MECHANICAL PROPERTIES OF FLY ASH AND BLAST FURNACE SLAG BASED ALKALI ACTIVATED CONCRETE

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ABSTRACT

Cement is one of the commonly used materials in construction projects. In manufacture of Portland cement, clinker, which is the essential component of cement, is ground into smaller particles. During the formation of clinker, limestone ($CaCO_3$) is converted to lime (CaO) and carbon dioxide is emitted as a by-product of this chemical reaction. Cement production is an environmentally hazardous process due to high carbon dioxide emission during clinker production and fossil-fuel consumption for providing energy in production. Alternative construction materials which are more energy efficient and environmentally friendly can be preferred for sustainability. In order to use alternative materials and production methods, mechanical and physical properties of these materials should be examined thoroughly. In concrete production, strength, durability and workability should be in proper limits as well as considering economical factors. In this study, geopolymeric materials were used as an alternative to conventional concrete, and alkali activated concrete was produced. In this process, no cement was used. Pozzolanic materials such as fly ash and blast furnace slag were activated with alkaline liquids and gained binding property. In production of geopolymer concrete, pozzolanic materials, aggregates and alkaline activators were used. Mechanical properties of fly ash and blast furnace slag based geopolymer concrete were investigated. Compressive strengths of the cubic concrete specimens at the ages of 7 and 28 days were determined and the effect of ambient conditions on geopolymer concrete was examined. As a consequence, it was found that the increase in the amount of blast furnace slag resulted in higher compressive strength values.

Keywords: Alkali activated concrete, cement-free concrete, geopolymer, sustainability, waste management.

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ALKALİ İLE AKTİVE EDİLMİŞ UÇUCU KÜL VE YÜKSEK FIRIN CÜRUFU ESASLI BETONLARIN MEKANİK ÖZELLİKLERİ

ÖZET

Çimento, inşaat projelerinde en çok kullanılan yapı malzemelerinden biridir. Portland çimentosunun üretiminde, çimentonun temel bileşenlerinden biri olan klinker öğütülerek daha ince parçacıklar haline getirilir. Klinker oluşumu esnasında kireçtaşı ($CaCO_3$), kirece (CaO) dönüştürülür ve bu kimyasal reaksiyonun yan ürünü olarak karbondioksit açığa çıkar. Klinker üretimi sırasında açığa çıkan karbondioksitin yanı sıra üretim aşamasında kullanılan fosil yakıtların tüketimiyle de yüksek miktarda karbondioksit salımı gerçekleştiğinden, çimento üretimi çevreye zarar veren bir süreçtir. Sürdürülebilirlik açısından bakıldığında, enerji verimliliği daha fazla ve çevreye dost alternatif yapı malzemelerinin tercih edilmesi daha uygun olacaktır. Alternatif malzemelerin ve üretim yöntemlerinin kullanılabilmesi için, bu malzemelerin mekanik ve fiziksel özellikleri kapsamlı olarak incelenmelidir. Beton üretiminde dayanım, dayanıklılık ve işlenebilirlik özelliklerinin uygun sınırlarda olması gerekirken ekonomik faktörler de göz önünde bulundurulmalıdır. Bu çalışmada, geleneksel beton üretimine alternatif olarak geopolimer malzemeler kullanılmış ve alkali ile aktive edilmiş beton üretimi gerçekleştirilmiştir. Bu üretim sırasında çimento kullanılmamıştır. Uçucu kül ve yüksek fırın cürufu gibi puzolanik malzemeler, alkaliler ile aktive edilerek bu malzemelere bağlayıcı özellik kazandırılmıştır. Geopolimer beton üretimi sırasında, puzolanik malzemeler, agregalar ve alkali aktifleştiriciler kullanılmıştır. Üretilen uçucu kül ve yüksek fırın cürufu esaslı geopolimer betonların mekanik özellikleri incelenmiştir. Küp şeklinde dökülmüş beton numunelerin 7 ve 28 günlük basınç dayanımları belirlenmiş ve ortam koşullarının geopolimer beton üzerindeki etkisi gözlenmiştir. Çalışma sonucunda, yüksek fırın cürufu miktarındaki artışın beton basınç dayanımını arttırdığı görülmüştür.

Anahtar kelimeler: Alkali ile aktive edilmiş beton, çimentosuz beton, geopolimer, sürdürülebilirlik, atık yönetimi.

1. INTRODUCTION

The annual consumption of Portland cement in the world reaches 4-5 billion tonnes per year and there is an increasing demand of 5% per year. Taking into consideration that the other components of concrete production such as aggregates and water, it can be observed that the annual consumption of concrete reaches more than thirty billion tonnes. Besides, one tonne of carbon dioxide is released per one tonne of cement production, and other greenhouse gases are emitted during production. The other factors damaging environment are the depletion of stone quarries and water in conventional concrete production. All these factors make the sustainability of conventional concrete as a construction material questionable [1].

By taking concrete produced with Portland cement into account as a waste management issue, it can be seen that by-products such as fly ash and blast furnace slag are used in concrete as 40-60% by weight of cement for economic and recycling purposes. On the other hand, only 35% of fly ash released by thermal plants can be reused in this way [2]. The developing technologies should make cement production cleaner and more energy-efficient.

It is possible to produce energy-efficient, low cost building materials with geopolymers, which is the main element of this study. Geopolymers are produced with processing natural geological minerals’ chemical composition. Geopolymers are used in a wide variety of applications for different purposes such as refractory building materials having high thermal resistivity, high-strength concrete, bricks, mortar based strengthening materials, electrical fuse and radioactive waste storage units [1].

Geopolymers are obtained by activating binders such as fly ash, slag, kaoline, metakaolin, etc. For activation process, alkaline solutions like sodium silicate, sodium hydroxide and potassium hydroxide are used. Alkali activated pozzolanic material can also be called as geopolymer paste. Silicate and aluminate which are contained in fly ash based geopolymers, are activated by alkaline. The main material used for geopolymerisation can be one, or a combination of different materials [3]. The commonly used alkaline are sodium silicate-sodium hydroxide and sodium silicate-potassium hydroxide [4-7].

The chemical composition of geopolymers is similar to the zeolites, but geopolymers have amorphous microstructure [5]. The molecule groups of geopolymers are as follows [1, 7 and 8]:

- Si-O-Si-O-siloxo, poly(siloxo)
- Si-O-Al-O- sialate, poly(sialate)
- Si-O-Al-O-Si-O- sialate-siloxo, poly(sialate-siloxo)
- Si-O-Al-O-Si-O-Si-O- sialate-disiloxo, poly(sialate-disiloxo)
- P-O-P-O- phosphate, poly(phosphate)
- P-O-Si-O-Al-O-P-O- phospho-sialate, poly(phospho-sialate)
- (R)-Si-O-Si-O-(R) organo-siloxo, poly-silicone

Fly ash is a by-product which is released from thermal plants, having hollow circular particles. Fly ash particles contain amorphous silicate structured crystals such as mullite, hematite and quartz. Fly ash transforms into fine crystals having large amounts of silicate, aluminate and iron oxide with the effect of high temperature in thermal plants, and an efficient raw material for geopolymerisation process is obtained [9].

Fly ash balances the hydration energy and increases the amount of silicate hydrate (binder) with the silicate contained in fly ash, when it is used as pozzolans in conventional concrete. It also prevents alkali-aggregate reaction and provides toughness.

The advantage of fly ash in geopolymer production is the composition of large amounts of Al_2O_3 and SiO_2. Especially F-type fly ash contains large amounts of these components. Fly ash having fine, hollow and circular particles and having large amounts of silicate is convenient for geopolymerisation. These particles can be obtained when the temperature is higher than 1200ºC in a thermal plant.

The first product which is produced with fly ash and alkali silicate, is CAFA cement and it is patented in US [10]. Concrete specimens cured at 90ºC temperature for 18 hours had compressive strength values reaching 85 MPa. Zeolite matrixed geopolymers can also be synthesised with solutions containing only alkaline salts, instead of soluble silicates but this casting process is harmful for producer because of the high alkaline media [1].

The main properties of fly ash composition to produce high-strength and durable geopolymeric materials are stated as follows [11]:

- SiO_2/Al_2O_3 compounds should exist in fly ash composition in the range between 2-3.5% by weight.
- CaO amount should be limited just like pozzolans.
- There should not be sulphite compounds and metals in composition.
- Fe_2O_3 compound, and crystals of hematite and magnetite decelerate the geopolymerisation process and decrease the compressive strength.
- The amount of unburnt carbon particles in coal should be in minimum because of their negative effects on material properties.

2. MATERIALS & METHODS

In this experimental study, fly ash, blast furnace slag, fine aggregate (sand), coarse aggregate with maximum aggregate size of 20 mm (crushed stone II), coarse aggregate with maximum aggregate size of 12 mm (crushed stone I) and alkaline activators were used. 12 Molar potassium hydroxide solution was prepared and this solution was used after 24 hours. Then, potassium hydroxide solution and liquid sodium silicate were mixed and this new solution was used as alkaline activator. Blast furnace slag was used as a weight of 4, 10 and 20 percents of total binder. Pozzolanic binders were activated with alkaline activator for geopolymer concrete production and 15 cm × 15 cm × 15 cm cubic concrete specimens were produced. Concrete specimens were left in outdoor and in laboratory conditions without any curing, before compressive strength test was applied. Compressive strengths of specimens were determined at the ages of 7 and 28 days. The geopolymer concrete mix design was shown in Table 1.

Table 1. The geopolymer concrete mix design.

	Component amount (kg/m^3)								
	Fly ash	Blast furnace slag	Fine aggregate (Natural sand)	Coarse aggregate (20 mm) Crushed limestone II	Coarse aggregate (12 mm) Crushed limestone I	Sodium silicate solution	12 Molar potassium hydroxide solution	Alkaline activator-fly ash ratio	Sodium silicate solution-potassium hydroxide solution ratio
4% BFS	643	27	600	320	650	121	121	0.37	1
10% BFS	603	67	600	320	650	121	121	0.40	1
20% BFS	536	134	600	320	650	121	121	0.45	1

BFS: Blast furnace slag

3. RESULTS & DISCUSSION

Compressive strength test results of geopolymer concrete at the ages of 7 and 28 days were indicated in Table 2 and Table 3. For each sample group, six cubic specimens at the sizes of 15 cm × 15 cm × 15 cm were prepared and tested under compressive loads. As it can be seen from tables below, outdoor conditions provided an increment on early age compressive strength of alkali activated concrete while laboratory conditions provided higher 28-day compressive strength. It was found that blast furnace slag provided higher compressive strength values of alkali activated concrete.

Table 2. Compressive strength test results of geopolymer concrete specimens which were left in laboratory conditions without curing.

Mixture Code	*Compressive Strength (MPa)*	
	In laboratory conditions	
	7-days	*28-days*
4% BFS	6.60	15.40
10% BFS	12.34	28.20
20% BFS	21.53	42.70

Table 3. Compressive strength test results of geopolymer concrete specimens which were left in outdoor and in laboratory conditions without curing.

Mixture Code	*Compressive Strength (MPa)*			
	In outdoor conditions		*In laboratory conditions*	
	7-days	*28-days*	*7-days*	*28-days*
15% BFS	27.07	38.25	18.90	45.74
25% BFS	37.26	49.29	27.75	67.00

4. CONCLUSIONS

The main outcomes of this research can be summarized as follows:

- As the amount of blast furnace slag increased, compressive strength of geopolymer concrete increased.
- When blast furnace slag was used at 25% by weight of cement, it was reached higher compressive strength values such as 67 MPa without using cement. This indicates that geopolymer can be used for specific-targeted projects in future.
- The use of geopolymers is substantial in concrete production as lowering energy consumption and decreasing carbon dioxide emission.
- Environmentally friendly concrete can be produced by using waste materials. With alkaline activators and recycled materials, and by using different methods (pressurized forming, extrusion, etc.) in designs of semi-dry mix, the prefabricated elements, paving

stones, curbs, decorative tiles, facing tiles, concrete pipes, bricks and refractory building materials can be produced.

- For future research, the use of geopolymers in buildings placed in highly seismic zones can be investigated. The following methods can be suggested for future studies: Obtaining alkaline activators from industrial wastes can be a beneficial study for environmentally friendly concrete production processes. Geopolymer concrete can be produced with different pozzolanic binders such as silica fume. Facing tiles in different sizes can be produced with geopolymeric materials. Instead of using commercial silicate chemicals, solid silicate resources can be investigated to reduce the cost of geopolymer production. The use of solid silicate resources can lower the cost of production.

ACKNOWLEDGEMENT

We would like to thank Ersin DANIŞ (Chairman of Danış Group Company) and Umut DANIŞ. We would also like to thank Şenol ALDEMİR, Ali EKEN and Gurbet BATAN (Atılım Beton Quality Control Staffs) for their great support on performing this study.

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