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Acidic corrosion-abrasion resistance of concrete containing fly ash and silica fume for use as concrete floors in pig farm

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ABSTRACT

The objective of this study is to investigate the resistance of concretes to organic acid corrosion and abrasive corrosion, which occurs in typical pig farms. For the concrete mixtures, cement was replaced by fly ash and silica fume with different weight percentages up to 30%. The cubic mortar and concrete specimens were prepared and tested for compressive strength and mass loss due to organic acid corrosion. The test results indicated that fly ash and silica fume mixed together significantly enhance the compressive strength of the concrete, especially at long-term curing periods. The resistance of the concrete and mortar against organic acid corrosion was greatly improved by the substitution of fly ash and silica fume. Moreover, two testing machines were developed to simulate the abrasion-corrosion attack on concrete floors in pig farms (one for organic acid corrosion tests in wet-dried conditions and the other one for an abrasion testing machine with steel brushes). The concrete slab was cast and tested with a wet-dry switching system in an organic acid solution cooperating with an abrasion test. The test results demonstrated that applying a large amount of fly ash and silica fume is not effective for increasing the resistance of the concrete against organic acid corrosion and abrasive corrosion. The concrete mixture with 5 wt% of silica fume shows the highest resistance to organic acid corrosion together with abrasive corrosion with a mass loss reduction for 7.14% compared to the reference mixture.

1. Introduction

Concrete corrosion is characterized as a damage and deterioration of concrete constructions by chemical and physical effects [1]. There are many factors which lead to the deterioration of concrete. The most common factors are the environmental factors, the materials, as well as the preparation procedures and the deterioration from their applications. Various concrete building components in agricultural constructions are subjected to acid attack, whereby the main aggressive agents are lactic acid, acetic acid and sulfuric acid [2]. Various organic acids such as lactic and acetic acids can be produced in the natural degradation process of organic materials and in particular agricultural products. In animal houses and farms, the decomposition of an animal meal or agricultural products in the presence of water leads to the formation of lactic and acetic acids resulting in an acidic environment [3,4]. Under low pH less than 4, organic acid reacted with cement hydrated compounds and then occurred the decomposition of hydration products (calcium

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hydroxide calcium silicate hydrate or C-S-H) to form mainly calcium salts, which are highly soluble in water [5]. Consequently, the poorly soluble calcium salts lead to an increase in permeability and porosity, resulting in a decrease in the compressive strength of concrete [3,5]. The research conducted by Wang et al. [6] revealed that a decrease in the Ca/Si ratio of cement paste under the NH_4NO_3 dissolution due to the decalcification of hydration products can lead to a weakening in the microhardness of the cement paste and continuously affected the mechanical properties of concrete. Besides, the organic acid corrosion causes damage to the concrete floors in animal houses, and the mechanical abrasion due to cleaning processes also accelerates the corrosion process. Fig. 1 shows typical damage observed on concrete floors in pig farm showing damage around the feeding machine due to it was attacked by lactic acid, formed in spilled and soured meal-water mixtures.

The use of several types of industrial waste as pozzolanic materials in concrete have been intensively investigated from such different perspectives as strength, permeability, durability, and corrosion resistance [7–11]. The most common industrial wastes used as pozzolanic materials in concrete industry to are fly ash, silica fume from silicon smelting and ground granulated blast-furnace slag. Previous studies have revealed the fact that utilization of fly ash and/or silica fume in concrete improves the mechanical properties [12–16]. Wongkeo et al. [12] performed a study on the combined use of fly ash and silica fume as cement replacement materials for blended cement mortars under autoclaved curing. The compressive strength results suggested that fly ash blended cement mortar tends to decrease with the increase of the fly ash fraction and exhibits a lower compressive strength than the OPC mortar. However, the compressive strength was improved by adding silica fume, and the compressive strength of the binary blended of fly ash and silica fume to cement mortars was higher than the OPC mortar. Mehran Khan et.al [13] performed an investigation to find the effects of fly ash and silica fume on such mechanical properties of concrete as modulus of elasticity, compressive strength and toughness. They replaced cement by silica fume for 15 wt% combine with the substitution of fly ash to cement up to 15 wt% (at the substitution levels of 0%, 5%, 10%, 15%) of total cement. Results show that the compressive strength increased by 15–28% compared to that of the OPC concrete. The modulus of elasticity increased by 7–13% upon fly ash percentage, and the sample which substitutes cement by 10 wt% of silica fume and 10 wt% of fly ash has over all best properties. In case of abrasion resistance of concrete, previous studies have suggested that this ability is correlated with the concrete porosity and the pore surface fractal dimensions [17,18]. Wang et. al. [17] suggested both the fly ash and silica fume could decrease the porosity and increase the pore surface fractal dimensions of concrete. The utilization of 5 wt% silica fume together with 20 wt% fly ash as cement replacement enhances the abrasion resistance of concrete by about 4–9% at various ages.

Beside improved mechanical properties, many studies reveal that the utilization of fly ash and silica fume also led to better acid resistance through lower calcium content and less porosity in the concrete [19–22]. Baert et al. [23] also reported that replacing 60 wt % of the cement content by low-calcium fly ash induced better resistance when exposed to 5% H_2SO_4 acid solution compared to reference OPC concrete. Ravindrarajah [4] reported partial replacement of cement with silica fume up to 15% by weight caused lower hydrochloric acid attack in high-strength concrete. Goyal et al. [24] studied the mass loss and compressive strength loss of concrete exposed in a hydrochloric acid solution. The testing results demonstrated that the ternary mixes with a combination of silica fume and fly ash to cement show better acid resistance ability than the corresponding binary mixes with only silica fume as the mineral admixture.

Although several studies demonstrated the improvement of durability ability of concrete with fly ash and silica fume, little research has been performed on its resistance to acid attack. The use of acid-resistant concretes in the construction industry needs further research regarding their mechanical properties, which are key aspects in the design and manufacturing of special infrastructure. Especially, the corrosion is occured due to organic acid cooperating with abrasive corrosion from cleaning processes on concrete floors in pig farm. The simulation testing methods and tools are necessary topics to develop to reflect the real applications and environment.

And so, the intention of this research is to investigate the mechanical properties, acid resistance, and acid-abrasive resistance of

Fig. 1. Concrete destroyed surface in pig's farm.

concrete with cement binders incorporating solid wastes like fly ash (FA) and silica fume (SF). Organic acid resistance was examined via soaking the prepared mortar and concrete in the lactic acid solutions with starting pH of 2.5 ± 0.1. The special testing machines for organic acid corrosion – abrasion resistant test sets were also developed. Finally, intensive tests and analyses of the utilization of FA and SF in concrete applied for building pig farm floors were performed.

2. Research significance

Thailand is one of the largest pig producers in Asia, with more than 19.5 million pigs in 2017 were raised by 180,000 pig farms [25]. In typical applications of concrete structure agricultural area such as floors in animal houses and silage structures, concrete can be exposed to aggressive organic acid attack [26]. The acid solution which strongly damages concrete farm floors mainly consists of lactic and acetic acids. After surveyed, concrete floors in pig farm showed severe damage, especially on the area near feeding machines, so annual repairs are required. This increases the cost of production and causes farming operation problems. This damage on concrete floor is due to organic acid corrosion together with abrasive corrosion by the cleaning processes. Most of the available studies have investigated the mechanical properties of concrete modified with fly ash and silica fume. However, the area of combination of acid and abrasion resistance of concrete with fly ash and silica fume has not gained much attention yet. Furthermore, special test methods and equipment were developed in this work to investigate the acid and abrasion corrosion of concrete on pig farm floors.

3. Material and experimental methods

3.1. Materials

Ordinary Portland cement (OPC) was used for the casting of the specimens based on ASTM C1157 with physical and chemical properties certified. Fly ash (FA), a fine powder that is a byproduct of burning pulverized coal in electric generation power plants, was delivered from Mae Moh power plant, Thailand. The used silica fume (SF) was dry-densified with 93.51 wt% SiO_2. Well-graded natural sand was used as fine aggregate with the specific gravity and the modulus of fineness of 2.60 and 2.72 respectively while the crushed limestone was used as coarse aggregate with the maximum size of 20 mm. Naphthalene based superplasticizer (SP) was used to improve the workability of the material without increased water content. Fig. 2 shows SEM images of the Ordinary Portland cement , fly ash and silica fume utilized in this investigation. OPC particles are irregular and angular, while FA particles are spherical in different sizes. Normally, silica fume is densified before use in concrete for easy transportation and storage, and for more comfortable mixing into concrete. Hence, the size of densified silica fume agglomeration is up to several micrometers. In general, the agglomeration is hard to be dispersed into individual silica fume sphere [27]. The chemical compositions and typical physical properties of OPC, FA and SF are summarized in Table 1. The chemical composition of OPC used in this work was within the typical composition of OPC and their quality conforming to the ASTM C1157–11 [28]. The chemical composition of fly ash comprised mainly SiO_2 (35.89 wt%), Al_2O_3 (19.26 wt%), CaO (16.08 wt%) and Fe_2O_3 (10.64 wt%). The cumulative summarization of SiO_2, Al_2O_3 and Fe_2O_3 in the fly ash was lower than 70 wt%. Moreover, the FA contains 16.08 wt% CaO, suggesting that it belongs to class C according to ASTM C618–19 [29]. Silica fume consisted of dominant SiO_2 and a small fraction of minor elements. FA is brown gray and SF is off-white. According to the measurement results, the specific gravity of FA and SF are 2.20 and 2.21, respectively. The laser diffraction particle size analyzer was used to measure the particle size distribution and specific surface area as listed in Table 1. The specific surface area of OPC is 292.20 m^2/kg with mean particle size of 41.45 μm. FA shows slightly lower specific surface area and larger mean particle size compared to OPC. In the case of SF, agglomeration from densified processed resulting in the mean particle size be higher than that of OPC and FA.

An X-ray diffractometer was used to determine XRD patterns to observe the phase structure and mineralogy. The phase content of various components in OPC can be calculated using the Rietveld refinement analysis, as shown in Fig. 3. The major components in OPC are alite (Ca_3SiO_5, C_3S) and belite (Ca_2SiO_4, C_2S). The alite, belite, and calcium alumino ferrite phases constitute approximately 62 wt

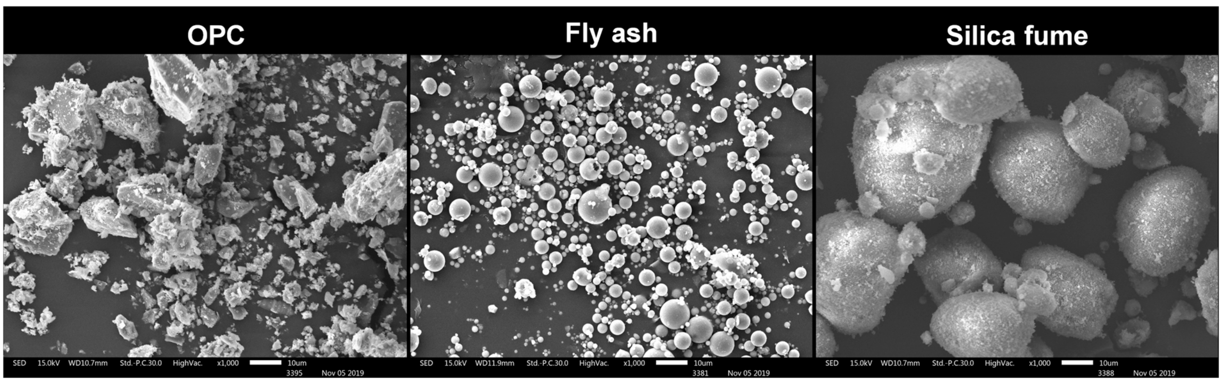

Fig. 2. SEM images of OPC, fly ash, and silica fume.

Table 1
Chemical composition and physical properties of raw materials.

Sample description	OPC	Fly ash	Silica fume
Chemical composition			
SiO_2 (wt%)	19.81	35.89	93.51
Al_2O_3 (wt%)	4.88	19.26	–
Fe_2O_3 (wt%)	3.15	10.64	0.22
CaO (wt%)	64.47	16.08	2.06
MgO (wt%)	1.36	2.45	0.40
K_2O (wt%)	0.46	2.31	0.34
Na_2O (wt%)	0.13	1.05	–
SO_3 (wt%)	3.04	4.08	0.56
Physical properties			
Specific gravity	3.15	2.20	2.21
Mean particle size, D [3,4] (μm)	41.45	63.60	119.00
Uniformity	0.929	1.588	0.809
Specific surface area (m^2/kg)	292.20	218.80	63.44

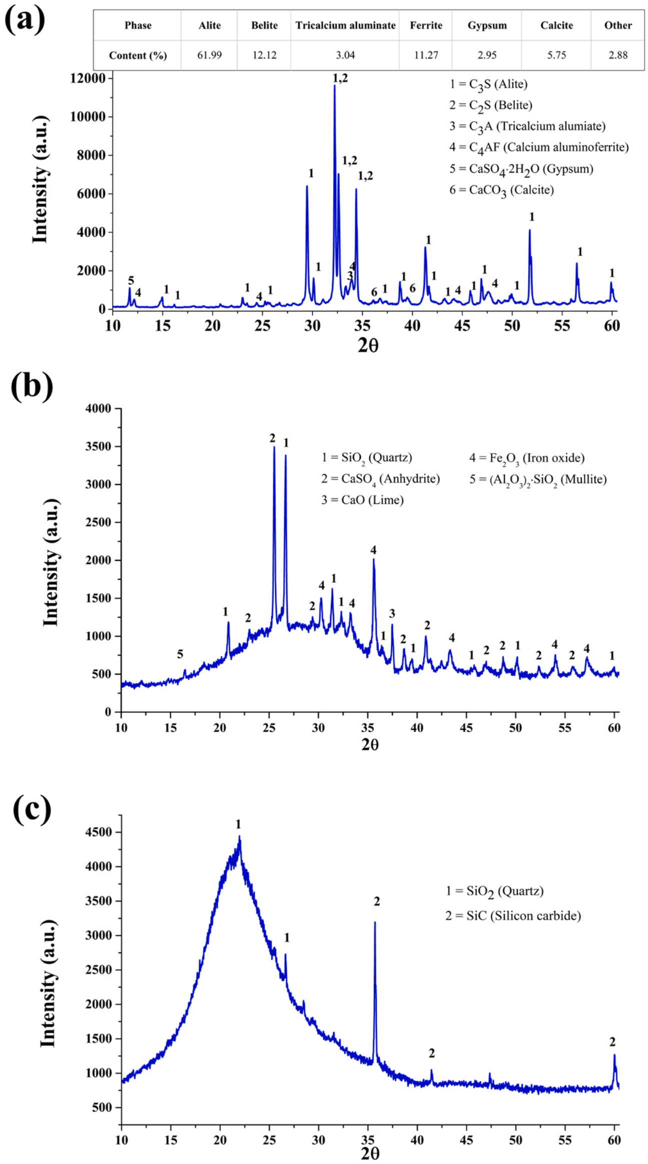

Fig. 3. X-ray diffractometry patterns of raw materials; (a) OPC, (b) fly ash and (c) silica fume.

%, 12 wt%, and 11 wt% of cement, respectively. In the case of FA and SF, phase quantitative analysis by the Rietveld refinement method was not investigated due to its amorphous nature. The broad hump located at $2\theta = 15^{\circ}– 40^{\circ}$ suggested that FA mainly comprised of amorphous phases, and some peaks of crystal of quartz, anhydrite, ferric oxide, and lime were also identified. The XRD analysis of SF shows that a broad hump between $2\theta = 10–40^{\circ}$ implies the presence of an amorphous phase, the most prominent peaks are quartz and silicon carbide. Through XRD, both FA and SF were found to be substances with an amorphous structure that could be used as pozzolanic materials.

3.2. *Mix design and preparation of the specimen*

3.2.1. *Mortar*

The mixture proportions of the mortar specimens are given in Table 2. All the specimens were prepared with a constant water-to-binder ratio (w/b) of 0.5 and a sand-to-binder ratio of 2.75. OPC was considered as the basic binder material, which was partially replaced by FA and/or SF (Table 2) to evaluate the influence of pozzolanic materials on the compressive strength and acid resistance of specimens. All mortar mixes used in the experimental program were prepared using a standard mortar mixer in accordance with ASTM C305–14 [30]. To secure the mortar mix with the required flow in the range of 110 ± 5%, the superplasticizer (SP) was varied from 0 to 1 wt% of the binder as given in Table 2. The mortars were cast into 50 mm × 50 mm × 50 mm cubic molds and kept in plastic sheet for 24 h to avoid the evaporation of water. After removing the specimens from the molds, the specimens were cured in saturated limewater at ambient temperature for distinct durations (7, 14, 28, and 56 days).

3.2.2. *Concrete*

Concrete specimens were prepared according to ACI-211.1–91 [31]. Because the results of this work are to be applied in the agricultural sector, economic factors have to be considered; therefore, we used a binder content of only 350 kg per cubic meter of concrete. The proportion of the cement and cement replacement materials at various mixture designs was consistent with the mortar mixture, as shown in Table 3. In all concrete mixtures, the total volumetric aggregate content was 74% (32% fine aggregate and 42% coarse aggregate by volume). The dose of SP was variated in every mix to maintain the slump in the range of 17.5 ± 2.5 cm whilst the concrete slump test was carried out according to the ASTM C143 [32]. After completing the fresh properties tests, two different dimension specimens were cast for evaluating the hardened properties. The specimens of 100 mm × 100 mm × 100 mm cubes were cast for the evaluation of compressive strength and mass loss due to acid corrosion, and the 300 mm × 300 mm × 50 mm plate shape specimens were prepared for acid corrosion-abrasion resistance testing. All cast specimens were cured in saturated limewater at 25 ± 2 °C before testing.

3.3. *Testing on mortar and harden concrete*

3.3.1. *Compressive strength*

Two series of compressive strength tests were carried out in accordance with the ASTM C109 standard [33]: (1) a mortar mixture with three evenly cubical specimens of 50 mm size with a loading rate of 1.2 kN/s within periods of 7, 14, 28, and 56 days of curing; (2) a concrete mixture with three evenly cubical specimens of 100 mm cubic specimens with a loading rate of 1.5 kN/s within periods of 7, 14, 28, and 56 days of curing. The compressive strength value for each mixture was the average of results obtained for three specimens, respectively.

3.3.2. *Organic acid resistance*

In order to be able to correlate the degradation behavior of the samples by organic acids with the actual problem, the methods for testing the resistance of mortar and concrete to organic acids from the ASTM C267 and ASTM C1898 standards were adapted [34,35]. The sets of three samples of 50 mm mortar cubes and 100 mm concrete cubes for each mix were used to study the effect of pozzolanic type and proportion on the samples' resistance to organic acids. All specimens were cast and covered with plastic sheets and kept at room temperature for 24 h. After 24 h of casting, the specimens were demolded and immersed in saturated limewater for 24 days before starting the organic acid resistance testing. The specimens were at first totally immersed in lactic acid solutions with pH of 2.5 ± 0.1, which is the highest concentration registered on floors in stables during the preliminary investigations [2]. To maintain the pH

Table 2
Mixture proportions of the mortars.

Mix id	OPC (kg/m^3)	Fly ash (kg/m^3)	Silica fume (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)
OPC	500	–	–	1375	252	3
10FA	450	50	–	1375	252	2
20FA	400	100	–	1375	252	1
30FA	350	150	–	1375	252	0
5SF	475	–	25	1375	252	1
5FA5SF	450	25	25	1375	252	5
15FA5SF	400	75	25	1375	252	3
25FA5SF	350	125	25	1375	252	2

Table 3
Mixture proportion of the concretes.

Mix id	OPC (kg/m^3)	Fly ash (kg/m^3)		Silica fume (kg/m^3)	Aggregate (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)
				Coarse	Fine		
OPC	350	–	–	1098	832	147	7
10FA	315	35	–	1095	826	147	5.25
20FA	280	70	–	1087	821	147	5.25
30FA	245	105	–	1079	815	147	5.25
5SF	332	–	18	1087	828	147	5.19
5FA5SF	315	18	18	1089	826	147	6.32
15FA5SF	280	53	18	1084	821	147	5.27
25FA5SF	245	88	18	1076	815	147	5.27

of the solution, the organic acid solution was weekly refreshed. The performance of the specimens against organic acid attack was evaluated from their mass loss in relation to soaking (or holding) time. The mass of the specimens before immersion in the organic acid solution (a surfaced-dried sample after soaking in the saturated lime water) was measured and recorded as the initial mass (m_i). After immersion in organic acid solution at every designated age, the samples were gently rinsed with tap water, and then the surface moisture was removed with a damp towel. The mass of the samples was also measured and recorded as the residual mass (m_n). Subsequently, the samples were again immersed in the acid and repeatedly tested at 3, 7, 14, 28 and 56 days. The mass loss percentage due to organic acid corrosion was calculated using Eq. (1).

$$Mass \quad loss = \frac{m_n - m_i}{m_i} \times 100 \tag{1}$$

3.3.3. *Organic acid corrosion – abrasion resistant testing*

The organic acid corrosion–abrasion resistance of concrete was conducted on three concrete plates with a dimension of 300 mm × 300 mm × 50 mm for each concrete composition. In order to reconcile the test methods with the actual durability issues related to the concrete slab in the pig farm, two accelerated degradation test apparatuses were developed (a modification of the standards of ASTM C779 [36]), as shown in Fig. 4 and Fig. 5. The dissolution of the ingredients in the feed leads to lactic acid, which corrodes the concrete slab in the pig farm. This is a major corrosion factor. The testing procedures were designed to achieve faster deterioration processes through alternate wetting and drying, which simulates the real-life situations under investigation [2]. Moreover, the cleaning process with a scrubbing brush causes abrasion corrosion on the concrete slab. The combination of the acid corrosion–abrasion corrosion accelerates the deterioration process of concrete slab. Hence, we used two-step corrosion tests in this work:

(1) First, an organic acid corrosion process, in which all specimens were cast and cured in saturated limewater for 24 days before the tests. After being air dried for one day, the specimens were coated with an acid-resistant epoxy on the bottom and four sides of cast specimens, while the top surface was in contact with the organic acid solution. The specimens were immersed in the organic acid solution, which was prepared similar to the organic acid resistance test, as mentioned in the previous section. The soaking machine (Fig. 4) immersed the specimens in an organic acid solution for one hour and lifted them up to be dried in air

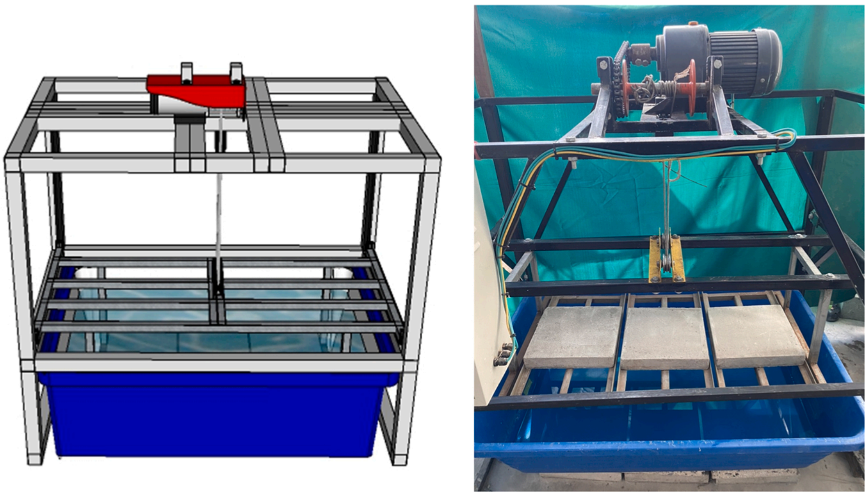

Fig. 4. Organic acid-soaked machine.

Fig. 5. Abrasion corrosion testing machine.

for one hour. This test was conducted for 48 h for one acid corrosion test cycle. The pH of the solution was maintained by refreshing every 48 h.

(2) Second, the specimens were gently rinsed with tap water and then dried in air at room temperature for two hours before being placed into the abrasion corrosion testing machine, which consists of a steel brush set moving horizontally with a vertical load of 50 N on the brush (Fig. 5). Test specimens were abraded by the steel brush on the top surface, which was corroded by an organic acid solution, for 60 min. After cleaning and drying of the surface, the weight of the specimens was measured to calculate the mass loss percentage (Eq. (1)) at each circle of the organic acid corrosion–abrasion corrosion test. Five cycles of the organic acid corrosion–abrasion corrosion testing were conducted for all specimens.

4. Results and discussion

4.1. Compressive strength

4.1.1. Mortar

Fig. 6 shows the compressive strength development for various curing periods of mortars for OPC, FA and SF with different replacement ratio. It can be seen that the compressive strength of blended cement with FA (binary blended cement) are lower than that of OPC at all replacement ratios (Fig. 6(a)). As the level of replacement increased, the early-age strength decreased. However, an increase of the curing period effectively improved the long-term strength to closer values to the control samples, which is in accordance with the results presented by previous investigations [37–40]. In case of using SF replacement to cement for 5% (binary blended cement), the compressive strength development of mortar exhibited approximately similar results to those of OPC mortar (Fig. 6(b)). The blended cement with fixed 5% for SF and FA for various fractions (ternary blended cement) also contributed to lower compressive strength than that of OPC control. However, when compared for similar replacement fraction such as 10FA compared to 5FA5SF or 20FA compared to 15FA5SF, the incorporation of SF and FA in blended cement had a beneficial effect on the compressive strength development when compared with only FA blended mortar (Fig. 6(c)). This can be attributed to the higher pozzolanic reaction rate of SF compared to that of FA due to higher content of amorphous SiO_2. Amorphous SiO_2 in SF reacted with the calcium hydroxide from cement hydration to give C–S–H formation, thus leading to increased long-term strength [40–42].

4.1.2. Concrete

The result in Fig. 7(a) shows the strength development of the concrete specimens with FA series compared to the OPC control. After seven days, the 10FA, 20FA and 30FA concrete specimens gained 101%, 90% and 77% compressive strength of the OPC concrete, respectively. The initially lower compressive strength of the FA substitutes due to the lower activity of the fly ash is increasingly approaching that of the OPC. The compressive strength of 10FA and 20FA reaches comparable value to conventional concrete from 28-day age onwards. Moreover, the compressive strength of the 10FA concrete is slightly higher than that of conventional concrete after curing for 56 days. The significant improvement of long-term strength of concrete mixtures with FA due to the pozzolanic reaction is consistent with several previous studies [43–46]. The variation of compressive strength of concrete which combined pozzolan of fixed 5 wt% of SF with several fractions of FA are shown in Fig. 7(b). The compressive strength test results at 7 days curing period suggests that the compressive strength at the early age significantly improved by SF, which was observed from 10% and 5% strength increment in the 5SF and 15FA5SF concretes when compared to the control mixture, respectively. This can be attributed to the pore size refinement and matrix densification, the reduction in the content of $Ca(OH)_2$ and the cement paste-aggregate interfacial zone refinement [47]. At 28-day age, the compressive strength of the 5FA5SF concrete increased rapidly and higher than the 5SF concrete. When considering the higher compressive strength of the 5SF, 5FA5SF and 15FA5SF concrete compared with the OPC concrete, these results demonstrate the mutual encouragement of strength improvement of concrete for the early age by SF and for long-term by FA additives. Fig. 7(c) shows the comparison of strength development of concrete with FA and SF-FA at similar replacement fraction. The results suggest that the cooperation of SF-FA materials shows better efficiency for improving strength when compare to the application only FA material for all replacement fraction. Moreover, it can be noted that the compressive strength results between mortars and

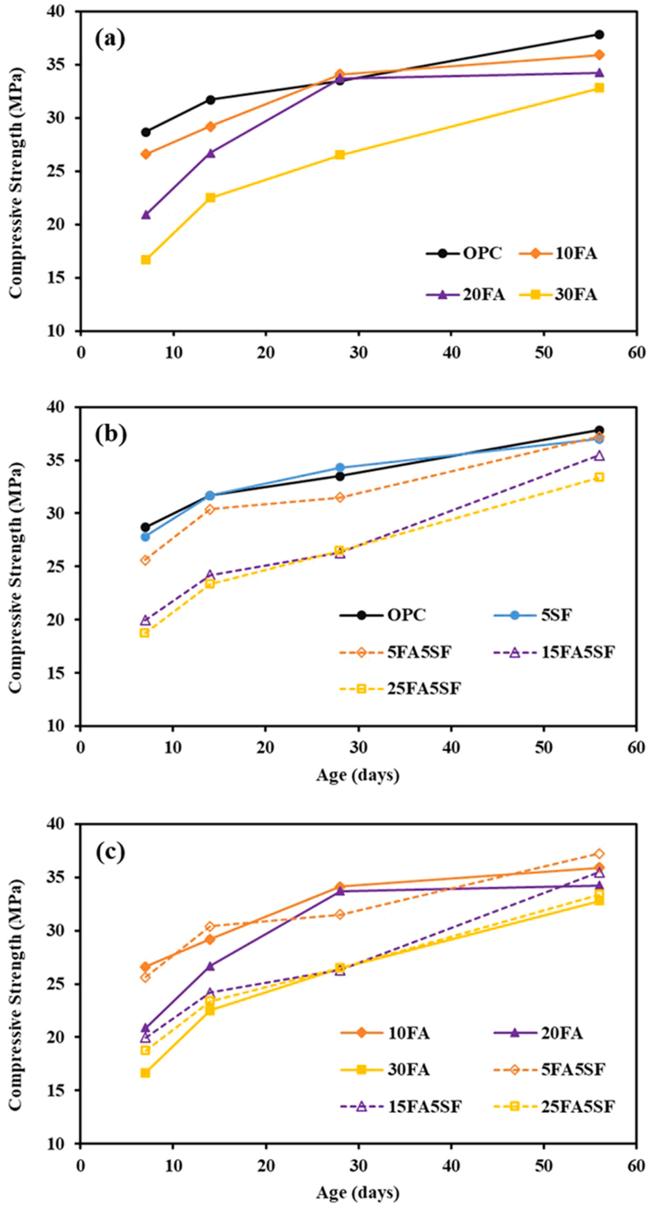

Fig. 6. Age-dependent compressive strength development of mortar; (a) FA system, (b) FA-SF system and (c) comparison of the similar pozzolan content.

concrete are correlated.

4.2. Organic acid resistance

4.2.1. Organic acid resistance of mortar

Organic acids induce corrosion and degradation of the cement-based composites. This can be explained by the reaction between the acid solution and free lime $Ca(OH)_2$ of the concrete producing very soluble calcium salts, which are easily leached away by the aggressive solution [48]. Moreover, when the pH decreases to values lower than stability limits of cement hydrates, the corresponding hydrate loses calcium and decomposes to amorphous hydrogel [3]. The chemical reactions of the $Ca(OH)_2$ or the cement hydrates, i.e. calcium silicate hydrates, with a mono-proton acid of the general formula HA are shown in Eq. (2) and Eq. (3), respectively [49].

$$Ca(OH)_2 + 2HA \rightarrow CaA_2 + 2H_2O \tag{2}$$

$$xCaO \cdot ySiO_2 \cdot nH_2O + 2xHA \rightarrow xCaA_2 + ySi(OH)_4 + (x + n - 2y)H_2O \tag{3}$$

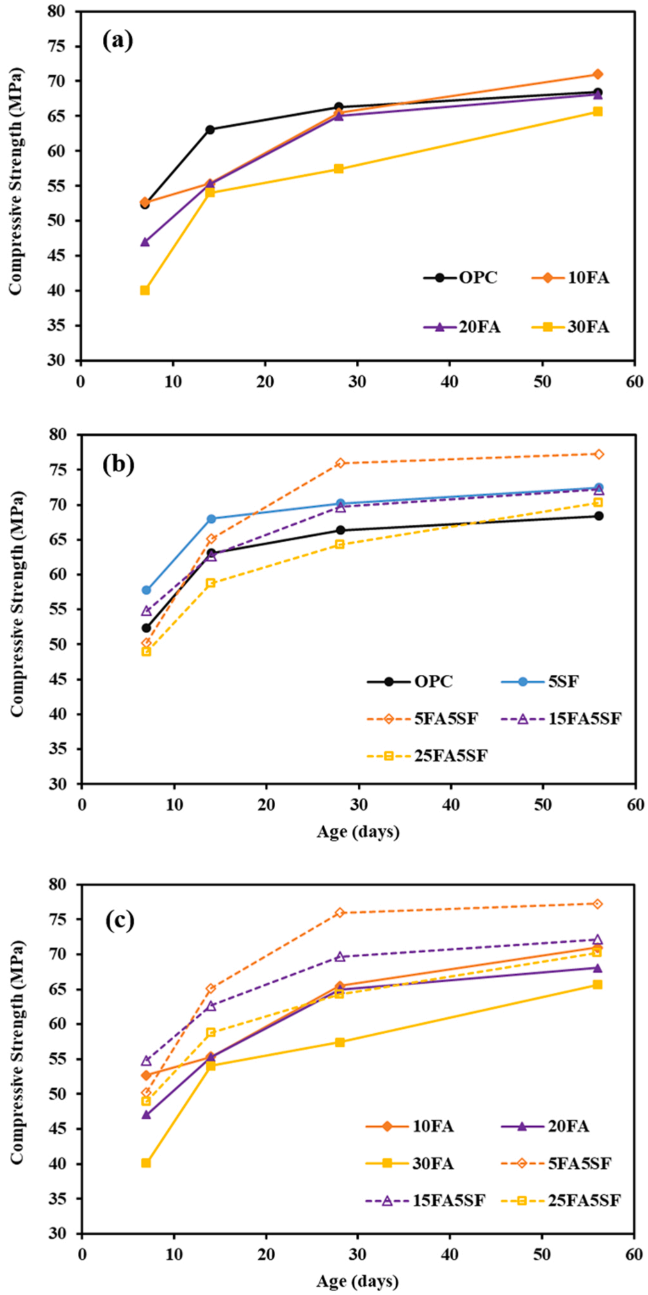

Fig. 7. Age-dependent compressive strength development of concrete; (a) FA system, (b) FA-SF system and (c) comparison of the similar pozzolan content.

The application of FA as a cement replacement for improving acid resistance of mortar was evaluated through the loss rate of mortar mass with different replacement fractions at different exposure times (Fig. 8(a)). The mass loss characteristics of OPC, 10FA and 20FA shows a similar behavior during the early soaking period. However, the mass loss rate of 10FA and 20FA mortar significantly lower than that of the OPC mortar at longer soaking times. This may be due to amorphous silica in fly ash lowering the $Ca(OH)_2$ content via the pozzolanic reaction, which results in a lower leaching rate. In case of the 30FA mortar, a rapid loss of mass occurred at the early age exposed period and then decreased for a longer exposed period. Regarding the effect of FA and SF on the acid resistance mortar with a fixed SF content at 5%, the FA content varied from 0% to 25% as shown in Fig. 8(b). It was observed that at the early age of the soaking period, the mass loss of specimens due to organic acid corrosion of the OPC, 5SF5FA and 25SF5FA mortars were similar. In the same soaking period (during early 14 days of soaking), 5SF and 15FA5SF mortars suffered the highest mass loss percentage. In later stages of immersion, the mass of OPC specimens was continuously lost and showed the highest degree of damage. After 56 days of

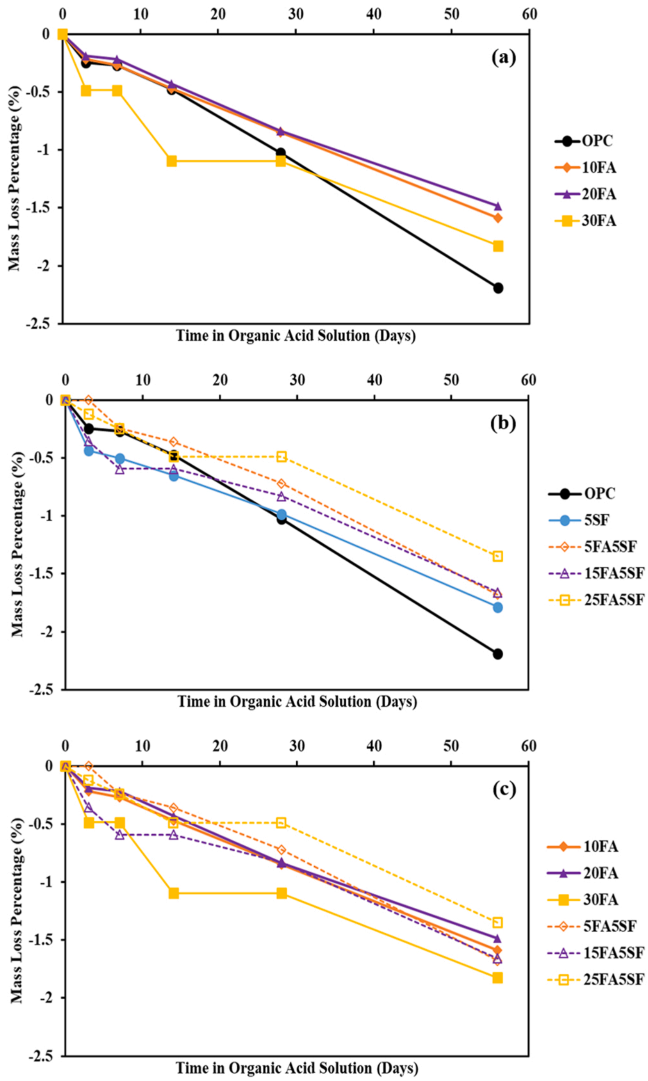

Fig. 8. Age-dependent mass loss of mortar due to organic acid corrosion; (a) FA system, (b) FA-SF system and (c) comparison of the similar pozzolan content.

soaking, the mass loss percentage of 5SF, 5FA5SF and 15FA5SF was lower than that of the OPC at − 40%, − 44% and − 45%, respectively. The 25FA5SF mortars exhibited the lowest mass loss from acid corrosion with − 55% compared with the OPC. The increase of the acid resistance of mortars due to FA and SF agents can be explained by the reduction in overall $Ca(OH)_2$ production when high silica/low calcium-containing supplementary cementitious material replace OPC [50]. Moreover, silica fume decreases the porosity and sorptivity of mortar specimens, which leads to slower penetration of the acid solution into the specimens [51]. For 30 wt% of cement replacement conditions, the mortars containing both FA and SF gained lower mass loss from acid corrosion at long term periods compared to mortar containing only FA for equal replacement fraction, which suggests the combination of SF and FA can improve the resistance of mortars to acid attacks (Fig. 8(c)).

4.2.2. Organic acid resistance of concrete

Fig. 9 shows the variation in mass for the concrete specimens exposed to the lactic acid solution at various soaking times. The slope of the experimental curves is negative, which suggests that the concrete mass was corroded due to the acid solution reacting with the alkaline substances in the concretes (cement paste and aggregate) [52]. At the early age of immersion, the mass losses of OPC concrete and concretes with FA as cement replacement material are similar (Fig. 9(a)). With increasing acid exposure time, the slope of mass loss for concretes with FA is significantly lower than that of the OPC concrete. The increase in FA content causes a decrease of the mass loss rate. The application of FA as the cement replacement agent for 30 wt% significantly improves the acid resistance ability of the concretes, which is different from the mortar test results may be attributed to the aggregate affect. The chemical composition of the aggregates may also play a role in increasing the resistance of the concrete against organic acids since such aggregates as limestone

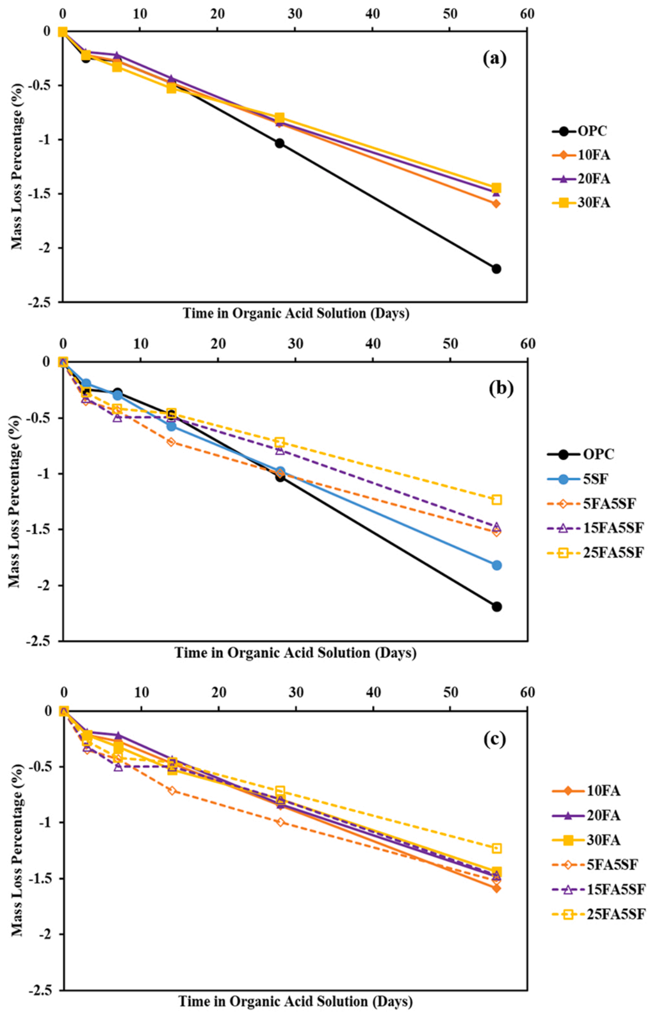

Fig. 9. Age-dependent mass loss of concrete due to organic acid corrosion; (a) FA system, (b) FA-SF system and (c) comparison of the similar pozzolan content.

may react with acids and provide a buffer to protect the hydrated phases [53]. In the FA and SF series, the specimens showed slightly higher mass loss rates than the OPC specimens at the early age of immersion (Fig. 9(b)). The mass loss rates decreased and were lower than that of the OPC specimens at longer immersion age, which is consistent with the mortar test results. Furthermore, concrete specimens containing only FA showed lower efficiency of the acid resistance compared with the specimens containing both FA and SF at similar fractions (Fig. 9(c)).

4.3. Abrasion resistance with organic acid corrosion

Fig. 10 shows the surface of the concrete test specimens after five cycles in the wet-dry switching system with an organic acid solution adding to the abrasion test. The variation in mass of the concrete samples, when exposed to organic acid solution with the system after various cycles, is shown in Fig. 11. The outcomes reveal that the mass loss due to acid and abrasion corrosion tends to increase when a large amount of FA or SF as cement substitution materials increases (Fig. 11 (a) and Fig. 11 (b)). The 10FA concrete mixture shows a slight increase in resistance to acid and abrasion corrosion compared to the OPC mixture. The application of FA for 20 wt% and 30 wt% decreases acid and abrasion resistance significantly. The incorporation of SF with 5 wt% in concrete mixtures slightly improves the acid and abrasion resistance compared with the OPC mixture (Fig. 11 (b)). However, the 15FA5SF and 25FA5SF mixtures exhibit a large mass loss due to acid and abrasion corrosion. It can be noticed that the substitutions of FA and FA-SF at equivalent fractions show similar mass loss rate due to acid and abrasion corrosion (Fig. 11 (c)).

Although the organic acid resistance test results in the previous section suggests that the use of FA and/or SF replacements of OPC provides an effective solution to improve the organic acid corrosion performance of concrete mixtures, the performance regarding acid and abrasion resistance appears to be different. Previous studies indicated that the concrete containing FA or SF might affect the abrasion resistance in concrete to decrease [54–57]. Naik et al. [54] conducted a study to evaluate abrasion resistance of high-volume

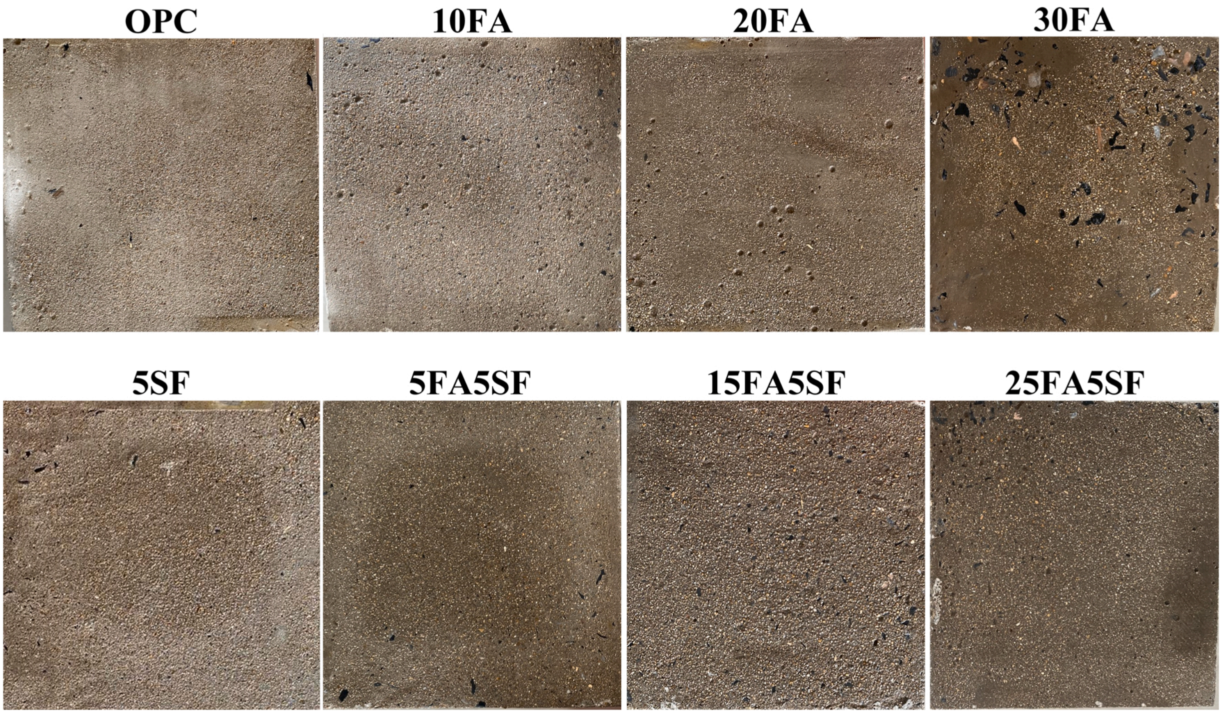

Fig. 10. Surface of test specimens after 5 cycles of wet-dry condition switching system in an organic acid solution cooperating with abrasion corrosion test.

fly ash concrete, and their test results demonstrated that high-volume fly ash (Class C) concrete exhibited low abrasion resistance compared to plain Portland cement concrete. Moreover, Liu carried out an experiment to investigate the effect of silica fume on the abrasion resistance of hydraulic concrete containing surface cracks [58]. The results demonstrated that the abrasion rate of concretes with 5 wt% and 10 wt% silica fume, prepared at water-to-cementitious materials ratios of 0.38 and 0.40, showed a decrease of the abrasion rate by about 10% and 16%, respectively, compared to the one of the control concrete.

The use of pozzolanic materials (such FA and SF) as a cement replacement is well known for improving not only mechanical properties but also acid corrosion resistance of concrete due to pozzolanic reaction and filler effects. This work suggests that the combination of OPC with FA, OPC with SF, and OPC with FA and SF might induce both positive and negative effects on the resistance of concrete from organic acid and abrasion corrosion. In addition, the application of FA and/or SF as supplementary cementitious materials of less than 10 wt% improves the resistance of concrete exposed to organic acid corrosion together with mechanical abrasion.

5. Conclusions

This paper has detailed experiments and results regarding compressive strength, acid resistance, and acid corrosion-abrasion corrosion resistance of concrete containing fly ash and silica fume. Based on the results of these experiments, we can state the following:

1. Adding FA leads to a decrease of compressive strength at the early age, while the long-term strengths display results close to the OPC control mix. However, materials containing both SF and FA show better efficiency for compressive strength compared to materials using only FA material for all replacement fractions.
2. Adding FA and/or SF enhances the organic acid resistance of the mortar and concrete specimens. In terms of mass loss due to acid corrosion, a total of 25% of FA together with 5% SF can potentially reduce the mass loss at 55% and 43% compared to the control mixture for mortar and concrete, respectively.
3. Adding of FA and SF reduces the mass loss from the acid corrosion and abrasion at initial period of testing compared with the OPC concrete. However, the mass loss from acid corrosion-abrasion corrosion increases more than that of the OPC concrete at longer periods of soaking.
4. The utilization of pozzolanic materials (FA and SF) as a partial cement replacement of less than 10 wt% leads to the improvement of the organic acid corrosion together with abrasion corrosion resistance of concrete, which is beneficial for concrete floors in pig farms.

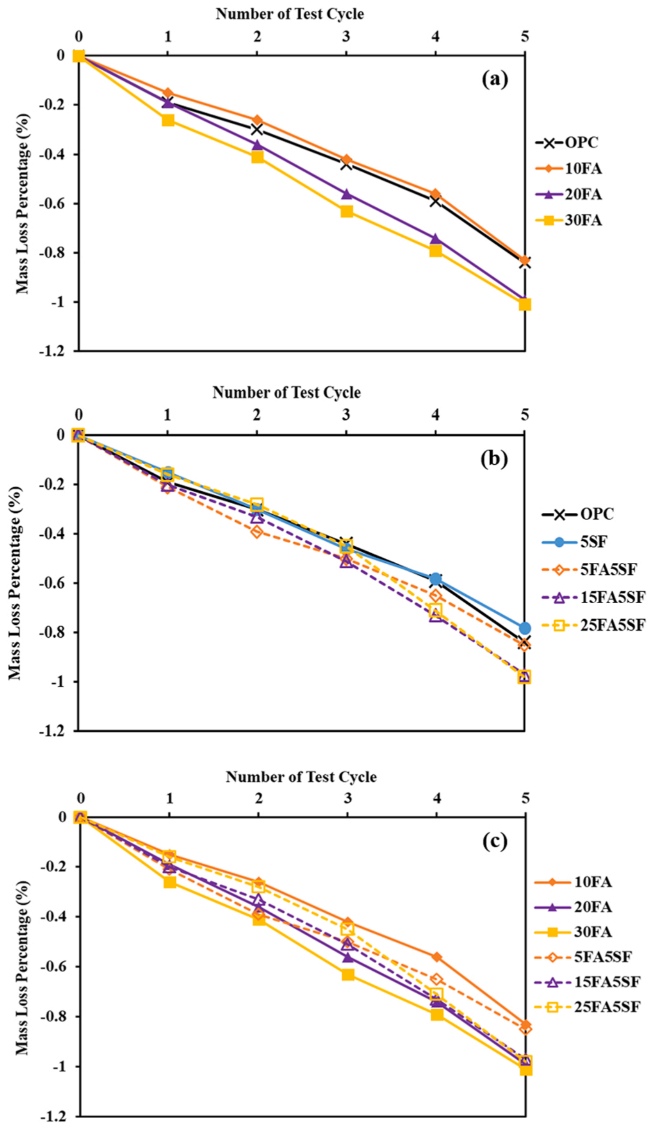

Fig. 11. Mass loss of concrete due to combination of organic acid corrosion and abrasion corrosion; (a) FA system, (b) FA-SF system and (c) comparison of the similar pozzolan content.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] I. Chromková, R. Čechmánek, Effect of agents of organic origin on concrete degradation, in IOP Conference Series: Materials Science and Engineering, 2018, 379.
[2] N. De Belie, J. Monteny, L. Taerwe, Accelerated degradation testing of concrete in acidic environment: resistance to lactic and sulfuric acid. in: Proceedings of the 9th International Conference on Durability of Building Materials and Components, Brisbane, Australia, 2002, 72, 1–10.
[3] A. Allahverdi, F. ŠKVÁRA, Acidic corrosion of hydrated cement based materials, Ceramics Silikáty 44 (2000) 152–160.

[4] R. Sri Ravindrarajah, Acids attack on silica fume high-strength concrete, in: Proceedings of 22nd Australasian Conference on the Mechanics of Structures and Materials, Sydney, Australia 2012.
[5] S. Park, L. Castellano, M.A. Barlaz, M. Pour-Ghaz, Abrasion resistance of concrete exposed to organic acids, J. Mater. Civ. Eng. 32 (2020) 04020205, doi: 10.1061/(ASCE)MT.1943-5533.0003251.
[6] L. Wang, M. Jin, S. Zhou, S. Tang, X. Lu, Investigation of microstructure of C-S-H and micro-mechanics of cement pastes under NH_4NO_3 dissolution by 29Si MAS NMR and microhardness, Measurement 185 (2021), 110019, https://doi.org/10.1016/j.measurement.2021.110019.
[7] J. Yang, J. Huang, Y. Su, X. He, H. Tan, W. Yang, B. Strnadel, Eco-friendly treatment of low-calcium coal fly ash for high pozzolanic reactivity: a step towards waste utilization in sustainable building material, J. Clean. Prod. 238 (2019), 117962, https://doi.org/10.1016/j.jclepro.2019.117962.
[8] G. Aruna, A.K. Rao, K.S. Kadrekar, Studies on drying shrinkage and water permeability of fine fly ash high performance concrete, Mater. Today. Proc. 46 (2021), https://doi.org/10.1016/j.matpr.2021.01.069.
[9] S. Sahoo, P. Kumar Parhi, B.C. Panda, Durability properties of concrete with silica fume and rice husk ash, Clean. Eng. Technol. 2 (2021), 100067, https://doi.org/10.1016/j.clet.2021.100067.
[10] Z. Guo, T. Jiang, J. Zhang, X. Kong, C. Chen, D.E. Lehman, Mechanical and durability properties of sustainable self-compacting concrete with recycled concrete aggregate and fly ash, slag and silica fume, Constr. Build. Mater. 231 (2020), 117115, https://doi.org/10.1016/j.conbuildmat.2019.117115.
[11] E. Güneyisi, M. Gesoğlu, S. Karaoğlu, K. Mermerdaş, Strength, permeability and shrinkage cracking of silica fume and metakaolin concretes, Constr. Build. Mater. 34 (2012) 120–130, https://doi.org/10.1016/j.conbuildmat.2012.02.017.
[12] W. Wongkeo, P. Thongsanitgarn, A. Chaipanich, Compressive strength of binary and ternary blended cement mortars containing fly ash and silica fume under autoclaved curing, Mater. Environ. Prot. Energy Appl. 343–344 (2012) 316–321, https://doi.org/10.4028/www.scientific.net/AMR.343-344.316.
[13] M. Khan, M. Ali, Improvement in concrete behavior with fly ash, silica-fume and coconut fibres, Constr. Build. Mater. 203 (2019) 174–187, https://doi.org/10.1016/j.conbuildmat.2019.01.103.
[14] A. Fuzail Hashmi, M. Shariq, A. Baqi, An investigation into age-dependent strength, elastic modulus and deflection of low calcium fly ash concrete for sustainable construction, Constr. Build. Mater. 283 (2021), 122772, https://doi.org/10.1016/j.conbuildmat.2021.122772.
[15] T. Hemalatha, A. Ramaswamy, A review on fly ash characteristics – towards promoting high volume utilization in developing sustainable concrete, J. Clean. Prod. 147 (2017) 546–559, https://doi.org/10.1016/j.jclepro.2017.01.114.
[16] B. Szostak, G.L. Golewski, Improvement of strength parameters of cement matrix with the addition of siliceous fly ash by using nanometric C-S-H seeds, Energies 13 (2020) 6734, https://doi.org/10.3390/en13246734.
[17] L. Wang, M. Jin, F. Guo, Pore structural and fractal analysis of the influence of fly ash and silica fume on the mechanical property and abrasion resistance of concrete, Fractals 29 (2021) 2140003, https://doi.org/10.1142/S0218348×2140003X.
[18] L. Wang, G. Fan, Y. Hua, W. Yan, T. Sheng, Comparison of fly ash, PVA fiber, MgO and shrinkage-reducing admixture on the frost resistance of face slab concrete via pore structural and fractal analysis, Fractals 29 (2021) 2140002, https://doi.org/10.1142/S0218348×21400028.
[19] N.M.A. Akhras, Durability of metakaolin concrete to sulfate attack, Cem. Concr. Res. 36 (2006) 1727–1734, https://doi.org/10.1016/j.cemconres.2006.03.026.
[20] S.T. Lee, H.Y. Moon, R.N. Swamy, Sulfate attack and role of silica fume in resisting strength loss, Cem. Concr. Compos. 27 (2005) 65–76, https://doi.org/10.1016/j.cemconcomp.2003.11.003.
[21] S. Siddique, J.G. Jang, Acid and sulfate resistance of seawater based alkali activated fly ash: a sustainable and durable approach, Constr. Build. Mater. 281 (2021), 122601, https://doi.org/10.1016/j.conbuildmat.2021.122601.
[22] S. Zhang, K. Cao, C. Wang, X. Wang, J. Wang, B. Sun, Effect of silica fume and waste marble powder on the mechanical and durability properties of cellular concrete, Constr. Build. Mater. 241 (2020), 117980, https://doi.org/10.1016/j.conbuildmat.2019.117980.
[23] G. Baert, A.M. Poppe, N. De Belie, Strength and durability of high-volume fly ash concrete, Struct. Concr. 9 (2008) 101–108.
[24] S. Goyal, M. Kumar, D.S. Sidhu, B. Bhattacharjee, Resistance of mineral admixture concrete to acid attack, J. Adv. Concr. Technol. 7 (2009) 273–283, https://doi.org/10.3151/jact.7.273.
[25] R. Chan, C. Chiemchaisri, W. Chiemchaisri, A. Boonsoongnern, P. Tulayakul, Occurrence of antibiotics in typical pig farming and its wastewater treatment in Thailand, Emerg. Contam. 8 (2022) 21–29, https://doi.org/10.1016/j.emcon.2021.12.003.
[26] E. Gruyaert, P.V.D. Heede, M. Maes, N. De Belie, Investigation of the influence of blast-furnace slag on the resistance of concrete against organic acid or sulphate attack by means of accelerated degradation tests, Cem. Concr. Res. 42 (2012) 173–185, https://doi.org/10.1016/j.cemconres.2011.09.009.
[27] C. Ni, Q. Wu, Z. Yu, X. Shen, Hydration of Portland cement paste mixed with densified silica fume: from the point of view of fineness, Constr. Build. Mater. 272 (2021), 121906, https://doi.org/10.1016/j.conbuildmat.2020.121906.
[28] ASTM Standard C 1157, Standard Performance Specification for Hydraulic Cement, ASTM International, West Conshohocken, PA, 2011.
[29] ASTM Standard C 618, Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete, ASTM International,, West Conshohocken, PA, 2019.
[30] ASTM Standard C305, Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency, ASTM International, West Conshohocken, PA, 2014.
[31] ACI 211.1–91, Standard practice for selecting proportions for normal, heavyweight, and mass concrete, no. 9. Unites States, 2002, 120–121.
[32] ASTM Standard C143, Standard Test Method for Slump of Hydraulic Cement Concrete, ASTM International, West Conshohocken, PA, 2010.
[33] ASTM Standard C109/C109M, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (using 2-in. or [50-mm] Cube Specimens), ASTM International, West Conshohocken, PA, 2013.
[34] ASTM Standard C267, Standard Test Methods for Chemical Resistance of Mortars, Grouts, and Monolithic Surfacings and Polymerconcretes, ASTM International,, West Conshohocken, PA, 2012.
[35] ASTM Standard C1898, Standard Test Methods for Determining the Chemical Resistance of Concrete Products to Acid Attack, ASTM International,, West Conshohocken, PA, 2020.
[36] ASTM Standard C779, Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces, ASTM International,, West Conshohocken, PA, 2012.
[37] M. Seifan, S. Mendoza, A. Berenjian, Mechanical properties and durability performance of fly ash based mortar containing nano-and micro-silica additives, Constr. Build. Mater. 252 (2020), 119121, https://doi.org/10.1016/j.conbuildmat.2020.119121.
[38] J. Yu, G. Li, C.K.Y. Leung, Hydration and physical characteristics of ultrahigh-volume fly ash-cement systems with low water/binder ratio, Constr. Build. Mater. 161 (2018) 509–518, https://doi.org/10.1016/j.conbuildmat.2017.11.104.
[39] J. Yu, C. Lu, C.K.Y. Leung, G. Li, Mechanical properties of green structural concrete with ultrahigh-volume fly ash, Constr. Build. Mater. 147 (2017) 510–518, https://doi.org/10.1016/j.conbuildmat.2017.04.188.
[40] W. Wongkeo, P. Thongsanitgarn, A. Chaipanich, Compressive strength and drying shrinkage of fly ash-bottom ash-silica fume multi-blended cement mortars, Mater. Des. 36 (2012) 655–662, https://doi.org/10.1016/j.matdes.2011.11.043.
[41] D.O. Koteng, C.T. Chen, Strength development of lime–pozzolana pastes with silica fume and fly ash, Constr. Build. Mater. 84 (2015) 294–300, https://doi.org/10.1016/j.conbuildmat.2015.03.052.
[42] E.R. Grist, K.A. Paine, A. Heath, J. Norman, H. Pinder, Compressive strength development of binary and ternary lime–pozzolan mortars, Mater. Des. 52 (2013) 514–523, https://doi.org/10.1016/j.matdes.2013.05.006.
[43] A. Arulrajah, A. Mohammadinia, S. Horpibulsuk, W. Samingthong, Influence of class F fly ash and curing temperature on strength development of fly ash-recycled concrete aggregate blends, Constr. Build. Mater. 127 (2016) 743–750, https://doi.org/10.1016/j.conbuildmat.2016.10.049.
[44] P. Zhang, Q. Li, H. Zhang, Combined effect of polypropylene fiber and silica fume on mechanical properties of concrete composite containing fly ash, J. Reinf. Plast. Compos. 30 (2011) 1349–1358.
[45] S.C.K. Bendapudi, P. Saha, Contribution of fly ash to the properties of mortar and concrete, Int. J. Earth Sci. Eng. 4 (2011) 1017–1023.
[46] A. Hosan, F.U.A. Shaikh, Compressive strength development and durability properties of high volume slag and slag-fly ash blended concretes containing nano $CaCO_3$, J. Mater. Res. Technol. 10 (2021) 1310–1322, https://doi.org/10.1016/j.jmrt.2021.01.001.

[47] G.A. Rao, Investigations on the performance of silica fume-incorporated cement pastes and mortars, Cem. Concr. Res. 33 (2003) 1765–1770, https://doi.org/10.1016/S0008-8846(03)00171-6.
[48] O. Oueslati, J. Duchesne, The effect of SCMs and curing time on resistance of mortars subjected to organic acids, Cem. Concr. Res. 42 (2012) 205–214, https://doi.org/10.1016/j.cemconres.2011.09.017.
[49] C. Maraveas, Durability issues and corrosion of structural materials and systems in farm environment, Appl. Sci. 10 (2020) 990, https://doi.org/10.3390/app10030990.
[50] C. Shi, J.A. Stegemann, Acid. Corros. Resist. Differ. Cem. Mater., Cem. Concr. Res. 30 (2000) 803–808, https://doi.org/10.1016/S0008-8846(00)00234-9.
[51] P. Barnes, J. Bensted, Structure and Performance of Cements, CRC Press, 2019.
[52] F. Girardi, W. Vaona, R. Di Maggio, Resistance of different types of concretes to cyclic sulfuric acid and sodium sulfate attack, Cem. Concr. Compos. 32 (2010) 595–602, https://doi.org/10.1016/j.cemconcomp.2010.07.002.
[53] S. Park, L. Castellano, M.A. Barlaz, M.P. Ghaz, Abrasion resistance of concrete exposed to organic acids, J. Mater. Civ. Eng. 32 (2020) 04020205.
[54] T.R. Naik, S.S. Singh, M.M. Hossain, Abrasion resistance of concrete as influenced by inclusion of fly ash, Cem. Concr. Res. 24 (1994) 303–312, https://doi.org/10.1016/0008-8846(94)90056-6.
[55] R. Choudhary, R. Gupta, R. Nagar, A. Jain, Mechanical and abrasion resistance performance of silica fume, marble slurry powder, and fly ash amalgamated high strength self-consolidating concrete, Constr. Build. Mater. 269 (2021), 121282, https://doi.org/10.1016/j.conbuildmat.2020.121282.
[56] S. Malazdrewicz, L. Sadowski, Neural modelling of the depth of wear determined using the rotating-cutter method for concrete with a high volume of high-calcium fly ash, Wear 477 (2021), 203791, https://doi.org/10.1016/j.wear.2021.203791.
[57] X. Cai, Z. He, S. Tang, X. Chen, Abrasion erosion characteristics of concrete made with moderate heat Portland cement, fly ash and silica fume using sandblasting test, C, Constr. Build. Mater. 127 (2016) 804–814, https://doi.org/10.1016/j.conbuildmat.2016.09.117.
[58] T.C. Liu, Abrasion resistance of concrete, Am. Concr. Inst. J. 78 (1981) 341–350.