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Optimizing the Na_2O Dosage to Develop Mechanical Properties of Ferrochrome Slag-Based Alkali-Activated Mortar

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Alkali-activated cement,
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Ferrochrome slag,
Portland cement,
Compressive strength

Abstract: The purpose of this study is to investigate the effect of Na_2O dosage on the compressive strength and ultrasonic pulse velocity (UPV) of alkali-activated ferrochrome slag/Portland cement mortar. A total of eight mortar mixtures were produced. While four of the mixtures contain 15% Portland cement, the binder material of the other four mixtures consists entirely of ferrochrome slag. These alkali-activated mortar mixtures were prepared with four Na_2O dosages (4%, 6%, 8%, and 10%). The alkali modulus of all mixtures was kept constant at 1.4. Compressive strength and UPV tests were performed to examine the effect of alkali dosage on both PC-substituted and PC-free mortars. As the Na_2O dosage increased, the compressive strengths of both PC-substituted and unsubstituted mortar specimens increased. It was seen that the critical Na_2O dosage of the alkali-activated mortar was 6%. Compressive strength and UPV values of the mortar specimens increased significantly with PC substitution.

Ferrokrom Cüruf Bazlı Alkali-Aktif Harcın Mekanik Özelliklerini Geliştirmek İçin Na_2O Dozajının Optimize Edilmesi

Anahtar Kelimeler
Alkali-aktif çimento,
Alkali dozajı,
Ferrokrom cürufu,
Portland çimentosu,
Basınç dayanımı

Öz: Bu çalışmanın amacı alkali Na_2O dozajının alkali-aktif ferrokrom cürufu/Portland çimentosunun basınç dayanımı ve ultrases geçiş hızı (UGH) üzerindeki etkisini incelemektir. Bu amaç doğrultusunda toplamda sekiz harç karışımı hazırlanmıştır. Karışımların dördü %15 oranında Portland çimentosu içerirken, diğer dördünün bağlayıcı malzemesi tamamen ferrokrom cürufundan oluşmaktadır. Alkali-aktif harçlar dört farklı Na_2O dozajı (4%, 6%, 8% ve 10%) ile hazırlanmıştır. Tüm karışımların alkali modülü 1.4 olarak belirlenmiştir. Na_2O dozajının hem PÇ ikameli hem de PÇ içermeyen harçlar üzerindeki etkisini incelemek için basınç dayanımı ve UGH deneyleri gerçekleştirilmiştir. Na_2O dozajı arttıkça hem PÇ ikameli hem de ikamesiz harç numunelerinin basınç dayanımları artmıştır. Alkali-aktif harç için kritik Na_2O dozajının %6 olduğu görülmüştür. PÇ ikamesi ile harç numunelerinin basınç dayanımı ve UGH değerleri önemli ölçüde artmıştır.

1. INTRODUCTION

Portland cement (PC) is one of the building materials broadly used in the construction industry [1]. It is very advantageous in terms of strength and durability. However, despite all these great features, it has a disadvantage that pushes researchers to look for alternative materials to PC: High CO_2 emissions released into the atmosphere [2,3]. PC is responsible for about 7-8% of the CO_2 emissions released into the atmosphere from human activities. The emissions are mainly due to the decomposition of calcium carbonate ($CaCO_3$) to generate the calcium silicate and aluminate phases. Another cause of emissions is the use of fossil fuels [4,5].

Alkali-activated materials (AAMs) serve as an exemplary instance of alternative binders being developed with the primary objective of achieving environmental savings. These materials show promise in reducing the environmental impact associated with traditional cement production. The term of alkali activation refers to the reaction of a solid aluminum silicate material with alkali activator to obtain a hardened binder. Aluminum silicate materials are termed precursor materials [6]. Pozzolanic additives, which are

used to replace PC in certain proportions in traditional concrete production [7], can be used in AAM production. Some examples of these materials are blast furnace slag, metakaolin, fly ash and ferrochrome slag (FS) [4,8–10].
Karakoç et al. [11] studied the usability of FS in AAM production. It was stated that it is possible to produce AAM by using a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) as activator. Yadolahi and Dener stated [12] that the compressive strength of the paste sample consisting entirely of FS was 43.92 MPa. Nath [13] stated that FS addition resulted better compressive strength and well bridged microstructures.

In a study [9] examining the effect of PC substitution on alkali activated FS cement, it was stated that there were increases in compressive strength with PC substitutions. It was also stated that the highest compressive strength was obtained with 15% PC substitution. Mechanical properties and durability of AAM are primarily influenced by the dosage of the activator. Although there are many studies [14–17] examining the effect of Na_2O dosage on the properties of alkali activated blast furnace slag, studies examining the effect on alkali-activated ferrochrome slag (AAFS) are very limited [11]. Karakoç et al. [11] investigated the effect of Na_2O dosage on mixtures prepared using 100% FS. It was stated that the quality of AAFS cement highly depends on Na_2O dosage. It was stated that the highest 28-day compressive strength was obtained when the silica modulus was 0.7 and the Na_2O dosage was 7%.

The literature review shows that there aren't enough studies examining the effect of Na_2O dosage on AAFS based composites. To the best of the author knowledge, there is no study on how the alkali dosage will affect the strength of AAFS composite containing PC. Within the scope of this study, the effect of Na_2O dosage on PC-substituted AAFS mortar was investigated.

2. MATERIAL AND METHOD

2.1. Materials

In this study, the binder materials employed were FS and PC. The type of PC was CEM I 42.5 R [18] which corresponds to ASTM type 1. The properties of the FS and the PC are presented in Table 1.

Table 1. Chemical composition of PC and FS.

Constituent	PC	FS
SiO_2	18.48	33.8
Al_2O_3	4.4	25.48
Fe_2O_3	3.12	0.61
CaO	64.13	1.1
MgO	1.2	35.88
SO_3	0.17	-
Na_2O	0.66	-
K_2O	0.81	-
Cr_2O_3	-	2.12
Specific gravity	3.1	2.85

River aggregate with a maximum diameter of 4 mm was utilized. The size distribution of the aggregate used is shown in Fig 1.

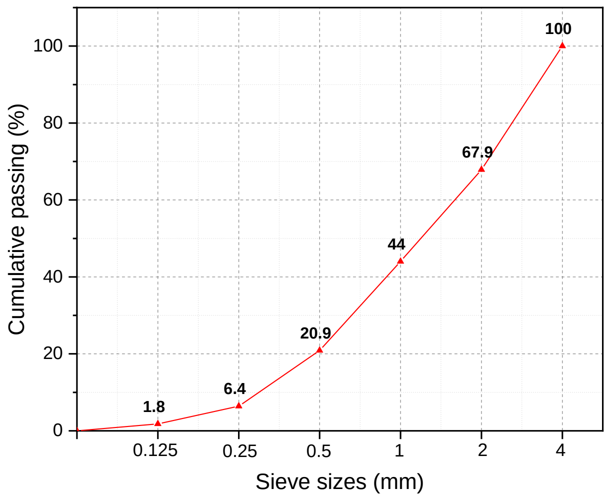

Figure 1. Size distribution of the aggregate.

A mix of Na_2SiO_3 and NaOH was used as alkali activator. NaOH (99% purity) solution was prepared by dissolving NaOH pellets in tap water, then kept at room temperature for 24 h to cool down. Na_2SiO_3 solution composed of 28% SiO_2, 9% Na_2O, and 63% water content by weight with a silica modulus of 3.11. NaOH and Na_2SiO_3 solutions were mixed to achieve the desired Na_2O dosage.

2.2. Mix Proportions and Test Procedure

A total of eight mortar mixes were prepared to examine the effect of Na_2O dosage. The mixture proportions are given in Table 2.

Table 2. Mix proportions.

Mix codes	FS (wt.%)	Na_2O dosage (%)	A/B	W/B
N4FS100	100	4	2.75	0.45
N6FS100		6	2.75	0.45
N8FS100		8	2.75	0.45
N10FS100		10	2.75	0.45
N4FS85	85	4	2.75	0.45
N6FS85		6	2.75	0.45
N8FS85		8	2.75	0.45
N10FS85		10	2.75	0.45

The term "Na_2O dosage" refers to the weight ratio of the total sodium oxide content in the activator mixture to the binder material. Silica modulus (Ms) indicates the ratio of silicon oxide-to-sodium oxide (SiO_2/Na_2O) in the activator mix. A set of AAFS mixtures were prepared with four Na_2O dosages (4%, 6%, 8% and 10%). The Ms of all mixtures were kept constant at 1.4. Aggregate-to-binder (A/B) ratio of all mixtures was determined as 2.75/1. All mixes were produced with a water-to-binder (W/B) ratio of 0.45. Four of the mixtures contain 15% PC, while the other four are produced entirely from FS. All samples were cured at 75 °C for 24 hours and then kept at room temperature until testing day (28 day).

The compressive strength test was conducted following the guidelines outlined in ASTM C109 [19]. The ultrasonic pulse velocity (UPV) test was performed in accordance with ASTM C597 [20]. Fig. 2a and Fig. 2b show the compressive strength and UPV measurement tests, respectively.

Figure 2. a) compressive strength test b) UPV test.

2.3. Specimen preparation

Firstly, dry materials (FS or FS + PC, and aggregate) were mixed for 30 seconds. Then, NaOH and Na_2SiO_3 solutions were added to the dry mixture. The mixing process continued until a homogeneous mixture (2 min) was obtained. One of the prepared fresh mortars are shown in Fig. 3.

Figure 3. A fresh mortar mixture.

Prepared fresh mortar mixtures were cast into steel molds (50*50*50 mm^3). After that, the steel molds were wrapped with a stretch film as shown in Fig. 4.

Figure 4. A wrapped mold.

3. RESULTS AND DISCUSSION

3.1. Compressive strength results

Fig. 5 presents the 28-day compressive strength results for mortar specimens without PC substitution.

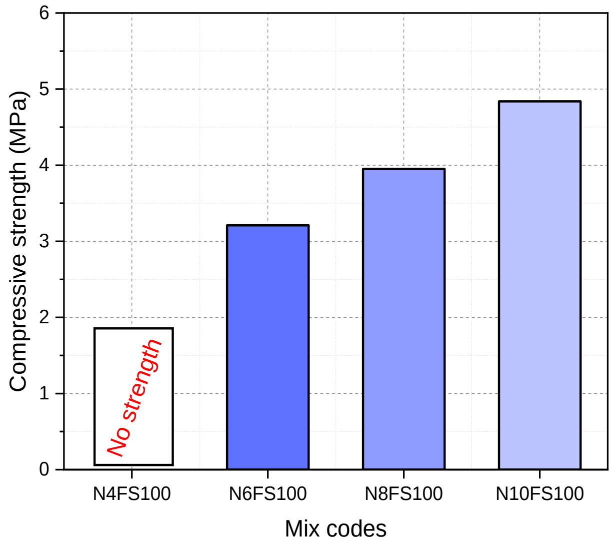

Figure 5. Compressive strength of PC-free specimens.

Mortar specimen with 4% Na_2O dosage, coded as N4FS100, did not have any compressive strength. N4FS100 coded mortar specimen is shown in Fig. 6. The mortar specimen was easily dispersed. The compressive strengths of the N6FS100, N8FS100 and N10FS100 mortar specimens with 6%, 8% and 10% Na_2O dosages were 3.21, 3.95 and 4.84 MPa, respectively. Regardless of the Na_2O% used, the 28-day compressive strength of all PC-free mortar specimens was quite low. However, it was noted that the compressive strength exhibited an increase with an increase in the Na_2O dosage.

Figure 6. N4FS100 coded mortar specimen.

Raising the Na_2O dosage intensifies hydration, leading to a denser microstructure and increased compressive strength [16]. While the strength of samples without PC did increase with an increase in dosage, the highest compressive strength attained remained low at 4.84 MPa. Employing a higher curing temperature to enhance the geopolymerization process can indeed lead to an improvement in compressive strength. However, it's worth noting that this approach comes with a drawback in terms of increased energy consumption. To enhance compressive strength without the need to raise the curing temperature, a 15% PC substitution was introduced in the mixtures. Fig. 7 presents the 28-day compressive strength results for mortar specimens with 15% PC substitution.

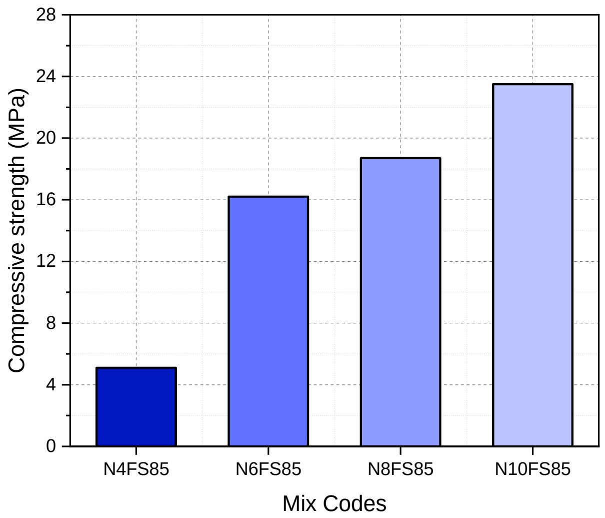

Figure 7. Compressive strength of PC-substituted specimens.

The first thing to note is that the compressive strength increased considerably with the PC substitution. At 4% Na_2O dosage, a compressive strength of the specimen without PC substitution was not obtained, while the compressive strength of the specimen with 15% PC substitute was 5.1 MPa. The compressive strengths of the N6FS85, N8FS85 and N10FS85 mortar specimens with 6%, 8% and 10% Na_2O dosages were 16.2, 18.7 and 23.5 MPa, respectively. It was observed that the critical Na_2O dosage for the alkali activated FS/PC mortar was 6%. Compressive strength of N4FS85 coded specimen was 5.1 MPa. When the Na_2O dosage was increased from 4% to 6%, the compressive strength increased by 217%. The highest compressive strength was obtained from N10FS15 specimen with the highest Na_2O dosage. When 15% PC was added to N6F100, N8F100, N10F100 coded specimens, their compressive strengths increased by 404, 374 and 385%, respectively. The enhancement in compressive strength with PC replacement may be attributed to the formation of calcium silicate hydrate (CSH) and calcium aluminate silicate hydrate (CASH) gels [21].

3.1. Ultrasonic pulse velocity results

Fig. 8 presents the 28-day UPV results for mortar specimens without Portland cement substitution.

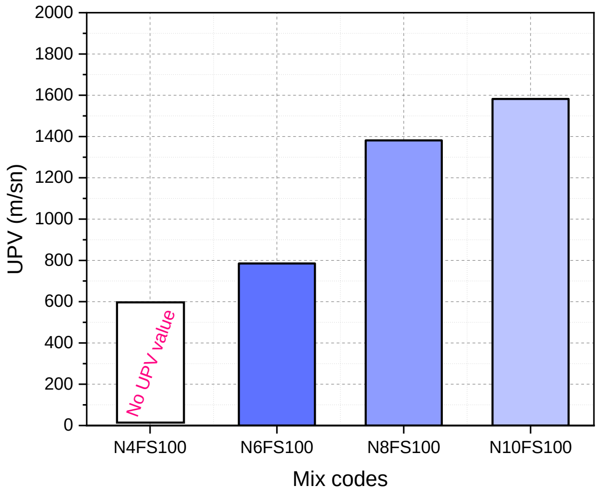

Figure 8. UPV results of PC-free specimens.

Consistent with the compressive strength results, no UPV value was obtained from the N4FS100 coded mortar specimen with 4 Na_2O dosage. The UPV values of the N6FS100, N8FS100 and N10FS100 mortar specimens with 6%, 8% and 10 Na_2O dosages were 785, 1381 and 1582 m/s, respectively. As the Na_2O increased, the UPV values increased. Fig. 9 presents the 28-day UPV measurement results for mortar specimens with 15% PC substitution.

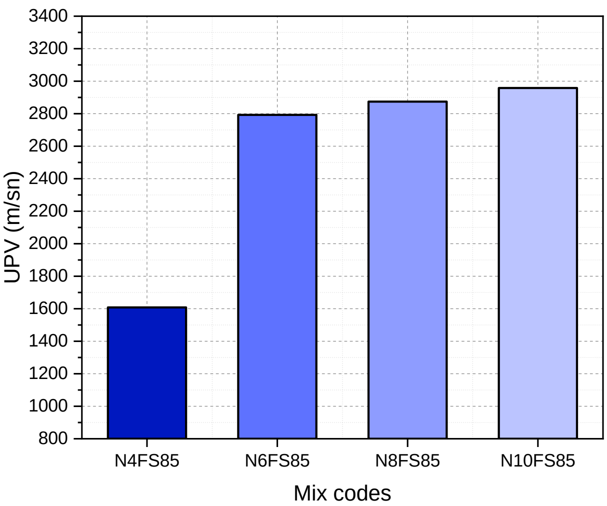

Figure 9. UPV results of PC-substituted specimens.

Like the compressive strength results, significant increases occurred in UPV values with the PC substitution. While No UPV value could be obtained in the mortar specimen coded N4FS100, the UPV value of the N4FS85 coded mortar specimen with 15% PC substitution was 1608 m/s. The UPV values of the N6FS85, N8FS85 and N10FS85 mortar specimens with 6%, 8% and 10% Na_2O dosages were 1608, 2793, 2874 and 2958 m/s, respectively. Compressive strength increased by 74% when Na_2O dosage was increased from 4% to 6% for 15% PC substitution. The UPV values of the N6FS85, N8FS85 and N10FS85 coded mortar specimens were 105, 108 and 87% higher than their PC unsubstituted counterparts. The relationship between the compressive strength and the UPV values of the specimens with no PC substitution and with 15% PC substitution is given in Fig. 10.

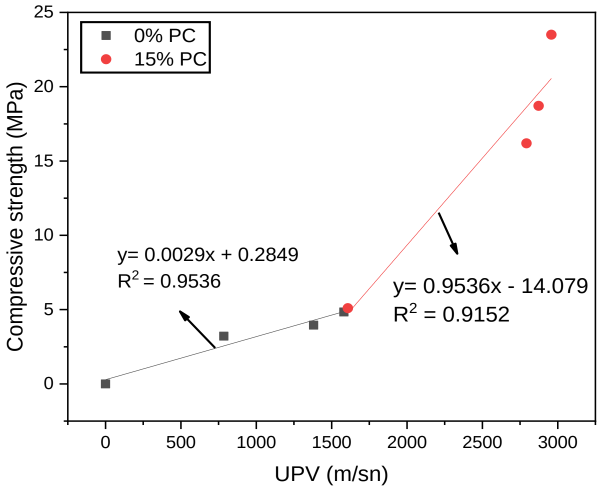

Figure 10. Correlation between compressive strength and UPV values

While the coefficient of determination (R^2) between the compressive strength and the UPV value was 0.95 for the samples without PC substitution, this coefficient was 0.92 for the samples with PC substitution.

4. CONCLUSION

In this study, the effect of Na_2O dosage on the compressive strength and UPV value of alkali-activated FS/PC cement was investigated. In terms of both compressive strength and UPV value, it was observed that the critical Na_2O dosage of the alkali-activated mortar was 6%. As the Na_2O dosage increased, the compressive strength of both PC-substituted and unsubstituted specimens increased. Even at the highest Na_2O dosage, the compressive strength of the mortar specimen without PC substitution were quite low. Both compressive strengths and UPV values increased significantly with PC substitution. The compressive strengths of the N6FS85, N8FS85 and N10FS85 coded mortar specimens were 404, 374 and 385% higher than their PC unsubstituted counterparts. It was observed that the production of AAM using entirely FS was challenging, even with an increasing alkali concentration. It was concluded that to effectively utilize FS in AAM production, it should be blended with materials possessing a high CaO content, such as PC.

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