A study on investigating the properties of alkali-activated roller compacted concretes

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Abstract. In this study, it was aimed to contribute to a more environmentally friendly concrete production by using alternative binders, which are waste or by-products that can be used instead of cement. For this purpose, alkali-activated materials were used, a cleaner production process was supported by reducing the amount of activator, a different production method was preferred to prevent the workability problem caused by dry consistency, and roller compacted concrete was produced. Ground granulated blast furnace slag (GGBFS) and fly ash were used as precursors, and an activator solution prepared by mixing 10 M sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃), which has a Na₂SiO₃/NaOH ratio of 2.5, was used in production of alkali-activated roller compacted concretes. Also, Portland cement roller compacted concrete was produced with the same dosage for comparison purposes. Unit weight, total water absorption, ultrasonic pulse velocity (UPV), modulus of elasticity, abrasion resistance, 7 and 28-d compressive strength values of the alkali-activated RCCs were determined. While the roller compacted concretes produced with fly ash were weaker than Portland cement RCCs in terms of compressive strength, the specimens produced using blast furnace slag have been found to be superior.

Keywords: alkali-activation; blast furnace slag; fly ash; mechanical properties; roller compacted concrete

1. Introduction

With the increasing need for cement in developing economies, the increase in environmental damage due to high energy consumption and greenhouse gas emission during cement production has created a need for cleaner and sustainable building materials. Therefore, building materials that can replace cement are being investigated. Alkali-activated materials contribute to cleaner production as they are produced using waste or by-products such as slag and fly ash, but the alkaline solution used in alkali-activation may prevent a more economical production. In order to eliminate this problem, the idea of applying an alternative production technique, roller compaction method, was created in order to solve the consistency problem that occurs when reducing the amount of solution in alkali-activated concretes. Roller compacted concrete (RCC) pavements are advantageous materials because they can be constructed using asphalt equipment and have similar properties to traditional concrete pavements in terms of durability and strength. RCC can be produced using the main components used in conventional concrete production such as cement, supplementary cementitious materials, water and aggregates.

Contrary to the negative effects such as the high amount of carbon dioxide emission and energy demand in cement production, alkali-activated materials are preferred as they can be produced by using various pozzolanic waste or by-products of industrial processes as binders. Recently, studies are carried out to contribute to the reduction of environmental damage by reducing the use of cement. Pranav et al. investigated the feasibility of utilization of alternative materials to replace cement, which includes fly ash, coal ash, silica and ground granulated blast furnace slag, for wearing course of concrete pavements such as conventional concrete, self-compact concrete and roller compacted concrete (Pranav et al. 2020). In addition, efforts are also made to recycle waste materials in concrete industry (Hosseini 2020). Lirer et al. studied the properties of composite materials made of dredged sediments in a fly ash based geopolymer and stated that the dredged mixtures were classified as non-hazardous in terms of environmental impact (Lirer et al. 2017). Similarly, studies are carried out to evaluate waste or by-products in the production of roller compacted concrete (Chi and Huang 2014, Debieb et al. 2009, Madikhan et al. 2012, Meddah et al. 2014, Modarres and Hosseini 2014, Yerramala and Ganesh Babu 2011). Courard et al. (2010) studied the use of concrete road recycled aggregates for roller compacted concrete, and indicated that recycled concrete aggregates are similar to natural aggregates with regard to solid compactness. Fakhri et al. (2017) tested different concrete mixtures produced with waste materials and investigated the crack behavior of roller compacted concretes containing crumb rubber and reclaimed asphalt pavement.

In recent years, studies examining the properties of alkali-activated materials and investigating their disadvantages as well as their advantages have been carried out. According to Allahverdi et al. in alkali-activated slag
concretes, relatively lower alkali content causes not only carbonation during first few days, but also microstructural defects which leads to low compressive strength. Carbonation at early ages can reduce the alkalinity of the surface of the material and neutralize this layer, which affects the mechanism of activation and leads to the binding compound formation with different molecular structure. However, despite their high compressive strength, efflorescence formation becomes a problem in mixtures having high alkali content (Allahverdi et al. 2017). Ibrahim et al. activated the natural pozzolan with sodium silicate and sodium hydroxide solutions and found that the increased sodium hydroxide molarity increased strength, 14 M NaOH resulted in a dense and uniform microstructure compared to milder solutions and led to the enhanced C-A-S-H formation (Ibrahim et al. 2019). In order to eliminate the negative environmental impacts of alkaline activators such as silicate solutions, Baloglu et al. synthesized inorganic polymers using metakaolin, and cotton shell ash that was collected from an oil processing factory as activator (Baloglu et al. 2018). Bastani and Behfarnia studied the application of alkali-activated slag in roller compacted concrete and found that the mechanical properties of roller compacted alkali-activated slag concretes with a minimum cementitious content were comparable to those of conventional roller compacted concrete (Bastani and Behfarnia 2020).

In this study, it was aimed to contribute to the economy and the environment by recycling waste or by-products and to develop a material that can be used as a structural element. The potential of utilization of materials as an alternative to conventional production with cement was investigated, and strength and durability tests were carried out on the materials produced. By using roller compaction method, which allows production with dry mixture, the amount of alkaline activator that can cause environmental damage could be reduced, the water/binder ratio could be reduced and the problem of consistency was solved. Ground granulated blast furnace slag (GGBFS) and fly ash were used as precursors, and alkali activator solution was prepared by mixing 10 M sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃), which has a Na₂SiO₃/NaOH ratio of 2.5. In addition, Portland cement roller compacted concrete was produced with the same dosage for comparison purposes. Unit weight, total water absorption, ultrasonic pulse velocity (UPV), modulus of elasticity, abrasion resistance, 7 and 28-d compressive strength values of the alkali-activated RCCs were determined.

2. Materials and methods

In production of roller compacted concretes, crushed stone I which has a Los Angeles abrasion resistance value of 20%, and natural sand was used as aggregates. The sieve analysis of the aggregates is shown in Table 1. The specific weights of the aggregates were 2.80 and 2.72 g/cm³ for crushed stone I and natural sand, respectively.

The grain size distribution of the aggregates is shown in the Fig. 1. The granulometric curve of the mixture remains for the upper and lower limits proposed by Harrington et al. (2010) for RCC production. Aggregate mixture contains 60% natural sand (fine aggregate) and 40% crushed stone I (coarse aggregate).

Ground granulated blast furnace slag used in production was provided from Oyak Bolu Cement located in Turkey. Technical properties of ground granulated blast furnace slag are given in Table 2. Standard values for blast furnace slag are defined in the TS EN 15167-1 (2006) standard.

The chemical composition of fly ash is given in Table 3. Alkali-activation was achieved by using 10 M sodium hydroxide solution and sodium silicate in liquid form. Since dissolving sodium hydroxide in water is an exothermic reaction, the activator solution was prepared 24 h before concrete production to let the alkaline solution cool down to room temperature. The ratio of Na₂SiO₃/NaOH was 2.5 in activator solution.

<table>
<thead>
<tr>
<th>Table 1 Sieve analysis of the aggregates</th>
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<td>Sieve Size (mm)</td>
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<td>16</td>
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<td>12.5</td>
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<td>0.063</td>
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<th>Table 2 Technical properties of GGBFS (Url-1, 2020)</th>
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<td>Typical Specifications</td>
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<td>------------------------</td>
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<tr>
<td>Activity, 7 days %</td>
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<tr>
<td>Activity, 28 days %</td>
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<tr>
<td>Volume Expansion mm</td>
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<tr>
<td>Specific Surface cm²/g</td>
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<td>MgO %</td>
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<td>Cl %</td>
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<td>Loss on Ignition (LOI)%</td>
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<td>Moisture %</td>
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<tr>
<td>CaO+MgO+SiO₂ %</td>
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<td>(CaO+MgO)/SiO₂ %</td>
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Technical properties of sodium silicate are given in Table 4.

Mix proportions of roller compacted concretes are given in Table 5, for 1 cubic meter of concrete. In this table, concrete code BFS represents the specimens produced with blast furnace slag. In addition, FA shows the concrete produced with fly ash and PC shows the mixture containing Portland cement as binder. Roller compacted concrete specimens were produced in accordance with ASTM C 1435 (ASTM C 1435 2014). 15 cm×15 cm×15 cm cube specimens were produced in two layers by compacting fresh concrete with a vibrating hammer, and each layer was compacted for ten seconds. The design of RCC was made to have a slump value of zero. The spherical structure of the fly ash allows the concrete to have a high slump value compared to other mixtures with the same water/binder ratio. Since the consistency was very fluid in the production with fly ash, the amount of activator solution was decreased and the amount of aggregate was increased.

Since the purpose of this study is to use by-products such as fly ash or slag instead of cement as binders, the dosage is quite high for traditional RCC production, and cement-based production was made for comparison purposes. It was reported in the studies performed that the optimal cement dosage in the roller compacted concrete mixture is about 225±25 kg/m³ (Hazaree et al. 2011). All the specimens were cured in lime-saturated water until the day of testing.

The compressive strength of the 15 cm×15 cm×15 cm cube specimens was determined at the ages of 7 days and 28 days in accordance with TS EN 12390-3 (TS EN 12390-3 2010). The concrete loading rate during the uniaxial compression test was 0.602 MPa/s (13.545 kN/s). Water absorption tests were carried out in accordance with EN 772-11 (BS EN 772-11, 2011). After 7 and 28 days, the modulus of elasticity and ultrasonic pulse velocity were determined. The Proceq Pundit PL200 Ultrasonic Tester was used in the tests to determine the ultrasonic pulse velocity and dynamic modulus of elasticity. The passband of the S-wave transducers used to determine the elastic modulus is 250 kHz, the aperture size is Φ41 mm×32 mm, the passband of the P-wave transducers is 54 kHz and the aperture size is Φ50 mm×46 mm. To determine the frequency of ultrasonic pulses, 54 kHz P-wave transducers with a wavelength of 68.5 mm were used. To determine the modulus of elasticity, the first measurement was performed using a 54 kHz P-wave transducer with a wavelength of 68.5 mm, and then these sensors were removed and replaced with a 250 kHz S-wave transducer that has a wavelength of 10 mm, and a second measurement was performed. After measurements using S and P wave transducers, the elastic modulus of the RCCs was determined with the digital display of the device. When calculating the wavelengths, the pulse frequency was 3700 m/s (longitudinal wave) and 2500 m/s (shear wave) (Url-3, 2019). In obtaining all the experimental data, three cube specimens were tested for each test group, and mean values were calculated. The abrasion resistance of the concretes was measured by using an abrasive material with a wearing machine made of a wide abrasion wheel, in accordance with BS EN 1342 (BS EN 1342, 2012) standard.

### 3. Results and discussion

#### 3.1 Unit weight and water absorption

The unit weight of alkali-activated concretes and water absorption percentages of the specimens are given in Table 6. The specific weight of the materials used in production has a direct influence on the unit weight of concrete. Also, the compaction process affects the unit weight values as it changes the air content of the material. In this study, the difference between the unit weights of the concrete produced with slag and fly ash is 0.4% and there is not a significant difference. While making this determination, it should be taken into consideration that the amount of aggregate has been increased in order to have a low slump value in production with fly ash. However, the unit weight of the reference concrete produced with cement was lower. Unit weight of slag concretes was 5.1% higher than that of Portland cement specimens. Since the design of the Portland cement RCC was changed to reference alkali-activated concrete, different values were obtained from the unit weights of conventional RCCs. The unit volume of RCC contains more solids, the density of the roller compacted concrete is approximately 1-3% higher than that of ordinary concrete, and usually exceeds 2.4 t/m³ (ACI 207.5R 2011). These comparisons are made to see how the weight of the structure will be affected if these materials are used alternatively, the results will be affected as the mixture design changes.
Water absorption percentages, which ranges between 4.33% and 5.40%, are high in all specimens produced, this is associated with the excess amount of fine material in mixture design. In terms of durability, it is more convenient to have low water absorption percentages. Water absorption of the concretes produced with fly ash was 18.7% more than that of PC specimens; the amount of aggregate used in production has an effect on obtaining this result. On the other hand, the water absorption values of the slag concretes were obtained closer to those of the PC roller compacted concretes, the water absorption values of the slag RCCs were 4.8% lower than the reference specimens. Changing the dosage and aggregate amounts will affect the water absorption percentages.

### 3.2 Ultrasonic pulse velocity and modulus of elasticity

Ultrasonic pulse velocity and modulus of elasticity values of the roller compacted concretes are shown in Table 7.

The variation of UPV values of specimens at different ages are shown in Fig. 2.

According to ASTM C 597 (ASTM C 597 2016), the quality of concrete is considered to be good if the ultrasonic pulse velocity is between 3.5 and 4.5 km/s. It can be said that the higher the ultrasonic pulse velocity, the less the voids in the concrete, so the concrete is more impermeable and durable. The specimens with the lowest ultrasonic pulse velocity and thus worse in terms of durability were those produced with fly ash. In other RCCs, the UPV was greater than 3.5 km/s, and these specimens’ quality was considered as good according to the ASTM C 597 standard (ASTM C 597 2016). As it is affected by the amount of voids in the concrete, ultrasonic pulse velocity values are expected to be directly proportional to the concrete compressive strength, and UPV can give an idea about concrete compressive strength without causing any destruction in concrete.

In general, it is expected that the modulus of elasticity in alkali-activated materials will be lower than the concrete produced with cement. However, in this study, the highest modulus of elasticity value was obtained with alkali-activated slag RCCs as shown in Fig. 3. In productions containing GGBFS, the 28-d modulus of elasticity was 37.4% greater than cementitious specimens but in productions containing fly ash, this value was 46.0% lower than the reference specimen.

### 3.3 Compressive strength and abrasion resistance

Abrasion resistance and compressive strength values of the alkali-activated roller compacted concretes at the ages of 7 and 28-days are given in the Table 8. Thanks to the use of roller compaction method, which allows production in dry consistency, the water/binder ratio has been reduced and high strengths have been obtained even at early ages with GGBFS and Portland cement binders. The maximum compressive strength value at 7-days, which was 11.2% higher than the control specimen, was obtained with blast furnace slag. In parallel with this result, the same trend was achieved in 28-day strengths, but this time the compressive strengths were found 40.3% higher than the Portland cement-based control specimen.

Wearing resistance of the specimens produced with Portland cement and the specimens produced with blast furnace slag were compatible with each other, while wear in specimens produced with fly ash was higher. From this point of view, it can be said that the wear resistance is low in the specimens with low compressive strength. It is known
that cement dosage, water/cement ratio, slump, air content, type of finish and curing affect the characteristics of the surface layer and abrasion resistance of concrete (Prior 1966).

The compressive strength values obtained with fly ash RCCs are applicable depending on the purpose of use, but are very low compared to other productions. Nevertheless, compressive strength of 27.9 MPa was achieved in 28 days, which is 55.8% lower than Portland cement specimens. This difference was greater at early ages; 7-day compressive strength is 83.3% lower than the control specimen, which has a high dosage of cement. As a result, it can be said that although a low strength value is obtained compared to other specimens, the compressive strength values that can be used in the application can be reached, considering that the binder used is a waste product.

As seen in Fig. 4, although the water/binder ratio was lower and the aggregate amount was higher, the concrete compressive strength was low in specimens containing fly ash. The reason for this finding is the structure of the fly ash, as well as heat curing, alternative productions can be made with different activators in order to improve the strength values of fly ash based alkali-activated concretes. The main hydration products in alkali-activated slag concretes are calcium silicate hydrate (C-S-H), having a low ratio of Ca/Si, hydrotalcite and Aluminate-Ferrite-mono (sulphate) hydrate phase (AFm) (Wang and Scrivener 1995, Jiang et al. 1997). Furthermore, in alkali-activated fly ash geopolymers, the glassy component of fly ash reacts with sodium silicate and the main hydration product is amorphous alkali aluminosilicate gel, the low compressive strengths obtained with fly ash is related with the degree of reaction, and the low degree of reaction associated with low reactivity of fly ash used (Mužek et al. 2012). Fly ash based alkali-activated concretes show slow geopolymerization reactions at ambient curing conditions, and generally requires elevated temperatures above 60°C for increasing the reaction rate of geopolymerization and early strength development (Bakharev 2005). Due to the heat-curing requirement for the strength development, the fly ash utilization alone can be limited in the precast concrete industry (Nis 2019). On the other hand, it was reported that wet curing does not have considerable effects on strength development of roller compacted alkali-activated slag concretes and sealed curing is suggested for both sodium silicate and caustic activated slag RCCs, since slag is activated by an alkaline solution, wet curing does not significantly affect slag activation, and water can weaken the activation process due to a decrease in the alkalinity of the pore solution (Bastani and Behfarnia 2020).

The specimens after uniaxial compression test are shown in Fig. 5, besides the color difference, the aggregate distribution in the specimens can be seen.

4. Conclusions

Based on the experiments conducted, the outcomes of this study can be summarized as follows:

• When fly ash was used as a binder, the slump values were high and it was necessary to increase the amount of aggregate used to provide dry consistency for roller compacted concrete production.
• The amount of water absorbed, which is affected by cement dosage, fine material content and the amount of aggregates has taken its greatest value in concretes produced with fly ash.
• The production that gives the best results in terms of strength and durability was the GGBFS based alkali-activated RCCs, which had the highest UPV value, the least amount of voids, the highest modulus of elasticity, and the highest compressive strength. With the blast furnace slag, which is a by-product, better results can be obtained than roller compacted concrete produced by using high dosage of Portland cement.
• The 28-d compressive strengths of alkali-activated RCC specimens produced with GGBFS were found 40.3% higher than the Portland cement-based control specimen. With the use of fly ash, compressive strength of 27.9 MPa was achieved in 28 days, which is 55.8% lower than specimens produced by using Portland cement.
• While the abrasion resistance of Portland cement and slag-based specimens was similar, the abrasion resistance was lower in the production with fly ash. This result shows compatibility with concrete compressive strength.
• It was observed that the wear in the RCC productions made with fly ash is 18.9% greater than that of cement-based and blast furnace slag based concretes.
• The problem of consistency that can be encountered in alkali-activated materials has been solved by roller compaction method, which allows production with dry mixture, so that the amount of activator used can be reduced, and waste or by-products are re-evaluated. By using this production method, environmentally friendly concrete can be produced; this method will be
particularly beneficial in the production of prefabricated structural elements.

- When the prices of 1 m³ of concrete were compared, the price of RCC produced with blast furnace slag was approximately 93.7 dollars, while the price of concrete produced with fly ash was 64.0 dollars and concrete produced with Portland cement was 44.8 dollars. Concretes produced with Portland cement are expensive as they have a high cement content for reference use. These costs have been calculated based on the amount of materials used for this study and should not be generalized. Material prices may vary by country. Alkali activated materials are expensive materials compared to traditional cementitious concretes due to the high price of the chemicals used as activators. On the other hand, considering the effects on the environment, it will be beneficial in terms of reducing the use of cement and evaluating waste materials. Research can be conducted to reduce this cost by using alternative waste activators.

Further studies conducted with different activators and different curing conditions are recommended. By this way, it is thought that the results obtained with fly ash can be improved and environmentally friendly concrete will be produced.

References

ACI Committee 207.5R-11 (2011), Roller-Compacted Mass Concrete, ACI Committee Report.


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STP-169A, ASTM, Philadelphia.

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