Utilization of Yatagan Power Plant Fly Ash in Production of Building Bricks

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Abstract. Fly ash is a by-product of coal combustion, which accumulates in large quantities near the coal-fired power plants as waste material. Fly ash causes serious operational and environmental problems. In this study, fly ash from Yatağan thermal power plant was used to produce light-weight building bricks. The study aimed to reduce the problems related to fly ash by creating a new area for their use. The optimum process parameters were determined for the production of real size bricks to be used in construction industry. The commercial size bricks (200 x 200 x 90-110 mm) were manufactured using pilot size equipment. Mechanical properties, thermal conductivity coefficients, freezing and thawing strengths, water absorption rates, and unit volume weights of the bricks were determined. Etrangite (Ca₆Al₂(SO₄)₃(OH)₁₂·25(H₂O)) and Calcium Silicate Hydrate (2CaO·SiO₂·4H₂O) were identified as the binding phases in the real size brick samples after 2 days of pre-curing and 28 days curing at 50° C and 95% relative moisture. The water absorption rate was found to be 27.7 % in terms of mass. The mechanical and bending strength of the brick samples with unit volume weight of 1.29 g.cm⁻³ were determined as 6.75 MPa and 1.56 MPa respectively. The thermal conductivity of the fly ash bricks was measured in average as 0.340 W m⁻¹ K⁻¹. The fly ash sample produced was subjected to toxic leaching tests (Toxic Property Leaching Procedure (EPA-TCLP 1311), Single-step BATCH Test and Method-A Disintegration Procedure (ASTM)). The results of these tests suggested that the materials could be classified as non-hazardous wastes / materials.

1. Introduction
Every year, hundreds of millions of tons of coal are burned at power plants all over the world. The amount of waste as fly ash and slag formed as a result of combustion of the coal is quite high. These wastes can be effectively used in the building industry, especially in the production of autoclaved blocks and bricks [1, 2]. Turkey produces more than 15 million tons of fly ash per year, but only a small amount of this product is used in the production of cement and concrete. However, the use of fly ash is much lower than in other countries, since it is difficult to obtain a fly ash product in consistent quality [3]. The various studies carried out on the feasibility of fired or cured bricks produced in certain proportions or 100% with fly ash gives quite encouraging results [4-17]. The use of these bricks is approved by the competent authorities in countries such as Germany, United Kingdom, India etc. In addition, many patents are granted regarding the use of fly ash in making bricks [18, 19]. As is the case in India, due to the increased environmental concerns legislations have been introduced stipulating enterprises that produce conventional clay brick, to use 25% fly ash in the brick composition if it is less than 100 km way from a thermal plant [20].
It is known that the pozzolanic reaction of fly ash and lime under heat treatment results in an increase in mechanical strength by forming strong structures [21]. This reaction involves the formation of calcium silicate hydrate (CSH) and calcium aluminosilicate hydrate (CASH) and enhances the strength of the materials [22]. The method of producing fly ash-lime bricks is based on the CaO–SiO₂–H₂O (C–S–H) formula as a result of the reaction that occurs between lime and silica [23-26]. The fly ash brick hardening in a steam autoclave is due to the formation of this C-S-H phase. Besides this phase, it was found that hydrogarnet was formed in the presence of C-A-S-H, Al₂O₃ [27, 28]. Because of this, since the fly ash includes high mounts of Al₂O₃ and SiO₂, the type of C-S-H and C-A-S-H phases plays a very important role in the strength development of the final product due to the effect of intermolecular forces such as Van Der Waals which is important for the hydration products of very small objects in the colloidal area [29].

Liu et al. have developed a method by compressing the fly ash sample in molds and curing it in steam environment for 24 hours [30-34]. In this method, since the class C fly ash contains high amounts of calcium and formed its strength by establishing a bond by itself, no other contribution was required. In this study, it is concluded that the products can be cured in a humid environment for 24 hours until the products are hardened and chemical reaction with water is completed, as it is in concrete curing [31,34]. Li et al. studied the heat transfer properties of fly ash blocks. The tests were conducted on four walls samples produced from clay bricks, RCB (recycled concrete bricks) and fly ash blocks to evaluate the heat transfer performance. A composite wall including fly ash blocks has shown enhanced isolation effect. It is concluded that, with the fly ash blocks, the new construction of the brick wall is not only good for the environment but also for good heat insulation [35]. Çiçek and Çinçin have investigated the production of light, high heat-insulated bricks made of fly ash and lime. In the study, to obtain mechanically strong bricks and to define optimum conditions, brick samples in actual sizes are produced by curing the Seyitömer thermal plant fly ash and lime composites and its properties were examined [36].

In this study, fly ash from Yatağan thermal power plant was used to produce low cost-light weight building bricks. The study aimed to reduce the environmental problems related to fly ash by creating a new use area. The optimum parameters were determined for the production of real size bricks to be used in construction industry.

2. The Material and the Method

The fly ash generated in Yatagan power plant as a by-product was used in this study. Optimal production conditions of laboratory size cylindrical small bricks from this fly ash samples have been investigated thoroughly. After determination of the optimum conditions for laboratory size bricks, fly ash bricks in actual sizes were produced. The particle size distribution of the fly ash is shown in Figure 1 and the chemical analysis results are shown in Table 1.

![Figure 1. The Particle-size distributions of fly ash samples from Yatağan Power Plants](image-url)
The fly ash samples are below 800 micron particle size. 84.14% of the particles are in the 0/212 micron size fraction.

Table 1. The chemical analyses of fly ash sample from Yatağan Power Plant

| Particle Size (micron) | Weight (%) | Loss of Ignition (%) | SiO2 (%) | Al2O3 (%) | CaO (%) | MgO (%) | Na2O (%) | K2O (%) | MnO (%) | Fe2O3 (%) | TiO2 (%) | SO3 (%) | Free CaO (%) |
|------------------------|------------|----------------------|----------|-----------|---------|---------|----------|---------|---------|-----------|---------|---------|-------------|
| 800/300                | 4.36       | 1.97                 | -        | -         | -       | -       | -        | -       | -       | -         | -       | -       |             |
| 300/212                | 11.50      | 0.80                 | -        | -         | -       | -       | -        | -       | -       | -         | -       | -       |             |
| 212                    | 15.86      | 1.12                 | 50.68    | 17.99     | 17.42   | 2.33    | 0.67     | 2.36    | 0.05    | 6.80      | 0.28    | 0.61    |             |
| 212/150                | 16.55      | 0.77                 | 50.77    | 15.99     | 16.11   | 2.23    | 0.75     | 2.26    | 0.04    | 6.33      | 0.26    | 0.62    |             |
| 106/63                 | 16.99      | 0.66                 | 51.84    | 16.84     | 17.35   | 2.29    | 0.84     | 2.14    | 0.05    | 6.88      | 0.27    | 0.80    |             |
| 63/45                  | 6.42       | 0.87                 | 54.84    | 15.42     | 16.07   | 2.12    | 0.86     | 2.20    | 0.05    | 6.33      | 0.26    | 0.95    |             |
| 45/0                   | 23.01      | 0.77                 | 53.28    | 22.13     | 10.08   | 2.21    | 0.72     | 2.80    | 0.04    | 6.60      | 0.21    | 1.12    |             |
| 212/0                  | 84.14      | 0.71                 | 52.97    | 18.19     | 14.97   | 2.25    | 0.75     | 2.40    | 0.04    | 6.61      | 0.25    | 0.82    | 2.18        |

As can be seen from Table 1, the ratio of unburned carbon in coarse size fractions is 1.12%, and the fraction of 0/212 micron sieve contains 0.71% unburned coal. The free lime amount of this fraction was analyzed as 2.18%. The distribution of other elements in the ash by sieve fractions is similar.

The SiO2+Al2O3+Fe2O3 (S+A+F) ratio in the 0/212 micron sieve fraction is 77.77% in total. Because of the S + A + F ratio being over 70% and the CaO ratio being higher than 10% (14.97%), the Yatağan fly ash has a qualification between F class siliceous ash and C class lime ash according to ASTM C 618 standard.

Figure 2. The X-Ray diffractogram of Yatağan fly ash sample

The mineralogical composition of fly ash was determined by powder diffraction method (0-900 2ϴ) in Rigaku Miniflex II brand (Cu-X ray tube, 30kV, 15mA) X-ray diffractometer. Quartz (SiO2), Lime (CaO), Hematite (Fe2O3), Anorthite (CaAl2Si2O8), Sanidine [(K, Na) (Si, Al) 4O8], Mullite (Al6Si2O10), Anhydrite (CaSO4) and Dolomite (CaMgCO3) mineral phases are found in the Yatağan fly ash. The surface structures of the fly ash sample were examined by a secondary electron image method on a Jeol JXA733 Superprob brand scanning electron microscope. The microsphere particles are small in amount and the ash is composed of shapeless porous particles. It was found in the microanalysis that there are major formations of calcium alumina silicate and aluminum silicate (Fig.3).
3. Experimental Works

3.1. Preliminary investigation with cylindrical fly ash brick samples.

The brick samples were produced using lime at different consumption rates. They were prepared by applying a forming pressure of 1000 kg (about 6.37 MPa) with a computer-aided hydraulic press with a press capacity of 5 tons in a mold having a diameter of 45 mm and a length of 100 mm. After the preparation stage, the bricks were cured in the curing cabinet at 50°C and 95% Relative Humidity. The cured brick samples were examined for their shape changes and their hardness. Hardness of the samples were examined simply by scratching of their surfaces by a steel knife.

| Table 2. Test conditions, (FA: fly ash, L: Lime, G: Gypsum, RH: Relative Humidity) |
|---|---|---|---|---|---|---|
| Sample | FA (%) | L (%) | G (%) | Moisture (%) | Forming Pressure (MPa) | Curing Parameters |
| Y 1 | 100 | 0 | 0 | 19.11 | 6.37 | 50°C, % 95 RH |
| Y 2 | 92 | 8 | 0 | 20.23 | 6.37 | 50°C, % 95 RH |
| Y 3 | 90 | 10 | 0 | 22.78 | 6.37 | 50°C, % 95 RH |
| Y 4 | 88 | 12 | 0 | 17.56 | 6.37 | 50°C, % 95 RH |
| Y 5 | 83 | 12 | 5 | 19.10 | 6.37 | 50°C, % 95 RH |

The aim of these tests is to monitor the reactions of the Yatağan fly ash with lime in an environment of constant humidity and get preliminary information for pilot size samples.

| Table 3. Hardness of the samples in 28 days |
|---|---|---|---|---|
| Y 1 | Y 2 | Y 3 | Y 4 | Y 5 |
| Dispersed | Medium hard | Medium hard | Medium hard | Hard |

It is found that the expansion of the bricks made with curing at 28 days to 95% RM is low. The gypsum application is found to make an expansion-reducing effect on the brick samples.
Table 4. Unit volume weights and expansion of the cured brick samples in 28 days at 95% RH

| Sample | Weight per Unit Volume (g/cm³) | Diameter Expansion (%) |
|--------|-------------------------------|------------------------|
| Y 1    | 0.92                          | 2.67                   |
| Y 2    | 1.05                          | 0.67                   |
| Y 3    | 1.14                          | 0.89                   |
| Y 4    | 1.09                          | 1.11                   |
| Y 5    | 1.15                          | 0.89                   |

It was found that brick samples made with 10-12% lime showed sufficient strength and acceptable expansion characteristics. Although better quality brick is obtained with the gypsum application, it is not taken into consideration due to its cost.

The determination of the free CaO in fly ash, Lime, uncured and cured brick samples were done in accordance with the TS EN 451-1 and TS 687 standards. The results were given in Table 5 and 6.

Table 5. Free CaO content of the fly ash and lime

| Sample           | Free CaO % |
|------------------|------------|
| Yatağan Fly ash  | 2.18       |
| CaO Sample       | 66.26      |

Table 6. Change in free CaO content after curing of fly ash brick samples for 28 days

| Sample | Curing Time (Day) | Water Curing Time (Day) | Lime (%) | Gypsum (%) | Free CaO% |
|--------|-------------------|-------------------------|----------|------------|-----------|
| K 1    | 0                 | -                       | 8        | -          | 7.31      |
| K 2    | 28                | -                       | 8        | -          | 3.44      |
| K 3    | 0                 | -                       | 10       | -          | 8.59      |
| K 4    | 28                | -                       | 10       | -          | 3.51      |
| K 5    | 0                 | -                       | 12       | -          | 9.87      |
| K 6    | 28                | -                       | 12       | -          | 5.08      |
| K 7    | 7                 | 21                      | 12       | 5          | 5.28      |
| K 8    | 7                 | 21                      | 12       | 5          | 5.28      |

Figure 4. XRD analysis of Yatağan thermal plant fly ash, K7 and K8 brick samples.
As it can be seen from table 6 there is a substantial reduction of free CaO after curing which indicates the reaction of lime with fly ash. Although the ratio of unreacted free lime content of the bricks is high after curing, there was no expansion or cracking in these bricks. XRD analyzes were carried out for fly ash, K7 and K8 brick samples to determine different phases formed in the bricks.

The XRD analysis in the Figure 4 shows the formation of Ettringite phase in brick samples. Again, this phase is quite evident in the K8 brick sample to which gypsum is applied. C-S-H and C-A-S-H phases were not formed. In both bricks, unreacted [Ca (OH)2] was detected.

Since the free CaO ratio, unit volume weight and expansion by diameter values of the brick samples obtained by 12% lime addition are in acceptable levels in the orientation-type studies, the real-size brick production was conducted with 12% lime addition.

The free CaO is formed at a very high temperature in the combustion chamber of thermal power plants. For this reason, it has a very low reactivity and hence unreacted with water in preparation of the brick sample, however, it turns into Ca (OH)2 reacting with water in the curing cabinet. Therefore, it can cause volumetric expansion and deformations, cracks and dispersion in the bricks. 2 days pre-curing of the fly ash/lime mixture before shaping of the bricks was found to be necessary for better quality of bricks.

3.2. Production of Real-size Fly ash/Lime Bricks

A concrete mixer which has 100 liters of gross volume and 60 liters of mixing capacity was employed for the preparation of the mixture consisting of 88% Yatağan fly ash and 12 % lime which was procured 2 days in the cure cabin. The mixture was later poured into a mold (200x200x300 mm) and was pressed at 7.35 MPa using a 300 tons’ capacity hydraulic press. After forming, bricks 200 x 200 x 90-100 mm in size was obtained (Figure 5).

Table 7. Real-size brick production parameters

| Fly Ash (%) | Lime (%) | Water in Mortar (%) | Pre-curing (day) | Moisture before pressing (%) | Forming Pressure (MPa) | Temperature (°C) | Relative Humidity % | Curing Time (Day) |
|-------------|----------|--------------------|-----------------|-----------------------------|-----------------------|-----------------|-------------------|------------------|
| 88          | 12       | 20                 | 2               | 20                          | 7.35                  | 50              | 95                | 28               |

Figure 5. Mortar preparation and forming process for real size bricks
3.2.1. Determination of the Mineralogical Composition of the bricks

The mineralogical composition of the bricks produced in large size was examined at 0-900 2Ɵ range by powder diffraction method in X-ray diffractometer. Quartz (SiO$_2$), Ettringite (Ca$_6$Al$_2$(SiO$_4$)$_3$(OH)$_{25}$(H$_2$O)), Anorthite (CaAl$_2$Si$_2$O$_8$), Portlandite (Ca(OH)$_2$), Hematite (Fe$_2$O$_3$), Calcium Silicate Hydrate (2CaO. SiO$_2$. 4H$_2$O) are found to be the main phases in the bricks. According to XRD results, it was found that the binding phases in all bricks cured at atmospheric pressure, in 95% relative humidity and in 50 °C were Ettringite and Calcium Silicate Hydrate.

![X-Ray diffractogram of the real size Yatağan fly ash bricks](image)

**Figure 6.** The X-Ray diffractogram of the real size Yatağan fly ash bricks

3.2.2. Water Absorption Test and Weight per Unit Volume

Five pieces of actual size bricks were used to determine the unit volume weight and water absorption rate. The volume of bricks were determined by the measurement of the brick sizes and their weights were determined after drying at 70 °C. Water absorption tests were conducted on bricks pieces which were cut in form of cubes (7x7x7 cm). The bricks were submerged in water for 24 hours during absorption tests. The water absorption rate was found to be 27.70 % in terms of mass.

| Weight per Unit Volume | Water Absorption |
|------------------------|------------------|
| g/cm$^3$                | %                |
| 1.29                   | 27.70            |

**Table 8.** Unit volume weight and water absorption ratios of the bricks

3.2.3. Compressive and Flexural Strength Tests

A modified and computerized laboratory type hydraulic press was used in compressive and flexural strength tests (Fig.7). Compressive strength tests were conducted on 10 bricks (7x7x7cm) and their breaking points were determined, whose average was 6.74 MPa. Flexural strength of the bricks was determined using rectangular prisms (200x100x50mm) that were cut out of the bricks. It was found that the average flexural strength of the bricks was 1.56 MPa.
3.2.4. Freeze – Thaw tests
Out of the big size bricks cubes of 7x7x7 cm were cut. These cubes were subjected to freeze and thaw test as described in TS EN 13755 Article 7. Freeze – thaw process was repeated 25 times and the observable changes in the samples were recorded. As a result, the mass loss was found to be 4.89 %. The mechanical strength test results after freeze-thaw tests was found as 11.02 MPa. The reason for the increase in compressive strength after freeze-thaw tests is that water curing is occurring while the bricks are kept in water during the thawing periods.

3.2.5. Determination of the thermal conductivity
The thermal conductivity of the bricks were determined using Hot-wire method with a Showa Denko Shotherm QTM thermal conductivity measuring device according to Turkish Standards of TS 825. The thermal conductivity of the fly ash bricks were measured in average as 0.340 W m$^{-1}$ K$^{-1}$.

3.2.6. Leaching Tests
By means of toxic leaching tests, it has been tried to determine the potential contaminants in the Yatağan fly ash samples. In this context, the transition of inorganic materials to water has been investigated by means of experimental methods. Toxicity Characteristic Leaching Procedure (EPA-TCLP 1311), Single-Step Batch Test, and Method-A Solving Procedure (ASTM American Society of Testing and Materials) were applied for this purpose.

| Trace Element (mg/kg) | As | Ba | Ca | Cd | Co | Cr | Cu | Fe  | Mo | Pb | Sr | Zn | Ni | Hg |
|-----------------------|----|----|----|----|----|----|----|-----|----|----|----|----|----|---|
| TCLP                  | ND | 7.305 | 86330.93 | 0.161 | 2.272 | 8.824 | 5.835 | 1759.533 | 1.284 | 0.003 | 13.539 | 9.302 | 11.52 | ND |
| ASTM                  | 8.024 | 14369.48 | 0.028 | ND | 0.284 | ND | 0.006 | 1.021 | 0.015 | 19.459 | 0.591 | ND | ND |
| BATCH                 | 1.572 | 14015.88 | 0.014 | ND | 0.424 | ND | ND | 1.443 | 0.044 | 37.53 | 0.15 | 7 | ND |
| TCLP (limits)         | 100** | 2000 | 20 | 1600** | 100 | ND | ND | ND | ND | ND | ND | ND |
| Consideration         | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| WAC (limits)          | 5 | 10 | 100 | 50 | 200 | ND | ND | ND | ND | ND | ND | ND |

*WAC: Waste acceptance criteria, mg/kg  **N.D.: Not Dangerous
**Finkelman, B.R. Environmental impacts of trace elements in coal. Short course notes, MTA, Ankara, Turkey, 1996
* Mn, Ag elements are ignored.
It can be said that when comparing the concentrations of dissolved heavy metals with the limit values specifically determined for the TCLP test and with the hazardous waste limit values determined for solid wastes, there is no risk to the environment arising from Yatagan fly ash samples. Accordingly, it is understood that the bricks will not cause any heavy metal pollution to the environment.

4. Conclusion
The properties of the real-size fly ash/lime bricks produced under optimum conditions are summarized in table below.

| Parameters                              | Yatağan Fly Ash Bricks |
|-----------------------------------------|------------------------|
| Brick size mm                           | 200x200x90-110         |
| Weight Per Unit Volume (g/cm³)          | 1.29                   |
| Heat Conductivity (W m⁻¹ K⁻¹)           | 0.34                   |
| Single axis compressive strength (MPa)  | 6.75                   |
| Flexural Strength (MPa)                 | 1.56                   |
| Water Absorption Rate (wt. %)           | 27.70                  |
| Mass Loss After Freeze-Thaw (%)         | 4.89                   |
| Mechanical Strength After Freeze-Thaw (MPa) | 11.02                |

Based on the results of this study the following can be concluded:

The Yatağan fly ash has a characteristic of between F class silicate ash and C class lime ash. The microsphere particles are small in amount in the fly ash and composed of shapeless porous particles through the ash. In the microanalyses, calcium alumina silicate and aluminum silicate were mostly found.

In all cured bricks, the binding phases were found to be Ettringite (Ca₆Al₂(SO₄)₃(OH)₁₂ 25(H₂O)) and Calcium Silicate Hydrate (2CaO. SiO₂.4H₂O). According to the toxic leaching tests conducted on fly ash, it can be said that the thermal plant fly ash is in the non-hazardous waste / materials category and the use of these bricks in building materials do not pose a problem to the environment.

The use of coal combustion products, especially in the construction sector, reduces the amount of stored solid wastes in the environment, the cost of electricity generation and the gas emissions in the atmosphere and provides the protection of natural resources.

The production of bricks using fly ashes will pave the way for minimizing the environmental negative impacts of the fly ashes of the thermal power plants. Since the raw materials of fly ash bricks are cheap and the amount of energy consumed in its production is very low, the contribution of this product to the country's economy and the environment will be substantial.

Acknowledgement
This study was supported by the Scientific and Technological Research Council of Turkey (TUBITAK, Project No: 111M694). The authors would like to thank to TUBITAK for financial support.

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