# MATERIALS TECHNOLOGY LABORATORY

## Performance of Mortars Incorporating Finely-Ground Fly Ash

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# Performance of Mortars Incorporating Finely-Ground Fly Ash

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**Abstract**

This paper presents results on the compressive strength of mortars in which 10 and 20% of ASTM Type I cement has been replaced by ground fly ash from two different sources. The results are compared with those of the mortars made with ASTM Type I cement, and with the mortar in which 10% of portland cement has been replaced by silica fume. The results show that the mortars made with 20% replacement of cement by the fine Sundance fly ash that had been ground for 2 hours achieved a 28-day compressive strength that was 90 to 93% of the strength of the mortars incorporating 10% silica fume as cement replacement. However, for the coarse fly ash, the results were not encouraging. Even increasing the grinding times of the fly ash up to 10 hours, did not yield the compressive strengths approaching that of the silica fume mortars.

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## INTRODUCTION

In recent years beneficiated fly ash having high Blaine specific surface (>550 $m^2$/kg), and percent passing 45% :m exceeding 95% have become available in the USA and Europe. The above mentioned beneficiated fly ashes are being marketed as a substitute for silica fume for making high-performance concrete. However, the beneficiation process involves air classification that results in considerable amount of waste material to be disposed, and thus creating environmental problems.

In order to eliminate the waste disposal problem, it was considered that the grinding of fly ashes to achieve high fineness may overcome the above mentioned environmental issue, keeping in mind that grinding may affect the surface characteristics of the fly ash particles and will require more energy. This paper, therefore, presents results on the compressive strength of mortars in which 10 and 20% of ASTM Type I cement has been replaced by ground fly ash from two different sources. The results are compared with those of the mortars made with ASTM Type I cement, and with the mortar in which 10% of portland cement has been replaced by silica fume.

## SCOPE

Two ASTM Class F fly ashes were investigated in this program involving a total of forty-four mortar mixtures with two sets of twenty-two mixtures each. One set included the mortar mixtures made at constant flow, and the other set included the mixtures made at constant water-to-cementitious materials ratio (w/cm). For each set, the mixtures included two controls, and ten mixtures for each fly ash. Five of these mixtures made with 10% replacement of cement by fly ash, and the remaining five were made with 20% replacement of cement by fly ash. The fly ash used as a partial replacement for cement included unground fly ash, and fly ash ground for 1, 2, 6, and 10 hours. One control mixture was made with ASTM Type I cement, and the other was made with ASTM Type I cement in which 10% of the cement has been replaced by silica fume.

The compressive strength of the mortars was determined at 1, 7, and 28 days.

## MATERIALS

### Cement
ASTM Type I, normal portland cement was used. Its physical properties and chemical composition are presented in Table 1.

### Fly ash
Two ASTM Class F fly ashes from Sundance, and Genesee, Alberta, Canada were used in this study. Their physical properties and chemical compositions are also presented in Table 1.

Sundance fly ash meets the general requirements of ASTM Class F ash, has relatively high CaO content of 13.4% and alkali content ($Na_2O$ equivalent) of 4.0%. The Blaine fineness of the ash is 306 $m^2$/kg and the specific gravity is 2.08.
Genesee fly ash has a relatively low Blaine fineness of 195 $m^2$/kg, and the amount of the ash retained when wet sieved on a 45 :m sieve was 36.5%. This ash, therefore, fails to meet the fineness requirement of ASTM C 618[1]. The ash has a relatively low specific gravity, and this is primarily related to a large numbers of plerospheres that are hollow particles filled with smaller spheres in the sample. The ash has a CaO content of 5.8% and an alkali content ($Na_2O$ equivalent) of 3.6%. This ash meets the chemical requirements of ASTM Class F fly ash.

**Silica fume**
The silica fume used was a dry-uncompacted powder from the production of silicon metal supplied by SKW Canada Inc., Becancour, Québec. The chemical composition and physical properties of the silica fume are given in Table 1. Its $SiO_2$ content was 92.1%, and its specific surface as determined by the nitrogen adsorption method was 19.5 $m^2$/g.

**Superplasticizer**
A sulphonated, naphthalene-formaldehyde condensate type of superplasticizer in a powder form was used in all the mortar mixtures.

## GRINDING MILL

A ceramic grinding mill with a capacity of 1.5 kg (180 mm in length and 280 mm in diameter) was used for producing the cements. A combination of different sizes of steel balls was utilized for this grinding mill, and the weight ratio of the material to the grinding balls was 1:15.

## LABORATORY EXPERIMENTS

**Physical properties of the materials**
Fly ashes were ground for up to 10 hours, and samples were taken after 1, 2, 6, and 10 hours of grinding. The specific gravity, specific surface (Blaine fineness), % passing 45 :m sieve, and the particle size distribution of the unground and the ground fly ashes were determined.

The particle size distribution of the fly ashes was determined by The SediGraph 5100 particle size analysis system. The SediGraph uses a finely collimated X-ray beam to measure particle concentration in terms of the transmitted intensity of the X-ray beam through the suspension

[1] ASTM C 618 requires that the amount retained when wet-sieved on a 45 :m sieve be less than 34%.

relative to the clear or particle-free suspending fluid. The specific gravity, the specific surface, and the %

passing 45 :m sieve of the fly ashes were determined according to ASTM C 188, C 204, and C 430 methods, respectively.

**Mortar mixtures**

Two sets of twenty-two mixtures each were made. One set included the mixtures made at constant flow, the water demand of the mixtures was adjusted to have a mortar with a flow meeting the requirements of ASTM C 109; the other set included the mixtures made at a constant water-to-cementitious materials ratio (w/cm); a superplasticizer was added to the mixtures to have a mortar with a flow meeting the requirements of ASTM C 109.

Each set included two control mixtures, five mixtures with 10% replacement of cement by fly ash, and five mixtures with 20% replacement of cement by fly ash. At each replacement level, mixtures were made with unground fly ash, and fly ash ground for 1, 2, 6, and 10 hours. For the two control mixtures, one was made with ASTM Type I cement, and the other was made with ASTM Type I cement in which 10% of the cement has been replaced by the silica fume.

The compressive strength of the mortars was determined at 1, 7, and 28 days according to ASTM C 109.

## RESULTS AND DISCUSSION

**Effect of grinding on the physical properties of fly ash**

Table 2 summarizes the physical properties of the fly ashes as received, and after 1, 2, 6, and 10 hours of grinding.

<u>Specific gravity</u>

As reported previously (3), the grinding increases the specific gravity of a fly ash due to the crushing of the plerospheres and cenospheres that have relatively low specific gravity. This increase in specific gravity occurs during the initial stages of grinding, and becomes insignificant thereafter. For the Genesee, and Sundance fly ashes, the significant increase in the specific gravity occurred during the first hour of grinding when it increased from 1.95 to 2.25, and from 2.08 to 2.40, respectively (Table 2).

<u>Blaine Fineness</u>

The specific surface of the fly ashes increased with an increase in the grinding time, but high specific surface can be achieved only at the expense of more energy and time. The specific surface of the Genesee, and Sundance fly ashes increased from 195 to 345, and from 306 to 357 $m^2/kg$ after 1 hour of grinding, respectively; these values increased to 681, and 610 $m^2/kg$ after

10 hours of grinding, respectively. The grinding was more effective during the first hour, and it was even more so for the coarse Genesee fly ash (Table 2).

Percent passing 45 :m

The effect of the grinding on the percentage of material passing 45 :m was similar to that observed for the specific gravity and the Blaine fineness of the ashes. The % passing 45 :m for the Genesee, and Sundance fly ashes increased from 63.5 to 99.7%, and from 83.6 to 99.9% after 1 hour of grinding, respectively; the increase was insignificant thereafter (Table 2).

Particle size distribution

Figures 1 and 2 show the changes in the particle size distribution of the fly ashes after up to 10 hours of grinding. The particle size of the fly ashes decreased with increasing grinding time. The median particle size for the Genesee and the Sundance fly ashes decreased from 21.6 and 8.6 :m to 8.2 and 6.2 :m afetr 1 hour of grinding, and further decreased to 3.8 and 3.3 :m, respectively, after 10 hours of grinding (Table 2). For both fly ashes, the decrease in particle size was most significant during the first hour of grinding. After 1 hour of grinding, most of the large particles had been crushed so that all the particles were less than 45 :m, and 60 to 70% of the particles were less than 10 :m. Further increase in the grinding time was less effective in increasing the particle fineness. This is in line with the results of the specific gravity and specific surface as discussed above.

Morphology of fly ash particles

Figures 3 to 5 show the typical micrographs of the original unground fly ash (Sundance) and the fly ash after 2 and 10 hours of grinding. The unground fly ash contains mostly spherical particles with a small number of plerospheres, and irregular-shaped particles. The grinding of the fly ash for 2 hours broke up the plerospheres and the irregular shaped particles, but did not seem to affect the shape of the spherical particles significantly (Fig. 4). After 10 hours of grinding, more spherical particles were broken, and the amount of the irregular-shaped particles increased.

Water requirement

For both fly ashes, the grinding of the fly ash did not significantly affect the water requirement of the fly ashes, although the grinding did affect the spherical shape of fly ash particles. This is, however, in line with previous work that show that the grinding of some fly ashes for up to 10 hours increased the water requirement of the fly ash mortars by up to 0.8% compared with that of the corresponding unground fly ashes (3).

**Compressive strength of mortars**

Mortars made at constant flow

Tables 3 and 4 show the results of the compressive strength of mortars in which 10, and 20% of the portland cement has been replaced by the Genesee, and Sundance fly ashes, respectively.

The results show that the grinding of the fly ash increased the compressive strength of the mortars at all ages. As for the effect of the grinding on the physical properties of the fly ash, the grinding increased significantly the compressive strength of the mortars incorporating fly ashes that had been ground for two hours; however, there was only marginal increase in the compressive strength of the mortars incorporating fly ashes that had been ground for more than two hours.

The increase in the compressive strength was more significant for the mortars incorporating the coarse Genesee fly ash than for the finer Sundance fly ash. For example,the 28-day compressive strength of the mortars incorporating 10% of the Genesee and Sundance fly ashes that had been ground for one hour increased by 20% and 1%, respectively (mixtures 4, and 14). This is in line with previous investigations (4).

The results also show that when the percentage replacement of the cement by the fly ashes was increased from 10 to 20%, there was noticeable loss in compressive strength of the mortars at both 1 and 7 days, however, the compressive strength showed substantial increase at 28 days. This was especially so for the mortars incorporating fly ash that had been ground for more than two hours.

The grinding of the fly ash for up to 10 hours did not result in bringing up the compressive strength of the mortars to the strength level of the mortars incorporating the silica fume. However, the mortars incorporating 20% coarse Genesee fly ash that had been ground for 6 hours, and that made with 20% replacement of cement by the fine Sundance fly ash that had been ground for 2 hours achieved a 28-day compressive strength that was 90 % of that of the mortar incorporating 10% silica fume as cement replacement.

<u>Mortars made at a constant water-to-cementitious materials ratio</u>

When making the mortar mixtures described above, it was found that when 10% of the cement was replaced by silica fume, the water-to-cementitious materials ratio had to be increased to 0.52 to achieve the flow of 110 ∀ 5. Thus, when the strength of mortar mixtures incorporating fly ash is being compared with that of the mortar mixtures incorporating silica fume, one is comparing strengths at different w/cm, i.e. 0.47 or 0.45 for fly ash mortars versus 0.52 for silica fume mortars.

In order to avoid the above problem, another series of mortar mixtures was made. In this series, the water-to-cementitious materials ratio of the mortars was kept at 0.40, and a superplasticizer was used to overcome the increased water demand of the mortars to achieve the flow of 110 ∀ 5. The compressive strength of the mortars is shown in Tables 5 and 6.

The results show the same trend as that observed for the mortars made at constant flow and without the use of the superplasticizer. The grinding of the fly ash increased the compressive strength of the mortars at all ages. The rate of increase in the compressive strength was more significant for the mortars incorporating fly ash that has been ground for two hours, and it was even more so for the coarse Genesee fly ash.

In general, the increase in the percentage replacement of the cement from 10 to 20% by Genesee fly ash decreased the compressive strength of the mortars at all ages. At the corresponding replacement levels of cement by Sundance fly ash, there was noticeable decrease in the compressive strength of

the mortars at 1 and 7 days, but the strength showed significant increase at 28 days for mortars made with fly ash ground for 2 hours and more.

The grinding of the coarse Genesee fly ash for up to 10 hours was not sufficient to reach even 90% of the 28-day compressive strength of the mortar made with silica fume. For Sundance fly ash, the mortar made with 20% replacement of cement by the fly ash that had been ground for 2 hours achieved a 28-day compressive strength of 93% of that made with the silica fume.

To maintain the flow at 110 ∀ 5 the silica fume mortar required a dosage of the superplasticizer of 2.6% by the total mass of the cementitious materials, whereas, the dosage of the superplasticizer required by the fly ash mortars ranged from 0.2 to 1.4%. This should be taken into consideration when comparing the performance of such mixtures.

## CONCLUSIONS

Based on the present preliminary results, the following conclusions can be drawn:

1 The grinding of the fly ashes increased their specific gravity and fineness; the increase was more significant during the first two hours of grinding, and it was even more so for the coarse Genesee fly ash.

2. The morphology of the fly ashes was changed by grinding. Most of the plerospheres and large irregular-particles were crushed during the early period of grinding. Also, the number of spherical particles were reduced with increased grinding. This, however, did not affect the water requirement of the fly ashes.

3. The use of the fly ashes that had been ground for 2 hours resulted in significant increase in the compressive strength of the mortars; beyond this period of grinding, the strength increase was only marginal. For the corresponding period of grinding, the increase was more significant for the coarse Genesee fly ash.

4. At both constant flow and constant water-to-cementitious materials ratio, the mortars made with 20% replacement of cement by the fine Sundance fly ash that had been ground for 2 hours achieved a 28-day compressive strength that was 90 to 93% of the strength of the mortars incorporating 10% silica fume as cement replacement. However, for the coarse Genesee fly ash, the results were not encouraging. Even increasing the grinding times of the fly ash up to 10 hours did not yield the compressive strengths approaching that of the silica fume mortars.

## REFERENCES


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Table 1 - Physical properties and chemical analysis of the materials used

| | ASTM Type I Cement | Fly Ash | | Silica Fume |
|---|---|---|---|---|
| | | Sundance | Genesee | |
| <u>Physical Tests</u> | | | | |
| Specific gravity | 3.13 | 2.08 | 1.95 | 2.30 |
| Fineness | | | | |
| -passing 45:m, % | 93.1 | 83.6 | 63.5 | 97.2 |
| -specific surface, Blaine, $m^2/kg$ | 400 | 306 | 196 | - |
| -nitrogen adsorption, $m^2/g$ | - | - | - | 19.5 |
| -median particle size (:m) | 13.2 | 8.6 | 21.6 | - |
| Compressive strength of 51 mm cubes, MPa | | | | |
| -7-day | 29.6 | - | - | - |
| -28-day | 40.3 | - | - | - |
| Water requirement, % | - | 95.7 | 99.6 | 115.7 |
| Pozzolanic Activity Index, % | | | | |
| -7-day | - | 89.3 | 82.1 | 123.7 |
| -28-day | - | 113.5 | 89.4 | - |
| <u>Chemical Analyses, %</u> | | | | |
| Silicon dioxide ($SiO_2$) | 21.4 | 52.4 | 62.6 | 92.1 |
| Aluminum oxide ($Al_2O_3$) | 4.0 | 23.4 | 20.9 | 0.3 |
| Ferric oxide ($Fe_2O_3$) | 3.2 | 4.7 | 4.5 | 0.6 |
| Calcium oxide (CaO) | 62.4 | 13.4 | 5.8 | 0.8 |
| Magnesium oxide (MgO) | 2.6 | 1.3 | 1.5 | 0.7 |
| Sodium oxide ($Na_2O$) | 0.2 | 3.6 | 2.5 | 0.2 |
| Potassium oxide ($K_2O$) | 0.8 | 0.6 | 1.7 | 1.1 |
| Equivalent alkali ($Na_2O$+0.658$K_2O$) | 0.7 | 4.0 | 3.6 | 0.9 |
| Phosphorous oxide ($P_2O_5$) | 0.2 | 0.2 | 0.1 | 0.1 |
| Titanium oxide ($TiO_2$) | 0.2 | 0.8 | 0.7 | <0.01 |
| Sulphur trioxide ($SO_3$) | 3.4 | 0.2 | 0.1 | 0.2 |
| Loss on ignition | 1.7 | 0.3 | 0.3 | 2.0 |
| Bogue Potential Compound Composition | | | | |
| Tricalcium silicate $C_3S$ | 51 | - | - | - |
| Dicalcium silicate $C_2S$ | 23 | - | - | - |
| Tricalcium aluminate $C_3A$ | 5 | - | - | - |
| Tetracalcium aluminoferrite $C_4AF$ | 10 | - | - | - |

Table 2 - Effect of the grinding on the physical properties of the fly ashes

| | | Type of Fly Ash | |
|---|---|---|---|
| | | Sundance | Genesee |
| Specific gravity | before grinding | 2.08 | 1.95 |
| | after 1 hours grinding | 2.40 | 2.25 |
| | after 2 hours grinding | 2.53 | 2.44 |
| | after 6 hours grinding | 2.61 | 2.52 |
| | after 10 hours grinding | 2.63 | 2.54 |
| Specific surface area, Blaine, $m^2/kg$ | before grinding | 306 | 195 |
| | after 1 hours grinding | 357 | 345 |
| | after 2 hours grinding | 470 | 425 |
| | after 6 hours grinding | 584 | 593 |
| | after 10 hours grinding | 610 | 681 |
| Passing 45 :m, % | before grinding | 83.6 | 63.5 |
| | after 1 hours grinding | 99.9 | 99.7 |
| | after 2 hours grinding | 99.9 | 99.7 |
| | after 6 hours grinding | 99.7 | 97.4 |
| | after 10 hours grinding | 99.0 | 95.7 |
| Median particle size, :m | before grinding | 8.6 | 21.6 |
| | after 1 hours grinding | 6.2 | 8.2 |
| | after 2 hours grinding | 5.0 | 7.2 |
| | after 6 hours grinding | 3.5 | 4.4 |
| | after 10 hours grinding | 3.3 | 3.8 |
| Water requirement, % | before grinding | 95.7 | 99.6 |
| | after 1 hours grinding | 95.7 | 99.6 |
| | after 2 hours grinding | 95.7 | 99.6 |
| | after 6 hours grinding | 95.7 | 99.6 |
| | after 10 hours grinding | 95.7 | 99.6 |

Table 3 - Compressive strength of the mortars made with similar flow (Genesee fly ash)

| Mix No. | Cementitious materials type | FA[1], % | W/CM[2] | Compressive strength, MPa | | |
|---|---|---|---|---|---|---|
| | | | | 1 day | 7 days | 28 days |
| 1 | ASTM Type I | - | 0.47 | 16.6 | 31.9 | 38.6 |
| 2 | ASTM Type I + 10% of Silica fume | - | 0.52 | 19.7 | 38.7 | 52.6 |
| 3 | ASTM Type I + unground fly ash | 10 | 0.47 | 14.4 | 29.4 | 34.1 |
| 4 | ASTM Type I + fly ash ground for 1 hr. | | 0.47 | 16.0 | 31.4 | 40.8 |
| 5 | ASTM Type I + fly ash ground for 2 hr. | | 0.47 | 15.2 | 30.9 | 39.9 |
| 6 | ASTM Type I + fly ash ground for 6 hr. | | 0.47 | 16.6 | 32.9 | 44.9 |
| 7 | ASTM Type I + fly ash ground for 10 hr. | | 0.47 | 16.2 | 32.9 | 42.8 |
| 8 | ASTM Type I + unground fly ash | 20 | 0.47 | 10.2 | 26.2 | 34.5 |
| 9 | ASTM Type I + fly ash ground for 1 hr. | | 0.47 | 11.4 | 30.0 | 40.8 |
| 10 | ASTM Type I + fly ash ground for 2 hr. | | 0.47 | 11.2 | 30.5 | 42.0 |
| 11 | ASTM Type I + fly ash ground for 6 hr. | | 0.47 | 12.0 | 31.7 | 47.3 |
| 12 | ASTM Type I + fly ash ground for 10 hr. | | 0.47 | 12.2 | 32.6 | 47.8 |

1 Fly ash
2 Water-to-cementitious materials ratio

Table 4 - Compressive strength of the mortars made with similar flow (Sundance fly ash)

| Mix No. | Cementitious materials type | FA[1], % | W/CM[2] | Compressive strength, MPa | | |
|---|---|---|---|---|---|---|
| | | | | 1 day | 7 days | 28 days |
| 1 | ASTM Type I | - | 0.47 | 16.6 | 31.9 | 38.6 |
| 2 | ASTM Type I + 10% of Silica fume | - | 0.52 | 19.7 | 38.7 | 52.6 |
| 13 | ASTM Type I + unground fly ash | 10 | 0.47 | 14.2 | 31.5 | 42.3 |
| 14 | ASTM Type I + fly ash ground for 1 hr. | | 0.47 | 14.6 | 32.6 | 42.8 |
| 15 | ASTM Type I + fly ash ground for 2 hr. | | 0.47 | 14.7 | 33.0 | 43.8 |
| 16 | ASTM Type I + fly ash ground for 6 hr. | | 0.47 | 14.2 | 32.7 | 44.8 |
| 17 | ASTM Type I + fly ash ground for 10 hr. | | 0.47 | 14.3 | 32.3 | 43.9 |
| 18 | ASTM Type I + unground fly ash | 20 | 0.45 | 12.5 | 28.5 | 43.8 |
| 19 | ASTM Type I + fly ash ground for 1 hr. | | 0.45 | 13.4 | 30.5 | 44.5 |
| 20 | ASTM Type I + fly ash ground for 2 hr. | | 0.45 | 13.6 | 31.0 | 47.0 |
| 21 | ASTM Type I + fly ash ground for 6 hr. | | 0.45 | 13.1 | 32.2 | 49.8 |
| 22 | ASTM Type I + fly ash ground for 10 hr. | | 0.45 | 15.4 | 33.4 | 47.8 |

1 Fly ash
2 Water-to-cementitious materials ratio

Table 5 - Compressive strength of the mortars made with constant water-to-cementitious materials ratio of 0.40 (Genesee fly ash)

| Mix No. | Cementitious materials type | FA[1], % | SP[3], % | Compressive strength, MPa | | |
|---|---|---|---|---|---|---|
| | | | | 1 day | 7 days | 28 days |
| 23 | ASTM Type I | - | 2.0 | 21.6 | 40.6 | 46.0 |
| 24 | ASTM Type I + 10% of Silica fume | - | 2.6 | 23.0 | 51.4 | 64.0 |
| 25 | ASTM Type I + unground fly ash | 10 | 1.4 | 18.3 | 38.6 | 42.9 |
| 26 | ASTM Type I + fly ash ground for 1 hr. | | 1.4 | 17.5 | 38.7 | 48.2 |
| 27 | ASTM Type I + fly ash ground for 2 hr. | | 1.4 | 19.7 | 39.8 | 49.9 |
| 28 | ASTM Type I + fly ash ground for 6 hr. | | 1.0 | 21.9 | 41.4 | 53.5 |
| 29 | ASTM Type I + fly ash ground for 10 hr. | | 1.0 | 22.4 | 44.1 | 53.8 |
| 30 | ASTM Type I + unground fly ash | 20 | 0.6 | 17.5 | 34.9 | 42.4 |
| 31 | ASTM Type I + fly ash ground for 1 hr. | | 0.4 | 20.1 | 36.5 | 47.7 |
| 32 | ASTM Type I + fly ash ground for 2 hr. | | 0.4 | 20.4 | 35.7 | 48.5 |
| 33 | ASTM Type I + fly ash ground for 6 hr. | | 0.4 | 20.0 | 40.1 | 52.4 |
| 34 | ASTM Type I + fly ash ground for 10 hr. | | 0.4 | 19.5 | 37.1 | 50.5 |

1 Fly ash
3 Superplasticizer

Table 6 - Compressive strength of the mortars made with constant water-to-cementitious materials ratio of 0.40 (Sundance fly ash)

| Mix No. | Cementitious materials type | FA[1], % | SP[3], % | Compressive strength, MPa | | |
|---|---|---|---|---|---|---|
| | | | | 1 day | 7 days | 28 days |
| 25 | ASTM Type I | - | 2.0 | 21.6 | 40.6 | 46.0 |
| 26 | ASTM Type I + 10% of Silica fume | - | 2.6 | 23.0 | 51.4 | 64.0 |
| 35 | ASTM Type I + unground fly ash | 10 | 0.4 | 24.6 | 39.2 | 48.3 |
| 36 | ASTM Type I + fly ash ground for 1 hr. | | 0.4 | 23.4 | 38.7 | 46.2 |
| 37 | ASTM Type I + fly ash ground for 2 hr. | | 0.6 | 24.0 | 42.3 | 53.2 |
| 38 | ASTM Type I + fly ash ground for 6 hr. | | 0.6 | 23.7 | 43.7 | 53.6 |
| 39 | ASTM Type I + fly ash ground for 10 hr. | | 0.6 | 23.5 | 43.2 | 52.9 |
| 40 | ASTM Type I + unground fly ash | 20 | 0.2 | 16.8 | 33.4 | 45.7 |
| 41 | ASTM Type I + fly ash ground for 1 hr. | | 0.3 | 19.6 | 35.3 | 49.1 |
| 42 | ASTM Type I + fly ash ground for 2 hr. | | 0.3 | 21.5 | 42.6 | 59.5 |
| 43 | ASTM Type I + fly ash ground for 6 hr. | | 0.4 | 17.8 | 35.5 | - |
| 44 | ASTM Type I + fly ash ground for 10 hr. | | 0.4 | 18.0 | 37.0 | 56.6 |

1 Fly ash
3 Superplasticizer

Table 7 - Compressive strength of the mortars made with similar dosage of superplasticizer* (Genesee fly ash)

| Mix No. | Cementitious materials type | FA[1], % | W/CM[2] | Compressive strength, MPa | | |
|---|---|---|---|---|---|---|
| | | | | 1 day | 7 days | 28 days |
| 45 | ASTM Type I | - | 0.43 | 22.2 | 43.1 | 50.6 |
| 46 | ASTM Type I + 10% of Silica fume | - | 0.47 | 19.8 | 39.1 | 55.1 |
| 47 | ASTM Type I + unground fly ash | 10 | 0.42 | 17.6 | 39.1 | 45.0 |
| 48 | ASTM Type I + fly ash ground for 1 hr. | | 0.41 | 19.5 | 41.8 | 50.7 |
| 49 | ASTM Type I + fly ash ground for 2 hr. | | 0.41 | 20.0 | 42.0 | 50.9 |
| 50 | ASTM Type I + fly ash ground for 6 hr. | | 0.41 | 19.4 | 41.8 | 50 |
| 51 | ASTM Type I + fly ash ground for 10 hr. | | 0.41 | 18.7 | 41.7 | 52.9 |
| 52 | ASTM Type I + unground fly ash | 20 | 0.42 | 16.7 | 32.6 | 40.9 |
| 53 | ASTM Type I + fly ash ground for 1 hr. | | 0.41 | 18.0 | 35.9 | 50.3 |
| 54 | ASTM Type I + fly ash ground for 2 hr. | | 0.41 | 18.5 | 37.0 | 51.8 |
| 55 | ASTM Type I + fly ash ground for 6 hr. | | 0.4 | 19.1 | 40.1 | 60.1 |
| 56 | ASTM Type I + fly ash ground for 10 hr. | | 0.4 | 18.8 | 39.4 | 57.0 |

* A dosage of superplasticizer of 0.54% by the total mass of cementitious materials was used for all mixtures.
1 Fly ash
2 Water-to-cementitious materials ratio

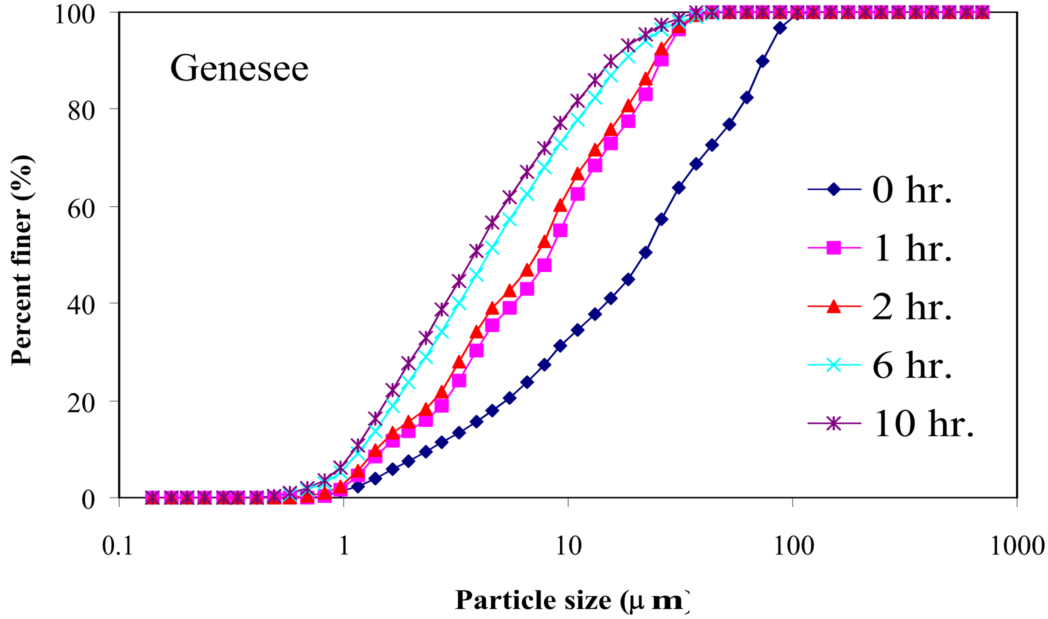


Fig. 1 - The effect of grinding on the particle size distribution of Genesee fly ash

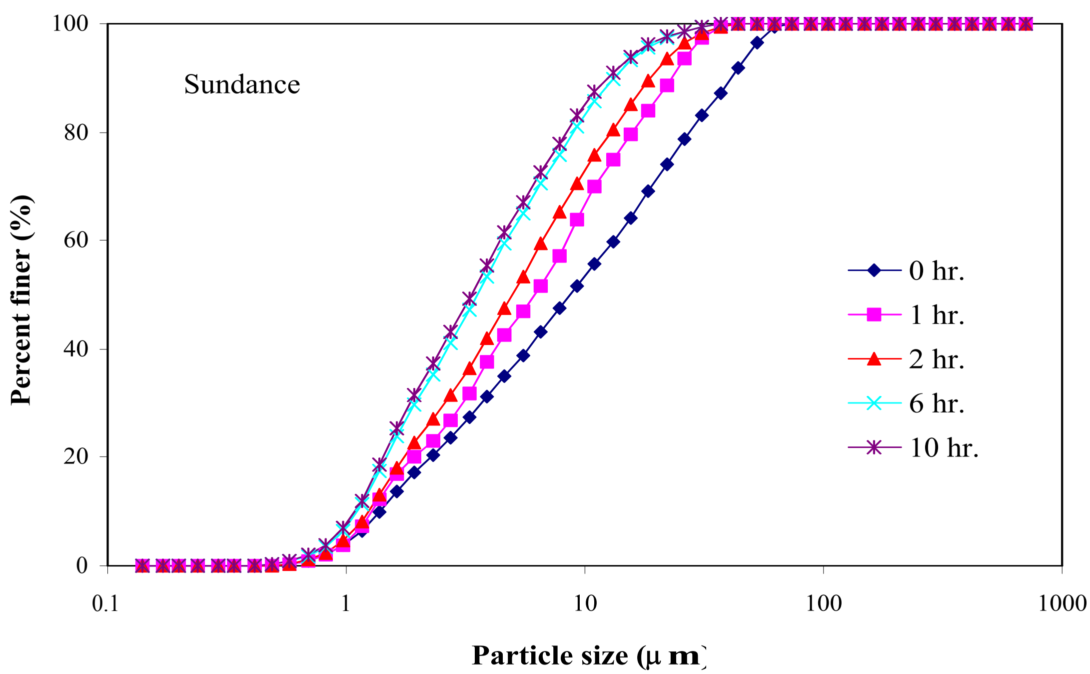


Fig. 2 - The effect of grinding on the particle size distribution of Sundance fly ash

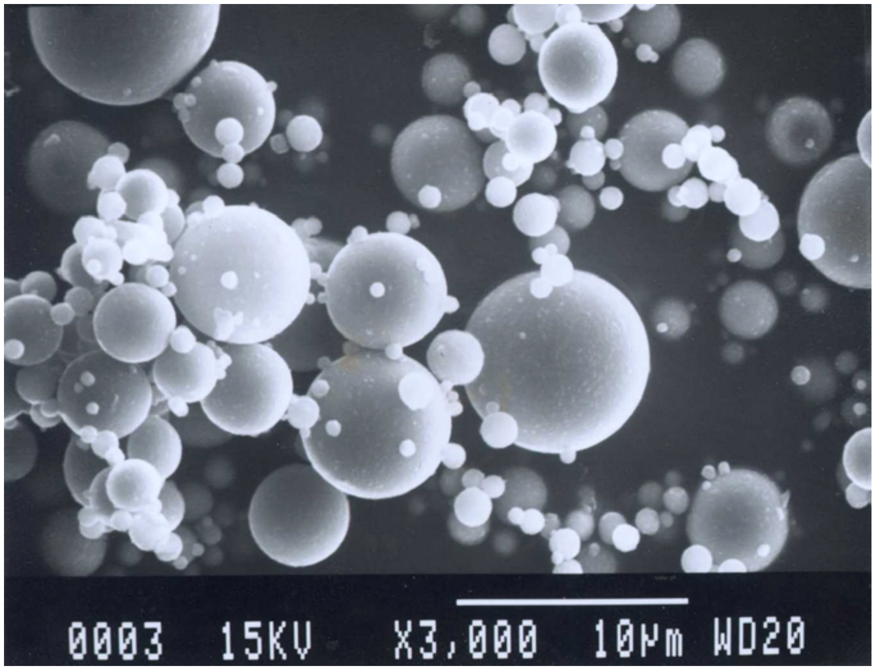


Fig. 3 - Scanning electron micrograph: Sundance fly ash (as received)

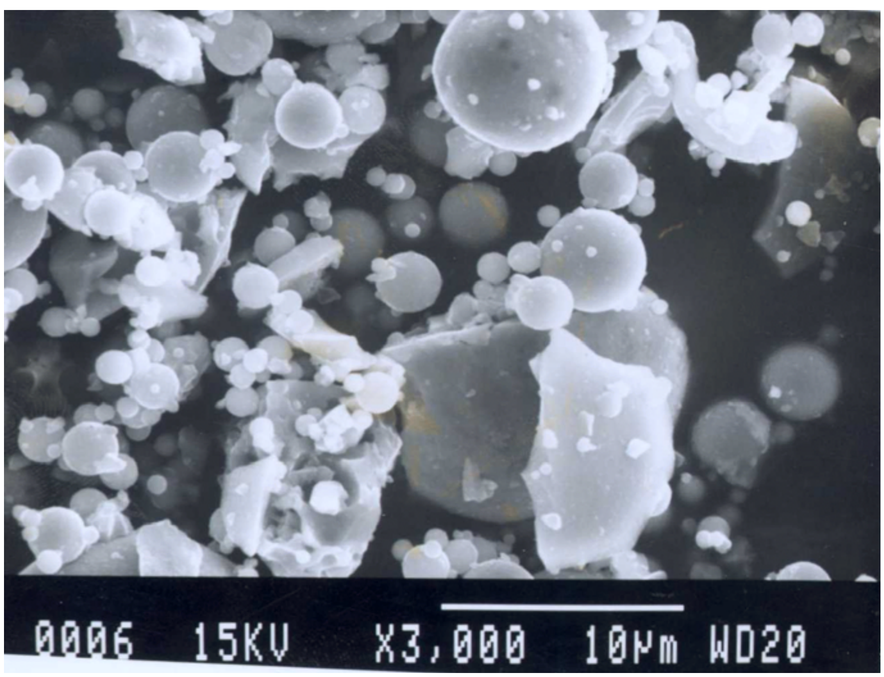


Fig. 4 - Scanning electron micrograph: Sundance fly ash after 2 hours of grinding

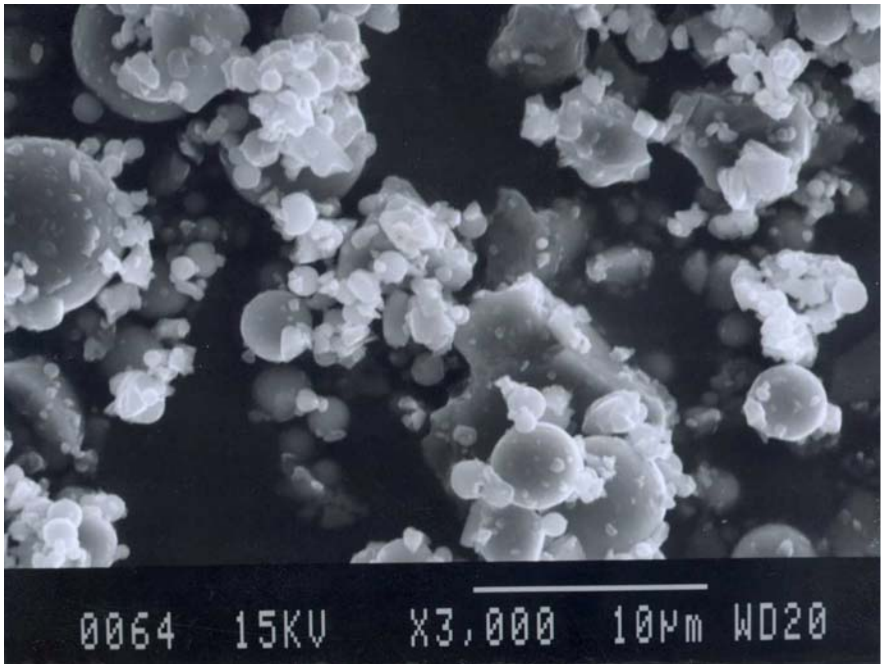


Fig. 5 - Scanning electron micrograph: Sundance fly ash after 10 hours of grinding