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## *Harçların alkali-silis reaksiyonu ve kuruma büzülmesini kontrol etmek için silis dumanı ikamesi ile yüksek kirece sahip uçucu külün içeriğinin optimizasyonu*

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# Optimising High Lime Fly Ash Content By Means of Silica Fume Incorporation to Control Alkali-Silica Reaction And Drying Shrinkage of Mortars

*Araştırma Makalesi / Research Article*

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## ABSTRACT

In this study, the effect of binary and ternary cementitious systems composed of portland cement, high-lime fly ash and silica fume on the compressive strength, alkali-silica reaction (ASTM C 1567) and drying shrinkage of mortar mixtures was researched. For this purpose, binary and ternary binders were prepared with partial replacement of cement with either fly ash (15wt% and 30wt%) or silica fume (5wt%) or both mineral admixtures (15wt%+5wt% and 30wt%+5wt%). An alkali reactive basalt aggregate was used in this study. It was found that partial replacement of cement with high-lime fly ash reduced the strength of mortar mixtures even up to 28-days. Besides, addition of 5% silica fume had not a significant effect on the early strength of fly ash-bearing mixtures. However, silica fume inclusion improved the 28-day strength of mixtures. In terms of alkali-silica reaction (ASR), the fly ash with lower lime content reduced the 14-day expansion more than that of fly ash with higher lime content. The opposite results were the case in 28-day ASR expansions. The ASR expansions of the fly ash-bearing mixtures were significantly reduced by the introduction of the additional 5% silica fume to these mixtures. However, silica fume incorporation remarkably increased the drying shrinkage values of the mixtures. Finally, fly ash with higher lime content was found to be more satisfactory in terms of compressive strength, alkali-silica reaction and drying shrinkage in the ternary binder system.

**Keywords:** Mortar, lime content of fly ash, silica fume, compressive strength, alkali-silica reaction, drying shrinkage.

## Harçların Alkali-Silis Reaksiyonu ve Kuruma Büzülmesini Kontrol Etmek için Silis Dumanı İkamesi ile Yüksek Kirece Sahip Uçucu Külün İçeriğinin Optimizasyonu

### ÖZ

Bu çalışmada, portlant çimentosu, yüksek kireçli uçucu kül ve silis dumanından oluşan ikili ve üçlü çimentolu sistemlerin harç karışımlarının basınç dayanımı, alkali-silis reaksiyonu (ASR) ve kuruma büzülmesi üzerindeki etkisi araştırılmıştır. Bu amaçla, ikili ve üçlü bağlayıcılar uçucu kül (%15 ve %30) veya silis dumanı (%5) veya her ikisinin birlikte (%15+%5) çimento ile ağırlıkça kısmi ikamesiyle hazırlanmıştır. Çalışmada, reaktif bir bazalt agregası kullanılmıştır. Sonuç olarak, çimentonun yüksek kireçli uçucu küllerle kısmen ikamesi harçların dayanımını 28 güne kadar bile düşürmektedir. Ayrıca %5 silis dumanı ikamesinin uçucu küllü karışımların erken yaş dayanımlarına önemli bir etkisi yoktur. Ancak silis dumanı kullanımı karışımların 28 günlük dayanımlarını iyileştirmiştir. ASR bakımından göreceli olarak düşük kireç içerikli uçucu kül, 14 günlük genleşmeleri yüksek kireç içerikli uçucu külden daha fazla azaltmıştır. 28 günlük genleşmelerde ise zıt bir sonuç elde edilmiştir. Uçucu kül içeren karışımların ASR genleşmeleri %5 oranında silis dumanı ikamesinde önemli oranda azalmıştır. Ancak silis dumanının ikamesi karışımların kuruma büzülmesini kayda değer oranda artırmıştır. Nihai olarak, daha yüksek kireç içeriğine sahip uçucu kül ve az miktarda silis dumanı içeren karışımlarının basınç dayanımı, alkali-silis reaksiyonu ve kuruma büzülmesi açısından daha iyi sonuçlar göstermiştir.

**Anahtar Kelimeler:** Harç, uçucu külün kireç içeriği, silis dumanı, basınç dayanımı, alkali-silis reaksiyonu, kuruma büzülmesi.

### 1. INTRODUCTION

Utilization of the cementitious wastes such as fly ash has been an essential topic for the sustainability of cement

and concrete industry in addition to its benefits on physical, mechanical and chemical properties of the cementitious systems. However, high lime fly ashes are generally less effective in controlling alkali-silica reaction (ASR) expansion, thus, it becomes necessary to increase its replacement level even up to 60% to control

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the ASR expansion [1]. Researchers emphasize some drawbacks of the high volume fly ash cementitious systems such as insufficient early strength due to poor reaction rate [2-5]. Moreover, drying shrinkage of the concrete containing mineral admixture may be higher than that of the plain concrete due to higher paste volume and presence of higher amount of smaller capillary pores in the matrix [6]. Therefore, in practice optimising the inclusion level of the mineral admixture in the binder to meet all of the requirements including strength, volume stability and durability is challenging.

Some physical, mechanical and durability properties of the cementitious systems can be improved by using ternary systems containing silica fume [7-10]. However, owing to its less availability, the use of silica fume increases the cost of the binder compared to that of the ordinary portland cement [11]. Thomas et al. [1] reported that high lime fly ash requirement to suppress ASR expansion can be significantly reduced by the addition of a small amount of silica fume to the mixture.

In this study, the performance of binary and ternary cementitious systems containing high lime fly ashes (having different lime contents) and small amount of silica fume was researched from compressive strength, alkali-silica reactivity and drying shrinkage of mortar mixtures viewpoints.

## 2. MATERIAL AND METHOD

### 2.1. Materials

In this study, an ordinary portland cement (CEM I 42.5R) was used. Two types of fly ashes having 15.94% and 39.45% lime contents were supplied from Çayırhan and Soma Power Plants (Turkey), respectively. According to Thomas et al. [12], the Çayırhan and Soma fly ashes can be classified as intermediate calcium fly ash (IFA) and high calcium fly ash (HFA), respectively. Silica fume (SF) was supplied from Antalya Etibank Ferrochrome Plant (Turkey). Basalt aggregate with maximum size of 4.75 mm was used in preparation of the mortar mixtures. A polycarboxylate ether-based superplasticizer (SP) was used in some of the mixtures to improve their flow to the desired value ( $16 \pm 1$  cm). Some properties of the cement, fly ashes and silica fume are presented in Table 1.

### 2.2. Mix Proportions

Table 2 shows the proportions of mortar mixtures used in the compressive strength and drying shrinkage test specimens. The samples are designated by their mineral admixture type and replacement level. For example, I15/S5 indicates a mixture containing 15wt% intermediate calcium fly ash and 5wt% silica fume.

Moreover, the mix proportions prescribed in ASTM C1567 [13] for the ASR test specimens are given in Table 3.

**Table 1.** Some properties of cementitious materials

Item %	Portland cement	IFA	HFA	Silica Fume
SiO <sub>2</sub>	18.40	47.07	32.80	78.82
Al <sub>2</sub> O <sub>3</sub>	4.51	11.56	13.77	0.00
Fe <sub>2</sub> O <sub>3</sub>	3.16	7.22	4.78	0.98
SiO <sub>2</sub> +Al <sub>2</sub> O <sub>3</sub> +Fe <sub>2</sub> O <sub>3</sub>	-	65.85	51.35	79.80
CaO	63.9	15.94	39.45	2.35
MgO	1.6	7.77	2.05	6.41
SO <sub>3</sub>	3.62	2.78	4.22	1.00
Na <sub>2</sub> O	0.46	1.59	0.4	-
K <sub>2</sub> O	0.75	3.04	1.18	3.69
Na <sub>2</sub> O <sub>eq</sub>	0.95	3.59	1.18	2.42
Loss on ignition	3.2	0.42	0.72	3.01
Blaine fineness, cm <sup>2</sup> /g	3630	-	2992	200000
Specific gravity	3.10	2.55	2.42	2.37

**Table 2.** Mix proportions of compressive strength and drying shrinkage test specimens

Mixtures	Cement (g)	IFA (g)	HFA (g)	Silica Fume (g)	Water (g)	SP (%*)	Fine aggregate (g)	Flow, cm
Ref	500	0	0	0	317	0	1375	16
S5	475	0	0	25	317	0	1375	16
I15	425	75	0	0	317	0	1375	16
I15/S5	400	75	0	25	317	0	1375	15.5
I30	350	150	0	0	317	0.2	1375	16
I30/S5	325	150	0	25	317	0.2	1375	15.5
H15	425	0	75	0	317	0	1375	15.5
H15/S5	400	0	75	25	317	0	1375	15.5
H30	350	0	150	0	317	0.2	1375	17
H30/S5	325	0	150	25	317	0.2	1375	16.5

\* Percent by weight of cementitious material

### 2.3. Methods

Mortar mixtures were placed into the 50 mm-cube molds for determination of compressive strength, and into the 25×25×285 mm- prism molds for determination of alkali-silica reactivity and drying shrinkage. The molded specimens were kept at 23±2°C and at least 90% relative humidity for first 24 hours. After demolding, the cube specimens were kept in water at 20±2°C for further 2, 6 and 27 days for compressive strength. Alkali-silica reaction test was performed in accordance with the ASTM C 1567 [13] (accelerated mortar bar method). For drying shrinkage test, mortar bar specimens were cured in water at 20±2°C up to 28 days, and then exposed to drying at 23±2°C and 55-65% relative humidity up to 28 days. The gage length of the specimens was considered as 250 mm.

## 3. RESULTS AND DISCUSSION

### 3.1. Compressive Strength Test Results

The actual and relative compressive strength results of

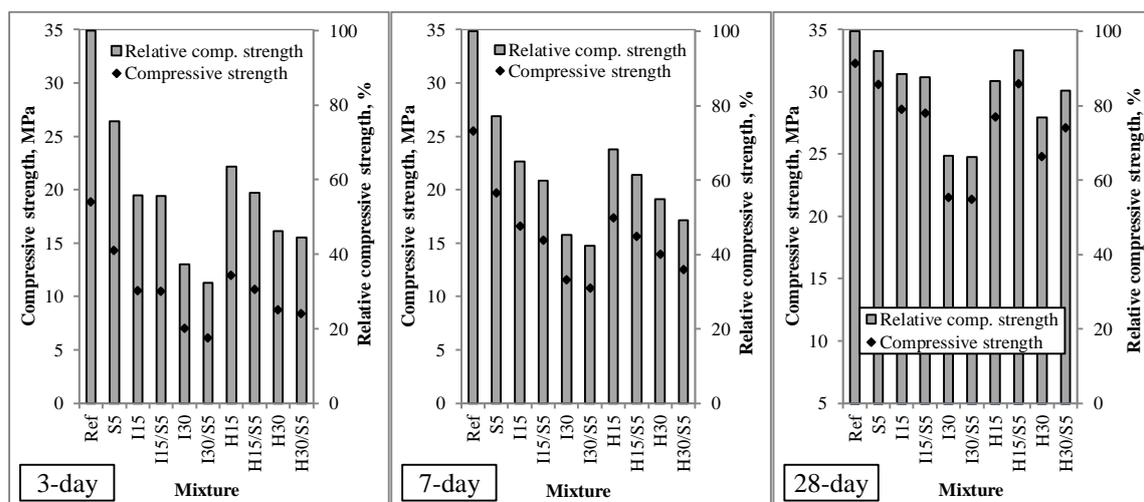
compressive strength of the mortars according to reference mixture up to 68% and 58% for 3 days and 7 days, respectively. The reductions were found more remarkable in the mixtures containing IFA compared to those containing HFA. Prolonging the curing time reduced the difference between the strength of mineral admixture-bearing mixtures and the control mixture. However, the strength of binary and ternary mixtures was found to be lower (up to 34%) than that of the control mixture even at 28 days. Silica fume incorporation improved the 28-day compressive strength of the mixtures containing HFA.

The presence of large amount of lime affects both the nature of the glassy and crystalline phases of the fly ash. The amorphous phase in high-lime fly ash may be simply described as calcium-alumino-silicate glass [14], although different glass types may probably coexist over wide range of compositions [15-17]. The presence of lime in fly ash affects its reactivity. Calcium substitution in the glassy phase of the fly ash is generally considered to increase the reactivity of its glassy phase. Thus, in

**Table 3.** Mix proportions for ASR as prescribed in ASTM C1567 (water/binder ratio: 0.47, sand/cement ratio: 2.25)

Mixtures	Cement (g)	IFA (g)	HFA (g)	Silica Fume (g)	Water (g)	SP (%*)	Sand (g)
Ref	444	0	0	0	209	0	1000
S5	422	0	0	22	209	0	1000
I15	377	67	0	0	209	0	1000
I15/S5	355	67	0	22	209	0	1000
I30	311	133	0	0	209	0.2	1000
I30/S5	289	133	0	22	209	0.2	1000
H15	377	0	67	0	209	0	1000
H15/S5	355	0	67	22	209	0	1000
H30	311	0	133	0	209	0.2	1000
H30/S5	289	0	133	22	209	0.2	1000

\* Percent by weight of cementitious material



**Figure 1.** Compressive strength of mortar mixtures

the mortars are given in Figure 1 for 3, 7 and 28-day curing times, respectively. Introduction of the fly ash and silica fume significantly reduced the early age

high-lime fly ashes, the presence of lime causes the formation of calcium-silicate or calcium-aluminate hydrates in the absence of an additional source of lime.

The self-cementitious behaviour of high-lime ashes is attributed to the hydration and reaction of lime-bearing crystalline phases [12]. Mehta [18] stated that calcium content and particle size distribution of fly ash are the most important parameters governing the strength development in normally cured portland cement mixtures containing fly ash. Thomas et al. [12] reported that the introduction of high lime fly ash results in higher compressive strength values than that of low lime fly ash at curing ages up to 28 days.

**3.2. ASR Test Results**

ASR expansions of mortar bars are shown in Figure 2. Although, 14 days soaking period in NaOH solution is prescribed in the standard, the duration of the test was extended to 56 days in the present study. The basalt aggregate, showing 0.747% 14-day expansion, was found to be significantly reactive in terms of ASR. However, as it was expected, the expansions significantly

decreased by the use of mineral admixtures, in spite of higher  $Na_2O_{eq}$  contents of the mineral admixtures than that of the portland cement.

Figure 3 shows the relative 14-day and 28-day expansion of mortar bars compared to that of the control mixture containing no mineral admixture. The IFA mixtures showed somewhat lower 14-day ASR expansion values than those of HFA mixtures. The expansion of mix I30/S5 was found lower by 95% according to reference mix. However, beyond 14 days the opposite results were observed, i.e., HFA bearing mixtures showed slightly lower expansions than those of IFA containing mixtures. Further, addition of 5% silica fume to the mixtures significantly reduced the ASR expansions. The 28-day expansion of mix H30/S5 was found lower by 88% according to reference mix. Thomas et al. [12] reported that the efficiency of high lime fly ash in controlling ASR expansions is reduced in concrete specimens cured over

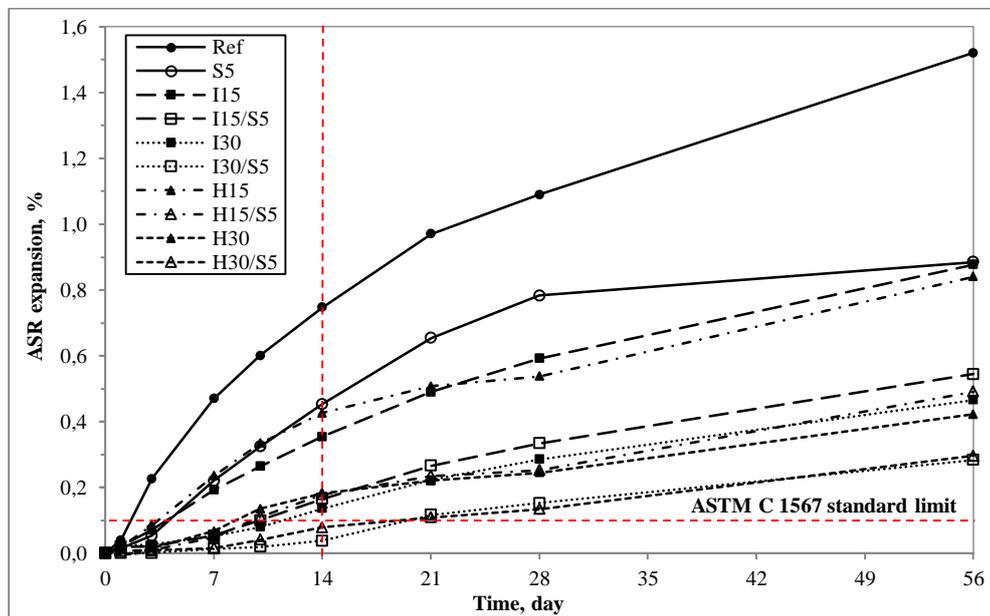


Figure 2. ASR expansions of mortar bars

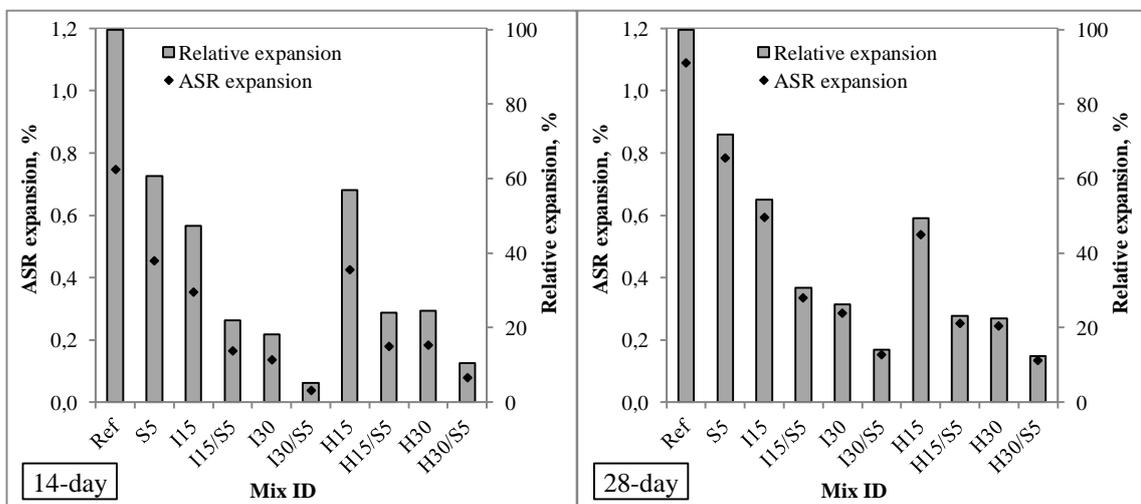


Figure 3. 14-day and 28-day ASR expansions of mortar bars

water at 38 °C for 24 months. Shehata and Thomas [19] similarly reported that 5% silica fume incorporation significantly reduced the fly ash substitution level required for satisfactory expansions caused by ASR. The supplementary cementitious materials that are low in alkali and calcium, and high in silica tend to be the most effective in reducing alkalinity of the pore solution and these materials can be used at relatively lower replacement levels to eliminate damaging ASR expansion [20]. On the other hand, effect of the supplementary cementitious materials on the formation and expansion of ASR gel is reported to be more complex than the limited above mentioned assessments [21].

### 3.3. Drying Shrinkage Test Results

Drying shrinkage-time relationship and 28-day shrinkage values as well as the relative 28-day shrinkage of the mixtures (compared to that of the control mixture) are presented in Figure 4. As it can be seen from the figure, silica fume remarkably increased (up to 23% according to reference mixture) the shrinkage values of the mortars containing IFA. Nath and Sarker [22] reported that type F fly ash with 2% CaO can increase the 28-day drying shrinkage of concrete with a constant w/b ratio and a constant binder content. The drying shrinkage results can be affected by strength variation, paste volume and amount of small capillary pores in the matrix [6,22].

days. The effect was more pronounced in the mixtures containing fly ash with lower lime content.

- Addition of 5% silica fume had not a significant effect on the early strength of fly ash-bearing mixtures, even it caused a further reduction in the strength. However, silica fume inclusion improved the 28-day strength of mixtures containing fly ash having higher lime content.

- The fly ash with lower lime content reduced the 14-day ASR expansion more than that of fly ash with higher lime content. The opposite results were the case in 28-day ASR expansions. The ASR expansions of the fly ash-bearing mixtures were significantly reduced by the introduction of the 5% silica fume.

- Drying shrinkage of the mortars containing fly ash having lower lime content was adversely affected by the addition of silica fume. However, the presence of silica fume in the mixtures containing high lime fly ash had not a significant effect on the drying shrinkage.

- Further study seems to be necessary on the optimization of fly ash and silica fume contents in ternary cementitious systems in terms of lime content of fly ash to maximize compressive strength and minimize ASR expansion as well as drying shrinkage of the cementitious systems.

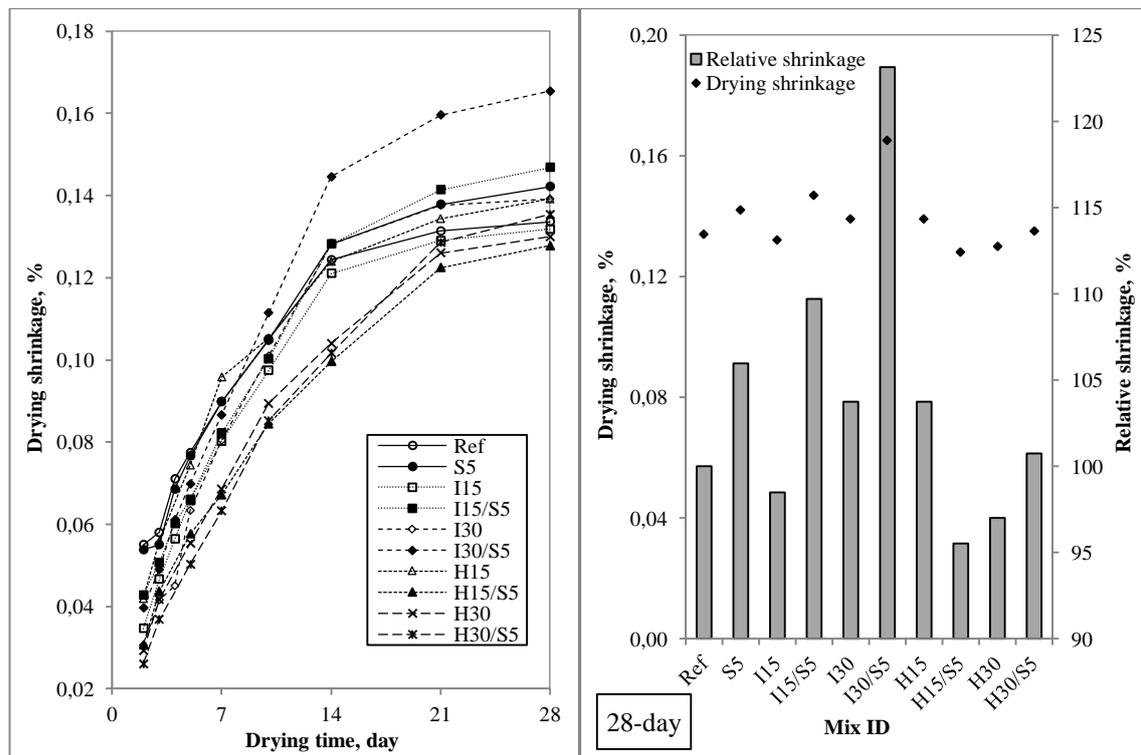


Figure 4. Drying shrinkage values of mortar specimens

### 3. CONCLUSION

The following results can be drawn for the materials used and tests applied in this study:

- Partial replacement of cement with high-lime fly ash reduced the strength of mortar mixtures even up to 28-

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