Abrasion Resistance of Cement Mortar with Different Pozzolanic Compositions and Matrices

Şükrü Yetgin, M.Sc., Ph.D.[1]; and Ahmet Çavdar, M.Sc., Ph.D.[2]

Abstract: Abrasion of concrete occurs due to scraping, rubbing, skidding, or sliding of objects on its surface. The abrasion resistance of concrete is influenced by a number of factors, such as compressive strength, surfacing finish, aggregate properties, types of hardeners, and curing. The main objective of this study is to determine the effects of the pozzolanic compositions and matrix structure (or voids) on the abrasion resistance of cement mortars. In this study, the mortars produced with cement samples with seven different compositions and varied with an air-entraining agent were subjected to the abrasive effects. Several examples of mortars were evaluated using samples cured for six different periods throughout 1 year. This study is supported by thin section investigations, in addition to being subjected to the basic tests, such as compression, flexure, and abrasion. The Bohme apparatus was used during abrasion tests. To summarize the most important findings from this study, a compact cement matrix is more effective against abrasive effects than mineral additives.

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Introduction

The abrasion resistance of concrete is relevant to essentially any application of concrete because rubbing, scraping, skidding, or sliding of objects on the concrete surface commonly occur (American Concrete Institute 1992). Although much attention has been given to the bulk mechanical properties of concrete, whether in compression, tension, flexure, or torsion, relatively little attention has been given to the surface mechanical properties, such as the abrasion resistance. The constitution of the concrete affects both the bulk and surface mechanical properties. Numerous admixtures (e.g., silica fume, latex, and fibers) have been shown to improve the bulk mechanical properties of concrete but the effects of many of these admixtures on the abrasion resistance of concrete have not been investigated. Silica fume is an admixture that improves the abrasion resistance of concrete (Çavdar 2008; Shi and Chung 1997; Papenfus 2002; Yazıcı and İnan 2006; Ghafoori and Diawara 2007). Some researchers have also studied the ability of nanoparticles to improve the abrasion resistance of concrete (Li et al. 2006).

Abrasive wear is known to occur in pavements, floors, hydraulic structures, such as tunnels and dam spillways, or other surfaces upon which frictional forces are applied due to relative motion between the surfaces and moving objects. The resistance of concrete to wear is influenced by variables such as strength, aggregate properties, surface finish, and type of hardeners or toppings. It is well established that concrete wear resistance increases with increasing compressive strength and tensile strength (Mehta and Monteiro 1993; Laplante et al. 1991; Hadchti and Carrasquillo 1988; Mindess and Young 1981; Naik et al. 2002). On the other hand, some researchers (Atiş and Çelik 2002) claim that the abrasion resistance of concrete is dependent mainly on its flexural tensile strength. They claim that a stronger relation exists between abrasion and flexural tensile strength than that between abrasion and compressive strength.

In order to develop concrete with high wear resistance, it is desirable to use a hard surface material, aggregate, and paste having low porosity and high strength (Naik et al. 2002). The wear resistance of concrete depends a great deal on the hardness of the aggregates used. High-strength concretes with a low water/cement (W/C) ratio is less dependent on aggregate type and the use of a low W/C can provide a dense, strong concrete that is resistant to wear (Mehta and Monteiro 1993; Laplante et al.,1991; Mindess and Young 1981). High strength is made possible by reducing porosity and microcracks in the concrete and in the interface between cement paste and aggregate (the transition zone). This can be achieved by using superplasticizers and supplementary cementing materials such as fly ash, silica fume, granulated

Table 1. Pozzolanic Composition of Cements (% Mass)

Samples	CEM I 42.5	Blast furnace slag	Silica fume	Natural pozzolan	Fly ash	Limestone
C I	100	—	—	—	—	—
C II/A-M	85	3	3	3	3	3
C II/B-M	75	5	5	5	5	5
C IV/A	70	—	5	15	10	—
C IV/B	55	—	5	20	20	—
C V/A	45	20	—	20	15	—
C V/B	35	40	—	15	10	—

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[1] Assistant Professor, Dept. of Civil Engineering, Faculty of Engineering, Gumushane Univ., Gumushane 29000, Turkey. E-mail: s.yetgin@hotmail.com

[2] Assistant Professor, Dept. of Civil Engineering, Faculty of Engineering, Gumushane Univ., Gumushane 29000, Turkey (corresponding author). E-mail: ahmcavdar@hotmail.com

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Table 2. Chemical Compositions of Cements and Other Materials (% Mass)

Sample	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI	Total
C I	18.81	5.43	3.05	58.75	1.21	2.94	5.14	95.33
C II/A-M	23.13	6.14	3.24	54.83	1.43	2.48	4.50	95.75
C II/B-M	34.83	6.56	3.29	40.33	2.32	2.45	4.51	94.29
C IV/A	30.29	6.31	3.17	50.17	2.21	2.11	3.86	98.12
C IV/B	45.03	12.69	3.77	28.08	1.74	1.40	3.40	96.11
C V/A	40.05	7.84	2.54	41.63	2.77	1.41	3.11	99.35
C V/B	36.76	10.12	2.92	36.28	1.75	1.44	2.52	91.79
B. F. slag	36.7	14.68	0.96	34.61	9.63	0.98	—	97.56
Silica fume	87.02	3.82	0.93	1.96	0.85	0.87	1.12	96.57
N. pozzolana	63.54	13.67	5.91	4.59	2.06	0.48	3.90	94.15
Fly ash	64.43	17.06	4.19	8.59	1.38	1.60	0.91	98.16
Limestone	4.55	1.89	1.57	48.95	1.06	—	40.57	98.59

blast furnace slag, and natural pozzolan (Shannag 2000; Haque and Kayalı 1998). Fortunately, most of these materials are industrial by-products and aid in reducing the amount of cement required; making the concrete less costly, more environmentally friendly, and less energy intensive (Shannag 2000).

The main objective of this study is to determine the factors that affect the resistance of the cement samples exposed to abrasive effects and discuss the precautions for expanding this resistance. In this study, the mortars are produced with seven different cement types composed with five different pozzolanic components, which are also varied by using an air-entraining (AE) agent. These mortars are subjected to flexural strength test, compressive strength test, and abrasion test six different times over the course of a year. In addition, the void structures of mortars are determined using petrographic investigations.

In other studies (Shi and Chung 1997; Yazıcı and İnan 2006; Ghafoori and Diawara 2007; Li et al. 2006; Laplante et al. 1991; Hadchti and Carrasquillo 1988), compact (not porous) mortars were used. As a result, the reason for the positive effects of the tests is not clearly defined. In other words, are the positive effects because of compact structure or mineral additives? In this study, relatively porous mortars are also produced with an AE agent to address this issue.

Materials and Methods

Cement Types

Seven different types of cements are used in the experimental process. These are produced by adding other components (fly ash, silica fume, tuff type of natural pozzolan, blast furnace slag, and limestone) to ordinary CEM I 42.5 R type cement. The compositions of the cements produced are given in Table 1. At least two compositions are comparable to each other when the compositions of the cements were chosen. The samples are named similarly to their classes in EN 197-1, for ease in identification. For example, CEM I 42.5 R is named as CI. In addition, if AE is added next to the sample name, this means that the sample contains an AE agent and that it has a more porous structure. If non-AE is added next to the sample name, this means the sample was produced without an air agent.

Table 3. Physical Properties of Cements

Samples	Initial setting times (min)	Final setting times (min)	Expansion according to Le Chatelier (mm)	Sieve analysis (%)	
				90µ	200µ
C I	205	260	2	1.2	0.1
C II/A-M	205	265	4	2.5	0.1
C II/B-M	225	295	6	2.4	0.1
C IV/A	220	270	2	4.1	0.1
C IV/B	235	295	3	9.4	2.5
C V/A	230	275	2	2.4	0.1
C V/B	210	275	4	4.4	0.2

Cement Components

The materials that constitute the cement samples are provided from different sources in Turkey. The chemical and physical properties of these materials and cements are given in Tables 2 and 3. The portland cement, ordinary CEM I 42.5 R, is derived from the Unye Cement Factory. The blast furnace slag is obtained from Eregli Iron-Steel Factory. The silica fume is from Antalya Eti Elektroferrokrom AS. The natural pozzolan is tuff-type rock and derived from Araklı-Trabzon District (Çavdar and Yetgin 2007; Yetgin and Çavdar 2006). The fly ash has siliceous fly ash properties and is obtained from the Manisa Soma Thermal Power Plant. Finally, the limestone is derived from Gumushane District. In addition, the AE material used in the experiments is Micro Air200 belonging to Degussa Inc. It is a material originating from ammonium salt and oil alcohol.

Fig. 1. Bohme abrasion apparatus

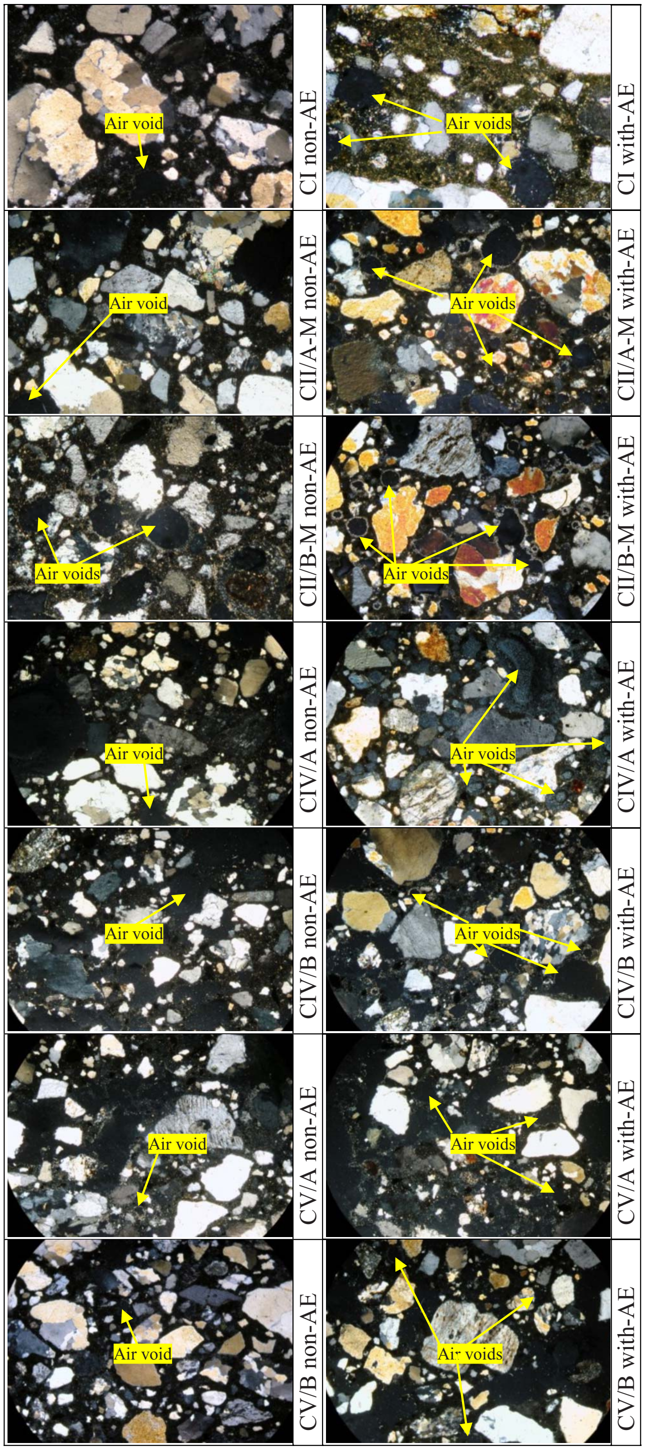

Fig. 2. Thin section images of the mortars (the scale is 900 μm for each 1 cm)

Methods

In accordance with the objective of the study, seven different cement types are prepared and two different types of mortars (with AE agent and without AE agent) are produced with these cements. The curing times of the samples are chosen as 7, 28, 90, 180, 270, and 360 days. When the curing time is completed, the samples are tested according to related standards. These tests are flexural strength, compressive strength, and Bohme abrasion tests.

Table 4. Specific Gravities of the Samples

Samples	AE content	Specific gravity $(\mathrm{g/cm^3})$
CEM I	Non-AE	2.50
	with AE	2.04
CEM II/A-M	Non-AE	2.45
	with AE	2.12
CEM II/B-M	Non-AE	2.45
	with AE	2.24
CEM IV/A	Non-AE	2.47
	with AE	2.12
CEM IV/B	Non-AE	2.52
	with AE	2.02
CEM V/A	Non-AE	2.48
	with AE	1.98
CEM V/B	Non-AE	2.49
	with AE	2.14

The flexural strength and compressive strength tests were conducted according to the suggested principles in EN 196. The "test mortar" consists of 450 g of the cement mixture, 1,350 g of graded standard sand, and 225 g of water, and consequently the W/C ratio is 0.50. If a more porous mortar is produced, one-half of the mixing water is first added to the cement and an AE agent is added to the other one-half of the water. In accordance with the product instructions, 0.4 mg of AE agent is used for 450 g of cement. After the molding process, the molds (with the mortars in them) were placed in the moist room at 23 ± 1.7 °C for 20–24 h and removed at the end of this period and the mortar cube specimens were stored in tap water until the day of testing. The flexural tests on the mortar prisms (40 × 40 × 160 mm) were conducted and compressive test was done on the broken pieces as equivalent cube test at 7, 28, 90, 180, 270, and 360 days according to the Rilem-Cembureau method in EN 196. Six specimens were tested for each type of mixture at each testing age.

On the other hand, the abrasion resistance of mortars is determined according to the Bohme method (Turkish Standards 1987), which is the most commonly used method for determining this resistance in Europe. According to this method, the surface of the specimen is pressed on to a rotating steel plate using a constant load (Fig. 1). Twenty grams of abrasive sand is put between the mortar and the steel plate. The mortar specimen's surface is 40 mm × 40 mm and its height is 50 mm. Subsequently, the plate is rotated 22 times and the specimen and plate are cleaned. This abrasion process is repeated 20 times for each specimen. Thus, the difference between the initial and final height of the specimen gives amount of abrasion.

In addition, changes in internal voids of the mortars because of air agent are investigated via petrographic observations. Petrographical properties of the mortar samples were identified under the polarizing microscope by using their thin sections (Fig. 2). Specific gravities of the hardened mortars are also given Table 4.

Results and Discussions

In this study, 14 different types of mortars are subjected to abrasive effects for 360 days. In this section, the mechanical properties of the mortars subjected to abrasive effects are discussed.

Table 5. Abrasion Depths of the Cement Samples during a Year (mm)

Samples	AE content	7 days	28 days	90 days	180 days	270 days	360 days
CEM I	Non-AE	7.70	6.12	5.20	4.66	4.56	4.15
	with AE	18.02	13.14	7.60	5.05	5.36	4.90
CEM II/A-M	Non-AE	10.5	9.12	6.10	4.16	4.00	3.91
	with AE	14.00	12.10	7.90	6.50	5.76	5.51
CEM II/B-M	Non-AE	9.26	7.47	5.60	4.89	3.98	3.96
	with AE	15.84	13.20	8.70	5.96	4.43	4.91
CEM IV/A	Non-AE	7.80	5.51	4.30	3.76	3.16	3.14
	with AE	9.80	7.14	6.00	5.41	5.52	4.88
CEM IV/B	Non-AE	11.10	8.76	6.75	5.00	4.01	3.60
	with AE	10.20	8.25	7.10	6.50	5.59	4.77
CEM V/A	Non-AE	11.25	9.53	7.40	6.52	5.38	5.30
	with AE	15.20	13.29	8.70	7.00	6.62	6.70
CEM V/B	Non-AE	9.90	9.17	6.90	5.10	5.26	5.30
	with AE	14.75	12.95	9.40	7.45	7.26	7.25

Table 6. Compressive Strengths of the Cement Samples during a Year (N/mm^2)

Samples	AE content	7 days	28 days	90 days	180 days	270 days	360 days
CEM I	Non-AE	40.3	48.8	50.50	53.76	58.22	58.69
	with AE	7.1	10.5	11.20	12.10	12.74	14.42
CEM II/A-M	Non-AE	36.7	49.4	51.50	53.80	59.49	59.91
	with AE	5.9	17.7	17.90	18.33	18.34	18.34
CEM II/B-M	Non-AE	31.5	42.8	46.70	49.81	53.65	53.77
	with AE	14.0	20.2	21.50	22.96	25.46	25.63
CEM IV/A	Non-AE	31.8	47.2	50.30	52.60	54.85	55.26
	with AE	12.4	18.4	20.10	22.55	22.72	22.83
CEM IV/B	Non-AE	16.1	26.4	32.20	37.66	38.98	39.92
	with AE	9.7	17.4	22.60	25.54	27.27	28.22
CEM V/A	Non-AE	13.6	23.7	29.90	34.21	35.30	36.00
	with AE	6.5	12.7	14.70	16.73	17.30	17.98
CEM V/B	Non-AE	17.1	33.6	37.80	41.92	45.74	47.10
	with AE	5.9	11.9	13.40	14.25	15.25	15.56

Table 7. Flexural Strengths of the Cement Samples during a Year (N/mm^2)

Samples	AE content	7 days	28 days	90 days	180 days	270 days	360 days
CEM I	Non-AE	4.90	6.89	7.24	7.66	9.58	10.69
	with AE	2.96	3.46	3.82	4.07	4.09	4.14
CEM II/A-M	Non-AE	5.98	8.01	8.55	8.99	9.70	10.01
	with AE	1.57	4.62	4.64	4.45	4.55	4.57
CEM II/B-M	Non-AE	6.63	8.59	8.93	9.61	9.65	9.70
	with AE	3.68	5.55	5.63	6.29	6.37	6.39
CEM IV/A	Non-AE	5.41	8.35	9.28	9.40	9.60	10.15
	with AE	3.10	4.91	5.26	5.51	6.23	6.39
CEM IV/B	Non-AE	3.16	5.33	6.41	7.58	8.31	8.59
	with AE	2.72	4.94	6.36	7.08	7.54	7.82
CEM V/A	Non-AE	3.38	6.11	7.67	8.83	8.97	9.36
	with AE	1.90	3.80	4.20	4.87	5.40	5.93
CEM V/B	Non-AE	3.80	7.30	8.59	9.61	10.09	11.15
	with AE	1.68	3.72	4.04	4.37	4.52	4.77

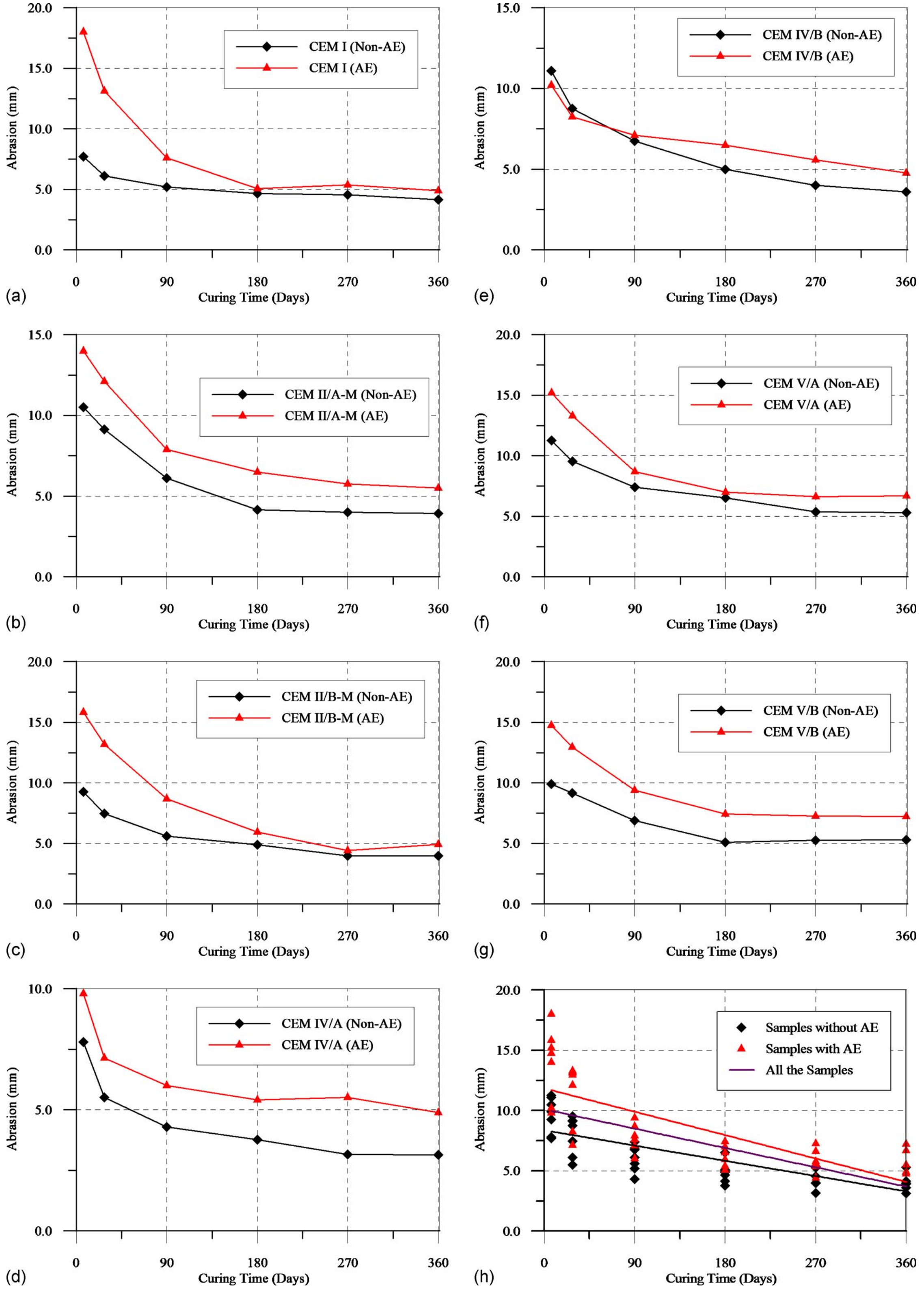

Fig. 3. Relationship between abrasion depth and curing time

Abrasion Resistance of the Cement Mortars

The mortars produced are subjected to abrasion via the Bohme apparatus. Abrasion depths, compressive strengths, and flexural strengths of the sample (Tables 5–7, respectively) are determined after 7, 28, 90, 180, 270, and 360 days. The relationship between abrasion depth and curing time (Fig. 3), compressive strength (Fig. 4), and flexural strength (Fig. 5) are discussed.

The changes in mortars because of the air agent are investigated with the help of specific gravity values (Table 4) and thin section images (Fig. 2). It is seen (Table 4) that the specific gravities change between 2.47 and 2.52 $\mathrm{g/cm^3}$ for the samples without the air agent and between 1.98 and 2.24 $\mathrm{g/cm^3}$ for the samples

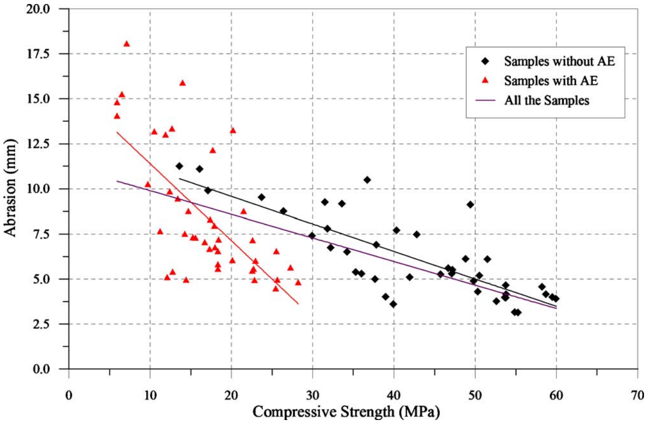

Fig. 4. Relationship between abrasion depth and compressive strength

with the air agent. In addition, thin section images show the air voids added with the air agent to mortars (Fig. 2).

The samples containing the air agent are abraded deeper, at a ratio of 15–35%, than the ones without the air agent [Figs. 3(a–h)]. The minimum abrasion depth (<4.0 mm) occurs in CIV/A (non-AE) and CEM II/A-M (non-AE) samples at the end of the year (Fig. 3, Table 5). The deepest abrasion (>7.5 mm) occurs in the samples from CV/B (with AE) (Fig. 3, Table 5). Thus, it can be said that the content of the pozzolanic material is restricted to about 25–30%. If these materials are added to the cement more than this ratio, abrasion resistant is negatively influenced.

Relationship between Abrasion Resistance and Curing Time

If abrasion depths of all the samples, without considering their composition, are determined, it is seen that the abrasion depth is shortened by extending the curing time (Table 5, Fig. 3). This means abrasion resistance increases. While the abrasion depths of two types of mortars (with/without air agent), produced from every different type of cement, are different from each other in the initial days, these values approach each other at the end of a year. The samples are projected to reach ultimate abrasion depth in 6–9 months. This means the abrasion resistances of the samples improve more slowly after 6–9 months.

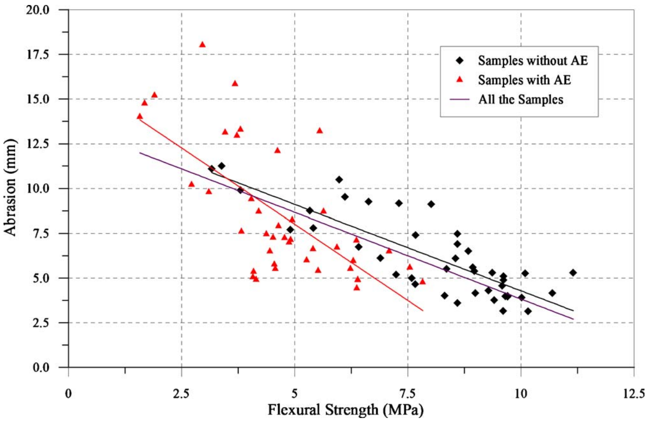

Fig. 5. Relationship between abrasion depth and flexural strength

If all the mortars are evaluated at the same time, the mortars containing the air agent are initially abraded more deeply than the ones with the nonair agent by about 35% and after a year by about 10% [Fig. 3(h)]. The correlation coefficient of the curves in Fig. 3(h) is about 77–80%, and the curve representing all the samples is about 70%.

Relationship between Abrasion Resistance and Compressive Strength

For all the mortars, if the relationship between abrasion resistance and compressive strength is examined, it is seen clearly that abrasion depths decrease as the compressive strengths increase (Fig. 4). However, it is notable that the samples with and without the air agent behave differently. Specifically, while both the samples with the air agent and the samples without air agent increase their abrasion resistance with the increase in their compressive strength, these samples have different void contents that do not present equal abrasion depths for the same compressive strengths. For example, the samples without the air agent show about 5-mm abrasion depth for approximately 50 N/mm^2 of compressive strength. However, the samples with the air agent achieve the same abrasion depth with 25 N/mm^2 of compressive strength (Fig. 4). In other words, as the compressive strengths of the samples containing the air agent increase by about five times, their abrasion depths decrease at a ratio of 2/3. The compressive strengths decrease more slowly for the samples without the air agent.

When the porous mortars were producing, AE agent is used in maximum level defined its instruction handbook because it is thought that filler effects of the mineral additives are entirely pacified by increasing porosity. Therefore, important levels of fallings in strengths occur. The correlation coefficient of the curves in Fig. 4 is about 70–80%, and the correlation coefficient of the curve for all the samples is about 65%.

Relationship between Abrasion Resistance and Flexural Strength

Similar to compressive strength, as flexural strength increases, the abrasion resistance increases or the abrasion depth decreases (Fig. 5). As seen in Fig. 5, the line symbolizing all the samples has the same slope as the line representing the mortar samples without the air agent. The correlation coefficient of the curves in Fig. 5 is about 75–85% and the coefficient for all the samples is about 70%.

Relationship between Abrasion Resistance and Pozzolanic Components

In this section, the relationship between abrasion depth and the pozzolanic components content of the samples is investigated at the end of the year. It is seen from Fig. 6 that there is a relationship between mineral components and abrasive resistance or depth. In addition, an important factor that influences this relation is curing time. In general, an increase of clinker, limestone, and silica fume content decreases the abrasion depth of cement mortars at the end of the year. Conversely, if the blast furnace slag, natural pozzolan, and fly ash contents are increased, this depth increases for the samples cured in a year. These results parallel the compressive and flexural strength of these samples.

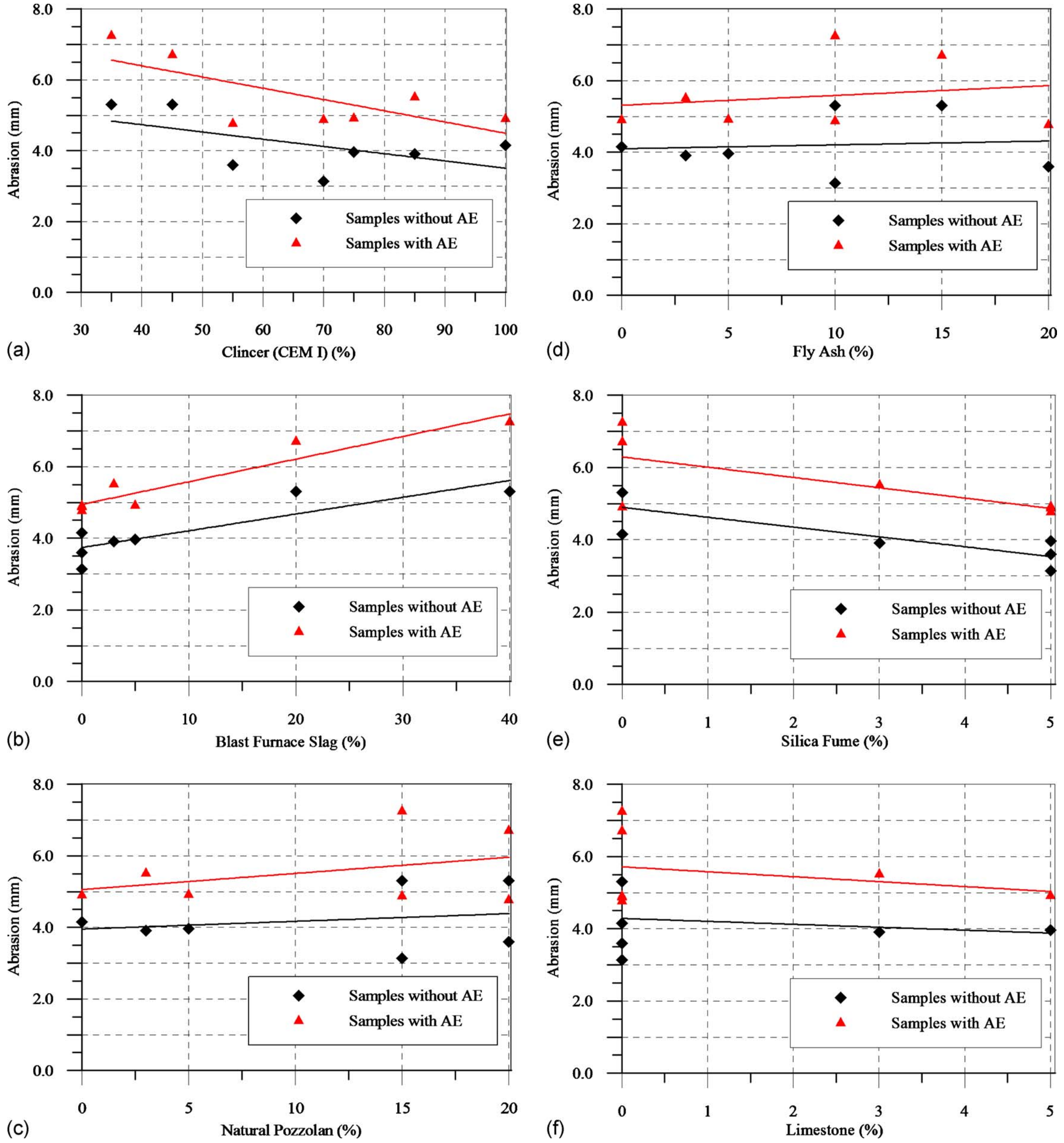

Fig. 6. Relationship between abrasion depth and pozzolanic components content at the end of a year

Relationship between Abrasion Resistance and Chemical Compositions

After investigating the relationship between abrasion resistance and pozzolanic components, the relationship between this property and chemical composition is discussed. The CaO component contributes to the abrasion resistance of the mortars over the course of a year, as do ultimate strength and resistance (Fig. 7), because of improving hydration. SiO_2 and Al_2O_3 components decrease the abrasion resistance or deepen the abrasion depth in the samples, whether or not they contain the air agent. It is seen that the relations between chemical component in question and abrasion are similar to the relation between compressive strength and chemical components.

Conclusions

In this study, the abrasion resistance of cement mortars having different pozzolanic composition and matrix are investigated. After all the comparisons, it can be said that the abrasion depths of the samples decrease while the curing time elapses. Compressive strength and flexural strength increase relative to the curing time. The samples approach the ultimate abrasion depth or abrasion resistance in 6–9 months. In general, the samples with the air agent are initially abraded deeper at a ratio of 35% and after a year by about 10%, than the samples without the air agent. Furthermore, the highest pozzolanic material ratio is restricted to about 25–30% by mass because this ratio is a boundary of abrasion resistance. In addition, a compact cement matrix is more effective against abrasive effects than mineral additives. Moreover, the increase of the clinker, limestone, and silica fume ratios increases the abrasion resistance at the end of the year. On the other hand, blast furnace slag, natural pozzolan, and fly ash conversely affect the resistance. Finally, the CaO component contributes to the abrasion resistance of the mortars over the course of a year. However, SiO_2 and Al_2O_3 components decrease the abrasion resistance of the samples, whether or not they contain the air agent.

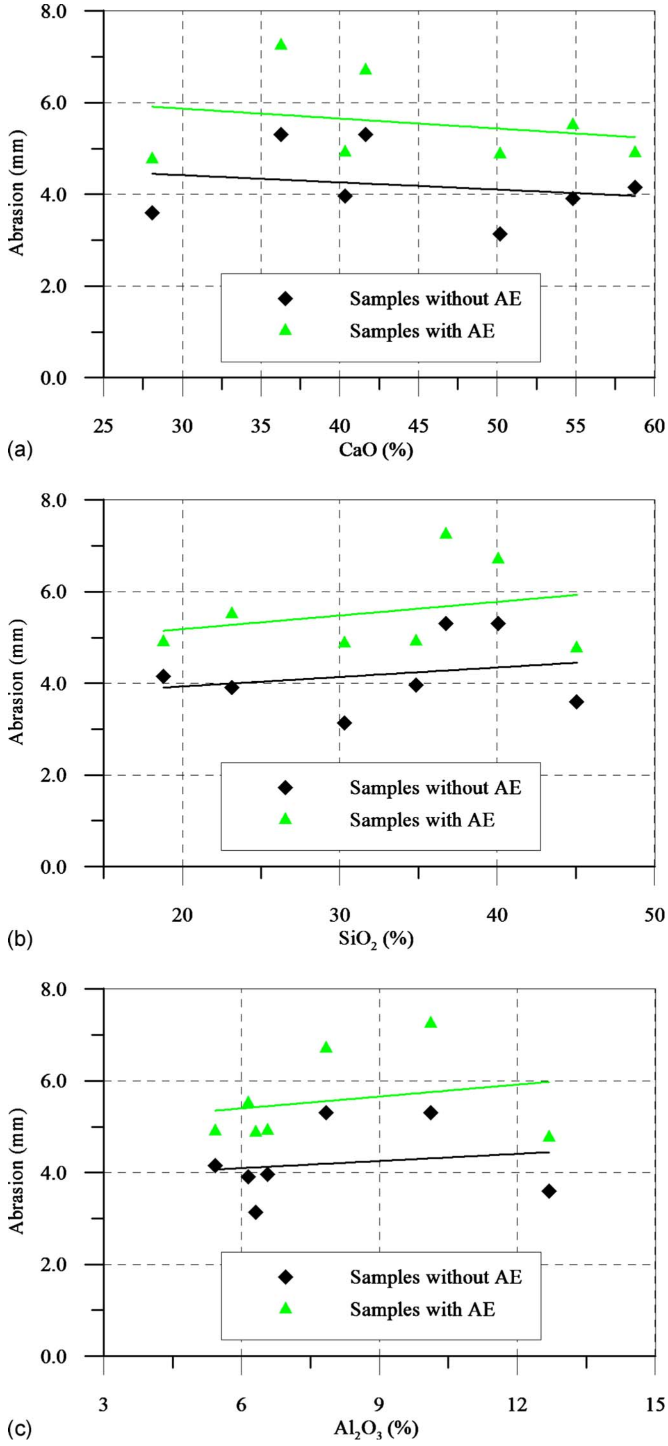

Fig. 7. Relationship between abrasion depth and chemical component content at the end of a year

Acknowledgments

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