# MATERIALS TECHNOLOGY LABORATORY

# Laboratory Produced High-Volume Fly Ash Blended Cements: Compressive Strength and Resistance to the Chloride-Ion Penetration of Concrete

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# LABORATORY PRODUCED HIGH-VOLUME FLY ASH BLENDED CEMENTS: COMPRESSIVE STRENGTH AND RESISTANCE TO THE CHLORIDE-ION PENETRATION OF CONCRETE

by

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## ABSTRACT

This paper presents data on the performance of the concrete made with HVFA blended cements using fly ashes from Canada and the U.S.A. The parameters investigated included the compressive strength of concrete and its resistance to the chloride-ion penetration. Regardless of the type of the fly ash used, the concrete made with the HVFA blended cements developed higher compressive strength at all ages than that of the HVFA concrete in which unground fly ashes and laboratory-produced portland cements had been added separately at the concrete mixer. The increase in the compressive strength was more significant for the HVFA blended cements produced with the cement without a superplasticizer and made with coarse fly ash. The use of the HVFA blended cements improved the resistance of the concrete to the chloride-ion penetration, and the improvement in the resistance increased with an increase in the intergrinding time of the fly ash and the cement.

**Keywords :** Air entrainment, blended cement, chloride-ion penetration, compressive strength, concrete, fly ash, grinding, superplasticizer.

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## 1. Introduction

In the mid 1990s, CANMET in collaboration with the Environment Canada, a Canadian federal government department, and Electric Power Research Institute, U.S.A., undertook a major research project to develop blended cements incorporating high volumes of ASTM Class F fly ash. The blended cement is made typically by intergrinding approximately 55% (weight percentage) of low-calcium fly ash, and 45% of ASTM Type I or Type III cement clinker together with a small amount of gypsum, and in some cases with a small amount of a dry superplasticizer [1-5].

Previous investigations had shown that the procedures in the production of high-volume fly ash (HVFA) blended cement that meet the ASTM requirements depend on the type of the fly ash used. Some fly ashes required a long period of grinding, whereas the others needed the incorporation of a certain amount of dry superplasticizer (SP) to achieve the strengths required by the ASTM standard. In some instances fly ashes could only be used after their proportion in the blended cement had been reduced to less than 55%.

This paper presents data on the performance of the concrete made with HVFA blended cements. These data were compared to those of the concrete in which the cement and the unground fly ash had been added separately at the concrete mixer. The parameters investigated included the compressive strength of concrete, and its resistance to the chloride-ion penetration.

## 2. Part I: HVFA Blended Cements Produced Without a Superplasticizer

### 2.1 Materials used

#### 2.1.1 Normal Portland Cement Clinker, and Gypsum

A portland cement clinker for the production of ASTM Type III cement designated as clinker 1 was used in this study. Its chemical composition is given in Table 1. The chemical composition of gypsum is given in Table 2.

#### 2.1.2 Fly Ash

Fly ashes from Point Tupper (Nova Scotia), Forestburg and Genesee (Alberta) were used in this study. Their physical properties and chemical compositions are also given in Table 1.

Point Tupper, and Forestburg fly ashes meet the requirements of ASTM Class F ash. For Genesee fly ash, the amount of the ash retained on a 45 µm sieve was 35.9% when wet sieved, thus this ash fails to meet the fineness requirements of ASTM C 618*.

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* ASTM C 618 requires that the amount of the ash retained when wet-sieved on 45 µm sieve be less than 34%.

### 2.1.3 Admixtures

A superplasticizer of sulphonated, naphthalene formaldehyde condensate in a dry powder form was used. A synthetic resin type of air-entraining admixture was used in all the concrete mixtures.

### 2.1.4 Aggregates

A crushed granite with a maximum nominal size of 19 mm was used as the coarse aggregate, and a local natural sand was used as the fine aggregate. The coarse and fine aggregates each had a specific gravity of 2.70, and the water absorption of 0.5 and 0.8%, respectively.

## 2.2 Production of the HVFA Blended Cements

To produce HVFA blended cements that meet the requirements of ASTM C 1157M, two procedures were used at CANMET. The first procedure involved two stages; these consisted of producing a cement with a Blaine fineness of 4000 $cm^2/g$ (LPC), and then intergrinding 45% of the above cement with 55% of the fly ash for a predetermined time of grinding. For example, blended cements made with Forestburg and Genesee fly ashes were produced by intergrinding the fly ashes with the laboratory-produced portland cement for 20 and 80 minutes, respectively. This procedure has the advantage to start with a fixed Blaine fineness of the cement thus ensuring that mortars or concrete made with blended cements have a basic minimum compressive strength. The second procedure consisted of producing a blended cement by grinding together the cement clinker, gypsum, and the fly ash for a predetermined time; for example, 160 minutes for the blended cement made with Point Tupper fly ash. This procedure was adopted because the use of the Point-tupper fly ash did not result in the satisfactory production of blended cement when the first procedure was used. Before the clinker was fed to the grinding mill, it was crushed so that all the particles were less than 0.6 mm.

Table 3 gives the designation and the procedure used for the cement production. The physical properties and chemical composition of these cements were determined, and are given in Table 4.

A ceramic grinding mill, 420 mm in length and 500 mm in diameter with a grinding capacity of approximately 10 kg material, was used for the production of the cements. A combination of 35 kg of large ceramic cylinders (30-mm thick and 30-mm diameter) and 35 kg of medium ceramic cylinders (20-mm thick and 20-mm diameter) was used for the grinding. The weight ratio of the materials to be ground to the grinding media was 1:7.

## 2.3 Proportions of Concrete mixtures

Six high-volume fly ash concrete mixtures were made. For each fly ash, one concrete mixture was made in which unground fly ash and the laboratory-produced normal portland cement were separately added at the concrete mixer, and the other mixture was made with the blended cement. The proportions of the concrete mixtures are summarized in Table 5.

The coarse and fine aggregates were weighed in a room dry condition. The coarse aggregate was then immersed in water for approximately 24 hours, the excess water was decanted, and the water retained by the aggregates was determined by the weight difference. A predetermined amount of water was added to the fine aggregate that was then allowed to stand for 24 hours.

All the concrete mixtures were mixed in a laboratory counter-current mixer for a total of five minutes. After the mixing, the slump, unit weight, and air content of the concrete were determined following ASTM Standards.

## 2.4 Preparation, Curing, and Testing of the Concrete

Twelve 102x203-mm cylinders were cast from each mixture. Eight of the cylinders were used for the determination of the compressive strength at various ages, and four cylinders were used for the determination of the resistance to the chloride-ion penetration. The cylinders were cast in two layers, with each layer being consolidated on a vibrating table. After casting, all the molded specimens were covered with plastic sheets and water-saturated burlap, and left in the casting room for 24 hours. They were then demolded and transferred to a moist-curing room at 23 ± 2°C and 100% relative humidity until required for testing. At the age of 1, 7, 14, and 28 days, two cylinders from each mixture were tested for compressive strength according to ASTM Standard C 39. The resistance of the concrete to the chloride-ion penetration was determined at 14 and 28 days in accordance with ASTM C 1202.

## 2.5 Results and Discussion

### 2.5.1 Characteristics of laboratory produced cements

Table 4 presents the physical properties and chemical composition of the laboratory produced cements. The LPC cement meets the requirement of ASTM C 150 Type III cement, and the HVFA blended cements meet the requirement of ASTM C 1157M.

Table 4 shows that the air content of the mortar made with the LPC was 6.6%, and that of the mortars made with the blended cements BCF, BCP and BCG, produced with the LPC cement, was 2.3, 3.4 and 3.9%, respectively. This shows that the use of the fly ash increased the packing density of the blended cement, and that, in turn, decreased the air content of the mortars made with the blended cements.

### 2.5.2 Properties of Fresh Concrete

The unit weight, slump and air content of the fresh concrete are given in Table 6.

#### *2.5.2.1 Dosage of the Superplasticizer and Slump*

The dosage of the superplasticizer used for the concrete mixtures to reach a slump of approximately 100 mm varied with the type of fly ash and the type of the blended cement. For mixtures 1, 3 and

5 in which unground Forestburg, Point Tupper and Genesee fly ashes had been added at the concrete mixer, the dosage of the superplasticizer ranged from 1.6 to 2.7 $L/m^3$ of concrete; the lower value corresponded to the coarser Genesee fly ash, and the higher value corresponded to the finer Point Tupper fly ash that had the highest loss on ignition (LOI) as well.

In order to obtain similar slumps, the concrete mixtures made with the blended cements (mixtures 2, 4, and 6) required more superplasticizer than the concrete mixtures in which unground fly ashes and laboratory-produced cements had been added separately at the concrete mixer (mixtures 1, 3, and 5). The increase in the dosage of the superplasticizer was due to the intergrinding of the fly ash with other cement ingredients that resulted in the increase in the fineness of the fly ash and clinker in the blended cement.

#### *2.5.2.2 Dosage of the Air-Entraining Admixture (AEA)*

The dosage of the AEA required for obtaining an air content in the range of 5 to 7 % was influenced by the type of the fly ash, the type of the blended cement, and the dosage of the superplasticizer required. It is known that a fly ash with higher loss on ignition requires a higher dosage of the A.E.A [6], furthermore Bouzoubaâ et al. [1] reported that the increase in the fineness of the fly ash leads to an increase in the dosage of A.E.A. for the concrete. However, mixture 3 made with Point Tupper fly ash that had a Blaine fineness of 2270 $cm^2/g$ and a LOI of 2.4% required less AEA than mixture 1 made with Forestburg fly ash that had similar Blaine fineness and lower LOI. This is probably due to the higher content of the SP in mixture 3 that contributed also to some entrainment of air in the concrete thus reducing the AEA dosage requirement to obtain a specified amount of entrained air in the concrete [1, 7].

Regardless of the fly ash used, the use of the blended cements had resulted in a higher dosage of the AEA due to the higher fineness of the fly ash in the blended cement.

### 2.5.3 Compressive Strength of Concrete

The unit weight and compressive strength of the concrete are given in Table 7. Regardless of the type of the fly ash, the use of the blended cements enhanced the compressive strength of the concrete at all ages. This is due mainly to the increase in the fineness of the fly ash in the blended cements. In fact, the intergrinding of the Forestburg fly ash with the cement for 20 minutes increased the 28-day compressive strength of the concrete by 33%, and the intergrinding of the coarse Genesee fly ash with the cement for 80 minutes increased the 28-day compressive strength of the concrete by 52%. The above data show that coarse fly ashes that fail to meet the ASTM requirements for fineness can be used successfully to produce blended cements.

For Point-tupper fly ash, the use of HVFA blended cement increased the 28-day compressive strength of the concrete by 54%. However, the intergrinding time of the Point-tupper fly ash with the clinker and gypsum was 160 minutes. This is too long compared to the grinding time required for the two other fly ashes. Thus, the energy requirement would have to be taken into account in the production of HVFA blended cements made with this type of fly ash.

#### 2.5.4 Resistance to the chloride-ion penetration

Table 8 presents data on the resistance of the concrete to chloride-ion penetration. The results show that the use of the blended cements improves the 14- and 28-day resistance to the chloride-ion penetration of concrete. The increase in the resistance was due primarily to the grinding of the fly ash that increased its fineness and resulted in a more dense microstructure of the paste in concrete compared to that of the concrete made with the unground fly ash. The increase in resistance to the chloride-ion penetration was marginal for concrete made with the Forestburg fly ash that had been interground with the LPC cement for 20 minutes, but was significant for concrete made with the Genesee fly ash that had been interground with the LPC cement for 80 minutes.

## 3. Part II: HVFA Blended Cements Incorporating a Superplasticizer

### 3.1 Materials used

#### 3.1.1 Portland Cement Clinker

A portland cement clinker for the production of ASTM Type I cement, designated as clinker 2 was used in this part. Its chemical composition is given in Table 1.

#### 3.1.2 Fly Ash

Fly ashes from Coal Creek (North Dakota), Belews Creek (North Carolina) and Monco (West Virginia) were used in this part of the study. Their physical properties and chemical compositions are also given in Table 1. All fly ashes meet the requirements of ASTM Class F fly ash.

#### 3.1.3 Gypsum, Superplasticizer, Air-Entraining Admixture and Aggregates

The sources of gypsum, superplasticizer, air-entraining admixture, and the aggregates used in this investigation were the same as in part I of the study .

### 3.2 Production of the HVFA Blended Cements

Previous investigations [5] had shown that the three fly ashes being investigated required to be interground with a cement incorporating a superplasticizer to produce HVFA blended cements that meet the requirements of ASTM C 1157M. HVFA blended cements were therefore, produced in two stages; these consisted of producing a superplasticized portland cement with a ceratin percentage of the SP and a certain Blaine fineness (LPC1, LPC2 and LPC3), and then intergrinding 45% of the above cement with 55% of the fly ash for a predetermined time of grinding. The HVFA blended cement made with the Monco fly ash (BCM), did not meet the ASTM requirement, and the ash content was therefore reduced to 40% by mass of the cementitious materials [5].

The percentage of the superplasticizer used was 0.6, 0.95, and 1.1% by mass of the clinker and gypsum for the blended cements made with the Coal Creek, Belews Creek, and Monco ashes, respectively. These percentages were selected from the previous studies on the subject so that the concrete made with the above blended cements will have a slump of approximately 100 mm.

Previous investigations had shown that, the optimum way to produce HVFA blended cements with Coal Creek (BCC), and Monco (BCM) ashes is by using superplasticized portland cements (LPC1 and LPC3, respectively) with a Blaine fineness of 4000 $cm^2/g$, and that with Belews Creek ash (BCB) is by using a superplasticized portland cement (LPC2) with a Blaine fineness of 3500 $cm^2/g$ [5]. The superplasticized portland cements LPC1, LPC2, and LPC3 were produced by grinding together the clinker, gypsum, and 0.6, 0.95, and 1.1% of the dry superplasticizer, respectively. The intergrinding time of the fly ash with the cements was 20, 40 and 80 minutes for the Coal Creek, Monco, and Belews Creek ashes, respectively.

Table 3 gives the designation and the grinding procedure used for the cements produced. The physical properties and chemical composition of these cements were determined, and are given in Table 4.

### 3.3 Proportions of Concrete mixtures

As for Part I, six high-volume fly ash concrete mixtures were made. For each fly ash, one concrete mixture was made in which unground fly ash and the corresponding superplasticized portland cement were added separately at the concrete mixer, and the other mixture was made with the HVFA blended cement. The proportions of the concrete mixtures are summarized in Table 5.

### 3.4 Preparation, Curing, and Testing of the Concrete

The procedure for the preparation, curing, and testing of the concrete were the same as those described in the first part of the present paper. Twelve 102x203-mm cylinders were cast from each mixture. Eight of the cylinders were used for the determination of the compressive strength, and four cylinders were used for the determination of the resistance to the chloride-ion penetration.

### 3.5 Results and Discussion

#### 3.5.1 Characteristics of laboratory produced cements

Table 4 presents the physical properties and chemical composition of the laboratory produced cements. The superplasticized cements meet the requirements of ASTM C 150 Type I cement. The results show that for similar Blaine fineness, LPC3 cement incorporating 1.1% of the SP has longer initial setting time and approximately similar final setting time compared with LPC1cement incorporating only 0.6% of the SP. This is in line with previous reported data that the SP retards significantly the initial setting time and affects only marginally the final setting time of the cement [8].

The HVFA blended cements BCC and BCB meet the requirement of ASTM C 1157M. The blended cement BCM that incorporates 40% fly ash by mass of the cementitious materials meets the requirements of ASTM C 595M.

It was found in the first part that the use of the fly ash decreased the air content of the mortars made with the HVFA blended cements compared to that of the mortar made with the laboratory-produced normal portland cement LPC. This effect, however, decreased with the presence of the SP in the cement (Table 4), which is probably due to the fact that SP might contributed to some entrainment of air in the mortar.

### 3.5.2 Properties of Fresh Concrete

The unit weight, slump, and air content of the fresh concrete are given in Table 6.

#### *3.5.2.1 Dosage of the Superplasticizer and Slump*

The dosage of the superplasticizer used for the concrete mixtures to reach a slump of approximately 100 mm varied with the type of fly ash and the type of the blended cement.

Mixtures 7, 9, and 11 were made with superplasticized portland cements and unground Coal Creek, Belews Creek and Monco ashes, respectively. For each fly ash the percentage of the dry superplasticizer to be interground with the cement was selected so that the HVFA concrete will have a slump of approximately 100 mm. No SP, therefore, was to be added at the concrete mixer for the mixtures 7, 9, and 11. This, however, was not materialized, and the dosage of the superplasticizer added at the concrete mixer to reach a slump of approximately 100 mm ranged from 0.5 to 2.1 L/m$^3$. This was primarily due to the fact that the HVFA concrete made for determining the percentage of the superplasticizer to be interground with the cement was made with an ASTM Type I cement that had a $C_3A$ content of 6%, whereas the superplasticized portland cements had a $C_3A$ content ranging from 8.5 to 9.5% (Table 4). It is known that the concrete made with a cement with a high content of $C_3A$ requires more quantity of the SP than the concrete made with a cement with a low content of $C_3A$ to achieve a given concrete workability [9]. Also, the reason for the additional demand of the superplasticizer could be the incorporation of the superplasticizer in the cement. It is known that the amount of superplasticizer required to achieve a given concrete fluidity is lower when the admixture is introduced as the last component in the concrete mixing process as the early cement-superplasticizer surface reactions apparently result in a high initial consumption of the superplasticizer [10].

For similar slumps, the concrete mixtures made with the blended cements (mixtures 8, 10 and 12) required more superplasticizer than the concrete mixtures in which the unground fly ashes and the superplasticized portland cements had been added separately at the concrete mixer (mixtures 7, 9 and 11). As mentioned earlier, the increase in the dosage of SP was due to the intergrinding of the fly ash with the superplasticized portland cement, that resulted in the increase in the fineness of the fly ash and the superplasticized portland cement in the blended cement.

*3.5.2.2 Dosage of the Air-Entraining Admixture (AEA)*

The dosage of the AEA required for obtaining an air content in the 5 to 7 % range was influenced by the type of the fly ash and the type of the blended cement used. As it was found in the first part, the use of the blended cement increased the dosage of the AEA due to the higher fineness of the fly ash in the blended cement.

### 3.5.3 Compressive Strength of Concrete

The unit weight and compressive strength of the concrete are given in Table 7. The results show that for the three fly ashes investigated, the use of the blended cement increased the compressive strength of the concrete at all ages. This is due mainly to the increase in the fineness of the fly ashes in the blended cements. In fact, the intergrinding of the Coal Creek fly ash with the cement LPC1 for 20 minutes increased the 28-day compressive strength of the concrete by 11%, and the intergrinding of the Belews Creek fly ash with the cement LPC2 for 80 minutes increased the 28-day compressive strength of the concrete by 22%. However, for some reason, the increase in the compressive strength was less significant than that observed for the concrete mixtures investigated in the first part of the study.

For Monco fly ash, the use of the blended cement increased the 28-day compressive strength of the concrete by 32%. This show that the fly ash that cannot be used for the production of HVFA blended cements can still be used successfully in the production of blended fly ash cements.

### 3.5.4 Resistance to the chloride-ion penetration

Table 8 presents the data on the resistance of the concrete to the penetration of chloride-ions. The results show that the use of the blended cement results in an improvement in the 14- and 28-day resistance of the concrete to the chloride-ion penetration due to the same reason given in part 1 of the present paper.

## 4. Grinding Process: Laboratory Grinding Mill versus Commercial Ball Mills

It should be recognized that the data are valid only to a closed circuit grinding, and probably more specifically, to grinding in similar mills and similar grinding cylinders Production of intergrinding fly ash and cement in commercial ball mills that practically all of them contain more than one compartment and equipped with air separator may yield different results. In view of this, this laboratory data should be considered as a starting point, and trial grinding runs should be performed in commercial ball mills before adopting this technology.

## 5. Concluding Remarks

1. HVFA blended cements can be produced with cement clinkers and fly ashes having a wide range of chemical compositions and physical properties. Most of the blended cements so produced can meet the ASTM requirement for blended cements.

2. For similar slumps and air contents, the concrete mixtures made with the high-volume fly ash blended cements required more superplasticizer and air-entraining admixture than the concrete mixtures in which unground fly ashes and laboratory-produced portland cements had been added separately at the concrete mixer. The above noted increases were due primarily to the intergrinding of the fly ash with the other cement ingredients, that resulted in the increase in the fineness of the fly ash and the clinker in the blended cement.

3. Regardless of the type of the fly ash used, the concrete made with the HVFA blended cements developed higher compressive strength at all ages than that of the HVFA concrete in which unground fly ashes and laboratory-produced portland cements had been added separately at the concrete mixer. The increase in the compressive strength was more significant for the HVFA blended cement produced with the cement without a superplasticizer and made with coarse fly ash.

4. The use of the HVFA blended cements improved the resistance of the concrete to the chloride-ion penetration, and the improvement in the resistance increased with an increase in the intergrinding time of the fly ash and the cement.

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Table 1 - Physical Properties and Chemical Analyses of the Materials Used

| | **PART I** | | | | **PART II** | | | | ASTM C 618 Class F |
|---|---|---|---|---|---|---|---|---|---|
| | Clinker1** | Forestburg | Point Tupper | Genesee | Clinker2*** | Coal Creek | Belews Creek | Monco | |
| Physical tests | | | | | | | | | |
| Specific gravity | 3.23 | 1.97 | 2.58 | 2.01 | 3.11 | 2.44 | 2.28 | 2.53 | - |
| Fineness | | | | | | | | | |
| -passing 45µm, % | - | 78.6 | 75.2 | 64.1 | - | 76.1 | 79.8 | 74.1 | 66.0 min. |
| -specific surface, Blaine, $cm^2/g$ | - | 2230 | 2270 | 2120 | - | 2050 | 2270 | 1880 | - |
| -median particle size (µm) | - | 17.8 | 14.0 | 21.2 | - | 13.0 | 17.6 | 16.9 | - |
| Water requirement, % | - | 93.5 | 95.6 | 95.8 | - | 94.7 | 94.7 | 97.9 | 105 max. |
| Pozzolanic Activity Index,* % | | | | | | | | | |
| -7-day | - | 82.4 | 79.6 | 76.0 | - | 85.8 | 77.5 | 85.4 | 75 min. |
| -28-day | - | 91.0 | 89.2 | 90.5 | - | 88.9 | 86.8 | 88.1 | 75 min. |
| Chemical analyses, % | | | | | | | | | |
| Silicon dioxide ($SiO_2$) | 22.3 | 56.8 | 42.7 | 62.6 | 21.7 | 50.5 | 56.2 | 45.2 | $SiO_2 + Al_2O_3 + Fe_2O_3$ 70.0 min. |
| Aluminum oxide ($Al_2O_3$) | 4.5 | 21.5 | 20.3 | 20.9 | 5.2 | 15.4 | 30.0 | 24.0 | |
| Ferric oxide ($Fe_2O_3$) | 3.4 | 4.9 | 23.7 | 4.5 | 3.0 | 8.8 | 5.1 | 16.2 | |
| Calcium oxide (CaO) | 65.5 | 8.8 | 4.2 | 5.8 | 64.9 | 15.6 | 1.1 | 6.8 | - |
| Magnesium oxide (MgO) | 2.9 | 1.6 | 1.2 | 1.5 | 3.2 | 4.0 | 0.8 | 1.1 | - |
| Sodium oxide ($Na_2O$) | 0.4 | 3.9 | 0.9 | 2.5 | 0.3 | 2.5 | 0.3 | 1.2 | - |
| Potassium oxide ($K_2O$) | 0.8 | 1.1 | 2.6 | 1.7 | 0.8 | 2.0 | 2.2 | 2.1 | - |
| Equivalent alkali ($Na_2O$+0.658$K_2O$) | 0.9 | 4.6 | 2.6 | 3.6 | 0.8 | 3.8 | 1.8 | 2.6 | - |
| Phosphorous oxide ($P_2O_5$) | 0.2 | 0.4 | 0.7 | 0.1 | 0.1 | 0.1 | 0.2 | 0.5 | - |
| Titanium oxide ($TiO_2$) | 0.2 | 0.5 | 0.9 | 0.7 | 0.3 | 0.7 | 1.7 | 1.2 | - |
| Sulphur trioxide ($SO_3$) | <0.01 | 0.1 | 1.6 | 0.1 | 0.4 | 1.5 | 0.4 | 1.0 | 5.0 max. |
| Loss on ignition | 0.01 | 0.3 | 2.4 | 0.3 | 0.3 | 0.3 | 2.1 | 1.4 | 6.0 max. |

* using ASTM Type I cement, ** obtained from a cement plant from Canada, and used for the production of cement LPC and blended cements using Forestburg, Point Tupper, and Genesee fly ashes, *** obtained from a cement plant from USA, and used for the production of cements LPC1, LPC2, and LPC3, and blended cements using Belews Creek, Cola Creek, and Monco fly ashes

min. minimum max. maximum

Table 2 - Chemical Composition of Gypsum

| | Chemical composition |
|---|---|
| Free water ($T < 45\ ^{0}C$) | 0.03 |
| Combined water ($T < 230\ ^{0}C$) | 16.4 |
| Carbon dioxide ($CO_2$ ) | 4.7 |
| $SiO_2$ and Insoluble matter | 2.7 |
| Iron and aluminum oxide ($Fe_2O_3 + Al_2O_3$) | 0.8 |
| Lime (CaO) | 33.4 |
| Magnesium oxide (MgO) | 1.5 |
| Sulphur trioxide ($SO_3$) | 41.0 |
| Chloride | 0.01 |
| $CaSO_4 \cdot 2H_2O$ | 78.3 |
| $CaSO_4$ | 7.8 |
| $SiO_2$ + insoluble matter | 2.7 |
| Iron and aluminum oxide | 0.8 |
| Calcium carbonate ($CaCO_3$) | 8.4 |
| Magnesium carbonate ($MgCO_3$) | 3.1 |
| Chloride | 0.01 |

Table 3 - Designation of the Laboratory-Produced Cements

| | Designation | Description |
|---|---|---|
| PART I | LPC | 97% of clinker1 for ASTM Type III cement and 3% of gypsum interground to a Blaine fineness of 4000 $cm^2/g$ |
| | BCF | 45% of cement LPC and 55% of Forestburg, interground for 20 minutes |
| | BCG | 45% of cement LPC and 55% of Genesee, interground for 80 minutes |
| | BCP | 43.7% of clinker1 for ASTM Type III cement, 1.3% of gypsum and 55% of Point Tupper interground for 160 minutes |
| PART II | LPC1 | 96.4% of clinker2 for ASTM Type I cement, 3% of gypsum and 0.6% of SP interground to a Blaine fineness of 4000 $cm^2/g$ |
| | BCC | 45% of cement LPC1 and 55% of Coal Creek, interground for 20 minutes |
| | LPC2 | 96.05% of clinker2 for ASTM Type I cement, 3% of gypsum and 0.95% of SP interground to a Blaine fineness of 3500 $cm^2/g$ |
| | BCB | 45% of cement LPC2 and 55% of Belews Creek, interground for 80 minutes |
| | LPC3 | 95.9% of clinker2 for ASTM Type I cement, 3% of gypsum and 1.1% of SP interground to a Blaine fineness of 4000 $cm^2/g$ |
| | BCM | 60% of cement LPC3 and 40% of Monco, interground for 40 minutes |

Table 4 - Physical Properties and Chemical Analyses of the Cements Used

| | PART I | | | | PART II | | | | | | ASTM C 150 | | ASTM C 1157M (GU) | ASTM C 595M (IP) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LPC | BCF | BCP | BCG | LPC1 | LPC2 | LPC3 | BCC | BCB | BCM | Type I | Type III | | |
| Physical tests | | | | | | | | | | | | | | |
| Specific gravity | 3.15 | 2.62 | 2.94 | 2.70 | 3.08 | 3.03 | 3.02 | 2.80 | 2.72 | 2.88 | - | - | - | - |
| Fineness | | | | | | | | | | | | | | |
| -passing 45µm, % | 88.5 | 94.1 | 93.8 | 97.9 | 83.5 | 82.5 | 78.4 | 88.7 | 96.9 | 88.2 | - | - | - | - |
| -specific surface, Blaine, $cm^2/g$ | 4000 | 2770 | 3880 | 3540 | 4000 | 3500 | 4000 | 2880 | 3480 | 2960 | 2800 min. | - | - | - |
| Compressive strength of 51 mm cubes, MPa | | | | | | | | | | | | | | |
| -1-day | 15.3 | - | - | - | - | - | - | - | - | - | - | 12.4 min. | - | - |
| -3-day | 24.2 | 13.8 | 11.9 | 13.1 | 17.0 | 19.9 | 17.4 | 12.5 | 11.4 | 15.2 | 12.0 min. | 24.1 min. | 10.0 min. | 13.0 min. |
| -7-day | - | 19.1 | 17.8 | 18.0 | 24.4 | 27.8 | 23.6 | 18.7 | 17.1 | 20.7 | 19.0 min. | - | 17.0 min. | 20.0 min. |
| -28-day | - | - | - | - | - | - | - | - | - | 32.8 | - | - | - | 25.0 min. |
| Time of setting, Vicat test, min | | | | | | | | | | | | | | |
| -initial setting | 130 | 305 | 245 | 275 | 165 | 245 | 190 | 270 | 335 | 275 | 45 min. | 45 min. | 45 min. | 45 min. |
| -final setting | 240 | 395 | 370 | 380 | 240 | 280 | 250 | 360 | 390 | 365 | 375 max. | 375 max. | 420 max. | 420 max. |
| Air content of mortar, volume % | 6.6 | 2.3 | 3.4 | 3.9 | 7.7 | 7.7 | 7.4 | 5.7 | 5.3 | 6.5 | 12 max. | 12 max. | - | 12 max. |
| Chemical analyses, % | | | | | | | | | | | | | | |
| Silicon dioxide ($SiO_2$) | 20.9 | 38.3 | 30.6 | 39.6 | 21.6 | 20.9 | 20.9 | 36.5 | 38.3 | 30.6 | - | - | - | - |
| Aluminium oxide ($Al_2O_3$) | 4.8 | 13.0 | 12.7 | 11.8 | 5.1 | 5.0 | 5.0 | 10.8 | 18.4 | 11.7 | - | - | - | - |
| Ferric oxide ($Fe_2O_3$) | 3.3 | 4.3 | 13.1 | 3.3 | 2.4 | 2.5 | 2.8 | 5.9 | 3.5 | 8.0 | - | - | - | - |
| Calcium oxide (CaO) | 62.4 | 35.8 | 34.3 | 36.9 | 62.3 | 62.5 | 62.1 | 36.2 | 31.0 | 40.8 | - | - | - | - |
| Magnesium oxide (MgO) | 2.8 | 2.0 | 1.9 | 2.1 | 2.9 | 3.1 | 2.9 | 3.6 | 1.8 | 2.2 | - | - | - | 6.0 max. |
| Sodium oxide ($Na_2O$) | 0.3 | 2.3 | 0.6 | 1.3 | 0.4 | 0.4 | 0.4 | 1.5 | 0.4 | 0.5 | 6.0 max. | 6.0 max. | - | - |
| Potassium oxide ($K_2O$) | 0.9 | 1.1 | 1.8 | 1.4 | 0.5 | 0.5 | 0.7 | 1.5 | 1.8 | 1.3 | - | - | - | - |
| Equivalent alkali ($Na_2O$+0.658$K_2O$) | 0.9 | 3.0 | 1.8 | 2.2 | 0.7 | 0.7 | 0.9 | 2.5 | 1.6 | 1.4 | - | - | - | - |
| Phosphorous oxide ($P_2O_5$) | 0.2 | 0.3 | 0.5 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | - | - | - | - |
| Titanium oxide ($TiO_2$) | 0.2 | 0.4 | 0.6 | 0.5 | 0.2 | 0.2 | 0.2 | 0.6 | 1.1 | 0.6 | - | - | - | - |
| Sulphur trioxide ($SO_3$) | 3.4 | 1.7 | 2.6 | 1.9 | 2.5 | 2.7 | 2.7 | 2.0 | 1.4 | 2.1 | 3.0 max. | 3.5 max. | - | 4.0 max. |
| Loss on ignition | 0.7 | 0.6 | 1.2 | 0.9 | 1.8 | 1.8 | 1.8 | 1.0 | 2.1 | 1.9 | 3.0 max. | 3.0 max. | - | 5.0 max. |
| Bogue potential compound composition | | | | | | | | | | | | | | |
| Tricalcium silicate $C_3S$ | 48.5 | - | - | - | 44.6 | 50.7 | 48.7 | - | - | - | - | - | - | - |
| Dicalcium silicate $C_2S$ | 23.3 | - | - | - | 28.3 | 21.7 | 23.2 | - | - | - | - | - | - | - |
| Tricalcium aluminate $C_3A$ | 7.1 | - | - | - | 9.5 | 9 | 8.5 | - | - | - | - | 15 max. | - | - |
| Tetracalcium aluminoferrite $C_4AF$ | 10 | - | - | - | 7.3 | 7.6 | 8.5 | - | - | - | - | - | - | - |

## Table 5 - Proportions of the Concrete Mixtures

|  | Mix. no. | $\frac{W}{(C+FA)}$* | Water, kg/m$^3$ | Cement |  | Fly ash added in the mixer |  | Fine aggregate, kg/m$^3$ | Coarse aggregate, kg/m$^3$ | AEA**, mL/m$^3$ | SP***, L/m$^3$ (added in the mixer) | SP***, L/m$^3$ (added in the grinding mill) | Total of SP*** used, L/m$^3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  | type | kg/m$^3$ | source | kg/m$^3$ |  |  |  |  |  |  |
| **PART I** | 1 | 0.32 | 130 | LPC | 180 | Forestburg | 222 | 754 | 1127 | 226 | 1.9 | 0 | 1.9 |
|  | 2 | 0.32 | 123 | BCF | 379 | - | - | 733 | 1098 | 312 | 3.0 | 0 | 3 |
|  | 3 | 0.32 | 121 | LPC | 168 | Point Tupper | 208 | 736 | 1099 | 177 | 2.7 | 0 | 2.7 |
|  | 4 | 0.32 | 125 | BCP | 386 | - | - | 755 | 1136 | 227 | 3.8 | 0 | 3.8 |
|  | 5 | 0.32 | 124 | LPC | 171 | Genesee | 212 | 718 | 1079 | 158 | 1.6 | 0 | 1.6 |
|  | 6 | 0.32 | 126 | BCG | 389 | - | - | 738 | 1108 | 183 | 3.5 | 0 | 3.5 |
| **PART II** | 7 | 0.32 | 124 | LPC1 | 171 | Coal Creek | 211 | 734 | 1107 | 130 | 0.46 | 2.1 | 2.56 |
|  | 8 | 0.32 | 122 | BCC | 379 | - | - | 737 | 1107 | 188 | 1.2 | 2.1 | 3.2 |
|  | 9 | 0.32 | 124 | LPC2 | 171 | Belews Creek | 211 | 734 | 1093 | 202 | 2.1 | 3.35 | 5.45 |
|  | 10 | 0.32 | 125 | BCB | 387 | - | - | 753 | 1125 | 296 | 1.9 | 3.35 | 5.25 |
|  | 11 | 0.32 | 122 | LPC3 | 229 | Monco | 153 | 745 | 1112 | 238 | 1.4 | 3.96 | 5.36 |
|  | 12 | 0.32 | 124 | BCM | 387 | - | - | 756 | 1137 | 290 | 2.2 | 3.96 | 6.16 |

* Water-to-(cement+fly ash) ratio

** Air-entraining admixture

*** Superplasticizer. The superplasticizer was used in a dry form. The value reported in this Table is the corresponding volume of liquid superplasticizer that was calculated knowing that its density is 1.21 kg/cm$^3$ and considering that its solids content is 40% by mass

Table 6 - Properties of the Fresh Concrete

| | Mix. no. | W/(C+FA) | Cement type | Source of fly ash added in the mixer | Unit weight, kg/m$^3$ | Slump, mm | Air content, % |
|---|---|---|---|---|---|---|---|
| **PART I** | 1 | 0.32 | LPC | Forestburg | 2306 | 90 | 7.0 |
| | 2 | 0.32 | BCF | - | 2334 | 115 | 6.2 |
| | 3 | 0.32 | LPC | Point Tupper | 2334 | 90 | 6.8 |
| | 4 | 0.32 | BCP | - | 2405 | 65 | 5.5 |
| | 5 | 0.32 | LPC | Genesee | 2306 | 100 | 6.3 |
| | 6 | 0.32 | BCG | - | 2362 | 95 | 5.0 |
| **PART II** | 7 | 0.32 | LPC1 | Coal Creek | 2348 | 100 | 6.3 |
| | 8 | 0.32 | BCC | - | 2348 | 90 | 6.2 |
| | 9 | 0.32 | LPC2 | Belews Creek | 2334 | 110 | 6.2 |
| | 10 | 0.32 | BCB | - | 2391 | 65 | 4.8 |
| | 11 | 0.32 | LPC3 | Monco | 2306 | 100 | 6.3 |
| | 12 | 0.32 | BCM | - | 2362 | 50 | 6.0 |

Table 7 - Compressive Strength of Concrete

| | Mix. no. | W/(C+FA) | Cement type | Source of fly ash added in the mixer | Density of hardened concrete (1-d) kg/m$^3$ | Compressive strength, MPa | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 1 d | 7 d | 14 d | 28 d |
| **PART I** | 1 | 0.32 | LPC | Forestburg | 2427 | 6.5 | 17.5 | 21.8 | 25.9 |
| | 2 | 0.32 | BCF | - | 2448 | 8.3 | 22.9 | 28.3 | 34.5 |
| | 3 | 0.32 | LPC | Point Tupper | 2475 | 7.0 | 17.9 | 22.4 | 28.3 |
| | 4 | 0.32 | BCP | - | 2475 | 11.6 | 27.7 | 34.6 | 43.6 |
| | 5 | 0.32 | LPC | Genesee | 2423 | 6.6 | 16.9 | 21.2 | 27.3 |
| | 6 | 0.32 | BCG | - | 2447 | 10.0 | 29.4 | 34.3 | 41.5 |
| **PART II** | 7 | 0.32 | LPC1 | Coal Creek | 2480 | 3.4 | 16.8 | 23.7 | 31.4 |
| | 8 | 0.32 | BCC | - | 2474 | 4.2 | 20.5 | 26.5 | 35.0 |
| | 9 | 0.32 | LPC2 | Belews Creek | 2440 | 1.6 | 17.4 | 23.5 | 31.6 |
| | 10 | 0.32 | BCB | - | 2445 | 5.1 | 23.9 | 31.2 | 38.7 |
| | 11 | 0.32 | LPC3 | Monco | 2448 | 3.3 | 26.0 | 32.8 | 38.9 |
| | 12 | 0.32 | BCM | - | 2467 | 9.5 | 37.7 | 43.0 | 51.3 |

Table 8 - Resistance of the Concrete to the Chloride-Ion Penetration

| | Mix. no. | W/(C+FA) | Cement type | Source of fly ash added in the mixer | Total charge passed, coulombs | |
|---|---|---|---|---|---|---|
| | | | | | 14 d | 28 d |
| PART I | 1 | 0.32 | LPC | Forestburg | 5160 | 2500 |
| | 2 | 0.32 | BCF | - | 4540 | 2180 |
| | 3 | 0.32 | LPC | Point Tupper | 7160 | 3520 |
| | 4 | 0.32 | BCP | - | 4280 | 1910 |
| | 5 | 0.32 | LPC | Genesee | 6650 | 2830 |
| | 6 | 0.32 | BCG | - | 2680 | 1190 |
| PART II | 7 | 0.32 | LPC1 | Coal Creek | 5030 | 1960 |
| | 8 | 0.32 | BCC | - | 4930 | 1840 |
| | 9 | 0.32 | LPC2 | Belews Creek | 5590 | 2890 |
| | 10 | 0.32 | BCB | - | 2990 | 1100 |
| | 11 | 0.32 | LPC3 | Monco | 5170 | 3220 |
| | 12 | 0.32 | BCM | - | 3550 | 1120 |