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Abrasion Resistance
of Cement-Based Composites

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1. Introduction

1.1 Background

Cement-based composites are among the most widely-used construction materials due to their low cost, high compressive strength, high durability, versatility, and easy-handling. Unfortunately, cement-based composites are intrinsically porous and may deteriorate as a result of exposure to harsh environments or poor construction quality. Over the last few decades, most research has focused on the strength characteristics of concrete, with far less attention paid to material parameters influencing durability. The deterioration of these materials often results in severe damage to concrete structures such as cracking, delaminating, spalling, and even fractures. This kind of damage is generally not detected until it has reached a critical level, at which point, rust is visible on the rebar and evidence of cover concrete deterioration can be found throughout the entire structure, as shown in Fig. 1-1. The degradation of cement-based composites is considered a key factor in the durability of structures and a major concern for civil engineers.

(a) Observation in July 2007   (b) Observation in April 2008

Fig. 1.1. Corrosion damage in a concrete wall

Degradation of concrete composites is classified as physical or chemical. Physical degradation can be divided into frost action, cracking, thermal cracking due to shrinkage, fire damage, and surface abrasion. Chemical degradation can be divided into corrosion of the rebar, attack by sulfates or acids, and degradation resulting from alkali aggregates. Degradation is often evaluated in terms of permeation, which is directly linked to the movement of aggressive agents into and out of cement-based composites. Expansion causes internal stress resulting in cracking or scaling. Chemical degradation alters hydration products and often leads to dissolution or leaching. Several forms of composite degradation are the result of combined physical and chemical attack. The thickness and quality of the cover or surface layer are important factors, which determine the ability of a material to resist physical and chemical attack. Measures that have proven effective in minimizing the problems of durability include the creation of less permeable composites or denser pastes, which inhibit the propagation of cracks, and provide a cover of adequate thickness [1-3]. The density of paste can be enhanced by lowering the water cementitious ratio or through the addition of supplementary cementitious materials (SCMs). SCMs such as silica fume, fly ash, and ground granulated blast furnace slag (ggbs), are commonly used to replace a portion of the cement in cement-based composites to improve the quality and/or durability of cement-based composites. Crack inhibition can be increased through the addition of fibers [4-6].

The influence of abrasion in cement-based composites is slight and weight loss or erosion resulting from abrasion is gradual; although the problem can be exacerbated through exposure to harsh environments (Fig. 1-2). A great deal of research has been dedicated to cracking behavior and the durability of cement-based composites; however, little effort has gone into the issue of abrasion resistance. A number of structures, such as existing dams, concrete nuclear structures, and underground storage or radioactive waste disposal containers, are in constant contact with water or abrasives for extended periods of time. Such exposure increases the risk of reduced service life. Indeed, further investigation of the abrasion resistance of cement-based composites could provide considerable benefits in ensuring that structures continue to serve their intended function.
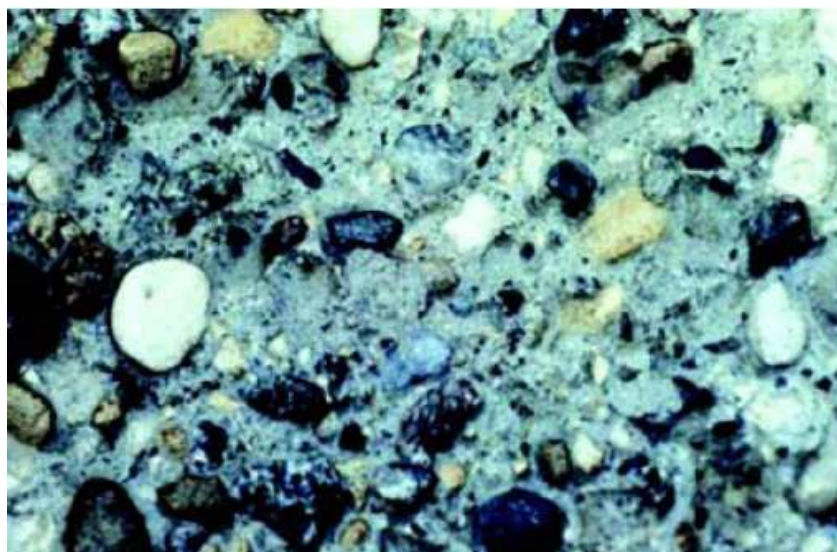

Fig. 1.2. Concrete disintegration due to abrasion [7]

1.2 Objectives

The aim of this study was to deepen our understanding of abrasion resistance in cement-based composites, through the evaluation of testing methods and material variables. The results of this study are presented in three parts:

1. Cement-based composites containing supplementary cementitious materials;
2. Cement-based composites containing fiber-reinforced materials;
3. Evaluation of indices of various testing methods.

The objectives of this study are outlined as follows:

4. Evaluate the effects of fibers and SCMs on the abrasion resistance of cement-based composites;
5. Compare the difference between the ASTM C418 (sand blast abrasion method) and the ASTM C131 (modified version, Los Angeles abrasion method).

The study includes four chapters. Chapter 1 provides an introduction to the durability and abrasion of concrete containing composites, including background information and the objectives of this study. Chapter 2 describes the testing program including ASTM C418, ASTM C779, ASTM C1138, and ASTM C131. Material variables including SCMs and fibers added to cement-based composites are also explained. Chapter 3 presents the results and discussion of abrasion resistance using various abrasion methods. Finally, Chapter 4 summarizes the main conclusions and provides recommendations for further study.

2. Literature review

2.1 Supplementary cementitious materials

In recent years, SCMs have often been used to replace a portion of the cement in cement-based composites, with the aim of improving mechanical properties or durability. The classification and function of the mineral admixtures are illustrated in Fig. 2-1.
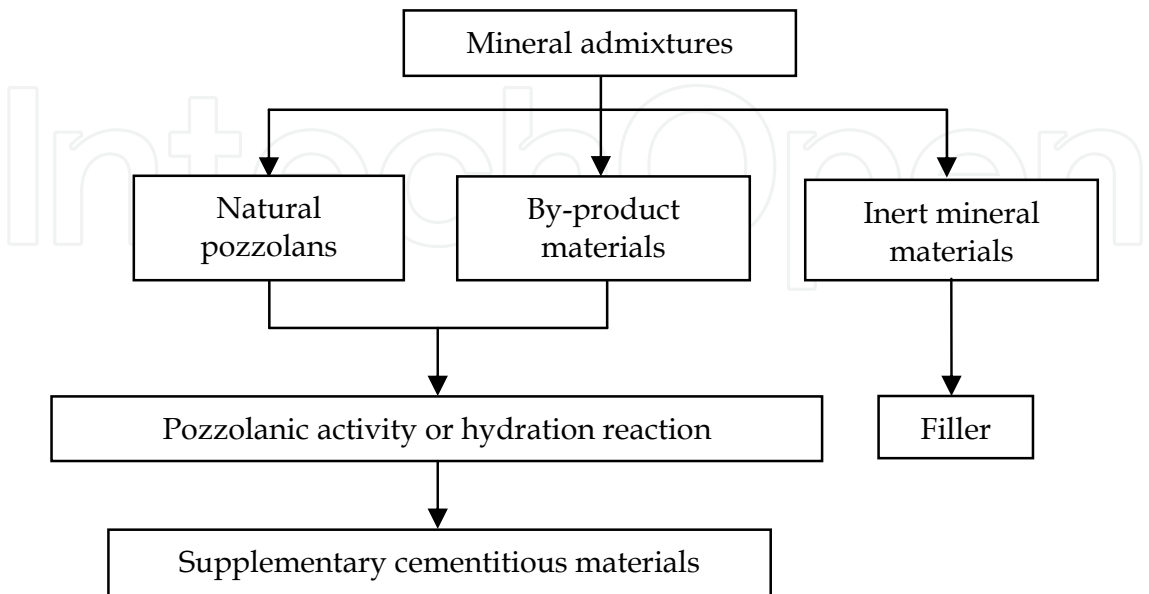

Fig. 2.1. Classification and function of mineral admixtures

Mineral admixtures can be divided into natural pozzolans, by-product materials, and inert mineral materials. Natural pozzolans and by-product materials are generally SCMs [8]. Natural pozzolans are volcanic ashes, diatomaceous earth, calcined clay, metakaolin clay, and rice hull ash. By-product materials include silica fume, fly ash, ggbs, and metakaolin [9-10]. SCMs contribute to the properties of cement-based composites through either pozzolanic activity or hydration reaction [11]. The replacement level varies widely from less than 10 % to more than 50 %, depending on the nature of the SCMs [12]. The physical properties and chemical composition of SCMs are presented in Table 2-1. Silica fume has a large specific surface area and high SiO2 content compared to those of fly ash and ggbs. Hence, the pozzolanic reaction rate of silica fume is considerably higher than that of fly ash or ggbs.

	Portland cement	Fly ash	ggbs	Silica fume
Physical properties of SCMs				
Specific surface area (m^2/kg)	350-500	300-600	300-500	15000-30000
Bulk density (kg/m^3)	1300-1400	1000	1000-1200	200-300
Specific gravity	3.15	2.30	2.90	2.20
Chemical compositions of SCMs				
SiO_2	20	50	38	92
Fe_2O_3	3.5	10.4	0.3	1.2
Al_2O_3	5.0	28	11	0.7
CaO	65	3	40	0.2
MgO	0.1	2	7.5	0.2
Na_2O+K_2O	0.5	3.2	1.2	2.0

Table 2.1. Physical properties and chemical composition of SCMs [32]

2.2 Silica fume

Research has indicated that silica fume is suitable for improving the properties of cement-based composites. The advantages of silica fume are illustrated by the following three points [13-15]:

1. Silica fume comprises very fine particles with a specific surface area ranging from 13000 to 30000 m^2/kg. The average particle size is approximately 1/100 that of cement.
2. Silica fume particles are spherical, producing a lubrication effect.
3. Silica fume has a higher silica content, making it a highly effective artificial pozzolan.

Silica fume is a highly reactive pozzolan when used in cement-based composites, reacting with calcium hydroxide to produce additional calcium hydrate. This reaction enhances the mechanical properties and durability of cement-based composites, resulting in stronger, denser, and less permeable materials [16, 17].

The use of silica fume also helps to increase the interfacial bond between paste and aggregate, resulting in an increased tensile strength [16]. Silica fume has a considerable influence on abrasion resistance [18]. Li et al. [19] claimed that replacing cement with silica fume not only reduces the tendency to form cracks, but also decreases the width of cracks in

restrained shrinkage test. Due to the increased density of its microstructure, silica fume is highly effective in reducing permeability to water and chloride penetration. The addition of silica fume beyond 5 wt.% of cement significantly reduces electrical conductivity and the addition of silica fume up to 7.5 to 10 wt.% significantly increases corrosion resistance [17].

The combination of silica fume with steel fibers has been shown to enhance compressive strength, splitting tensile strength, abrasion resistance, and impact resistance [20], and aids in the dispersion of fibers in cement-based composites [13,21]. Silica fume even improves the bonding between fibers and mortar [22,23].

2.3 Steel fibers and polyolefin fibers

Fiber reinforced composites are defined as composites incorporating relatively short, discrete, discontinuous fibers. These materials have been added to cement-based composites since 1960. According to ACI 544, there are four categories of fiber reinforced composites: steel fiber, glass fiber, synthetic fiber, and natural fiber reinforced composites.

The use of fibers has been steadily increasing in recent years. Various types of fibers, such as steel, polypropylene, glass, carbon, and cellulose fibers, are used to produce fiber reinforced composites. The properties of various types of fibers are listed in Table 2-2. Steel fibers, in particular, are frequently used in composites. The advantages of adding steel fiber to composites are as follows [24, 25]:

1. Reduced plastic cracking of composites;
2. Resistance to the propagation or growth of cracks;
3. Improved tensile, flexural, and impact strength, as well as increased toughness and energy absorption.

Fibers	Density (g/cm³)	Tensile strength (MPa)	Young's modulus (GPa)
Carbon fiber	1.81	3.8	228
PVA fiber	1.30	1.6	40
Polypropylene fiber	0.91	0.35-0.50	8.5-12.5
Hooked steel fiber	7.80	1172	200
Glass fiber	0.91-1.03	550-760	--
E-glass fiber	2.53-2.60	3600	75
Polyester fiber	--	875	13
Sisal fiber	1.11-1.37	31-221	15.2

Table 2.2. Properties of various fibers [26-29]

The properties of steel fiber reinforced composites are governed by shape, length, volume fraction, aspect ratio, and surface texture. High volume fraction leads to a decrease in workability and tends to increase material costs [30-32]. Research has suggested that an optimal volume fraction of steel fiber is approximately 2 % [33]. Three types of failure occur in fiber reinforced composites: fiber debonding, fiber pullout, and fiber failure [34]. The use of hooked steel fibers ensures the best possible bonding between the fiber and matrix and maximizing the tensile strength of the steel. The bonding between the fibers and the matrix is strongly influenced by many properties including geometric shape [35].

Polyolefin fibers are a new commercial product manufactured by 3M. Polyolefin fiber enables a high volume of fiber to be used in composites without the occurrence of fiber balling. Polyolefin fibers do not significantly enhance the compressive strength or first-crack flexural strength; however, the presence of polyolefin fibers influences the post crack behavior of composites [36]. In addition, impact resistance and flexural toughness increase as the content of polyolefin fiber increases [37].

A number of studies [36,38,39] have reported that the toughness of polyolefin fiber reinforced concrete is similar to that of steel fiber reinforced concrete. The addition of polyolefin fibers has been shown to increase flexural strength by as much as 13 % and reduce the growth or propagation of cracks by up to 70 % relative to control specimens. In addition, the impact resistance of polyolefin fiber reinforced composites is double that of steel fiber reinforced composites and 14 times greater than composites made without fibers.

2.4 Abrasion resistance

The abrasion of cement-based composites is caused by mechanical contact or exposure to flowing water or particulates. Abrasion results mainly in the localized loss of material from the surface and loosening between the aggregate and paste. The abrasion resistance of cement-based composites is influenced by a number of factors, including compressive strength, properties of the aggregate, water/cementitious ratio, the addition of SCMs, and the properties of supplementary strengthening materials, such as fibers. The ACI committee 201 report indicates that the abrasion resistance of cement-based composites depends primarily upon compressive strength, which is consistent with previous studies [5, 40, 41].

There appears to be a consensus among researchers that compressive strength is a key factor in abrasion resistance; however, opinions vary with regard to the claims of Nanni [42], who suggested that compressive strength is a poor index for evaluating abrasion resistance because it neglects surface and curing conditions. Nanni also reported that the addition of synthetic and steel fibers marginally enhances abrasion resistance. A number of studies have reported that the addition of SCMs, such as fly ash and silica fume, provides a significant increase in abrasion resistance [43-45]. In recent years, fibers and SCMs have been studied individually and in combination to determine their effects on abrasion resistance. The combination of SCMs and fibers has proven particularly interesting, providing considerable scope for further research.

2.5 Concrete abrasion testing

2.5.1 Sand blast abrasion test

Sand blast abrasion testing was conducted in accordance with ASTM C418-05 specifications. This method enables the evaluation of abrasion resistance of cement-based composites subjected to the impingement of air-driven silica sand to determine the abrasion coefficient. The abrasion coefficient, an index of abrasion resistance, is computed as follows:

$$A_c = \frac{V}{A} \tag{2-1}$$

where A is the abraded surface area and V is volume loss through abrasion. A sand blasting cabinet is shown in Fig. 2-2. For the sand blast abrasion test (SBAT) in this study, we prepared ϕ 150 x 64 mm circular discs of each mix.

Fig. 2.2. Sand blasting cabinet

2.5.2 Revolving disk abrasion test

A revolving Disk Abrasion Test (RDAT) was performed in accordance with ASTM C779-05 specifications, procedure A. An RDAT machine, such as the one shown in Fig. 2-3, introduces frictional forces through rubbing and grinding using rotating steel disks in conjunction with abrasive grit. The disks are free floating insofar as they are self supporting, transversely driven along a circular path at 12 rev/min (12 rpm) while individually turned on their own axis at 280 rev/min (280 rpm). In this study, cups attached to the top of the shaft of each disk were loaded with lead shot to produce a uniform total load of 22 N (5 lbf) on each abrading disk face. No. 60 silicon carbide abrasive was fed to the disks at a rate of 4-6 g/min. A test duration of 30 min was generally adequate to produce considerable wear on most concrete surfaces; however, we extended the test period to 60 min to obtain information related to long term abrasion resistance.

By comparing the measurements of average abrasion depth of representative surfaces following 30 and 60 min of exposure, we determined the relative abrasion resistance of these surfaces, using two abrasion coefficients: average abrasion depth and weight loss. In this study, 300 x 300 x 100 (mm) slab specimens were prepared for RDAT.

Fig. 2.3. Revolving disk abrasion test machine

2.5.3 Underwater abrasion test

An underwater abrasion test (UAT) was conducted in accordance with ASTM C1138-05 specifications. The apparatus comprised a drill press, an agitation paddle, a cylindrical steel container housing a disk-shaped concrete specimen, and 65 ±5 steel grinding balls of various sizes. Water in the container was circulated using an immersed agitation paddle powered by the drill press at 1200 rpm. The circulating water, in turn, moved the abrasive charges (steel grinding balls) across the surface of the concrete specimens to produce the abrasion. A total test duration of 24 h was generally adequate to produce significant abrasion in most concrete surfaces. The standard test adopted by this study consists of six 12 h test periods for a total of 72 h. This study prepared ϕ 300 x 100 mm circular discs for UAT.

The volume of the specimens is calculated as follows:

$$V_t = \frac{W_{air} - W_{water}}{G_w} \qquad (2\text{-}2)$$

where V_t is the volume of the specimen, W_{air} is the weight of the specimen in air, W_{water} is the weight of the specimen in water and G_w is the unit weight of water.

The volume of concrete lost at the end of any time increment of testing is calculated as follows:

$$VL_t = V_i - V_t \qquad (2\text{-}3)$$

where VL_t is the volume of material lost through abrasion and Vi is the volume of the specimen prior to testing.

In addition, the average depth of abrasion at the end of any time increment of testing is calculated as follows:

$$ADA_t = \frac{VL_t}{A} \qquad (2\text{-}4)$$

where ADA_t is the average depth of abrasion and A is the surface area of the top of the specimens. In this test, the volume of material lost and the average abrasion depth are used as indices of abrasion resistance.

2.5.4 Los Angeles abrasion test

The Los Angeles abrasion test (LAAT) was conducted in accordance with of ASTM C131-06 specifications, of which LAAT is a modified version. The machine comprises a steel cylinder, into which ϕ 100 x 200 mm specimens are placed with eight steel spheres. Following the rotation of the samples, the percentage loss (difference between the original mass and the final mass of the specimen) was calculated and used as an index of abrasion resistance.

3. Results and discussion

This study used two types of fiber (steel fiber and polyolefin fiber), three silica fume contents (0 %, 5 % and 10 % by weight of cement), four steel fiber dosages (0 %, 0.5 %, 1.0 % and 2.0 % by volume of cement-based composites), and two water/cementitious ratios (0.35 and 0.55) in the mix designs. We also investigated rock wool waste and the shape of fibers and particles, as they pertain to abrasion resistance.

3.1 Sand blasting abrasion test

The abrasion coefficient of specimens decreased with an increase in fiber and silica fume content, as illustrated in Fig. 3-1. The inclusion of 0.5 vol. % steel fibers in the composites decreased the abrasion coefficient considerably. However, the abrasion coefficient did not significantly change when the steel fiber content exceeded 1.0 vol. %. The abrasion coefficient also decreased with an increase in silica fume content for the specimens for both w/cm ratios. The addition of steel fibers produced a denser, stronger surface, resulting in superior resistance to wear. The abrasion coefficient of specimens containing 10 % silica fume and 2.0 % steel fibers with w/cm ratios of 0.35 and 0.55 were 2.21×10^{-3} and 3.21×10^{-3} (cm^3/cm^2), respectively. These results are approximately 50 % lower than those of the control specimen. Composites with 10 % silica fume and 2.0 % fiber also exhibited excellent abrasion resistance.
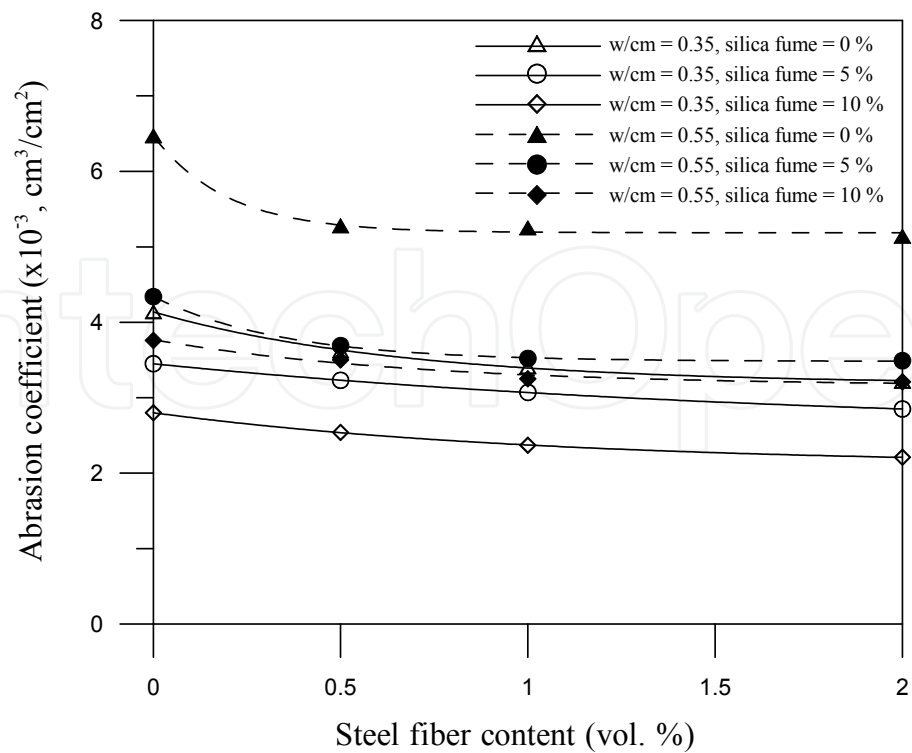
Fig. 3.1. Abrasion coefficient vs. steel fiber content curves

The abrasion coefficient appears to decrease exponentially with compressive strength as illustrated in Fig. 3-2. Clearly, compressive strength has more of an influence on the abrasion coefficient of specimens with higher w/cm than on those with lower w/cm.
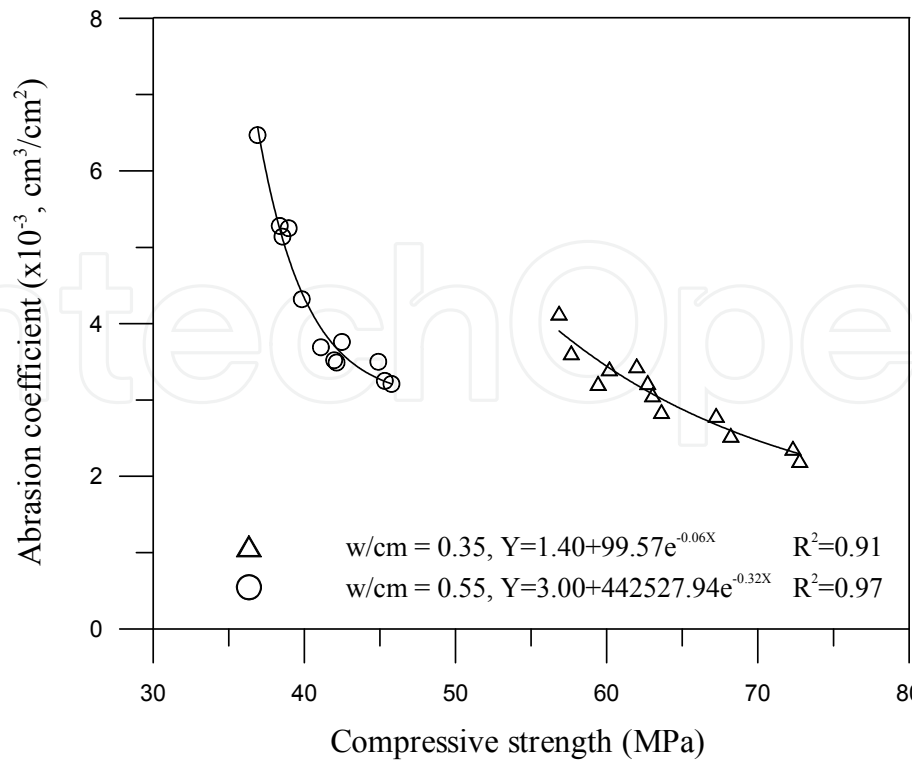

Fig. 3.2. Abrasion coefficient vs. compressive strength curves

The mechanical properties of steel fiber reinforced composites with silica fume are influenced by many factors. Multiple regression analysis was conducted to evaluate the influence and interaction of the material variables, through the selection of the following independent variables: water/cementitious ratio (w/cm), silica fume content (W_s) and steel fiber content (V_f) and the dependent variable, abrasion coefficient (A_c). To determine the effects of the interactions among all factors related to these materials, we assumed the following regression model:

$$Y = a1 + a2(w/cm) + a3(W_s) + a4(V_f) + a5(w/cm)(W_s)$$
$$+ a6(w/cm)(V_f) + a7(W_s)(V_f) + a8(w/cm)(W_s)(V_f) \tag{3-1}$$

where Y is the predicted value and w/cm, W_s, V_f are independent variables, a1 is the intercept and a2, a3, a4, a5, a6, a7, and a8 are the regression coefficients. The results of multiple regression analysis are presented below.

$$A_c = 0.88 + 8.88(w/cm) - 0.07(W_s) - 0.17(V_f)$$
$$-0.56(w/cm)(W_s) - 0.66(w/cm)(V_f) - 0.10(W_s)(V_f) \tag{3-2}$$
$$+0.70(w/cm)(W_s)(V_f)$$

As illustrated in Fig. 3-3, the experimental abrasion resistance was found to be strongly correlated with the estimated values, with a correlation coefficient of 0.91. The estimated values are plotted against the experimental values in Figs. 3-3. The deviation is defined as the distance of each point on the plot from the diagonal line. In general, points are uniformly scattered around the diagonal line for all assumed models. The above analysis indicates that the model parameters are strongly dependant on the mechanical properties tested, providing valuable information with which to predict the mechanical properties of steel fiber reinforced composites.
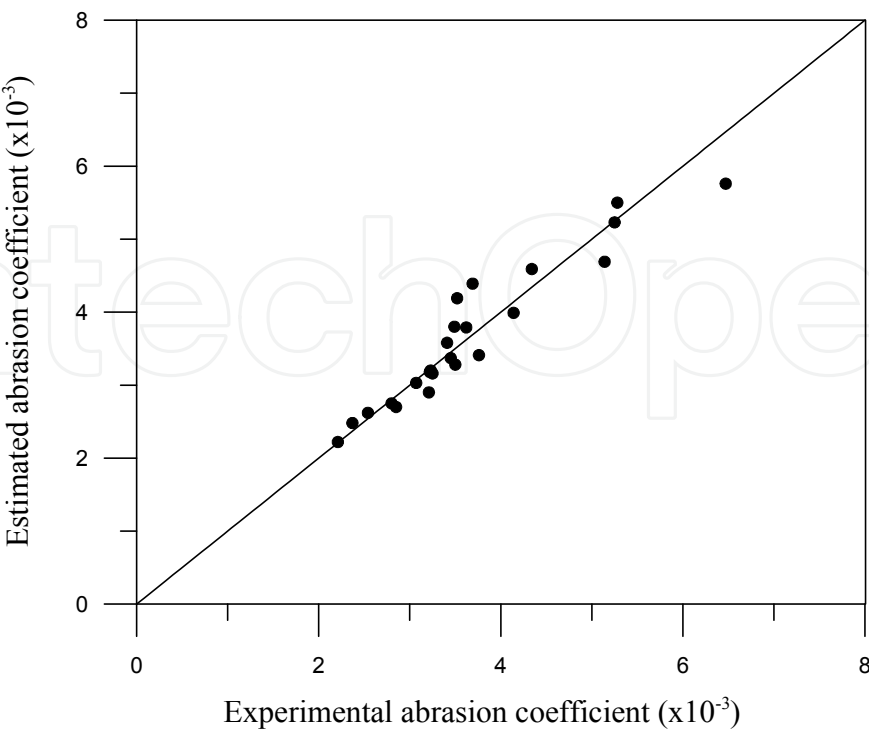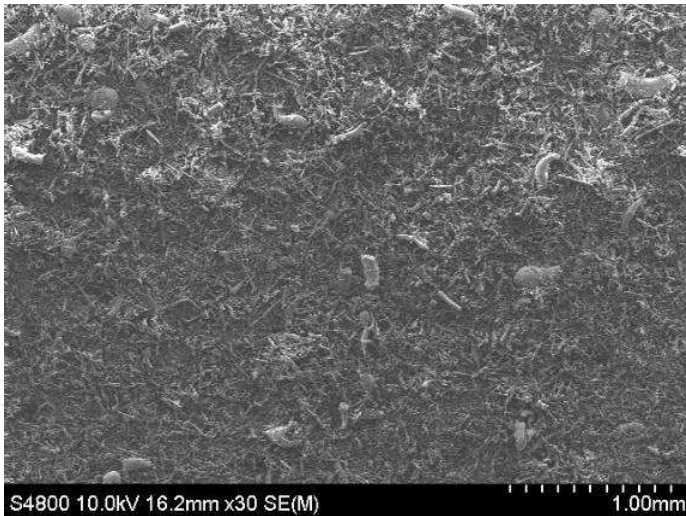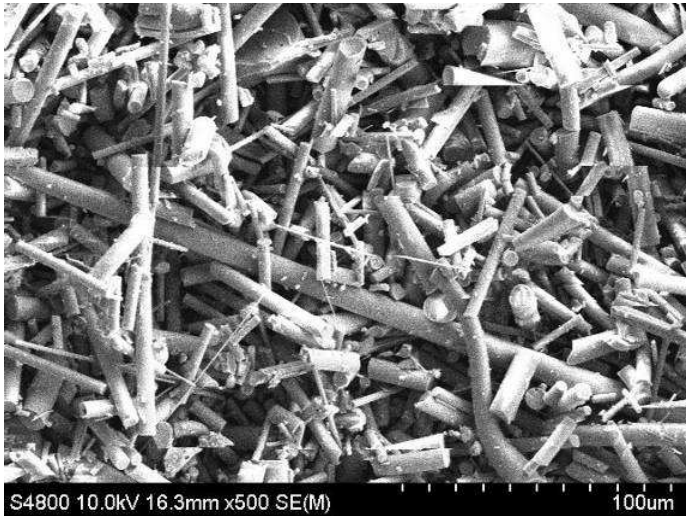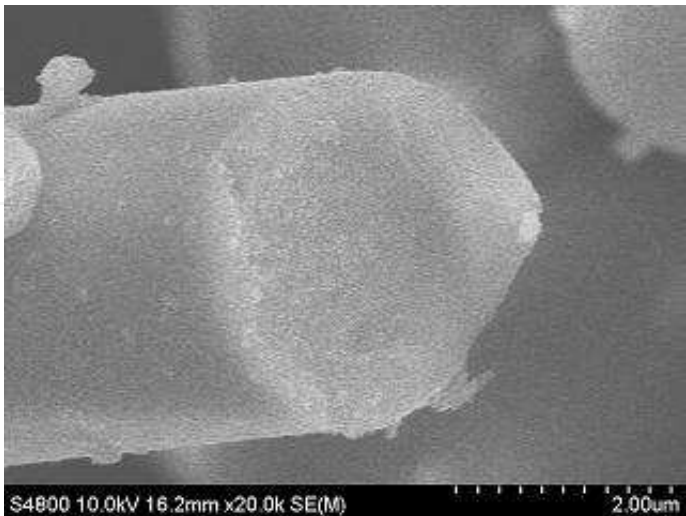

Fig. 3.3. Estimated vs. experimental values for abrasion coefficient

(a) x30

(b) x500

(c) x20000

Fig. 3.4. SEM images of rock wool waste

Rock wool waste is an inorganic fibrous substance produced by steam blasting and cooling molten glass. Rock wool waste obtained from thermal insulation materials is crushed and ground. Like other by-product materials, rock wool waste can be used as coarse aggregates, fine aggregates, cementitious material, or inert fillers in concrete, depending on its chemical composition and particle size. Figure 3-4 presents an SEM image of rock wool waste displaying cylindrical and fiber shapes.

The abrasion coefficient of specimens decreased with an increase in rock wool content (Fig. 3-5). The abrasion coefficients of specimens containing 10 wt. % rock wool waste at w/cm ratios of 0.55 and 0.65 were as much as 4 % and 5 % lower than control specimens, respectively. This indicates that when rock wool is used, abrasion resistance is strongly associated with the bond between the cement paste and fine aggregate. Finer rock wools enhances abrasion resistance, providing considerable performance benefits for cement-based composites.
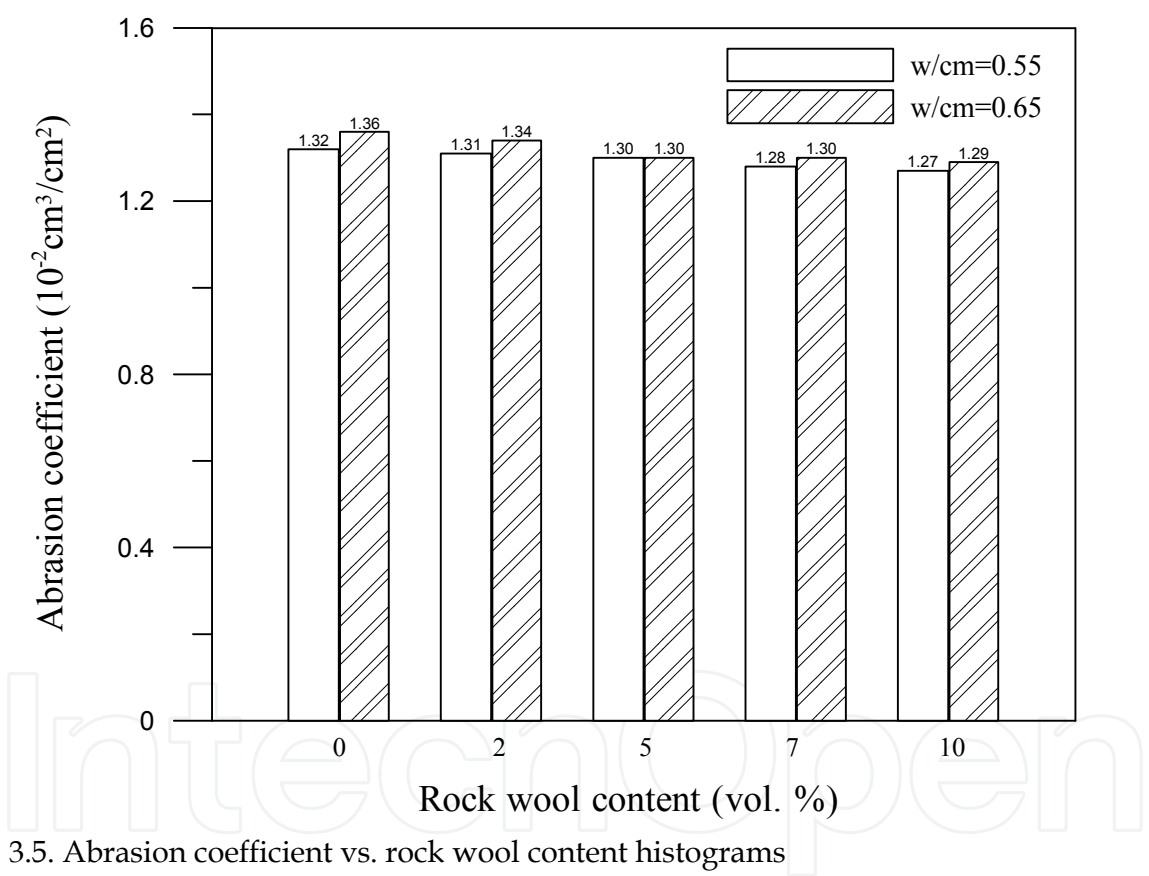

Fig. 3.5. Abrasion coefficient vs. rock wool content histograms

3.2 Los Angeles abrasion test

Composite samples aged 28 days were tested using the Los Angeles abrasion test, and the weight loss following 100, 300, and 500 rotations is summarized in Table 3-1. The relationships between weight loss and rotations for samples with w/cm ratios of 0.35 and 0.55 are shown in Figs. 3-6 and 3-7. As seen in the figures, weight loss and abrasion resistance index significant increased with an increase in the number of rotations and the w/cm ratio. The BF10 specimen demonstrated the greatest weight loss, due to balling and the poor dispersion of fibers, which may have been the result of weak bonding between

the fibers and paste in partial cement-based composites, particularly at higher w/cm ratios. These results indicate that the scaling of composites may increase weight loss. Conversely, silica fume helps to disperse fibers uniformly throughout composites, thereby significantly improving abrasion resistance. Silica fume with a particle size of approximately 0.2 μ m appears to improve the dispersal of fibers throughout the matrix. According to the testing results, specimens containing silica fumes demonstrated lower weight loss than control specimens. Specimens combining silica fume and polyolefin fibers demonstrated performance superior to that of specimens containing either silica fume or fibers. In conclusion, an appropriate combination of silica fume and fibers provides the highest abrasion resistance, from which we infer that silica fume not only helps to disperse fibers but also strengthens the bond between fibers and the cement-based matrix.

	Weight loss (%)		
Mix no.	100 rotations	300 rotations	500 rotations
A	4.22%	8.18%	11.34%
B	3.21%	14.88%	21.00%
AS5	3.35%	7.73%	11.25%
BS5	4.43%	11.15%	17.06%
APS	3.42%	7.65%	10.03%
BPS	4.37%	12.36%	17.92%
AS5PS	2.07%	5.93%	10.54%
BS5PS	1.97%	6.37%	14.25%
AF05	2.14%	4.51%	9.91%
BF05	2.11%	21.89%	27.42%
AF10	1.49%	3.37%	12.08%
BF10	2.40%	11.88%	18.59%

Note: A represents w/cm = 0.35
         B represents w/cm = 0.55
         S5 represent silica fume = 5 wt. %
         PS represent polyolefin fiber
         F05 represent steel fiber = 0.5 vol. %
         F10 represent steel fiber = 1.0 vol. %

Table 3.1. Weight loss following Los Angeles abrasion testing

Weight loss of specimens following 100, 300, and 500 rotations is shown in Figs. 3.8-3.10, respectively. The weight loss of specimens decreased in proportion to the addition of polyolefin fibers, steel fibers, or silica fume. This tendency is more obvious at 100 rotations than at 300 or 500 rotations, due to the poor bonding caused by composite scaling. Poor bonding could be overcome by long-term curing and the addition of SCMs. Control specimens also displayed severe weight loss, which may be due to the fact that the control specimens had much lower compressive strength, consistent with the results of SBAT. The combination of silica fume and steel fibers or polyolefin fibers is more effective in enhancing abrasion resistance, indicating that this combination enhances bond strength and compressive strength. In summary, bond strength between fibers and pastes is another important factor (in addition to compressive strength) in abrasion testing.
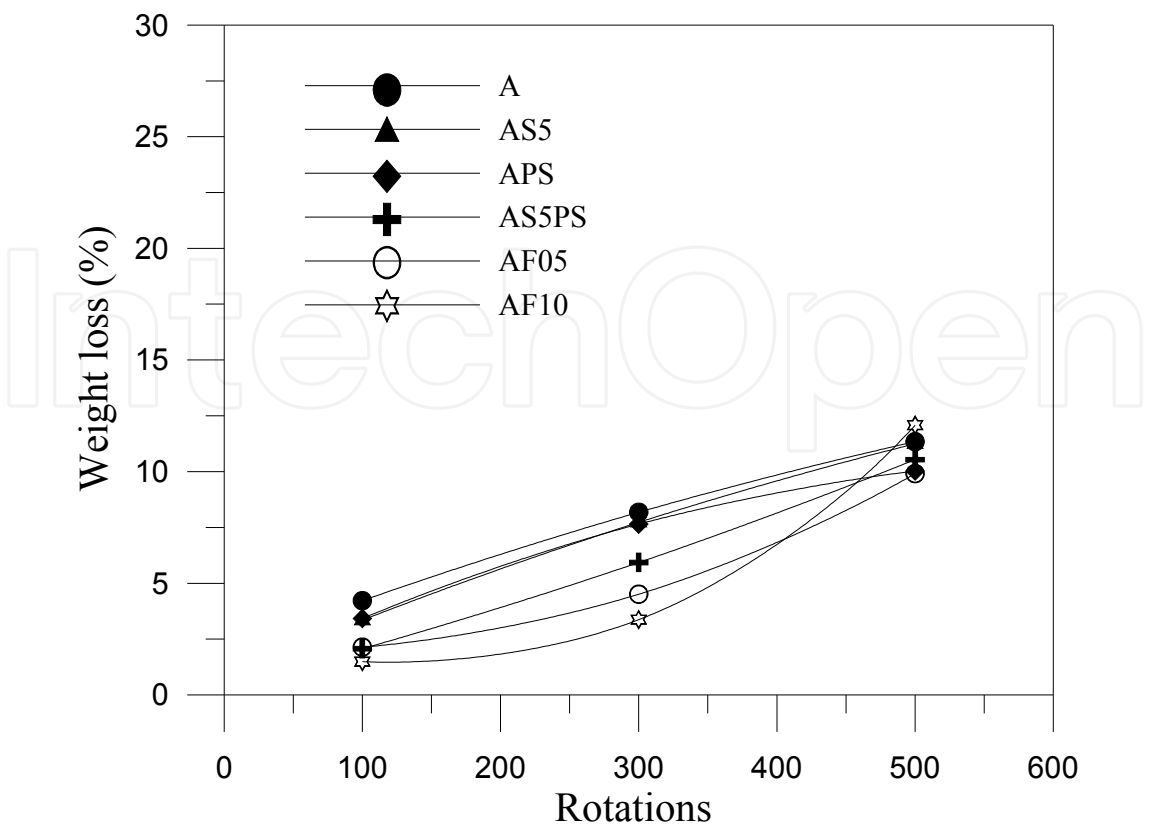
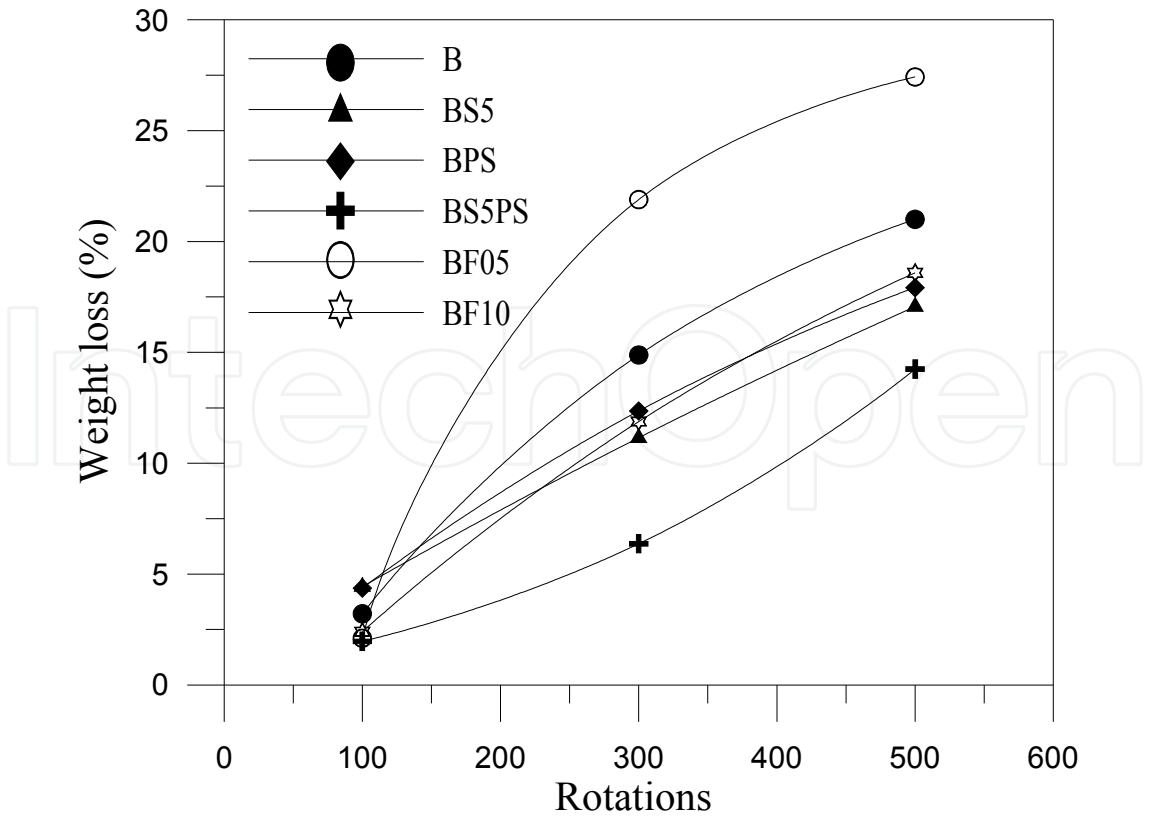Fig. 3.6. Weight loss vs. rotation curves (w/cm = 0.35)

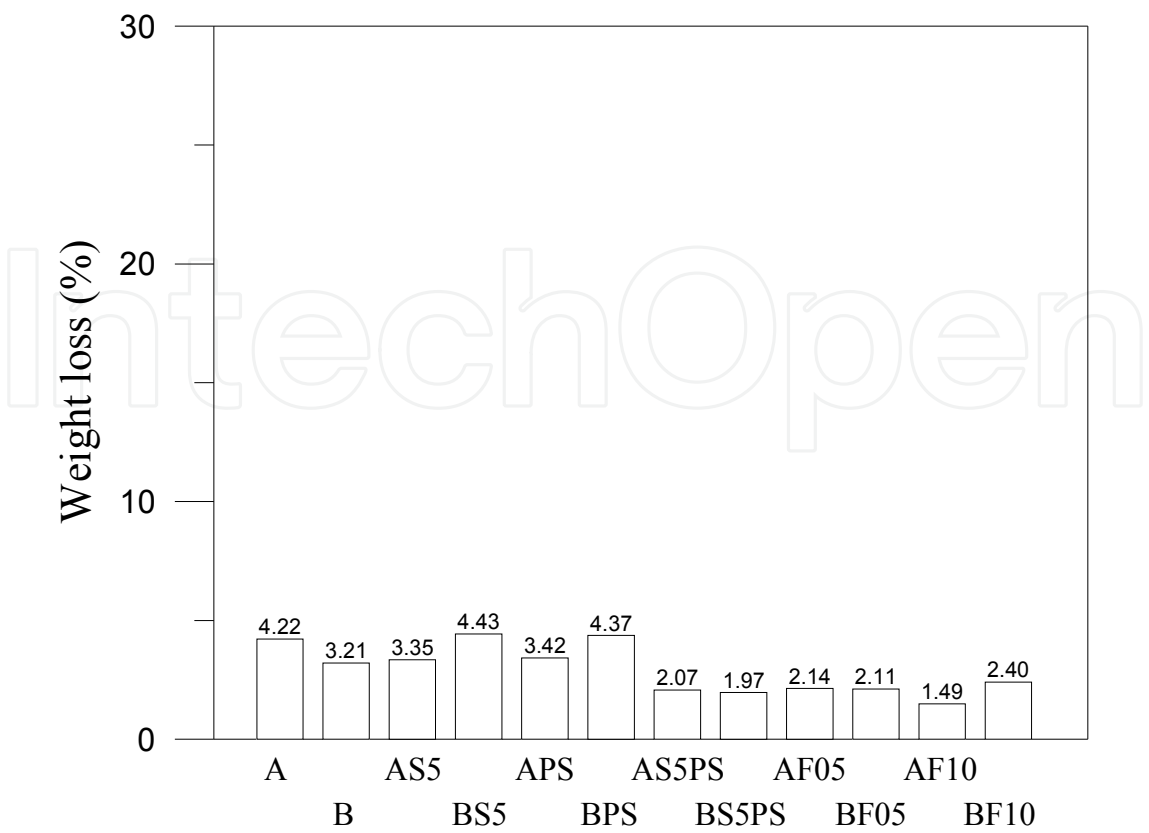Fig. 3.7. Weight loss vs. rotation curves (w/cm = 0.55)
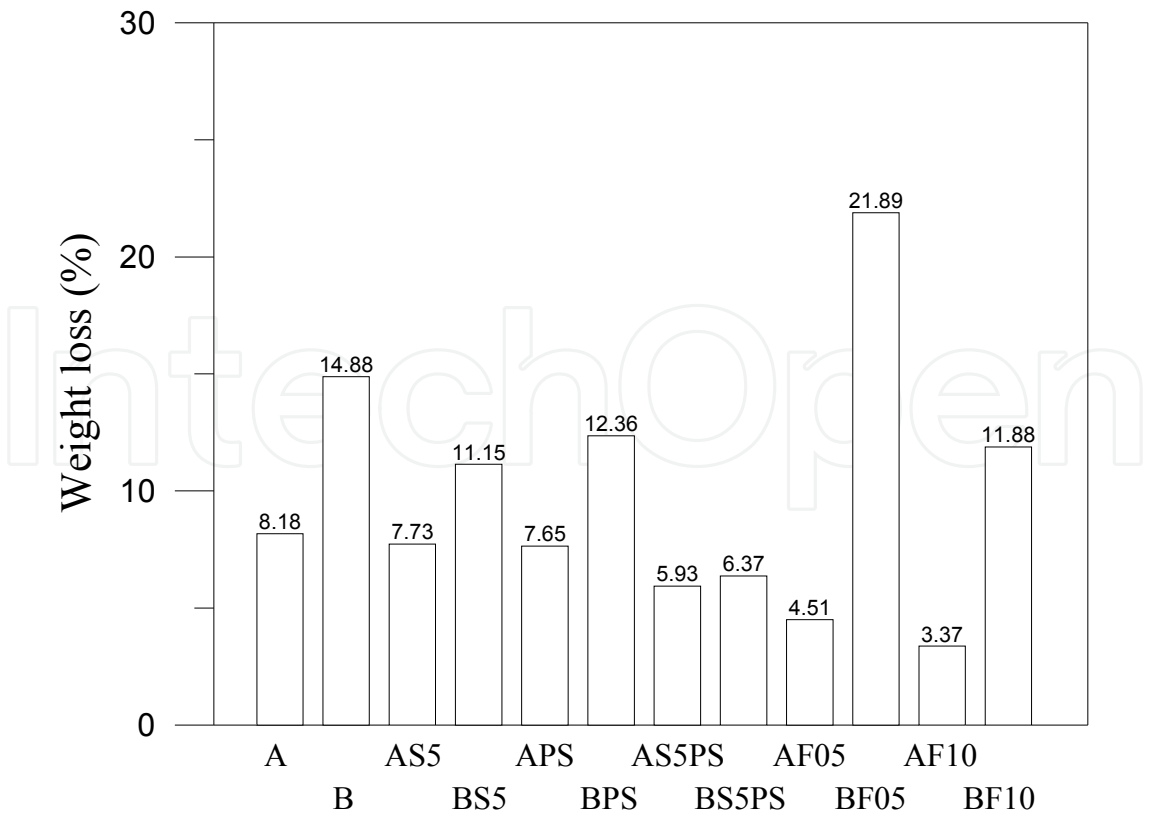
Fig. 3.8. Weight loss histogram following 100 rotations
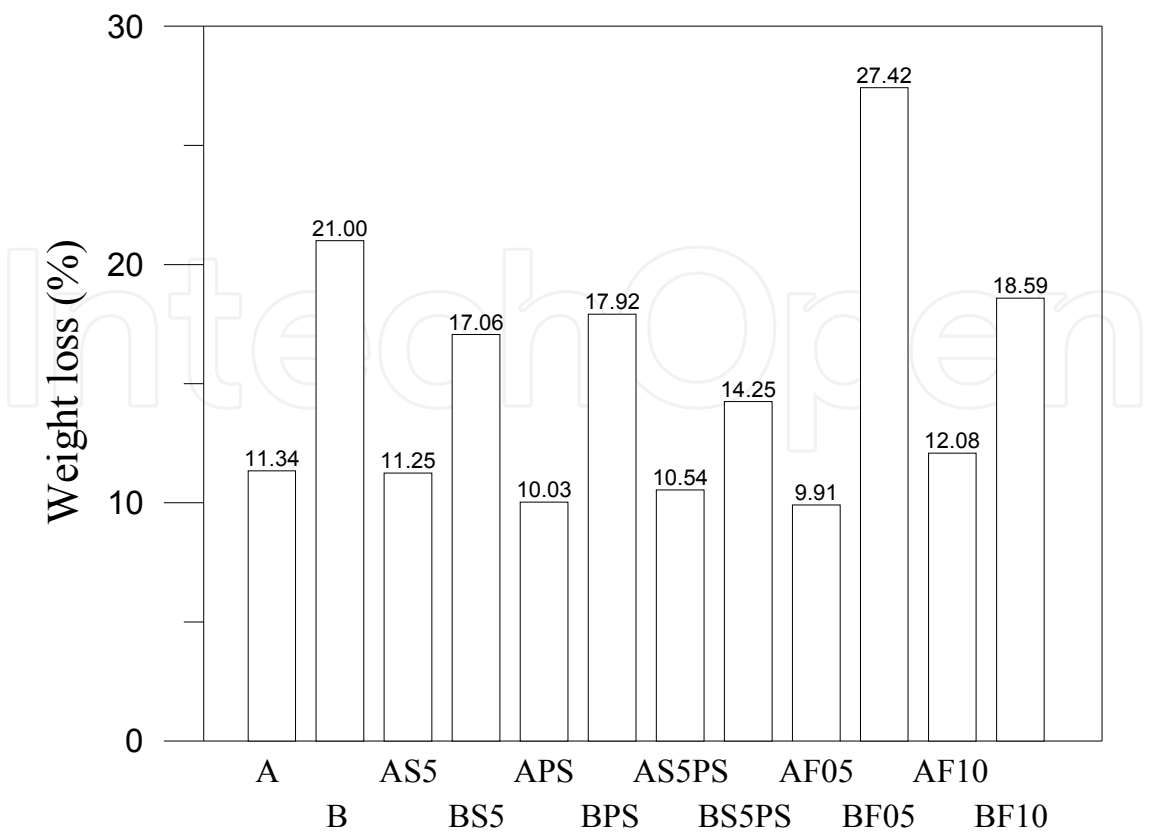

Fig. 3.9. Weight loss histogram following 300 rotations

Fig. 3.10. Weight loss histogram following 500 rotations

4. Conclusions

According to the previous results and discussion, our conclusions are presented as follows.

1. Abrasion resistance is clearly influenced by the addition of silica fume and steel fibers. The inclusion of silica fume in composites increases abrasion resistance (-32~-42 %), by increasing the dense hydrated calcium silicate to provide a more refined pore system. The inclusion of steel fibers marginally influences abrasion resistance. The combination of steel fibers and silica fume provides little improvement in abrasion resistance (-8~-15 %).
2. Based on the correlation coefficient of statistic analysis, the abrasion resistance of cement-based composites is strongly correlated with w/cm and silica fume and steel fiber content.
3. The addition of rock wool waste enhances abrasion resistance in a manner similar to that of SCMs in cement-based composites.
4. The modified Los Angeles abrasion test used in this study is suitable for the evaluation of abrasion resistance in cement-based composites.
5. The inclusion of silica fume in cement-based composites results in a denser microstructure with fewer pores, thereby enhancing abrasion resistance. The inclusion of silica fume also enhances the bond between fibers and paste. Specimens combining silica fume with polyolefin fibers demonstrated superior abrasion resistance compared to specimens containing individual constituents of silica fume or fibers.
6. Bond strength between fibers and paste is another important factor (in addition to compressive strength), associated with abrasion resistance.
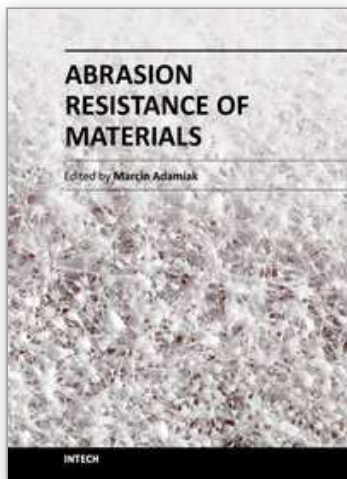
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