°F), and 38°C (100°F). Molds were removed from the specimens to be tested at 23°C (73°F) and 38°C (100°F) the following day. Because of slow strength development, molds were not removed from the specimens to be tested at 43°F until 3 days. After the molds were removed, the specimens kept at 23°C (73°F) were stored in the moist room and those kept at 6°C (43°F) and 38°C (100°F) were immersed in lime-saturated water. Four permeability specimens were prepared and moist cured using two procedures: (1) 14 days at 23°C (73°F), and (2) 3 days at 38°C (100°F) followed by 11 days at 23°C (73°F). Subsequent to moist

Table 4
MIXTURE PROPORTIONS FOR THE SECOND TEST SERIES (kg/m$^3$)

| Batch | PC/Slag/SF | w/c | Cement | Slag | Silica Fume | Fine Aggregate |
|---|---|---|---|---|---|---|
| 10 | 50/45/5 | 0.40 | 188 | 169 | 19 | 683 |
| 11 | 50/45/5 | 0.45 | 188 | 169 | 19 | 634 |
| 12 | 50/47/3 | 0.40 | 188 | 169 | 11 | 686 |

*Note*: Batches 10–12 were duplicated with the exception that one set had Type II and the other set Type III cement. The amount of coarse aggregate was 1,103 kg/m$^3$ (1,870 lb/yd$^3$).
1 kg/m$^3$ = 1.69 lb/yd$^3$.

curing, all specimens were kept dry in the laboratory at 73°F until tested at 28 days. These differences in curing procedures were included to show the effect of different temperatures during initial curing on the permeability of concretes containing slag and silica fume.

## RESULTS AND DISCUSSION

### First Test Series

The results of the first test series on air content, slump, and unit weight are given in Table 5; compressive strength in Table 6; and permeability in Table 7. The relations of the strengths of the various combinations at 1, 7, and 28 days are graphically depicted in Figure 1 and the relations of the permeabilities at 28 days and 1 year are shown in Figure 2.

In this test series, concretes made using Type III cement at a w/c of 0.45 had a slump that ranged from 75 to 130 mm (3 to 5 in) and an air content from 5.4 to 7 percent. The unit weight ranged from 2,262 to 2,339 kg/m$^3$ (141.2 to 146.0 lb/ft$^3$). All values were within the acceptable range.

The principal findings of this test series were as follows:

1. The 1-day compressive strength of concretes was 27.6 MPa (4,010 psi) for both the plain concrete and the SFC, whereas the strength of the concretes with the slag or a combination of slag and silica fume ranged from 8.5 to 15 MPa (1,240 to 2,170 psi).
2. The highest 7-day compressive strength, 41.0 MPa (5,950 psi), was developed by the SFC. The lowest 7-day strength, 32.1 MPa (4,660 psi), was obtained with the slag and silica fume combination where the lower amount of portland cement (50 percent) and the lowest amount of silica fume (3 percent) were used. At 7 days, the difference in strength between the plain concrete and the concretes with slag and silica fume was reduced greatly. This behavior is typical of concretes containing slag.[5]
3. The lowest 28-day strength, 44.3 MPa (6,430 psi), was developed by the plain concrete. Thus, all the 28-day strengths were well above the established criterion of 27.6 MPa (4,000 psi).
4. The highest 28-day chloride permeability value, 3,814 coulombs (moderate permeability), was obtained in the plain concrete, and the lowest permeability value, 645 coulombs (very low permeability), in the concrete with 50 percent cement, 43 percent slag, and 7 percent silica fume. Concretes with portland cement and silica fume only or with portland cement and silica fume in combination with slag generally had a value less than 1,000 coulombs, indicating very low permeability. The one exception was

Table 5
CHARACTERISTICS OF THE FRESHLY MIXED CONCRETE
FOR THE FIRST TEST SERIES

| Batch | w/c | Air Content (%) | Slump (mm) | Unit Weight (kg/m$^3$) |
|---|---|---|---|---|
| 1 | 0.45 | 5.4 | 85 | 2,339 |
| 2 | 0.45 | 5.9 | 130 | 2,313 |
| 3 | 0.45 | 5.4 | 95 | 2,339 |
| 4 | 0.45 | 6.8 | 100 | 2,262 |
| 5 | 0.45 | 6.9 | 100 | 2,262 |
| 6 | 0.45 | 7.0 | 105 | 2,268 |
| 7 | 0.45 | 6.5 | 90 | 2,300 |
| 8 | 0.45 | 6.1 | 85 | 2,332 |
| 9 | 0.45 | 5.9 | 75 | 2,326 |

1 mm = 0.04 in; 1 kg/m$^3$ = 0.06 lb/ft$^3$.

Table 6
COMPRESSIVE STRENGTH OF CONCRETES FOR THE FIRST TEST SERIES
(AVERAGE OF 3 SPECIMENS)

| | | Strength (MPa) | | |
|---|---|---|---|---|
| Batch | PC/Slag/SF | 1 Day | 7 Days | 28 Days |
| 1 | 100/0/0 | 27.6 | 37.2 | 44.3 |
| 2 | 50/50/0 | 10.9 | 32.8 | 46.1 |
| 3 | 93/0/7 | 27.6 | 41.0 | 53.4 |
| 4 | 50/47/3 | 8.8 | 32.1 | 45.8 |
| 5 | 50/45/5 | 9.0 | 33.1 | 46.1 |
| 6 | 50/43/7 | 8.5 | 34.5 | 48.5 |
| 7 | 60/37/3 | 13.9 | 32.8 | 45.6 |
| 8 | 60/35/5 | 14.6 | 34.4 | 48.5 |
| 9 | 60/33/7 | 15.0 | 37.7 | 52.9 |

1 MPa = 145 psi; 20.7 MPa = 3,000 psi; 27.6 MPa = 4,000 psi.

Table 7
CHLORIDE PERMEABILITY OF CONCRETES FOR THE FIRST TEST SERIES
(AVERAGE OF 2 SPECIMENS)

| Batch | PC*/Slag/SF | Coulombs, 28 days | Coulombs, 1 yr |
|---|---|---|---|
| 1 | 100/0/0 | 3,814 | 1,926 |
| 2 | 50/50/0 | 1,663 | 728 |
| 3 | 93/0/7 | 743 | 400 |
| 4 | 50/47/3 | 986 | 487 |
| 5 | 50/45/5 | 915 | 447 |
| 6 | 50/43/7 | 645 | 356 |
| 7 | 60/37/3 | 1,109 | 508 |
| 8 | 60/35/5 | 982 | 453 |
| 9 | 60/33/7 | 678 | 319 |

* Type III portland cement.

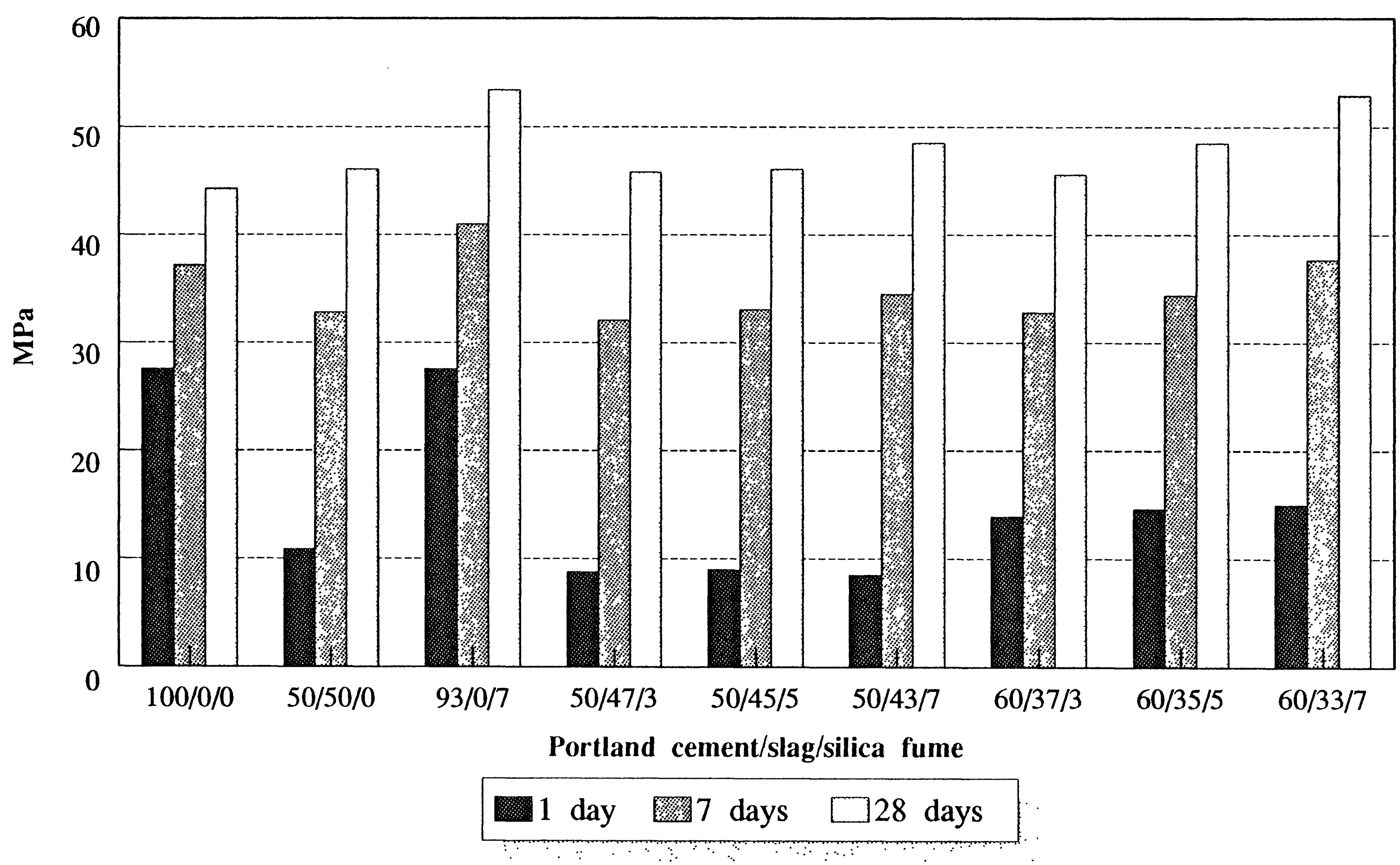


Figure 1. Compressive strength in the first test series. Concretes had Type III cement and a w/c of 0. 45.

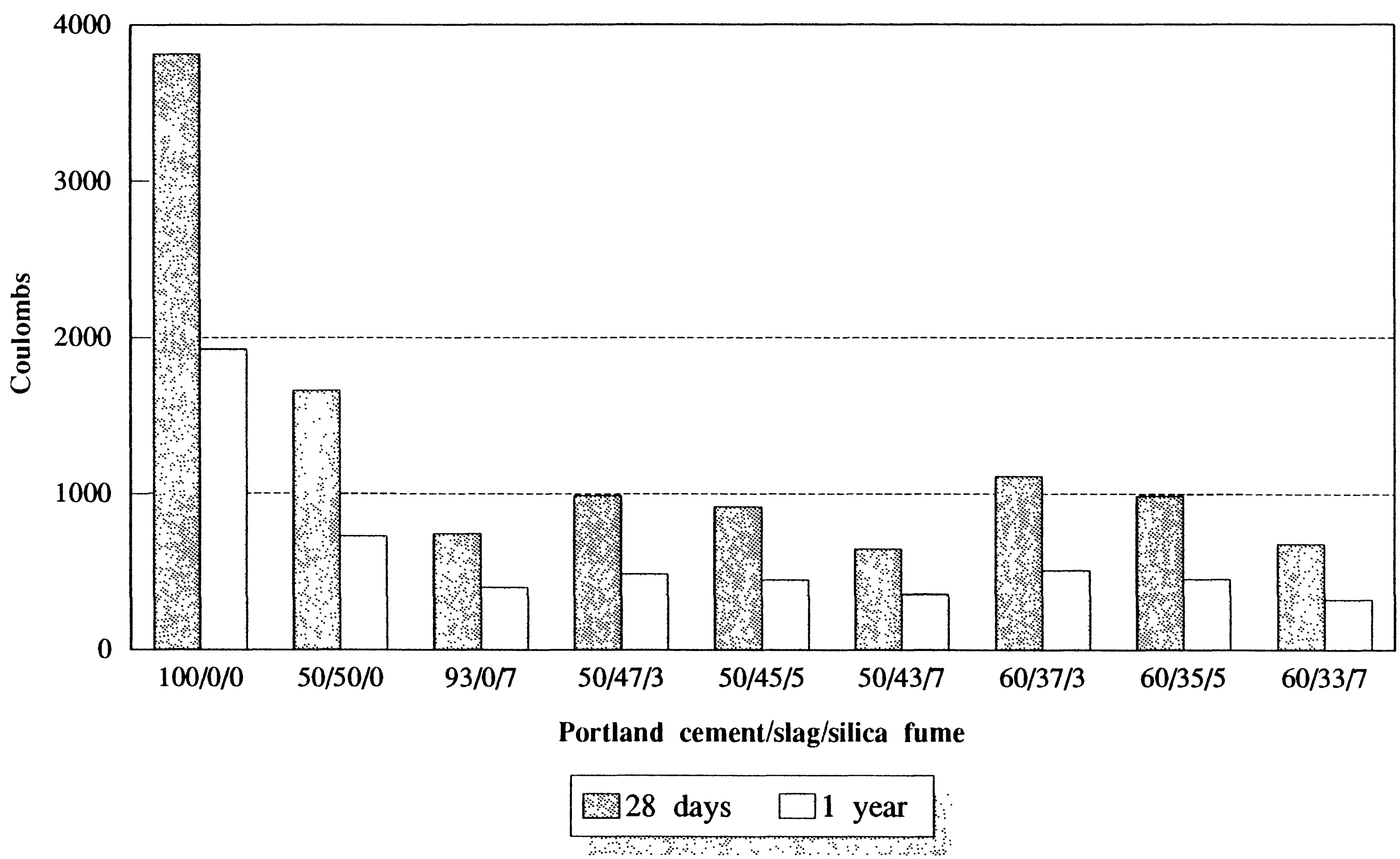


Figure 2. Permeability in the first test series. Concretes had Type III cement and a w/c of 0.45.

the concrete with 60 percent portland cement, 37 percent slag, and 3 percent silica fume that had a value of 1,109 coulombs, which is close to the very low permeability range. The permeability results at 1 year showed that except for the control concrete with the portland cement, which had a coulomb value of 1,926 (low permeability), all concretes had a coulomb value less than 1,000 (very low permeability) at the end of that period. The concrete with portland cement and slag had a coulomb value of only 728 at 1 year, which indicates very low permeability. This suggests the possibility that silica fume may not be needed in slag concretes when the early application of deicing salts is not expected. In all cases, the coulomb value for concretes exposed outdoors and tested at 1 year was approximately one half of the value for the same concrete at 28 days. The data also show that as the amount of silica fume increases, the chloride permeability decreases.

The results of the first test series showed that concrete with adequate strength and a very low permeability can be obtained at 28 days when a small amount of silica fume is used in combination with slag and Type III portland cement.

## Second Test Series

The results for the second test series on air content, slump, and unit weight are given in Table 8; compressive strength in Table 9; and permeability in Table 10. Figure 3 shows the relations of the 7-day compressive strength for the various combinations of materials at different temperatures, and Figure 4 depicts the values at 28 days. Figure 5 depicts the relations of permeability for the two curing conditions.

The air content of the concretes tested in the second test series ranged from 5.7 to 8.4 percent, the slump from 90 to 150 mm (3.5 to 6.0 in), and the unit weight from 2,236 to 2,313 kg/m$^3$ (139.6 to 144.4 lb/ft$^3$). All values were acceptable. The findings were as follows:

Table 8
CHARACTERISTICS OF THE FRESHLY MIXED CONCRETE
FOR THE SECOND TEST SERIES

| Batch | w/c | Air Content (%) | Slump (mm) | Unit Weight (kg/m$^3$) |
|---|---|---|---|---|
| 10 | 0.40 | 6.0 | 90 | 2,313 |
| 11 | 0.45 | 7.3 | 105 | 2,275 |
| 12 | 0.40 | 8.4 | 115 | 2,236 |
| 10A | 0.40 | 5.8 | 130 | 2,287 |
| 11A | 0.45 | 5.7 | 130 | 2,294 |
| 12A | 0.40 | 7.0 | 150 | 2,281 |

1 mm = 0.04 in; 1 kg/m$^3$ = 0.06/ft$^3$.

Table 9
COMPRESSIVE STRENGTH OF CONCRETES FOR THE SECOND TEST SERIES
(AVERAGE OF 3 SPECIMENS)

| Batch | Type of Cement | PC/Slag/SF | Curing Temp. (°C) | w/c | Strength (MPa) | |
|---|---|---|---|---|---|---|
| | | | | | 7 days | 28 days |
| 10 | II | 50/45/5 | 6 | 0.40 | 17.4 | 41.3 |
| | | | 23 | | 41.2 | 55.6 |
| | | | 38 | | 49.5 | 50.5 |
| 11 | II | 50/45/5 | 6 | 0.45 | 11.2 | 28.2 |
| | | | 23 | | 27.9 | 43.8 |
| | | | 38 | | 37.4 | 39.4 |
| 12 | II | 50/47/3 | 6 | 0.40 | 15.2 | 32.5 |
| | | | 23 | | 35.3 | 50.8 |
| | | | 38 | | 35.6 | 40.7 |
| 10A | III | 50/45/5 | 6 | 0.40 | 19.9 | 43.7 |
| | | | 23 | | 43.2 | 53.8 |
| | | | 38 | | 47.3 | 49.0 |
| 11A | III | 50/45/5 | 6 | 0.45 | 16.5 | 41.4 |
| | | | 23 | | 33.6 | 47.6 |
| | | | 38 | | 31.1 | 35.3 |
| 12A | III | 50/47/3 | 6 | 0.40 | 18.1 | 42.7 |
| | | | 23 | | 40.7 | 55.3 |
| | | | 38 | | 39.7 | 44.6 |

1 MPa = 145 psi; 20.7 MPa = 3,000 psi; 27.6 MPa= 4,000 psi.

Table 10
28-DAY CHLORIDE PERMEABILITY OF CONCRETES FOR THE SECOND TEST SERIES
(AVERAGE OF 2 SPECIMENS)

| Batch | Type of Cement | PC/Slag/SF | w/c | Coulombs | |
|---|---|---|---|---|---|
| | | | | A* | B* |
| 10 | II | 50/45/5 | 0.40 | 791 | 536 |
| 11 | II | 50/45/5 | 0.45 | 1,102 | 697 |
| 12 | II | 50/47/3 | 0.40 | 1,195 | 1,166 |
| 10A | III | 50/45/5 | 0.40 | 471 | 353 |
| 11A | III | 50/45/5 | 0.45 | 702 | 587 |
| 12A | III | 50/47/3 | 0.40 | 824 | 589 |

*A—moist cured 14 days at 23°C (73°F); B—moist cured 3 days at 38°C (100°F) and 11 days at 23°C (73°F).

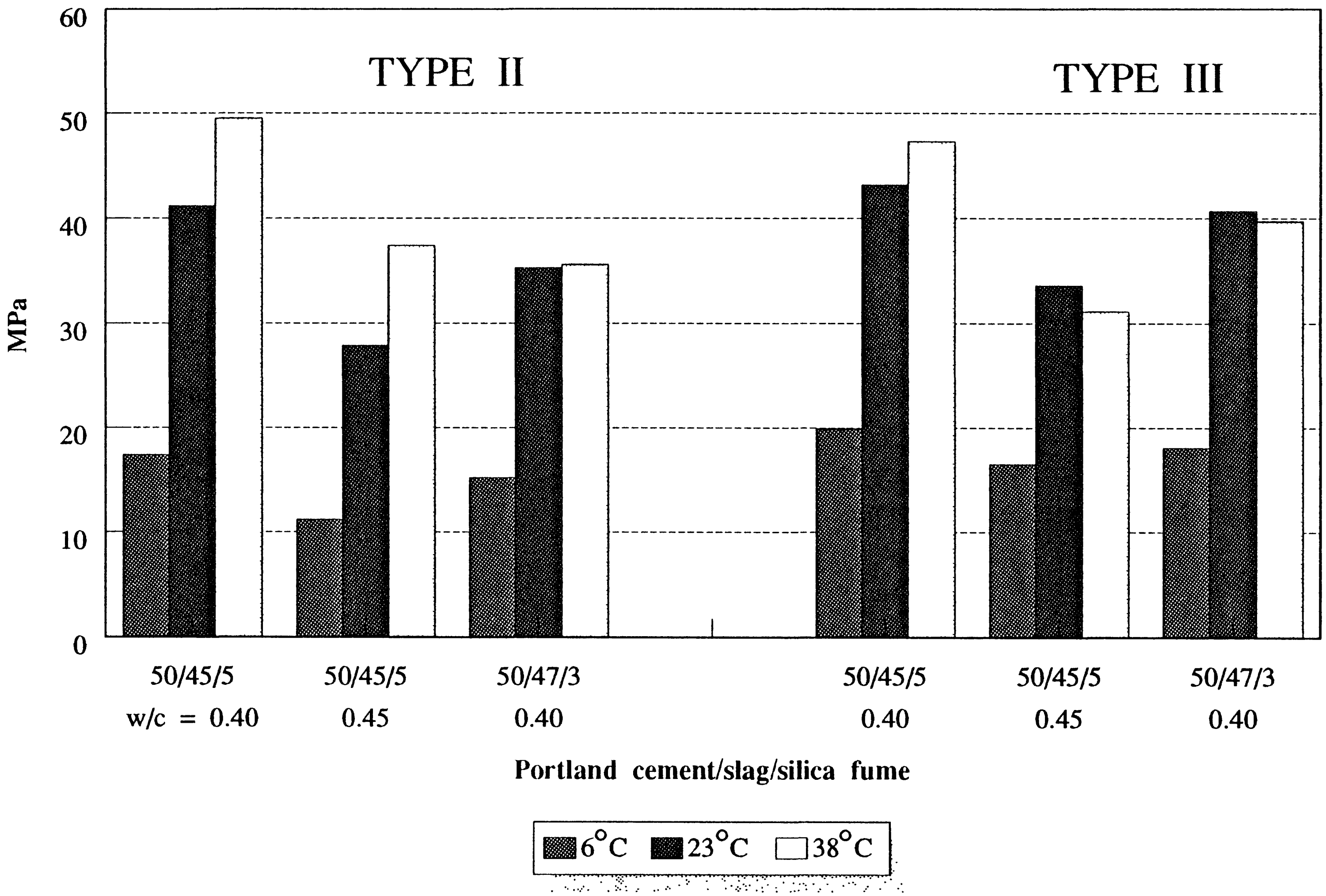


Figure 3. Seven-day compressive strength in the second test series.

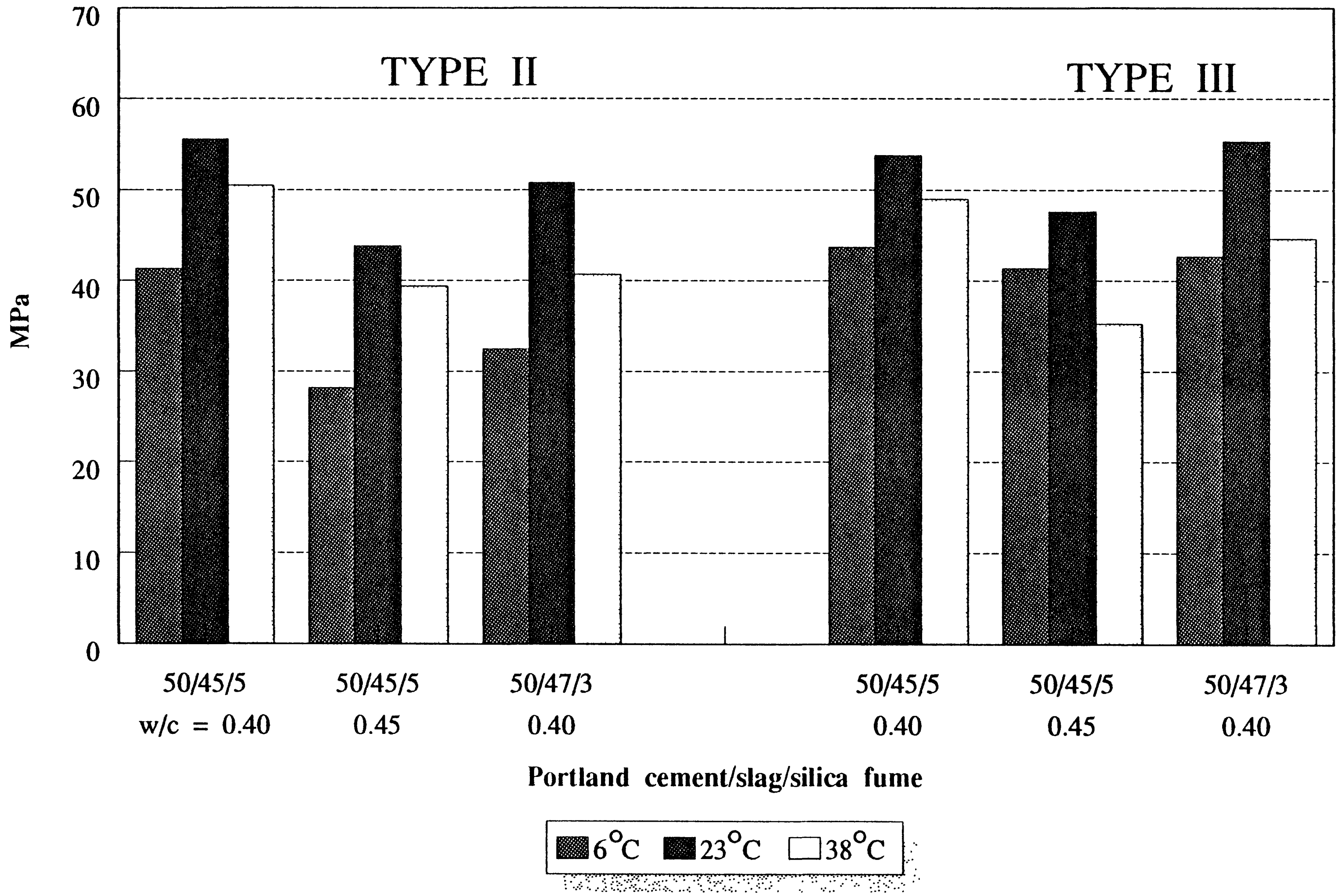


Figure 4. Twenty-eight-day compressive strength in the second test series.

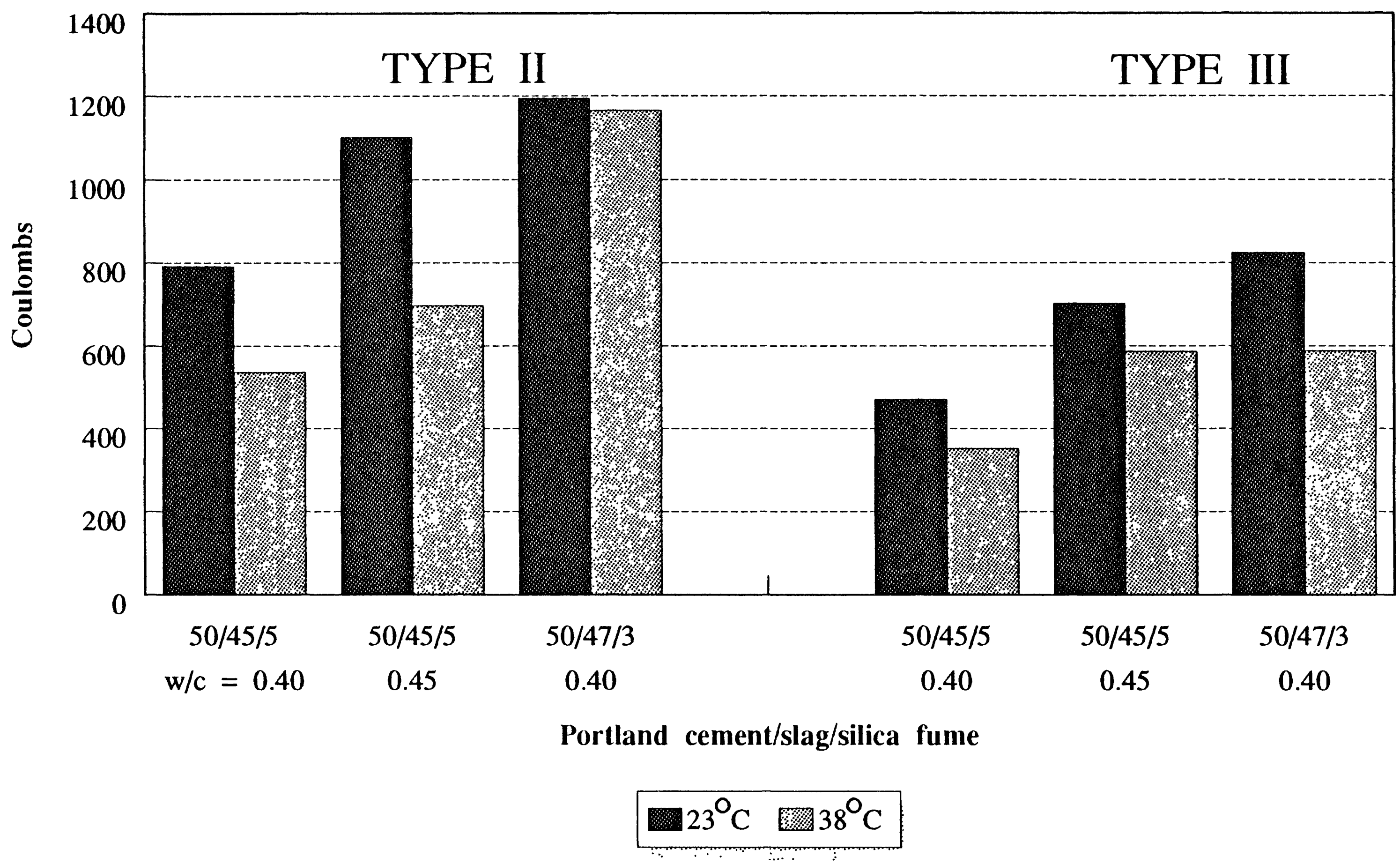


Figure 5. Twenty-eight-day chloride permeability in the second test series. One set of samples was moist cured for 2 weeks at 23°C. The other set was moist cured for 3 days at 38°C and 11 days at 23°C.

1. At 7 days, the compressive strength ranged from 27.9 to 49.5 MPa (4,040 to 7,180 psi) when cured at 23°C (73°F) and 38°C (100°F) and from 11.2 to 19.9 MPa (1,630 to 2,890 psi) when cured at 6°C (43°F). The concretes with the 50/45/5 (portland cement/slag/silica fume) combination had a higher strength than concretes with the 50/47/3 combination at the same w/c and cement type. Concretes with Type III cement had a higher 7-day strength when cured at 6°C (43°F) and 23°C (73°F) than similar concretes with Type II cement, but it was lower in two of the three cases when the concretes were cured at 38°C (100°F).

2. The 28-day strength was higher than the 7-day strength, and all were in excess of the criteria established for acceptable strength: 27.6 MPa (4,000 psi). The relationship between the strengths of Type II and Type III cements at 28 days was similar to those obtained at 7 days, and in general, concretes with Type III cement had equal or better strengths when cured at 6°C (43°F) and 23°C (73°F) than the concretes with Type II cement, but they were lower in two of three cases when cured at 38°C (100°F).

3. The permeability value ranged from 471 to 824 coulombs for concretes with Type III cement cured at 23°C (73°F) and 791 to 1,195 coulombs for those with Type II cement. Concretes cured the first 3 days at 38°C (100°F) had a permeability ranging from 353 to 589 coulombs for Type III cement and 536 to 1,166 coulombs for Type II cement. Thus, the higher initial curing temperature resulted in a lower permeability, which is consistent with earlier work, where a lower permeability value was obtained in concretes containing fly ash and silica fume when they were cured at 38°C (100°F) versus 23°C (73°F).[6] Similarly, in a recent study, concretes containing slag had a lower permeability when steam cured compared to moist cured at room temperature.[7]

## CONCLUSIONS

1. The use of slag as a portion of the cementitious material in concrete results in a product with an appreciably lower chloride permeability than similar concrete with only portland cement as the cementitious material. The addition of silica fume to such slag concrete further reduces the chloride permeability. Concretes containing as much as 47 percent slag and as low as 3 percent silica fume can develop a very low chloride permeability within 28 days at a w/c of 0.40 and even at 0.45, provided Type III cement is used.

2. When concretes with or without slag and silica fume are stored outdoors for 1 year, a large reduction in permeability occurs. Coulomb values approximately one half of the 28-day values are measured. Concretes containing slag at 1 year can have a coulomb value less than 1,000, indicating very low permeability.

3. Curing concretes containing slag and silica fume at a temperature that is higher than room temperature for some initial curing period is beneficial in that a lower permeability will be developed within 28 days.

4. Concretes containing slag and silica fume with Type III cement will normally have a lower 28-day permeability than similar concretes made with Type II cements.

5. Strength development of concretes containing slag and silica fume as portions of the cementitious material will be slower than that of the plain concrete or concrete containing portland cement and silica fume and will depend on the curing temperature. However, at 7 and 28 days, a satisfactory strength exceeding 27.6 MPa (4,000 psi) is developed in all concretes cured at 6°C (43°F), 23°C (73°F), and 38°C (100°F) except for the concretes cured at 6°C (43°F) and tested at 7 days.

## RECOMMENDATIONS

1. Concretes containing combinations of 50/45/5 (portland cement/slag/silica fume) and 50/47/3 should be evaluated in the field for suitability for use in the following situations:

    - as an alternative protective system in a minimum thickness of 32 mm (1 1/4 in) in bonded overlays for bridge decks
    - in full-depth bridge decks or substructures subjected to severe exposure (as in a marine environment).

Proportioning of concretes for such field evaluation should be based on attaining a minimum 28-day strength of 27.6 MPa (4,000 psi) and a maximum coulomb value of 1,000 (AASHTO T 277, ASTM C 1202).

Further laboratory and field tests should be conducted to evaluate the permeability of concretes containing slag and silica fume when cured at temperatures below 23°C (73°F).

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