BEHAVIOR OF SELF-COMPACTING CONCRETE CONTAINING BINARY AND TERNARY BLENDED CEMENTS IN ACIDIC ENVIRONMENTS

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Abstract

This paper presents an experimental investigation on the behavior of binary and ternary blended cements self-compacting concretes exposed to different acid environments, namely, sulfuric acid and hydrochloric acid solutions for different periods. Two types of mineral additives were used in this investigation; silica fume and fly ash. The percentage of addition of silica fume and fly ash were determined to obtain self-compacting concrete with the highest 28-day compressive strength. Compressive strength, weight change and water absorption of concrete were determined after exposure to acidic environments and compared with those of the specimens immersed in tap water. The scanning electron microscope test was carried out to determine the effect of acidic environments on the microstructure of the concrete. The investigation indicated that in general the ternary blended concrete had better acid resistance than the plain and binary blended cement concretes.

1. INTRODUCTION

Self-compacting concrete (SCC) represents one of the most significant advances in concrete technology. It is characterized by its ability to flow and compact under its own weight without the need of vibration. It flows into congested reinforcement areas and fills complicated formwork without any segregation or blocking [1-3]. It was developed in Japan in the late 1980s and then adopted in Europe and the rest of the world [1]. SCC has been considered as a "quiet revolution" in the concrete construction process, with major benefits with regard to traditional concrete (TC): increased productivity, easier casting in hardly accessible areas, enhanced construction quality and much improved working environment on site [1, 4-10].

Different mix design concepts for SCC have been worldwide developed. The key performance criterion of SCC is attaining two incompatible properties: a high flowability and a high segregation resistance. In general, SCC consists basically of the same components as TC. However, to achieve satisfactory combinations of high fluidity and stability, SCC
requires using a low water/powder ratio with significant quantities of superplasticizers to achieve a highly fluid concrete as well as using a large quantity of powder materials (cement and filler particles smaller than 125 μm) or viscosity modifying agents to maintain the stability of concrete. Furthermore, coarse aggregate content should be much lower in SCC than in TC to reduce the risk of blocking of concrete flow by congested reinforcement and narrow openings in the formwork [3-5, 11-15]. The European federation (EFNARC) [15] specified a typical powder content of SCC to be in the range 380 - 600 kg/m³, i.e. about 200 kg/m³ more powder than for TC. On the other hand, it has indicated that the use of high cement content may be dangerous because of the increased heat of hydration and shrinkage, while cement content less than 350 kg/m³ is suitable for SCC with the inclusion of other fine additives. Thus, the high powder content is often supplemented by mineral additives such as fly ash, slag, limestone powder, etc [7, 8, 11].

Due to the difference in the mixture design, placement and consolidation techniques, the durability of SCC may be different from that of TC, and thus urgently to be evaluated thorough investigation. However, since the development of SCC, extensive research has been carried out regarding the mix design [2, 3, 6, 8, 9, 13], fresh properties [12, 16, 17], placing methods [4] and evaluating the mechanical properties of SCC [10, 11], and very limited work has been done to assess its durability performance especially in acidic environments [7, 14, 18, 19]. Although with the growing use of SCC in various applications, it has become necessary to establish reliable data about the durability of SCC especially the higher powder content and volume of cementitious paste can make the concrete vulnerable to chemical attack. The objective of this study is to evaluate the behavior of SCC containing plain, binary and ternary blended cements to acid attack. In this respect, two mineral additives, namely, fly ash and silica fume were used in preparing SCCs. After 28 days of curing, the specimens were immersed in hydrochloric and sulfuric acid solutions for a period of 18 weeks. The weight change, absorption and compressive strength were recorded. The scanning electron microscope (SEM) test also was conducted to better understand the mechanism of deterioration of each type of concrete.

2. EXPERIMENTAL PROGRAM

2.1 Materials

The concrete mixtures investigated in this study were prepared with ordinary Portland cement CEM I 42.5 N (OPC) conforming to the European Standards EN-197/1. Silica fume (SF) and ASTM Class F fly ash (FA) were used as mineral additives. Silica fume and fly ash had a specific gravity of 2.15 and 2.6, and specific surface area of 264,500 and 21,000 cm²/g, respectively. The fine aggregate was natural sand with a fineness modulus of 2.80, a saturated surface dry specific gravity of 2.5 and 1.5% water absorption. Continuously graded crushed stone with a nominal maximum size of 14 mm, a saturated surface dry specific gravity of 2.65 and 0.83% water absorption was used as coarse aggregate. Sika Viscocrete 20HE, a polycarboxylate-based superplasticizer (SP) with specific gravity of 1.08, was used in all mixtures to obtain suitable flowability without segregation.

2.2 Mixture proportions, casting and testing

Four SCC mixtures were prepared using single, binary and ternary binders. Binder refers to Portland cement and the used mineral additives (i.e., silica fume and/or fly ash). SF and FA
were added at percentages determined based on the literature review related to the use of these mineral additives in SCC [5, 6, 14, 20]. The control mixture consisted of only OPC without any mineral additives (designated code M1). Binary blended cement mixtures were prepared by adding either 40% FA or 10% SF to Portland cement (by weight) (designated codes M2 and M3, respectively). Ternary blended cement mixture was prepared by adding 30% FA and 10% SF to Portland cement simultaneously (designated code M4). The cement content, water-to-cement ratio (w/c) and sand-to-total aggregate ratio (S/A) were kept constant at 400 kg/m$^3$, 0.45 and 50%, respectively. In this paper, the total binder content varied from 400 to 560 kg/m$^3$ reflecting typical SCC with limited to high volume of cementitious paste. Proportioning of the mixtures was carried out using the absolute volume method. The dosage of SP was adjusted to maintain an initial slump flow of 650±50 mm for all mixtures. Concrete mixture proportions are shown in Table 1.

Table 1: Proportions of the concrete mixtures

<table>
<thead>
<tr>
<th>Mixture ID</th>
<th>Binder description</th>
<th>Concrete ingredients, kg/m$^3$</th>
<th>w/c</th>
<th>w/b(1)</th>
<th>SP, l/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>OPC</td>
<td>400</td>
<td>0.45</td>
<td>0.45</td>
<td>7.6</td>
</tr>
<tr>
<td>M2</td>
<td>OPC+FA</td>
<td>400</td>
<td>0.45</td>
<td>0.32</td>
<td>6.0</td>
</tr>
<tr>
<td>M3</td>
<td>OPC+SF</td>
<td>400</td>
<td>0.45</td>
<td>0.41</td>
<td>8.0</td>
</tr>
<tr>
<td>M4</td>
<td>OPC+SF+FA</td>
<td>400</td>
<td>0.45</td>
<td>0.32</td>
<td>7.3</td>
</tr>
</tbody>
</table>

(1) water-to-powder ratio

Basic requirements for self-compacting concrete are those in the fresh state: filling ability, viscosity, passing ability and segregation resistance. A concrete can only be classified as SCC if the requirements for all characteristics are fulfilled. It should be noted that there is no single test can adequately measure the workability properties of SCC. In this study, after mixing, slump flow, V-funnel and J-ring tests were conducted according to EFNARC [15] to determine the self-compactibility properties of concrete. The slump flow test was conducted to evaluate the filling ability and segregation by visual inspection while the V-funnel and J-ring tests were conducted to evaluate the viscosity and the passing ability of SCC, respectively. Details of equipments used for testing fresh concrete and test procedures can be found in Ref. [15]. The test procedures are briefly described below:

**Slump flow test** is very similar to the test method used for determining the slump of traditional concrete. The difference is that the diameter of the spread concrete is measured in two perpendicular directions and the average is recorded as a slump flow [15].

**V-funnel test** consists of filling out a V-shaped funnel with concrete and the time that the concrete takes to flow through the funnel ($t_v$) is measured. A high V-time indicates a high viscous condition of concrete [15].

**J-ring test** is a simple way used to determine the passing ability of the concrete through reinforcement without blockage. It is an extension of the slump flow test in which a ring apparatus is used and the difference in the height ($\Delta H$) of concrete spread inside and just outside the J-ring bars is measured at four locations and the average is calculated.

After fresh tests, the specimens were cast from each mixture by pouring fresh concrete into steel moulds without compaction. The specimens were demoulded after 24 h and cured in
water at 20±2 °C for 28 days. The initial physical and mechanical properties (i.e., weight, absorption and compressive strength) of concrete mixtures were determined to be benchmark for comparison with the properties after exposure to acid attack. To evaluate the durability of SCC mixtures to acid attack, the specimens were divided into three groups. One group remained to be cured in tap water, while the other two groups were continuously submerged in 1% hydrochloric acid (HCl) and 3% sulfuric acid (H₂SO₄), respectively for 18 weeks. The specimens were kept covered throughout the testing period to minimize evaporation, and the temperature of the solutions was maintained at 20±2 °C. Acids were renewed every two weeks with fresh solutions to maintain the concentration constant throughout the test period. It should be mentioned that the periodic use of fresh acid solutions along with the use of small test specimens provided an accelerated evaluation of the acid resistance of concrete. After 6, 12 and 18 weeks of immersion, the specimens were taken out of the solutions, rinsed with a soft nylon brush under running water to remove loose materials from the specimen and the following tests were conducted:

**Visual inspection of concrete samples:** During the immersion period in acid solutions, the samples were periodically retrieved from the acids for visual inspection to record changes in surface appearance.

**Determination of weight and compressive strength:** These tests were carried out according to ASTM C 267 [21] on 100 mm cubic specimens. The specimens were left to dry for 30 min and their weights were measured using a balance with 0.001 g sensitivity followed by testing for compressive strength based on the original cross-sectional area. The compression test was carried out with a 2000 kN compression testing machine and a loading rate of 0.7 MPa/s. The weight change \( W_c \) was calculated based on the initial weight before immersion and the reduction in compressive strength \( R \) was calculated with respect to the compressive strength of concrete after immersion in water.

**Water absorption test:** This test was conducted using slices of 150 mm diameter and 50 mm length. The specimens were oven-dried at 100 °C until the change in weight during 24 h is less than 0.1%, and the dry weight was recorded. Afterwards, the specimens were immersed in water until reaching a constant weight. The absorption percentage is calculated as the ratio of absorbed water to the dry weight of the sample.

In each test period, all tests were carried on three replicate samples and the average was reported.

**Scanning electron microscope (SEM) test:** After compression test, scanning electron microscope (SEM) test was conducted on the fracture surfaces from selected concrete samples to investigate the damage mechanisms due to acid attack. The morphology and microstructure was studied by using a scanning electron microscope equipped with an energy dispersive X-ray (EDX) analyzer. The samples with a size of approximately 10 x 10 x 10 mm³ were taken at the near-surface zone, dried and coated with gold before SEM test.

3. TEST RESULTS AND DISCUSSION

3.1 Fresh concrete properties

In general, visual inspection of fresh concrete during slump flow test did not detect any segregation or bleeding in any mixture. Fresh properties of SCC mixtures are summarized in Table 2. In general the slump flow and V-funnel flow time values for all mixtures satisfied the recommended values suggested by the EFNARC [15] and needed for SCC. Slump flow
values varied between 645 and 680 mm, which is an indication of a good deformability. This was achieved by adjusting SP dosage as mentioned earlier. As can be observed from Table 1 that the SP dosage required in SCC mixture containing fly ash (M2) was significantly lower than that of the control mixture made with plain cement (M1). This is due to the smooth surface characteristics and the spherical shape of fly ash particles that reduces the friction at the aggregate-paste interface producing a "ball-bearing effect" at the point of contact thus improving the flowability of concrete [12, 22]. The effects of fly ash addition on the workability of concrete were reported by other researchers [1, 5, 8, 12]. For example, Khatib [5] found that SCC mixes containing fly ash had a further increase in workability compared with the control mixture at the same dosage of admixtures. On the other hand, the addition of silica fume increased the dosage of SP compared to that of the control mixture. This is due to its extremely high surface area leading to the adsorption of the free mixing water. The same findings were reported by Nehdi et al [23] that the use of silica fume decreases the flow of SCC compared to pure cement SCC. When silica fume was used in combination with fly ash in ternary blended cement concrete (M4), the dosage of SP was comparable to that used in control concrete, as one mineral additive hindered the negative effects of the other. The synergistic effects between the ingredients of ternary mixtures were also reported by other researchers [12].

Similarly in V-funnel test, all SCCs showed flow time values in the range of 4-8 s, indicating a quite viscosity which is necessary to avoid the segregation of coarse aggregate particles. It should be noted that V-funnel flow time increases by increasing the powder content and using binary or ternary blended cement indicating the increase in concrete viscosity. For the J-ring test, the increase in binder content enhanced the passing ability of SCCs (except M3 mixture). For example, the difference in the height of concrete inside and just outside the J-ring bars decreased from 16 mm to 9 mm by increasing the binder content from 400 to 560 kg/m³. The increase in binder content decreases the coarse aggregate concentration, reducing the degree of internal friction among solid particles and enhancing the ability to flow and pass in the presence of obstacles. However, the use of silica fume decreased the passing ability while the use of fly ash increased the passing ability.

From the above it can be concluded that the addition of fly ash increases filling and passing ability of concrete, whereas silica fume imparts viscosity to concrete and improving its segregation resistance. The use of ternary blended cement containing 30% fly ash and 10% silica fume improves the rheological properties of self-compacting concrete.

Table 2: Fresh concrete properties and 28-day compressive strength

<table>
<thead>
<tr>
<th>Mixture ID</th>
<th>Binder description</th>
<th>Slump flow, mm</th>
<th>V-funnel flow time, s</th>
<th>ΔH, mm</th>
<th>Compressive strength, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>OPC</td>
<td>660</td>
<td>4</td>
<td>16</td>
<td>36.9</td>
</tr>
<tr>
<td>M2</td>
<td>OPC+FA</td>
<td>680</td>
<td>6</td>
<td>9</td>
<td>40.0</td>
</tr>
<tr>
<td>M3</td>
<td>OPC+SF</td>
<td>645</td>
<td>7</td>
<td>20</td>
<td>47.1</td>
</tr>
<tr>
<td>M4</td>
<td>OPC+SF+FA</td>
<td>655</td>
<td>8</td>
<td>13</td>
<td>50.7</td>
</tr>
</tbody>
</table>
3.2 Acid attack test results

3.2.1 Visual inspection

Figure 1 shows the surface appearance of SCC cubes after 18 weeks of immersion in acids. It was observed that the color of specimens' surface gradually changed from gray to grayish yellow and orange-brown by increasing the immersion period in sulfuric and hydrochloric acid, respectively. All the specimens showed signs of attack but the characteristics of attack were different depending on the acid type. After exposure to sulfuric acid, the specimens had a softened surface zone covering an intact and sound material. This reflects the successive decomposition of concrete specimens starting from the exposed surface and moving inwards. After rinsing with water, the cubes' dimensions decreased considerably while their shape was still in a cubic form. Coarse aggregate became exposed and voids were observed. The damage commenced from the corners and edges of the cubes. On the other hand, after immersion in hydrochloric acid the concrete had better appearance and its surface was generally intact and appeared to have changed slightly.

Comparing concrete mixtures exposed to acid solutions, it can be observed that the ternary blended cement concrete cubes were the least affected among the four concretes, regardless of acid type. It had the least visible signs of deterioration, indicating the beneficial effect of using a blend of mineral additives to provide higher resistance to acid attack than the use of only one.

![Figure 1: Deterioration of concrete cubes after 18 weeks of immersion in acids](image)

3.2.2 Weight change

The results of weight change for concrete specimens exposed to acids are shown in Figure 2. In general, all specimens showed a continuous weight loss when exposed to acids and the percentage of weight loss increases with increasing the immersion period, regardless of the acid type or the inclusion of blended cement. In case of sulfuric acid attack, a faster rate of weight loss was observed at the beginning period and over time the weight loss continued with a slower rate, while the opposite was observed in case of hydrochloric acid attack. Furthermore, the weight loss of specimens immersed in hydrochloric acid was much lower than that for specimens immersed in sulfuric acid regardless of the binder type, indicating the damaging effect of sulfuric acid compared to hydrochloric acid. For example, after 18 weeks
of immersion, the weight loss for control concrete (M1) submerged in hydrochloric and sulfuric acids was 3.7% and 10.2%, respectively.

The binder type had a pronounced effect on the weight loss results. The control concrete (M1) made with plain cement suffered the most deterioration in terms of weight loss due to acid attack compared to the binary and ternary binder blended cement mixtures. Compared to the corresponding control concrete it can be found that the development of binary mixtures containing 40% FA and 10% SF (M2 and M3) reduced the weight loss by 9%-16% and 21%-74%, respectively after 18 weeks of immersion in acids. These results are consistent with other studies and confirm the beneficial effect of silica fume and fly ash addition on the acid resistance of concrete. Roy et al. [24] investigated the resistance of silica fume, metakaolin and fly ash-incorporated mortars to various acids. It was found that the use of supplementary cementing materials increased the chemical resistance of mortars over those made with plain cement. FA series showed the highest chemical resistance while SF series showed the lowest. The ternary blended cement concrete (M4), containing 30% FA and 10% SF, showed the highest resistance to acid attack, regardless of acid type. Only less than 7% and 0.5% weight loss was observed at the end of exposure to sulfuric and hydrochloric acids, respectively. Therefore, the resistance to acid attack is not only dependent on the type of acid but also on the binder type.

![Figure 2: Weight change of SCC mixtures immersed in (a) 3% sulfuric acid and (b) 1% hydrochloric acid](image)

### 3.2.3 Water absorption

The absorption of concrete indirectly represents the volume of pores and their connectivity. The absorption of concrete mixtures before and after 18 weeks of immersion in acids is shown in Figure 3. As a general trend, there was a substantial increase in the absorption of concrete after exposure to acids, regardless of the acid type. Moreover, all concrete mixtures had higher absorption capacity in the sulfuric acid than in the hydrochloric acid, reflecting the aggressiveness of sulfuric acid. In the average, the increase in concrete absorption was about 51% and 89% due to hydrochloric and sulfuric acid attack, respectively. It should be noted that the increased absorption of concrete would lead to a greater volume of material being attacked by the acid as the solution will penetrate the concrete.
Control concrete incorporating plain cement exhibited by far the highest absorption both before and after exposure to acids, indicating the presence of large pores and free Ca(OH)$_2$ in the concrete. Thus, the matrix will be more susceptible to further acid attack through the pores. On the other hand, the water absorption for binary and ternary blended cement concretes was much lower than that of the control concrete, indicating the very dense and compact microstructure of concrete. This is attributed to the pore refinement process and the generation of discontinuous pore structure occurs due to the conversion of Ca(OH)$_2$ into secondary C-S-H gel by pozzolanic reaction [25]. Compared with the corresponding control concrete, it can be found that the addition of 40% FA and 10% SF in binary mixtures reduced the absorption by 8%-38% and 32-44%, respectively depending on the immersion solution (i.e., water, sulfuric or hydrochloric acid). Thus, silica fume is superior to fly ash in improving the pore structure and acid resistance of concrete. Furthermore, ternary concrete mixture (M4) incorporating a blend of silica fume and fly ash had lower water absorption, even after exposure to acids, than binary mixtures, which in turn was more efficient than plain cement mixture. The reduction of absorption implies the improvement in porosity and slower rate of acid attack [20].

![Figure 3: Water absorption of SCC mixtures before and after immersion in acids](image)

3.2.4 Compressive strength

The 28-day compressive strength values before immersion in acids are summarized in Table 2. Compared with the control mixture (M1), it can be observed that the use of binary and ternary blended cements generally increased the compressive strength. The compressive strength of SCC mixtures containing binary and ternary blended cements was 8%-37% higher than that of control mixture containing plain cement. The addition of silica fume had a superior effect on the compressive strength than the addition of fly ash due to the higher fineness (as seen in table 1) and pozzolanic activity of silica fume compared with fly ash [24]. The highest compressive strength was obtained for mixture M4, containing 30% FA and 10% SF, indicating the beneficial effect of using a blend of mineral additives to provide more compressive strength than the use of only one.

Reduction in compressive strength of concrete mixtures versus immersion time in acids is presented in Figure 4. As mentioned earlier that the reduction in compressive strength is calculated with respect to the 28-day compressive strength. In general, the reduction in compressive strength for all concrete mixtures increased with increasing the immersion period.

![Figure 4: Reduction in compressive strength versus immersion time in acids](image)
in acids, but their amplitudes of increase are different. Compared to hydrochloric acid, it is clear that sulfuric acid is more aggressive to concrete as it caused a greater reduction in compressive strength regardless of the binder type. This is due to that sulfuric acid combines an acid attack and a sulfate attack.

The control concrete containing plain cement was severely affected by the acid attack. It showed the highest values and rates of strength reduction, regardless of the acid type or immersion period. On the other hand, the addition of 40% FA and 10% SF as mineral additives improved the acid resistance of concrete since the reduction in compressive strength after 18 weeks of immersion in acids decreased by 11%-15.2% and 31%-47.7%, respectively compared to the control concrete. This is because silica fume and fly ash consume Ca(OH)\(_2\) during pozzolanic reaction and develop secondary C-S-H gel which reduces the micropores of concrete and provides a denser microstructure. The dense impermeable concrete increases the resistance against chemical attack [25]. The use of ternary blended cement increased the acid resistance of concrete significantly and hence concrete mixture (M4) had the highest resistance to acid attack with only 28% and 13% reduction in compressive strength at the end of exposure to sulfuric and hydrochloric acid, respectively.

![Figure 4: Reduction in compressive strength (R%) of SCC mixtures immersed in (a) 3% sulfuric acid and (b) 1% hydrochloric acid](image)

3.2.5 Microstructure

Figures 5-7 show SEM images and EDX analysis for concrete samples immersed in water, sulfuric acid and hydrochloric acid, respectively for 18 weeks. For control mixture (M1) immersed in water it can be seen that there were great deals of plated-shaped calcium hydroxide, calcium silicate hydrate (CSH) and needle-shaped ettringite as hydration products of Portland cement (Figure 5-a). On the other hand, ternary blended cement mixture immersed in water (M4) had a denser microstructure compared with mixture (M1) and the interfacial transition zone cannot be distinguished easily (Figure 5-b). Only C-S-H gel was formed and no calcium hydroxide or ettringite can be observed. This is because the mineral additives such as silica fume and fly ash with high fineness and high silica content act as
microfiller, filling the interface, followed by a pozzolanic reaction to form additional C-S-H which strengthening the interface [18].

Micrographs of concrete samples exposed to sulfuric acid for 18 weeks (Figure 6-a) indicate that the surface of concrete containing plain cement underwent significant deterioration since it had a growth of white tabular crystals associated with micropores appeared on the matrix surface. Microanalysis performed by EDX confirmed that these crystals were gypsum as the most significant peaks being calcium, sulfur and oxygen, indicating the decomposition of hydration products. For the ternary blended cement mixture (M4) (Figure 6-b), no gypsum crystals can be observed and a dense microstructure was found although of the formation of micropores compared with the same mixture immersed in water (Figure 5-b) indicating the sulfuric acid effect. EDX showed that the most significant peaks were calcium, silica and oxygen, indicating the resistance of ternary blended cement concrete to sulfuric acid attack. The sulfur content in ternary blended cement mixture was significantly lower than that in control concrete (figure 6), indicating its higher resistance to sulfuric attack.

The SEM image showed the deterioration of concrete surface due to hydrochloric acid (Figure 7). The presence of calcium chloride salt is virtually non-existent in the concrete exposed to hydrochloric acid although it expected to result from the reaction between calcium hydroxide and hydrochloric acid. The scarcity of calcium chloride is due to its high solubility (46.1%) compared with the solubility of gypsum formed during the sulfuric attack (0.2%) [26], as well as washing of specimens after the period of immersion.

The action of acids on concrete consists of attacking the components of the hardened cement paste. This action leads to a conversion of all the calcium compounds to the calcium salt of the attacking acid. Calcium compounds are variably reactive in acids. Calcium hydroxide is the most reactive and completely dissociates, while calcium silicates are less reactive. The rate of acid attack depends on the quality of concrete, w/c ratio and the type of cement as well as on the acid type, concentration and pH, the mobility of the solution and the solubility of the resulting calcium salt [26-28].

Comparing the sulfuric acid and hydrochloric acid attack on concrete, it is apparent that the mechanisms involved are quite different. The effect of sulfuric acid on concrete is more detrimental than that of hydrochloric acid as seen in the results. It causes higher weight loss, strength loss and porosity in concrete. This is because sulfuric acid attack consists of attack by sulfate ions and a dissolution effect caused by hydrogen ions [19]. During sulfuric acid attack, calcium hydroxide converts to calcium sulfate hydrate (gypsum) which, in turn, may react with C₃A to form calcium sulfoaluminate (ettringite). Each of these reactions involves a significant increase in the concrete volume. The formation of gypsum leads to softening and expansion of the concrete. The formation of secondary ettringite results in a substantial expansion of concrete causing internal pressure and formation of cracks. These cracks will provide further sites of acid penetration into the concrete. When the reactions continue, the concrete gradually loses its strength and weight as seen in the results thus may cause eventual collapse of the structure [19, 20, 22, 26]. On the other hand, hydrochloric acid reacts with calcium hydroxide and creates a readily soluble salt (calcium chloride) and reacts with calcium silicate hydrate to form a porous silica gel layer that offers a little protection against further attack (the reason of slow rate of hydrochloric acid attack). However, continuous reactions results in the decomposition of the hydration products and hence the concrete starts to disintegrate. As a consequence, the strength decreases because of the higher porosity of the concrete and the decomposition of the hardened cement paste [22, 26, 28].
Concrete containing mineral additives performed better than plain cement concrete especially when exposed to acids as it had less weight loss, strength loss, absorption and less visible signs of deterioration than OPC concrete. Furthermore, the combination of silica fume and fly ash to produce ternary blended cement is complementary in SCC as one mineral additive hindered the negative effects of the other to improve the rheological properties of concrete. It is proved that the ternary blended cement concrete offered more advantages over the plain and binary blended cement concrete, either in the fresh state or in the hardened state. Furthermore, it had the highest strength and resistance to acid attack. The beneficial effect of mineral additives on the acid resistance is due to the refinement of the pore structure that prevents the penetration of acid readily into the matrix, and the consumption of the calcium hydroxide content which is the most vulnerable component to acid attack as described before [19, 26]. The ternary blended cement mixture had a very dense microstructure and limited calcium hydroxide content available for the acid reaction compared to that of the control mixture, thus resulting in the lowest rate of attack.

![Figure 5: SEM for concrete immersed in water; (a) M1 and (b) M4](image)

![Figure 6: SEM and EDX for concrete exposed to sulfuric acid; (a) M1 and (b) M4](image)
4. CONCLUSIONS

− The rheological properties of SCC depend mainly on the mineral additive type and content due to their different fineness and particle shape. SCC mixture containing fly ash required considerably smaller dosage of superplasticizer than did the SCC containing silica fume.

− The addition of fly ash increases filling and passing ability of concrete, whereas silica fume imparts viscosity to concrete and improving segregation resistance of the mix. Ternary blended cement can be utilized beneficially in producing SCCs, as one mineral additive hinders the negative effects of the other mineral additive yielding a SCC with the required rheological properties.

− The use of mineral additives may provide a way for improving the hardened and durability performance of SCC depending on the type and content of mineral additive used.

− The resistance of cement-based materials to acid attack is mainly dependent on the pore structure and alkalinity of concrete.

− SCCs containing binary and ternary blended cements have dramatically higher resistance to acid attack compared to control SCC made with plain cement, in spite of the type of acid.

− The use of mineral additives combination provides more compressive strength and excellent resistance to acid attack than the use of only one additive.

− In comparison with hydrochloric acid, sulfuric acid attack is more detrimental to concrete.

REFERENCES


