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Utilization of High Volume Fly Ash Cement Paste in Civil Engineering Construction Sites

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Abstract

End-products made with high volume fly ash (HVFA) have superior engineering properties, as well as economic benefits. The research was carried out to investigate the effects of using HVFA on strength properties of construction materials. Physical and mechanical tests were conducted on the Φ50 mm/100 mm specimens. Physical tests considered were apparent specific gravity, water absorption and dry unit weight. Mechanical properties considered were compressive strength, and flexural strength. In general, strength of HVFA was considerably affected by amount of fly ash. Also, the strength properties for the 20 % fly ash mixtures were either comparable or superior to the no-fly ash concrete. All the mixtures, with and without fly ash, tested in this investigation conformed to the strength requirements for excellent quality structural grade concretes. Based on the test results of this study indicates that the engineering performance of the final product can be adequate for using them in the manufacturing of construction materials and various civil engineering applications such as construction of structural fills, embankments, grouting injection, road bases and sub-bases.

Keywords

Fly ash, High volume, Carbon emission, Paste, Building products

1. Introduction

Large quantities of fly ash are produced from thermal power plants. Based on the Electric Power Research Institute (EPRI) report, more than 900 million tons of coal ash is produced annually in the world. The production of each ton of Portland cement releases one ton of CO_2 into the atmosphere, which is the major greenhouse gas implicated man-made climate change. There is now growing awareness in the scientific community that conventional Portland cement concrete mixtures are unsustainable. Production of cement not only consumes a large amount of energy but also contributes a significant amount of greenhouse gases to the atmosphere. Globally, Portland cement production is responsible for the release of 1.6 billion tons of CO_2, which represents 7 % of the World's total carbon emissions (EPRI Report, 2009).

In the early days of the power generation industry, coal combustion products (CCPs) were considered to be a waste material. The properties of these materials were not studied or evaluated seriously and nearly all of the coal combustion products were land filled (Wesche, 1991). In the course of time, the cementitious and pozzolanic properties of fly ash were recognized and studied by several individuals (Diamond, 1984; Naik, 1992) and institutions (BS EN 450, 1995. The products were tested to understand their physical properties, chemical properties and suitability as a construction material. During the last few decades these "waste" materials have seen a transformation to the status of "by-products" and more recently "products" that are sought for construction and other applications (Berry and Malhotra, 1986; Malhotra and Mehta; 2002).

According to the American Coal Ash Association (ACAA), combustion of coal in the United States alone generated approximately 128.7 million tons of coal combustion products in 2002, including approximately 76.5 million tons of fly ash, 19.8 million tons of bottom ash, 29.2 million tons of flue gas desulfurization (FGD) materials, and 1.9 million tons of boiler slag. Of the fly ash produced, approximately 12.6 million tons were used in cement, concrete, and grout applications; and another 14.1 million tons were used in various other applications (CCP Handbook, 2006; Kalyoncu, 2003).

There are eleven coal-burning power plants in Turkey; the annual fly ash production is about 18 million tonnes which is more than the rest of all industrial wastes in the country. However, the utilization ratio of fly ash is only 4 % (Kalyoncu, 2003). In some parts of the world, CCP utilization rates are much higher than that of the United States. For example, in the Netherlands CCP utilization is about 104 % (Netherlands imports ash, as their supply is less than demand). CCP utilization in Denmark is approximately 90 % and in Belgium over 73 %. CCP utilization in other parts of Europe varies widely from around 10 % to 60 %. The United States is the world's second largest producer of fly ash (second only to China). However, CCP utilization in the United States is relatively low. This presents opportunities to make use of this valuable mineral resource. By 2002, approximately 45.5 million tons (35.4 %) of coal combustion products were used in the United States. This percentage is expected to increase, as a result of the new uses for CCPs, increased awareness of proven technologies, and global focus on sustainable development (CCP Handbook, 2003; EPRI, 2009). Within the past 30 years, the concrete industry has given special attention to the safe and economical utilization of CCPs (Kalyoncu, 2003, Aydın and Döven, 2006; Aydın, 2009).

Based on the report published by the Governmental Development of Turkish Republic, for 1 tone of brick production 1.3 tone, and for 1 brick/tile production, 4 kilogram raw material (clay, shale, etc.) is needed. The replacement of fireclay and shale material by fly ash could save about $ 10 per tonne for materials, the cost of the energy, and the time required to complete burnout of the clay component is replaced by fly ash. The clay minerals in coals are fired during coal combustion, so the energy consumption from firing during brick manufacture is not needed, resulting in energy savings (EPA-452 Report, 2003). Few published literature is available on this subject and neither of them is included HVFA cement paste composites.

2. Methodology and Materials

Five different mix proportions were prepared for each of two different fly ashes (ASTM C 618 Type C and Type F) at 0 mm, 100 mm and 200 mm slump values 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 (TUBITAK Report, 2003). The design mix groups are presented in Table 1. 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 ± 1^0C 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.

Table 1: Mixture Combination for Manufacturing Building Materials

Group	Fly Ash	Cement	Silica Fume	Lime	Admixture
1	100	-	-	-	-
2	80	20	-	-	-
3	75	20	5	-	-
4	75	15	5	5	-
5	80	20	-	-	0.6 %

2.1 Material Properties

2.1.1 Cement

BS EN 197-1 CEM I 42.5N type cement was used. The chemical composition is presented in Table 2. The Blaine fineness of the cement is 2905 cm^2/gr and its specific gravity is 3.15. The grain size distribution of cement is given in Figure 1.

2.1.2 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 2. 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.

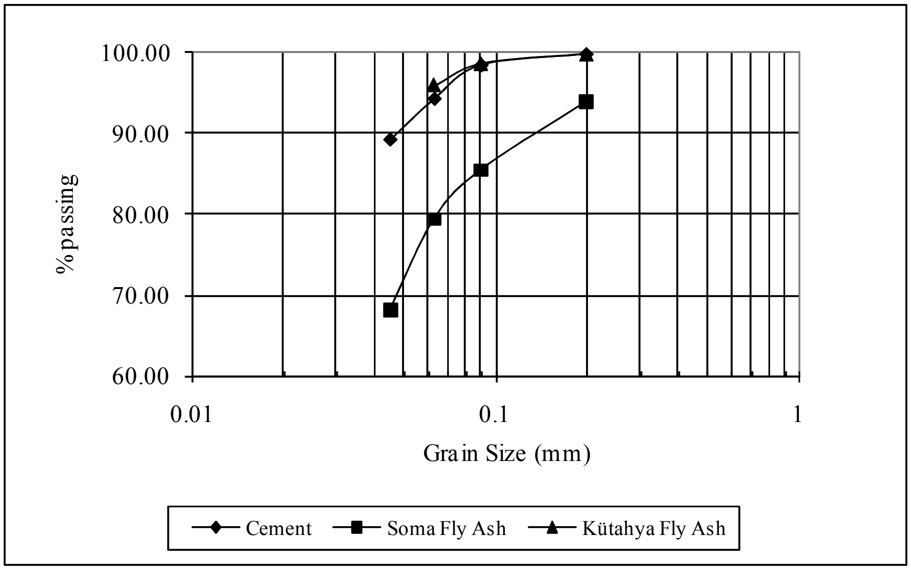

Figure 1: Grain Size Distribution of Soma Fly Ash and Cement

2.1.3 Silica Fume

The silica fume was obtained from the ferrochrome factory located in Antalya, Turkey. The specific gravity of silica fume is 2.20. Its chemical composition is presented in Table 2. The pozzolanic activity index of silica fume is 88.7 % according to ASTM C 311-02.

2.1.4 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 2.

2.1.5 Superplasticizer

A melamine based polymer dispersion water reducing admixture (WRA) was used in all of the groups of mixtures. The WRA is in liquid form with a brown color having 6 months shelf life. The recommended dosage range is in between 0.8 to 3.0 % by weight of cement. Physical and chemical properties of chemical admixture are presented in Table 3.

Table 2: 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

Table 3: Physical and Chemical Properties of Chemical Admixture

ASTM certification	ASTM-494 Types A & F
Color	Lear straw colored
Specific Gravity (g/ml)	1.25 ± 0.05
pH	> 8
Chloride (%)	< 0.1

3. Discussion of Experimental Results

3.1 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 4.

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. On the other hand, water to binder ratio (w/b) has no significant effect on the DUW of cement and, cement and lime enriched Soma fly ash mix groups as well as the Kütahya fly ash control group, however the DUW of the control and WRA enriched Soma fly ash and cement, lime and WRA enriched Kütahya fly ash mix groups vary inversely proportional with the w/b. The packing of cement particles at the boundary is less efficient than in the body of the paste, thus locally providing a region of higher water/cement ratio and lower density (Hewlett, 1998).. This reduction increases the specific gravity of a matrix and at the end harder and stronger matrix will be formed as in the case of Kütahya fly ash mıxture groups.

Table 4: 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

3.2 Mechanical Properties

Unconfined Compressive Strength (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.

The volume initially occupied by water in the fresh concrete can only be partly filled with hydration products: first, because the process of chemical combination of water involves an overall reduction in specific volume (solid + liquid), so that voids remain after combination of the water initially present; second, because any further potential for hydration of the cement is eventually stifled because of the very slow diffusion of additional water needed to continue the hydration, through the rapidly densifying hydrates. Consequently, the lower the initial water filled void fraction in the mix, the lower the final void fraction remaining at ultimate hydration and higher the final strength. The experimental results for compressive strengths at the age of 7, 28 and 90 days of Soma and Kütahya fly ash mixture groups were presented in Figure 2 and Figure 3, repectıvely.

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 and Mehta, 2002; Uygar and Aydın, 2005). 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 as shown in Figure 2 and in Figure 3.

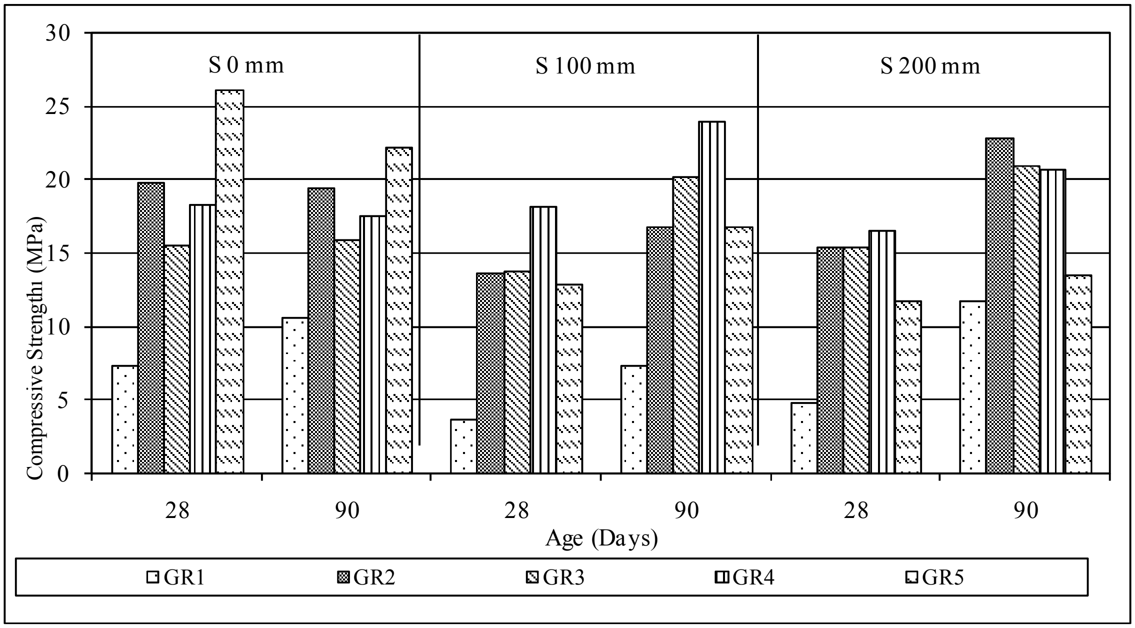

Figure 2: Compressive Strength versus Age for Soma Fly Ash Mix Groups (S0: Slump 0mm, S100: Slump 100 mm, and S200: Slump 200 mm)

Highest UCS values are obtained in Gr4 (silica fume enriched) for Soma fly ash mix groups and Gr2 for Kütahya mix groups. Highest Flexural Strength (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 as shown in Figure 3 and in Figure 4. 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.

Large planar crystals (calcium hydroxide) typically exist. These large crystals are very weak and tend to crack. As these cracks interconnect, the concrete becomes permeable, allowing water to seep in. When fly ash is added to the mix, the silica in the fly ash reacts with these large crystals and transforms them into more of the very same strong cement paste (calcium silicate hydrate) that binds the concrete together (i.e., the silica in fly ash combines with the calcium hydroxide crystals to form more calcium silicate hydrate paste). This eliminates the micro-cracking and creates concrete that is much less permeable, and therefore much more durable. Using high percentages of fly ash is the most effective and economical way to improve the durability. HVFA concrete mixes may gain strength slightly slower than ordinary mixes, but they continue to gain strength for a longer period of time and ultimately end up significantly stronger.

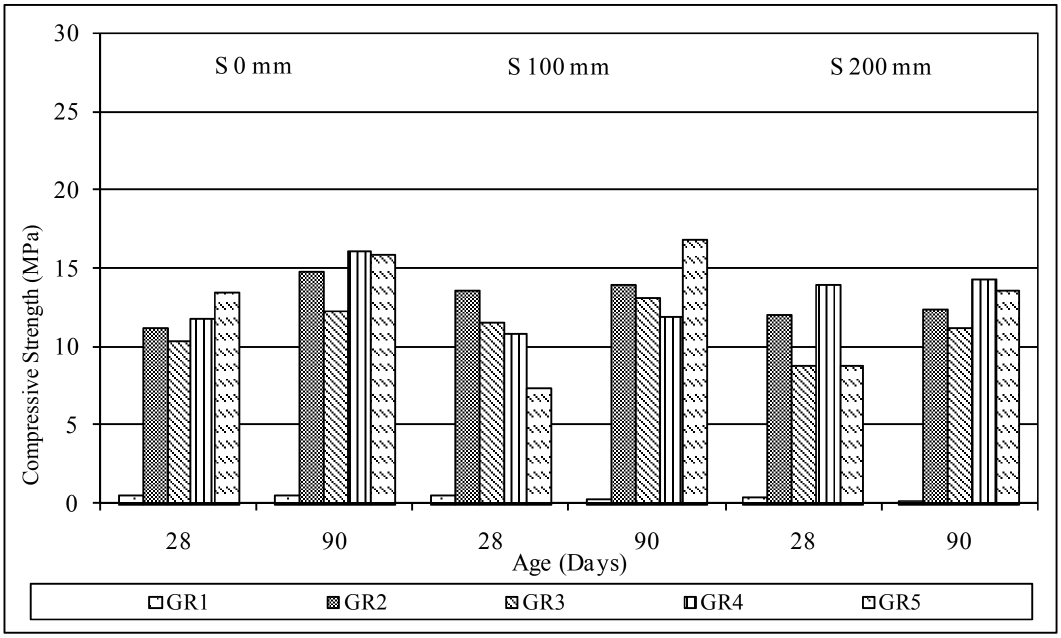

Figure 3: Compressive Strength versus Age for Kütahya Fly Ash Mix Groups (S0: Slump 0mm, S100: Slump 100 mm, and S200: Slump 200 mm)

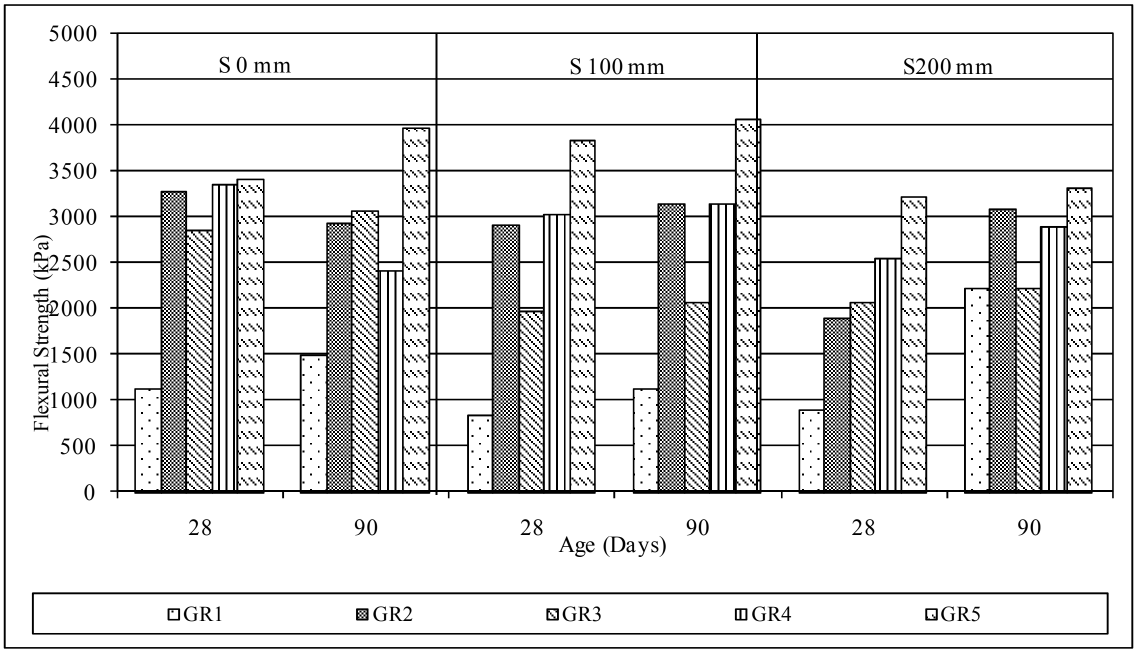

Figure 4: Flexural Strength versus Age for Soma Fly Ash Mix Groups (S0: Slump 0mm, S100: Slump 100 mm, and S200: Slump 200 mm)

There is a general agreement among the researchers that, the particle size and mineralogical characteristics (or type) of fly ash are the most important factors affecting flexural strength of concrete. 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. Adequate curing (i.e. availability of moisture and prevailing temperature) is a key factor in the development of strength as well as in achieving impermeability and durability in both plain concrete and fly ash concrete.

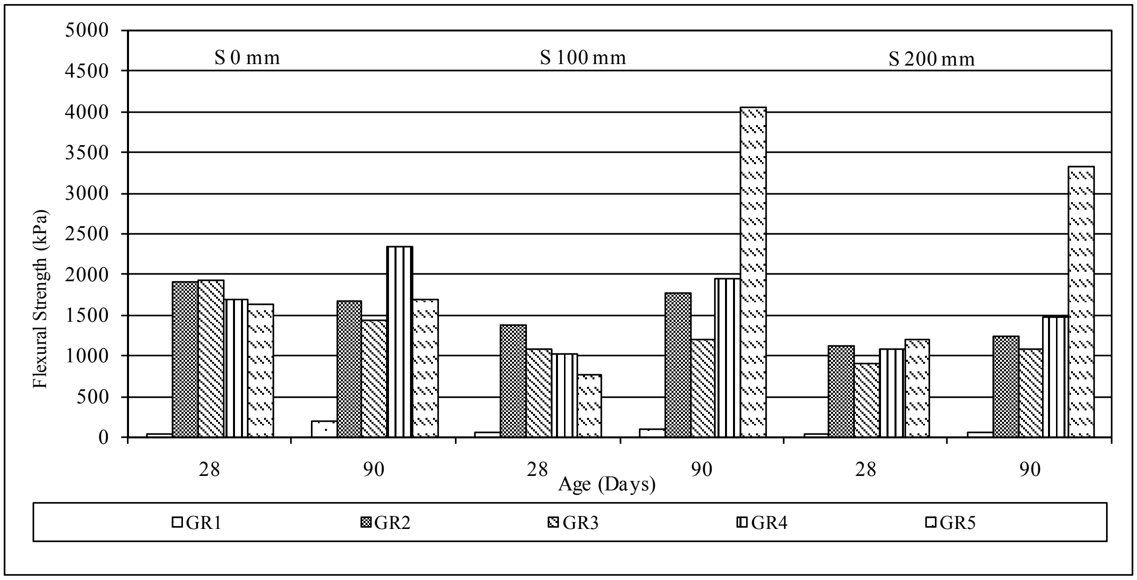

Figure 5: Flexural Strength versus Age for Kütahya Fly Ash Mix Groups (S0:Slump 0mm, S100: Slump 100 mm, and S200: Slump 200 mm)

4. Conclusions

The originality of this study is to manufacturing of cost-effective environmental friendly building products by using HVFA cement paste. Based on the report published by the Governmental Development of Turkish Republic, for 1 tone of brick production 1.3 tones, and for 1 brick/tile production, 4 kilogram raw material (clay, shale, etc.) is needed. The replacement of fireclay and shale material by fly ash could save about $ 10 per tone for materials, the cost of the energy, and the time required to complete burnout of the clay component is replaced by fly ash. The clay minerals in coals are fired during coal combustion, so the energy consumption from firing during brick manufacture is not needed, resulting in energy savings. Few published literature is available on this subject and neither of them is included HVFA cement paste composites.

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 low to medium technology applications such as 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 5 and Table 6).

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.

For structural fill applications; required minimum compressive strength may vary from 0.7 MPa to 8.3MPa (ACI 230, 1985). A rigid pavement structure is typically composed of a Portland cement concrete surface course built on top of either (1) the sub-grade or (2) an underlying base course.

Because of its relative rigidity, the pavement structure distributes loads over a wide area with only one, or at most two, structural layers. For flexible pavement applications asphalt or bituminous materials can be replaced by the fly ash materials effectively. The 28-day UCS values of the final products are also adequate for flexible pavement and rigid pavement applications as presented in Table 5. Depending on the strength requirements final product can also be used for foundation support.

Table 5: 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 Sub-base course	750 (5.18)	500 (3.45)
Subgrade	250 (1.73)	200 (1.38)

Table 6: 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

The properties of cement – based materials are primarily affected by the w/c ratio, chemical and mineral composition of binder material, microstructure and pore geometry of the cementitious materials. When siliceous by products are introduced, they change the behavior of cementitious composites significantly. The addition of fly ash can increase the fluidity of the fresh mixture. The effect of water reduction and the contribution of the fly ash to the mixture combination much depend on the source of the fly ash or the pozzolanicity. The w/b affects the strength and the durability of the material to a great extent due to its influence on the physicochemical (porosity and degree of hydration) properties of the cement paste in hardened state. Slump values of Soma fly ash mix groups are more sensitive to change in w/b ratio are due to its well graded grain size distribution. As the w/b increases, the slump increases as a consequence of the decrease in the friction between the cement and mineral admixtures.

The engineering properties of the material both in fresh and hardened state are highly influenced by the physical (fineness, grain size distribution, particle shape) and chemical (pozzolanic activity/rate and degree of hydration) properties of the mix ingredients, mainly by the properties of fly ash being the main constituent. The design water content in fresh state, thereby the porosity in hardened state are highly influenced by the physical properties of the mix ingredients; the Soma fly ash, having a well graded grain size distribution is more sensitive to the change in w/b in terms of variation in the slump and porosity.

The porosity of the paste depends on many factors and typically decreases by decreasing the water/cement ratio. The type of cement also has a major role in the amount of hydration products and thereby the pore/solid ratio as a result of the rate and degree of hydration within the time domain. The influence becomes less significant for mortar and concrete proportional to the increase in the aggregate/cement ratio.

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