*Sixth International Congress on Advances in Civil Engineering, 6-8 October 2004*
*Bogazici University, Istanbul, Turkey*

# The Engineering Properties of High Volume Fly Ash Cement Paste

**E. Aydın, A. Pekrioğlu, E. Uygar, C. E. Atak, A. G. Döven**

Eastern Mediterranean University, Department of Civil Engineering, Gazimagusa, North Cyprus

## Abstract

This paper presents the short term engineering properties of high volume fly ash cement paste composed of mainly fly ash, silica fume, lime and cement. Five different mix proportions were prepared for each of two different fly ashes (ASTM C 618 Type C and Type F) at 100 mm slump. Physical (apparent specific gravity, dry unit weight, water absorption) and mechanical (compressive strength and flexural strength) properties of the cement pastes were investigated. The results indicate that the engineering performance of the final product can be adequate for use as construction material in various civil engineering applications such as stabilization of waste materials, production of bricks, blocks and ceramic tiles and the construction of structural fills, embankments, road bases and sub-bases.

Keywords: Fly ash, cement paste, construction materials, consistency, porous materials.

## Introduction

More than 600 million tons of coal ash has been produce annually-105 million tons per year in the United States (EPRI, 2003). A small amount of these fly ashes is being utilized for various geotechnical and construction facilities. Huge amounts of fly ash are being disposed of landfills. This causes increased disposal costs for the producer, lost resources and energy, and environmental problems. Due to these problems coupled with scarcity of landfills, it has become essential to find large-scale alternative uses for fly ash (Naik, 1992).

Coal fly ash has been successfully used in Portland cement concrete as a mineral admixture, and more recently as a component of blended cement, for nearly 60 years. As an admixture, fly ash functions as either a partial replacement for or an addition to Portland cement and is added directly into ready-mix concrete at the batch plant. Fly ash can also be interground with cement clinker or blended with cement clinker (Popovics, 1992 and Neville, 1996). The principal benefits ascribed to the use of fly ash include enhanced workability due to spherical fly ash particles, reduced bleeding and less water demand, increased ultimate strength, reduced permeability and chloride ion penetration, lower heat of hydration, greater resistance to sulphate attack, greater resistance to alkali-aggregate reactivity and reduced drying shrinkage and also use of fly ash as a substitute for cement is a viable approach to reducing $CO_2$ emission (Erdoğan, 1997).

The particle size and mineralogical characteristics (or type) of fly ash are the most important factors affecting strength of the composites. The rate of strength development of high – lime fly ashes is comparable to that of control mix. However, cement replacement by low – lime fly ashes generally results in lower rates of strength gain up to three months (Hewlett, 1998).

A substantial amount of work in the literature suggests that the partial replacement of cement (either by weight or volume) in mortar or concrete by fly ash results in lower compressive strength at early ages (about 3 to 6 months), with development of greater strength as compared to neat concrete at and beyond six months. The higher later strength is result of increased pozzolanic reaction at later ages, producing an increasing amount of CSH at the expense of $Ca(OH)_2$. The time at which the strength of fly ash concrete will catch up with that of plain concrete will generally depend on the amount, reactivity and fineness of the fly ash, the water to cementitious materials ratio, and curing conditions such as humidity and temperature (Montgomery, 1981). To overcome the early – strength development of fly ash, silica fume is commonly used as a mineral admixture. The partial replacement of cement by silica fume increases the compressive strength of mortar/ concrete but has no effect on the compressive strength of paste. Partial replacement by silica fume decreases the tensile strength of both paste and mortar. The reduction in the strength of paste was greater than the reduction in the strength of mortar (Özturan, 1997).

ASTM C618 Class C fly ash has long been recognized and commercially demonstrated as a construction material used mostly in low technology applications such as structural fills, embankments, road bases and sub-bases; medium technology applications such as in production of blended cement, concrete pipes, precast/prestressed products, in construction of roller compacted concrete in dams, autoclaved cellular concrete, in production of bricks, blocks and paving stones and lightweight aggregates to be used in geotechnical applications such as material recovery, fillers for polymer matrix composites and metal matrix composites and other filler applications (Baykal, 2000). Although some research has been conducted on the utilization of Class F fly ash in concrete and concrete products, its utilization rate for cement-based products is much less than that of Class C fly ash. However, the low lime content of Class F fly ash is an advantage for producing fired bricks instead of cement-based products (Wesche, 1991). Compressive strength values for various construction materials are presented in Table 1, Table 2 and Table 3.

Table 1. Minimum Compressive Strength values of Base, Sub-base and Sub-grade Courses (ACI, 1985)

| Stabilized soil layer | Minimum unconfined compressive strength at 7 days, psi (MPa) | |
|---|---|---|
| | Flexible pavement | Rigid pavement |
| Base course<br>Sub-base course | 750 (5.18) | 500 (3.45) |
| Subgrade | 250 (1.73) | 200 (1.38) |

Table 2. Compressive Strength Requirements of Tiles (ASTM C212, 1996).

| Class | End-Construction Tile | | Side-Construction Tile | |
|---|---|---|---|---|
| | Min. Av.of 5 Tests (MPa) | Individual (MPa) | Min. Av.of 5 Tests (MPa) | Individual (MPa) |
| Standard | 9.7 | 8.9 | 4.8 | 3.4 |
| Special Duty | 17.2 | 13.8 | 8.3 | 6.9 |

Table 3. Compressive Strength Requirements of Paving Bricks (ASTM C902, 1995).

| Designation | Compressive Strength, (MPa) | |
|---|---|---|
| | Av.of 5 | Individual |
| Class I | 55.2 | 48.3 |
| Class II | 20.7 | 17.2 |
| Class III | 20.7 | 17.2 |

Researches on high volume fly ash utilization have been started by CANMET since 1980s (Bouzoubaa, 1999). Chemical compositions and physical properties of all kinds of fly ashes and their various usages in pastes, mortars and concretes have been studied by many researchers (Malhotra, 1989, Aimin, 1994 and Zhang, 1997). Although, using high volume fly ash (HVFA) has numerous advantages from the structural as well as the economic point of view (Aimin, 1994). Nevertheless, there is a lack of commercial products containing high volumes of Class F fly ash. If a large quantity of fly ash can be used in the manufacture of fired bricks and other related products, the disposal problem will be decreased, and a value-added construction product will be created. The main objective of this study is to investigate the short term engineering properties of high volume fly ash cement pastes composed of mainly fly ash, silica fume, lime and cement. For this reason, five different mix proportions were prepared for each of two different fly ashes (ASTM C 618 Type C and Type F) at 100 mm slump. Physical (apparent specific gravity, dry unit weight, water absorption) and mechanical (compressive strength and flexural strength) properties of the cement pastes were investigated. The results indicate that the engineering performance of the final product can be adequate for use as construction material in various civil engineering applications such as stabilization of waste materials, production of bricks, blocks and ceramic tiles and the construction of structural fills, embankments, road bases and sub-bases.

## Methodology

### Materials

The physical and chemical properties of the materials used in this study were analyzed by the quality control department of BEM (Boğaz Endüstri ve Madencilik Ltd. Şti. TRNC).

**Cement.** The cement used was Type I with strength class 42.5 MPa, the chemical composition being presented in Table 4. The Blaine fineness of the cement is 3192 $cm^2$/gr and its specific gravity is 3.09. The grain size distribution of cement is given in Figure 1.

**Fly Ash.** Two types of ASTM Class C and F fly ash from Soma and Kütahya Thermal Power Plants in Turkey were used. Their Blaine finenesses are 2062 $cm^2$/gr and 3191 $cm^2$/gr, the specific gravities are 2.07 and 2.19, the mean grain sizes are 27 μm and 23 μm respectively. The chemical compositions are presented in Table 4. The grain size distributions of fly ashes are given in Figure 1. The pozzolanic activity indices of Soma and Kütahya fly ashes are 109.5 % and 74.5 % respectively according to ASTM C 311.

**Silica Fume.** The silica fume was obtained from the ferrochrome factory located in Antalya, Turkey. The specific gravity of silica is 2.20. Its chemical composition is presented in Table 4. The pozzolanic activity index of silica fume is 88.7 % according to ASTM C 311.

**Lime.** It is hydrated calcium lime provided by a local company. The specific gravity of lime is 2.17 and its chemical composition is also presented in Table 4.

Table 4. The Chemical Composition of Fly Ashes, Cement, Silica Fume and Lime

| Oxides (%) | Soma Fly Ash (Type C) | Kütahya Fly Ash (Type F) | ASTM C 618 | | Cement | Silica Fume | Lime |
|---|---|---|---|---|---|---|---|
| | | | Type C | Type F | | | |
| $SiO_2$ | - | - | - | - | 19.24 | 25.90 | N/A |
| $SiO_2$ (Insoluble) | 43.72 | 58.07 | - | - | 0.71 | 50.66 | N/A |
| $Al_2O_3$ | 20.11 | 17.09 | - | - | 4.12 | 0.70 | 0.38 |
| $Fe_2O_3$ | 5.45 | 10.27 | - | - | 3.49 | 0.42 | 0.30 |
| CaO | 20.76 | 5.06 | - | - | 63.69 | 1.06 | 70.89 |
| MgO | 2.09 | 4.51 | <5.0 | <5.0 | 1.91 | 5.04 | 1.95 |
| $SO_3$ | 1.82 | 0.63 | <5.0 | <5.0 | 2.52 | 1.18 | N/A |
| LOI | 2.42 | 0.71 | <6.0 | <6.0 | 3.52 | 3.72 | 24.59 |

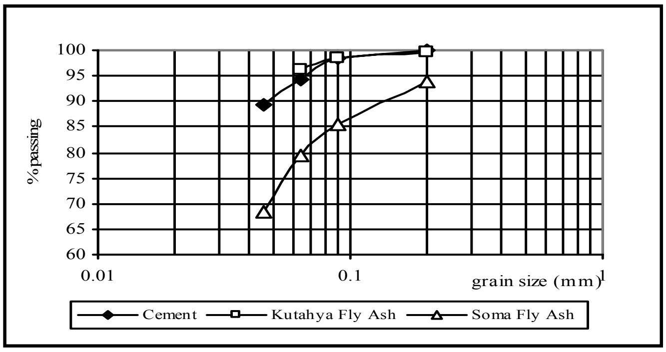


Fig 1. The Grain Size Distribution of Cement, Kütahya and Soma Fly Ashes

**Mix Proportioning**

Five different mix proportions were prepared for each of two different fly ashes (ASTM C 618 Type C and Type F) at 100 mm slump and it was measured according to ASTM C-143-90a. The w/b ratios of all mix groups were determined from the previous laboratory studies based on the relationship obtained for flow table – slump test, the corresponding flow value is 160 ± 10 mm for 100 mm slump, the w/b ratios and weight of the mix ingredients were presented in Table 5.

Table 5. Material Composition of Mix Groups

| Group No | Fly Ash | Cement | Lime | Silica Fume | Fly Ash Source | |
|---|---|---|---|---|---|---|
| | | | | | Soma | Kütahya |
| | By weight (%) | | | | w/b | |
| 1 | 100 | - | - | - | 0.32 | 0.45 |
| 2 | 80 | 20 | - | - | 0.30 | 0.42 |
| 3 | 80 | 15 | 5 | - | 0.31 | 0.42 |
| 4 | 75 | 20 | - | 5 | 0.32 | 0.44 |
| 5 | 75 | 15 | 5 | 5 | 0.31 | 0.43 |

**Experimental Program**

After the mixtures were mixed for 2 minutes in the mixer, they were cast and consolidated by vibration with 50 kHz frequency for approximately one minute in steel molds as described in the relevant standards. A minimum of three specimens were used in each experiment. The specimens were extracted from the molds after 2 – 4 days and continued to be kept in curing room at 20 ± $1^0$C temperature and 70 % relative humidity for the entire curing period.

Dry bulk density, apparent specific gravity and water absorption experiments were performed according to ASTM C127 – 73 on the fractured specimens, which were subjected to compressive and flexural strength tests.

The compressive strength tests were carried out on Φ55 mm/110 mm specimens according to the requirements of ASTM C109M-02. The flexural strength tests were carried out on 40 mm*40 mm*160 mm prisms according to the requirements of ASTM C348-02.

## Discussion and Analysis of Experimental Results

### Physical Properties

The dry unit weight (DUW), apparent specific gravity (ASG) and water absorption values of varies from 13.1 kN/m$^3$ to 16.5 kN/m$^3$, 2.02 to 2.39 and 10.22 % to 31.80 % for Soma fly ash mix groups and 11.9 kN/m$^3$ to 14.3 kN/m$^3$, 1.87 to 2.18 and 14.82 % to 33.69 % for Kütahya fly ash mix groups, respectively. Physical properties of Soma and Kütahya fly ashes mix groups are presented in Table 6.

Table 6. Physical Properties of Soma and Kütahya Fly Ashes Mix Groups

| Fly Ash | Soma | | | Kütahya | | |
|---|---|---|---|---|---|---|
| Group No | Dry U. Wt. (kN/m$^3$) | Apparent Sp. Gr. | Water Absorption (%) | Dry U. Wt. (kN/m$^3$) | Apparent Sp. Gr. | Water Absorption (%) |
| 1 | 13.1 | 2.28 | 31.80 | N/A | N/A | N/A |
| 2 | 14.0 | 2.39 | 28.50 | 13.9 | 1.93 | 18.79 |
| 3 | 16.5 | 2.02 | 10.22 | 14.3 | 1.87 | 14.82 |
| 4 | 14.9 | 2.37 | 15.58 | 13.8 | 1.95 | 19.82 |
| 5 | 14.4 | 2.03 | 18.53 | 11.9 | 2.18 | 33.69 |

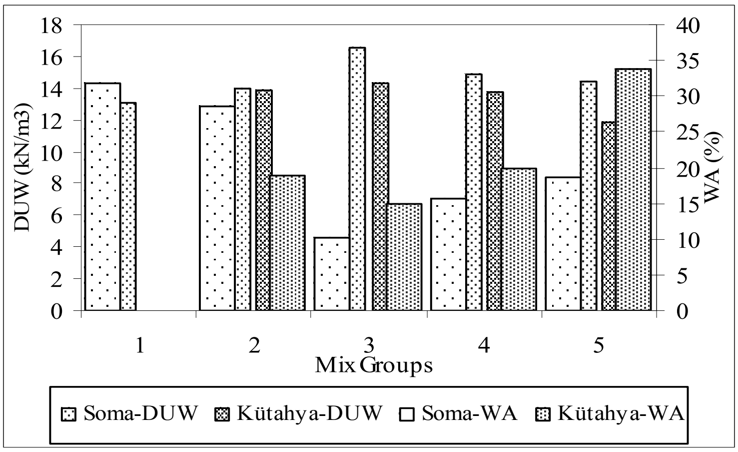


Figure 2. DUW and Water Absorption Values of Soma and Kütahya Mix Groups

DUW values in Soma fly ash mix groups are higher than those Kütahya mix groups. This fact is considering with the highest absorption values of Kütahya fly ash mix groups and the specific gravity of Soma fly ash (2.07), which is lower than Kütahya fly ash (2.19). Also higher DUW values are due to the fact that the combined grain size distribution of

Soma fly ash and the cement. Soma fly ash is disperse well with the other mineral admixtures such as silica fume and lime and this lead to the formation of better matrix properties (i.e. due to well grain size distribution). As a result; much more fly ash particles is available within the per unit volume. The results indicate that cement replacement for Soma fly ash, and cement and lime replacement for Kütahya fly ash increases the DUW for lower w/b ratios (Figure 2).

**Mechanical Properties**

The 28 – day unconfined compressive strength (UCS) and 28 – day flexural strength (FS) values varies from 3.6 MPa to 18.2 MPa and 0.82 MPa to 3.82 MPa for Soma fly ash mix groups and 0.4 MPa to 13.6 MPa and 0.05 MPa to 1.38 MPa for Kütahya fly ash mix groups, respectively. 28 – day UCS and 28 – day FS values of mix groups are presented in Table 7.

Table 7. 28 – day UCS and 28- day FS Values of Mix Groups

| | Unconfined Compressive Strength (MPa) and Flexural Strength (MPa) | | | |
|---|---|---|---|---|
| Fly Ash | Soma | | Kütahya | |
| Group No | UCS | FS | UCS | FS |
| 1 | 3.6 | 0.82 | 0.4 | 0.05 |
| 2 | 13.6 | 2.89 | 13.6 | 1.38 |
| 3 | 13.7 | 1.96 | 11.5 | 1.08 |
| 4 | 18.2 | 3.02 | 10.8 | 1.01 |
| 5 | 12.8 | 3.82 | 7.3 | 0.76 |

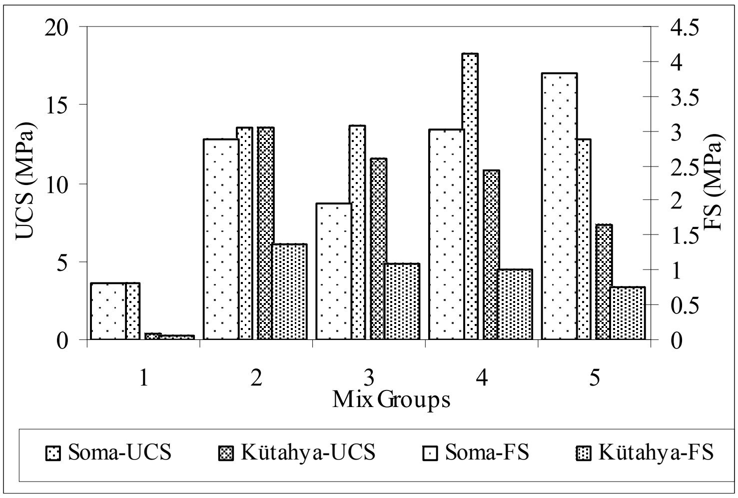


Figure 3. 28- day UCS and FS Values of Soma and Kütahya Fly Ash Mix Groups

The ultra-fine particle size of silica fume brings the potential of being much more reactive than other supplementary cementing materials. Silica fume particles when properly dispersed fill the interstices of the fresh cement paste structure, where they are available to react with the alkali hydroxide and $Ca(OH)_2$ liberated by the hydrating Portland cement, forming insoluble CSH (Malhotra, 1989). The addition of silica fume increases the compressive strength of the final product. This is due to the pore size reduction (filler effect). The bond strength of silica fume enriched composites is significantly higher than those without including silica fume (Erdoğan, 1997).

Highest UCS values are obtained in Gr4 (silica fume enriched) for Soma fly ash mix groups and Gr2 for Kütahya mix groups. Highest FS values are obtained in Gr5 for Soma fly ash mix groups and Gr2 for Kütahya fly ash mix groups. CaO is the dominant factor for developing strength in Kütahya fly ash. It has lower amount of CaO (5.06 %) than Soma fly ash (20.76). The FS/UCS ratio is lower in lime enriched mix groups for both fly ash types. This can be explained by the fact that the increase in UCS is significantly higher than increase in FS. Addition of silica fume and lime is more efficient in compressive strength instead of flexural strength. The FS/UCS ratio varies from 14 % to 19 % for Soma fly ash mix groups and 9 % to 12.5 % for the Kütahya fly ash mix groups. Good coefficient of correlation ($R^2$) is found by using the power equation. $R^2$ is 0.999 for Kütahya fly ash group and 0.8011 for Soma fly ash group (Figure 3 and Figure 4).

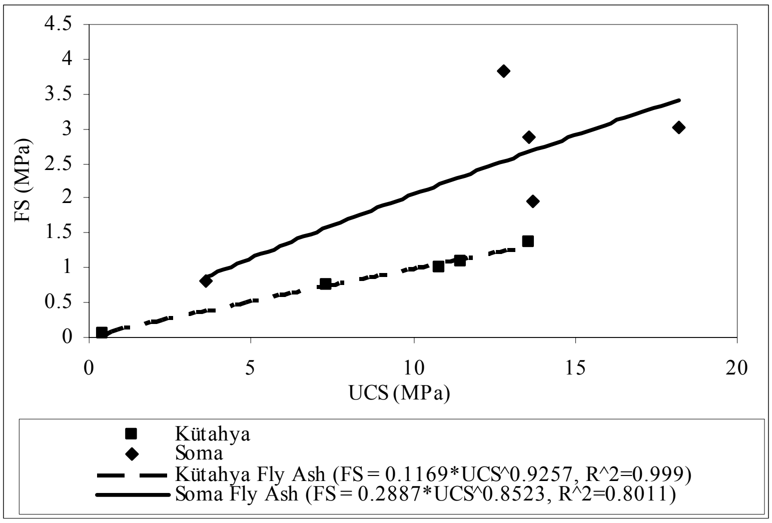


Fıgure 4.UCS vs FS of Soma and Kütahya Fly Ash Mix Groups

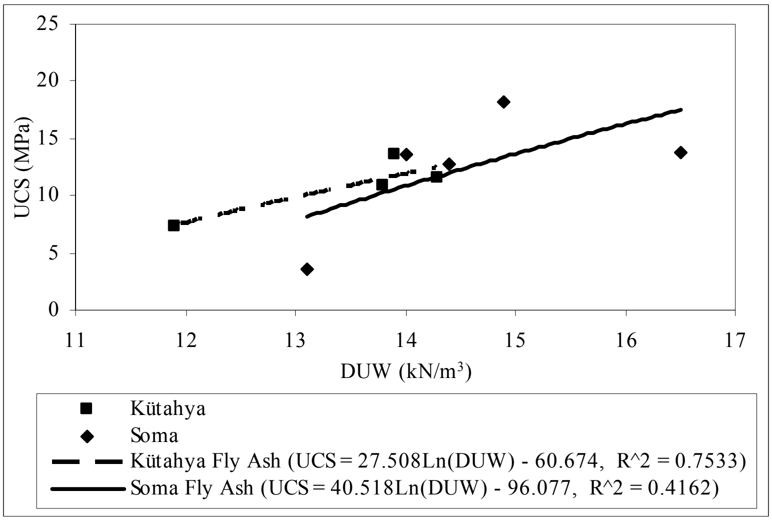


Figure 5. DUW versus UCS Values of Soma and Kütahya Fly Ash Mix Groups

UCS is affected by many factors such as grain and pore size distribution of mix ingredients (fly ash, silica fume, lime, and cement), and their effectiveness in the mix. DUW is a single parameter for determination of UCS. There is an optimum dry unit weight above which increase in DUW values can cause considerable reduction in UCS values for both fly ash mix groups. For Kütahya fly ash mix groups, fly ash and lime reacts together to form densified matrix. Addition of silica fume can cause to increase in water demand of the final composite. The increase in water demand weakens the bond between the fly ash particles and with the surrounding matrix. This causes the reduction in UCS values (Figure 5).

## Conclusions

Utilization of high volume fly ash as a resource has been studied for decades in many areas such as cement/concrete applications, brick, ceramic tile, lightweight aggregate, highway pavements. Based on the physical and mechanical tests of this study indicates that the engineering performance of the final product can be adequate for using them in the manufacturing of construction materials (brick, ceramic tile, paving stone and briquette) and various civil engineering applications such as construction of structural fills, embankments, grouting injection, road bases and sub-bases (Table 1, Table 2 and Table 3).

The following conclusions were drawn at the end of this study:

- Based on the DUW values; final product is considered as a light weight material and can be used satisfactorily in the manufacturing of light weight aggregates and semi-isolating materials. The ability to proportion mixtures having low unit weights is especially advantageous where weak soil conditions are encountered and weight of the fill must be minimized.

- Based on the compressive strength tests results; final products are adequate for using them in low to medium technology applications such as in road bases, manufacturing of bricks, tiles, and ceramic applications (Refer to Table 1, Table 2 and Table3).

- For structural fill applications; required minimum compressive strength may vary from 0.7 MPa to 8.3 MPa (ACI 230, 1985). The 28-day UCS values of the final products are also adequate for those applications. Depending on the strength requirements final product can be used for foundation support.

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