Use of Concrete Containing Slag Cement in Transportation Structures in Virginia

by C. Ozyildirim

Synopsis: Slag cement was introduced to Virginia Department of Transportation (VDOT) in the early 1980s. Laboratory investigations showed that slag cements can be used as an alternative to conventional portland cement concretes in replacement rates up to 50% for pavements and bridge structures. Concrete containing slag cement had lower permeability than the conventional portland cement concrete.

Since the mid 1980s, slag cement has been successfully used by VDOT in bridge structures and pavements to reduce permeability and improve the durability of concrete. In large footings, slag cement has been used at a replacement rate of 75% to control the temperature rise and to reduce permeability. Currently, slag cement is used in high-performance concretes to obtain high compressive strength and low permeability.

Slag cement is also used in ternary blends with portland cement and fly ash or silica fume to lower permeability, improve durability, and obtain the desired early strengths.

Keywords: bridge; durability; mass concrete; pavement; permeability; slag; slag cement; strength; temperature control.

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INTRODUCTION

Iron blast furnace slag is a nonmetallic product consisting essentially of silicates and aluminosilicates of calcium. This slag develops in a molten condition simultaneously with iron in a blast furnace.[1] Molten slag from the furnace is rapidly quenched with water forming a glassy, granulated material that is dried and ground to a fine powder.[2] Powdered slag possesses cementing properties either alone or with calcium hydroxide produced during the hydration reaction of portland cement. Use of slag cement makes the binder denser and leads to reduced permeability, increased strength and durability, and reduced temperature rise in mass concrete.[1,3]

When slag replaces 25% or more of the portland cement, then there can be a delay in setting time, especially in cold weather.[1] Setting time can also be affected by the amount of slag and portland cement, the water-cementitious materials ratio (*w/cm*), and the characteristics of the portland cement. Although concrete strength development is slower for the first few days, concrete containing slag cement can obtain higher ultimate strengths.[2]

The Virginia Department of Transportation (VDOT) started experimenting with slag cement in the early 1980s with the construction of the slag granulation facility in Sparrows Point, Maryland. Based on the initial laboratory work, VDOT permitted the use of slag cement as an alternative to conventional portland cement concrete (PCC). Since that time, concrete with slag cement has been used successfully in bridge structures, pavements, and mass concrete applications.

PURPOSE AND SCOPE

This paper summarizes the laboratory work with and subsequent field applications of slag cement conducted by VDOT. Concrete with slag cement was initiated as an alternative to conventional PCC mixtures. The workability, ultimate strength, and durability were evaluated. Binary cementitious system of portland cement with slag, and ternary systems of portland cement with slag and silica fume or slag and fly ash were also included in the study; they are used for reduced permeability without reduction in early strengths, especially in cold weather. Strength, permeability, heat rise, and resistance to freezing and thawing and alkali-silica reactivity (ASR) were determined in the laboratory. Field applications in bridge structures, pavements, and mass concrete (footings) illustrate the benefits of slag cement in concrete.

LABORATORY WORK

Before the inclusion of slag cement in transportation structures in Virginia, concretes with and without slag cement were tested and compared. The fresh and hardened properties of these concretes were determined to ensure that workable, strong, and durable concretes could be achieved. Concerning durability, in the early 1980s, concretes were mainly tested for resistance to freezing and thawing. Then, permeability and resistance to ASR drew attention. To determine permeability, the rapid chloride permeability and ponding tests were used. Laboratory work indicated that slag cement did resist ASR and did lower permeability, which is essential for durability, and in large amounts would be highly beneficial in controlling heat rise in mass structures.

In achieving satisfactory strength, there were concerns that at large replacement rates, early strengths would be low. In response to such concerns, ternary systems where lower amounts of slag cement are used were evaluated. The laboratory studies leading to the widespread use of slag cement in VDOT structures are summarized in the following sections.

Early testing

The goal of the work in the early 1980s was to evaluate the effect of slag cement on the properties of concrete used in transportation facilities. These studies made comparisons with PCC with respect to time of set, heat of hydration, compressive strength, flexural strength, permeability, resistance to freezing and thawing, length change, and petrographic examinations for air voids, carbonation, and hydration.[4]

Cements and slag cements from two sources and 20 material combinations were tested.[4] One of the cements was Type I-II with an alkali content of 0.49% and the other one was Type I cement having a 0.68% alkali content. The two slag cements had different slag activity indexes; Grade 120 and Grade 100. All of the batches contained a commercially available vinsol resin air-entraining admixture. Some of the batches had a water reducing and retarding admixture, and were proportioned to meet bridge deck requirements. These batches had a total cementitious material of 635 lb/yd^3 (377 kg/m^3), a minimum 28-day compressive strength of 4500 psi (31 MPa) [currently the minimum strength requirement is 4000 psi (28 MPa)], and a maximum water-cementitious material ratio (*w/cm*) of 0.45. Additional mixtures without the retarding admixture met the requirements for substructure concrete and had a cementitious materials content of 588 lb/yd^3 (349 kg/m^3), a minimum 28-day strength of 3000 psi (21 MPa), and a *w/cm* of 0.48. The maximum specified *w/cm* for substructure concrete is 0.49. Slag cement replacement rates were 50% in the mixtures with higher cementitious material and the retarding admixture for the bridge structure concrete, and 40, 50, and 65% in the mixtures without retarding admixture for the substructure concrete.

The results indicated that the addition of slag provided some improvements in workability.[4] Also the time of initial setting was delayed by about an hour and the final setting by two hours. The temperature rise at early ages was lower for the concrete containing slag, and the maximum temperature was also lower. The mixtures with the higher cementitious material had higher temperature rise as expected. After the maximum temperature, the temperature of the control concrete dropped at a faster rate than that of the mixture with the slag concrete.

All of the mixtures had satisfactory compressive strengths exceeding 3000 psi (21 MPa) at 7 days and beyond. Seven-day strengths were lower for the concretes containing slag, but their ultimate strengths were higher than the control batches except at the 65% replacement rate. The concretes with higher-grade slag displayed higher strengths. Mixtures with high-alkali cement had higher early strengths. With the exception of the mixture that replaced 65% of the portland cement, the flexural strengths of the slag concretes containing slag at 28 days were about equal to or higher than those of the control.[4]

Permeability was determined using the test method described in an FHWA report, which was later adopted as the rapid chloride permeability (penetrability) test, AASHTO T 277 and ASTM C1202.[5] The results for all of the test mixtures indicated high or moderate permeability. This elevated permeability was due to limited, insufficient curing time, where the specimens were moist cured for 2 weeks and then air-dried for 6 weeks. Regardless, concretes with slag cement had lower permeability, where the reduction in permeability was proportional to the amount of portland cement replaced by slag. Furthermore, petrographic examinations revealed less calcium hydroxide in the slag concretes, and the fluorescent dyed epoxy was unable to penetrate slag concrete, which is indicative of low permeability.[4]

The resistance to freezing and thawing in the presence of 2% NaCl was satisfactory, even though, higher surface scaling was observed in concretes with slag cement. The acceptance criteria for the weight loss was 7% or less, and for surface rating, 3 or less according to ASTM C672. The durability factors were above 95 for all mixtures. Drying shrinkage values were also similar.

Laboratory testing also evaluated the temperature effects on compressive strength.[6] Although the results indicated that all of the various concrete mixtures cured at lower temperatures had lower strengths at early ages, concrete with slag cement was more sensitive to temperature than the control concrete. However, concretes cured at lower temperature had higher ultimate strength.

Low-permeability concrete

The introduction of the rapid chloride permeability test made low permeability evaluations convenient. As discussed above, these tests showed the benefits of concrete with slag cement; however, the curing method used in the early studies did not indicate the full potential of the pozzolans or slag cements. Further laboratory work indicated the importance of time on the permeability of concrete, where permeability decreased with time, as shown in Fig. 1.[7] Concretes with slag cement had low permeability. Also, concretes with lower w/cm had lower permeability, especially for concretes with slag cement as shown in Fig. 2.

Long-term permeability can be estimated at 28 days by accelerating the curing process at higher temperatures. To show the effect of curing temperature, laboratory testing studied various temperatures during curing.[6] The specimens were cured at 50°F (10°C) for 28 days, 73°F (23°C) for 28 days, one week at 73°F (23°C) followed by three weeks at 100°F (38°C), one week at 73°F (23°C) followed by three weeks at 122°F (50°C), and one week at 73°F (23°C) and then outdoors for a year. The curing performed at 73°F (23°C) was done in a moist room and specimens cured at 50 or 100°F (10 or 38°C) were in lime-saturated water. The results, shown in Fig. 3, indicated that concretes had a lower 28-day permeability when cured at higher temperatures. Concrete containing slag subjected to accelerated curing and tested at 28 days or kept outdoors after 7 days of moist curing and tested at one year had similar permeability as the one-year specimens cured at 73°F (23°C). Currently, VDOT cures permeability specimens for 1 week at room temperature and then 3 weeks at 100°F (38°C), and tests the specimens at 28 days.[8]

Another less contested test procedure for permeability is the ponding test, where the intrusion of chlorides serves as an indication of a concrete's permeability.[7] Both slag concretes and control concretes having a *w/cm* of 0.45 were ponded for extended period of time and compared with each other. After 30 months of ponding, chlorides were detected down to the 2 in. (50 mm) depth in the control specimens but there were no chlorides below a 1 in. (25 mm) depth in the slag concretes.[7]

Ternary system

Since initial studies showed that low temperatures slow down strength development and reduction in permeability, especially when slag cement replaces a large portion of the portland cement, scientists extended their research to a ternary system that combined portland cement, slag cement, and silica fume.[9,10] With proper curing and the proper amount of slag cement low permeability is expected. In the ternary system with silica fume low and very low permeability were achieved using low amounts of slag cement as shown in Fig. 4.[10] Similar to previous tests, high temperature benefited ternary blends in reducing permeability. Again, accelerated curing can help to determine long-term permeability at 28 days.

The one- and seven-day strengths were higher in the control concretes, as shown in Fig. 5. Ternary blends had 7-day strengths close to the control and higher than binary systems. Ultimate strengths were higher in the concrete containing slag than the controls.

Ternary system of slag and fly ash was successfully used in a bridge deck on Route 11 over the New River and Norfolk Southern Railroad tracks. The mix proportions are given in Table 6. The test results from 31 sublots summarized in Table 6 indicate satisfactory strength and very low permeability and small variability.

Alkali-silica reactivity

Laboratory work also addressed ASR and showed that if cements with low alkali content are not available, slag cement can help inhibit ASR.[11] Tests conducted in accordance with ASTM C441 showed the benefit of slag cement in reducing expansion due to ASR. For satisfactory resistance to ASR, expansion should be 0.1% or less at 56 days when tested with ASTM C441.[12] A table in the VDOT Manual of Instructions shows that ASR protection is not needed for cement alkali contents of 0.45% or less. However, for higher alkali contents up to 1%, Class F fly ash, silica fume, or slag cement can be used at different percentages based on the alkali content of the cement. If the alkali content is between 0.45% and 0.60%, a minimum 25% slag cement (Grade 100 and above), for alkali content 0.60% to 0.90% a minimum of 35%, and between 0.90% and 1%, a minimum of 50% slag cement is required. Ternary systems with slag and silica fume also indicated improved resistance to ASR.[11] If the cementitious system is different than that in the VDOT table, a test conforming to ASTM C441 is specified and expansion of 0.1% or less at 56 days is required.

FIELD APPLICATIONS

Bridge structures

First application—The promising test results of the early laboratory work prompted the use of slag cement in the substructure of the bridge on Route 143 over the Hampton River in the city of Hampton, Virginia.[13] The minimum cementitious material content was 588 lb/yd^3 (349 kg/m^3) and the minimum 28-day design strength 3000 psi (21 MPa). The slag cement was used at the 50% replacement rate and the *w/cm* was 0.48. The strength and permeability values of concrete sampled in August 1983 are given in Table 1. The permeability specimens were moist cured for 2 weeks and then air-dried for 6 weeks, which is an insufficient curing period. The slag concrete obtained high strength and low to moderate permeability.

During placement in cold weather in December 1983, formwork settlement resulted in a large crack at the lower end of a pier footing. The failure was attributed to slippage of friction collars holding the horizontal formwork. It was noticed that the initially placed layers of mixture did not set as the subsequent layers were placed over. Concrete pieces were obtained from the failed footing before removal. A core at 4 months had a satisfactory compressive strength of 4910 psi (33.9 MPa). The permeability of two cores was 5020 and 2920 coulombs. The movement and the cracking could have affected the permeability values. This experience indicated that in cold weather, care should be exercised in preparing sturdy formwork and delayed setting and strength development should be accounted for.

HPC structures—Low permeability is essential for longevity in bridge structures and is the focus of high-performance concrete (HPC) in Virginia.[8,14] In the 1990s, the Federal Highway Administration initiated the HPC program. VDOT had used HPC in some structures because of the addition of Class F fly ash or slag cement. For example, the first slag cement application on Route 143 is explained above. Also, all concrete placed in bridges since 1992 can be considered HPC since those concretes contain a pozzolan or slag cement for inhibiting ASR. However, since the mid 1990s, VDOT has been testing those designated HPC for strength and permeability. Some projects have required that prestressed beams have strengths exceeding 7000 psi (48 MPa) and a maximum permeability of 1500 coulombs. The maximum permeability has been specified at 2500 coulombs for bridge decks and 3500 coulombs for substructure. Specimens are moist cured 1 week at 73°F (23°C) and for an additional 3 weeks at 100°F (38°C).

VDOT has used HPC for constructing seven bridges from 1995 to 1997. The bridge on Route 40 over Falling River is an example of how the slag cement provided low permeability concrete in the substructure and the deck.[15] The bridge deck had strengths that were double the minimum specified strength and permeability that was much less than that required as shown in Table 2. This project had the added difficulty of being placed in cold weather. To protect the concrete containing 50% slag cement from the cold temperatures, the contractor placed heaters on the pier caps and heated the deck from the underside.

Slag cement has been successfully used in Virginia projects with normal weight HPC with strengths exceeding 7000 psi (48 MPa). The first HPC lightweight concrete structure in Virginia is the bridge built in 2001 that carries Route 106 over the Chickahominy River. This bridge had beams made with lightweight concrete containing slag cement with a minimum 28-day compressive strength of 8000 psi (55 MPa).[16,17] Table 3 summarizes the mixture proportions, strength, and permeability of the concrete used in the beams.

Construction and experience with HPC structures indicated that concretes with slag cement had satisfactory workability and strength. The lab results and initial performance also indicate satisfactory durability.

Self-consolidating concrete

The introduction of self-consolidating concrete (SCC) has opened new horizons for concrete. SCC has high flowability, eliminating the problem with consolidation, and therefore enhances the strength and durability of concrete. In addition, SCC enables concrete placement in heavily reinforced and congested areas. Other advantages include rapid placement of concrete and smooth surfaces of formed elements. VDOT constructed its first SCC arch bridge in Fredericksburg in 2001.[18] The SCC for this project contained slag cement and had high workability, low permeability, and satisfactory strength as shown in Table 4.[18] In 2003, two bulb-T beams with a 45 in. (1.1 m) depth and 60 ft (18 m) length were cast using SCC. The mixture proportions and data on strength and permeability are given in Table 5. This project indicated that concrete with slag cement can be successfully used in applications where high flow is needed and the resulting concrete has satisfactory strength and durability based on lab testing and initial field exposure.

Pavements

The benefit of slag cement in pavements was well demonstrated in an experimental project using jointed plain concrete pavement on I-64 in Newport News.[19] In this project, large-sized aggregate and combined grading were tried. Most of the project used 1 in. (25 mm) nominal maximum size aggregate (NMS) and Class F fly ash. However, in two experimental sections, the producer used concrete with slag cement. One section with concrete containing slag cement used 1 in. (25 mm) NMS, and another 2 in. (50 mm) NMS for comparison. The mixture proportions and the permeability and strength of these concretes are shown in Table 7. The results show that both sections with concrete containing slag with different aggregate size had satisfactory strengths and low permeability. The use of large-size aggregate resulted in a reduction in the water and cement contents; however, these reductions were minimal due to the poor shape and grading of the aggregate.

In another application, a two-lane CRCP was built in Blacksburg, Virginia, as part of the Virginia Smart Road.[20] A total of 2247 ft (685 m) of pavement was placed. The mixture contained 35% slag as shown in Table 8. Number 57 coarse aggregate with 1 in. (25 mm) maximum size was used. The *w/cm* was low, 0.40, to achieve a high early strength since the contractor wanted trucks on the pavement in 7 days to allow construction of the adjacent lane. The strengths given in Table 7 indicate high flexural and compressive strengths. The permeability values were very low.

Slag cement in pavements resulted in satisfactory workability and strength and durability based on lab results and initial exposure. In the Smart Road project, the flexural strengths at 28 days were much higher than the 650 psi (4.5 MPa) specified and exceeded 1000 psi (6.9 MPa). This confirms the high ultimate strengths are attainable in concretes with slag cement.

Mass concrete

After the early success in achieving high strength and low permeability, work on HPC was extended to temperature control in mass concrete and to high workability. Temperature rise is always a concern in mass concrete. Specifications generally set a maximum temperature and a maximum differential between the core and the surface. Generally, limits are 160°F (71°C) for the maximum temperature and 35°F (20°C) or 40°F (22°C) for the temperature differential. Based on a thermal analysis considering the reinforcement in the bridge footings on I-895, VDOT approved a maximum temperature of 170°F (77°C). The footings averaged 730 yd^3 (21 m^3), but the two footings in the river crossing were much larger with each having about 4000 yd^3 (113 m^3) of concrete. The minimum cementitious material was 565 lb/yd^3 (335 kg/m^3) and the maximum *w/cm* was 0.49. The minimum 28-day compressive strength was 4350 psi (30.7 MPa). To reduce the heat rise, the designers replaced 75% of the portland cement with slag. Preliminary testing indicated that the strength development was slow at room temperature; however, greater and more satisfactory strengths were achieved at higher temperatures, as shown in Figure 6. During placement, even in hot weather, the temperature was kept below 160°F (71°C) and the differential temperature within 40°F (22°C) with the high amount of slag cement, as shown in Figure 7. Specified strengths were attained at 28 days and in some cases at 7 days due to high temperature. Permeability values measured from 2 cylinders were 561 and 840 coulombs.

VDOT's successful use of high slag cement in mass concrete indicates that temperature rise can be controlled to acceptable levels, thus avoiding cracking and damage to the structure. A cold environment delays setting and strength development, but a hot environment accelerates setting and strength development. In mass concrete applications, to determine the strength development, temperature-matched curing or maturity methods should be used since standard curing temperatures do not simulate the actual environment in which higher temperatures that accelerate the strength development are encountered.

CONCLUSIONS

Concrete containing slag cement has been successfully used in transportation facilities in Virginia since mid 1980s and has become an important component of VDOT's HPC program. Slag concrete provides:

- *Low permeability.*
- *High resistance to ASR at appropriate replacement rates depending on the alkali contents.*
- *High strength at later ages but reduced early strength development especially in cold weather.* Hot weather accelerates strength development. In cold weather, smaller replacement rates can be used. If permeability is not low enough, the addition of other pozzolanic material such as silica fume in small amounts would improve permeability and durability
- *Temperature control in mass concrete, especially when used in large replacement rates.* In such applications, temperature-matched curing or the maturity method should be used to simulate the conditions of the elements.
- *Improved workability and high flowability for successful placement of members.*

ACKNOWLEDGMENTS

Work summarized in this paper was conducted by the Virginia Transportation Research Council, Virginia Department of Transportation, with the support of the Federal Highway Administration.

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Table 1—Properties of slag concrete for Rte. 143 substructure

Test	Batch 1	Batch 2
Compressive strength, psi		
14 days	4590	4110
28 days	5940	5540
56 days	6020	6050
Flexural strength, psi		
28 days	700	685
Permeability, coulombs	1870	3000

Note: 1 lb/yd^3 = 0.59 kg/m^3; 1 psi = 6.89 kPa.

The permeability specimens were moist cured for 2 weeks and then air-dried for 6 weeks.

Table 2—First HPC structure on Route 40

Material, lb/yd^3	Substructure	Deck
Cement	352	329
Slag	235	329
Coarse aggregate	1773	1773
Fine aggregate	1254	1173
Water	259	263
Test (28 days)		
Compressive strength, psi	5930	8710
Permeability, coulombs	1094	778

Note: 1 lb/yd^3 = 0.59 kg/m^3; 1 psi = 6.89 kPa.

The permeability specimens were moist cured 1 week at 73°F (23°C) and 3 weeks at 100°F (38°C).

Table 3—Lightweight concrete for Route 106 bridge beams

Material, lb/yd^3	Amount
Cement	451
Slag	301
Coarse aggregate LW	696
Coarse aggregate NW	605
Fine aggregate LW	390
Fine aggregate NW	541
Water	255
Test	
28-day compressive strength, psi	8100
1-year permeability, coulombs	916

Note: 1 lb/yd^3 = 0.59 kg/m^3; 1 psi = 6.89 kPa.

Table 4—Arch bridge with SCC

Material, lb/yd^3	Amount
Cement	488
Slag	262
Coarse Aggregate	1451
Fine Aggregate	1451
Water	279
Test (28 days)	
Compressive strength, psi	7510
Permeability, coulombs	1229

Note: 1 lb/yd^3 = 0.59 kg/m^3; 1 psi = 6.89 kPa.

The permeability specimens shown in this table and the following tables were moist cured 1 week at 73°F (23°C) and 3 weeks at 100°F (38°C).

Table 5—SCC test beams

Material, lb/yd^3	Amount
Cement	480
Slag	320
Coarse Aggregate	1430
Fine Aggregate	1430
Water	267
Test (28 days)	
Compressive strength, psi	8570
Permeability, coulombs	642

Note: 1 lb/yd^3 = 0.59 kg/m^3; 1 psi = 6.89 kPa

Table 6—Ternary system of PC, fly ash, and slag cement

Material (lb/yd^3)	Amount
Cement	318
Class F fly ash	159
Slag	159
Coarse Aggregate	1755
Fine Aggregate	1101
Water	286
Test (28 days)	
Compressive strength, psi	5016 (305)
Permeability, coulombs	391 (72)

Note: 1 lb/yd^3 = 0.59 kg/m^3; 1 psi = 6.89 kPa

Test data are an average of 31 sublots. The standard deviation is in parenthesis.

Table 7—I-64 pavement

Material, lb/yd^3	NMS 2-in	NMS 1-in
Cement	375	395
Slag	160	169
Coarse Aggregate	1935	1840
Fine Aggregate	1171	1217
Water	242	250
Test (28 days)		
Compressive strength, psi	4530	4620
Flexural strength, psi	670	685
Permeability, coulombs	1774	1672

Note: NMS: nominal maximum size aggregate; 1 lb/yd^3 = 0.59 kg/m^3; 1 psi = 6.89 kPa

Table 8—Smart road pavement

Material, lb/yd³	Amount
Cement	384
Slag	206
Coarse Aggregate	1795
Fine Aggregate	1267
Water	236
Test (28 days)	
Compressive Strength (psi)	7260
Flexural str (psi)	1055
Permeability (coulombs)	611

1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa

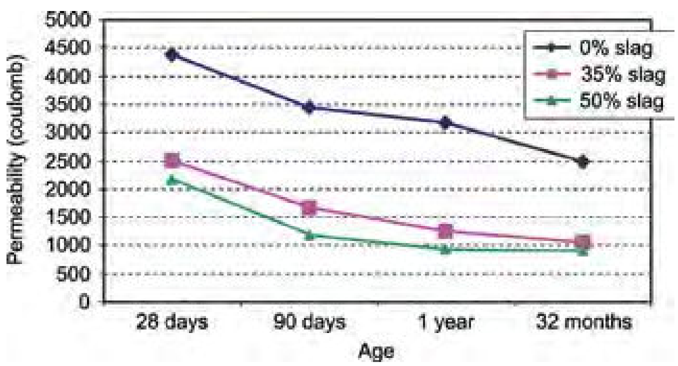

Fig. 1—Reduction in permeability with age. The *w/cm* was 0.45.

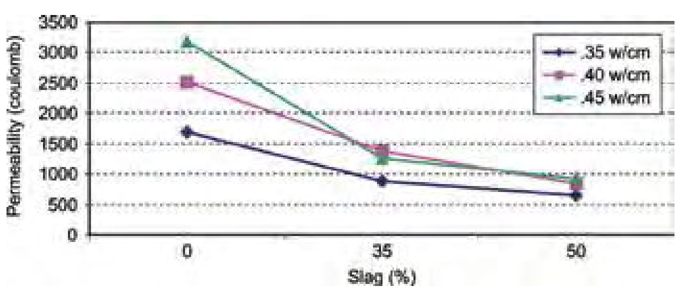

Fig. 2—Permeability of concrete with different percentage of slag for various *w/cm*. Test age is 1 year.