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Review

Durability of mortar and concrete made up of pozzolans as a partial replacement of cement: A review

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HIGHLIGHTS

- Durability of mortar/concrete containing blended pozzolans and cement is reviewed.
- Water absorption, permeability, sorptivity and shrinkage are discussed.
- Chloride, carbonation, corrosion, sulfate and acid resistance are highlighted.
- Durability of blended mortar/concrete is compared with the ordinary one.
- Based on past researches, few potential studies are suggested for future research.

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ABSTRACT

In recent years, researchers have been focusing on developing more sustainable cementitious systems in order to curb the negative environmental impacts and disintegration of concrete structures associated with ordinary Portland cement (OPC). Several attempts have been made to develop sustainable binders through the use of pozzolans such as slag, fly ash (FA), palm oil fuel ash (POFA), metakaolin (MK), silica fume (SF), rice husk ash (RHA) etc. with a relatively larger amount of replacement of OPC. A certain level of cement replacement with those pozzolans is highly advantageous in terms of cost, energy efficiency, ecological and environmental benefits as well as durability properties. More recently, researchers have mainly focused on the possibility of practical use of pozzolans (Slag, POFA, FA, SF, MK and RHA) as a partial replacement of cement in quest for improved long-term strength and durability properties. Based on published documents, this paper reviews the current state of knowledge on durability of mortar and concrete made up of pozzolans as a partial replacement of cement. A number of important properties of the made mortar and concrete among others compressive strength, sorptivity, permeability, water absorption, chloride penetration, sulfate resistance, carbonation, drying shrinkage, corrosion resistance, and resistance to acid attack have been discussed here. Finally, several potential studies have been suggested for the future research.

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1. Introduction

Over the past years, many industrial waste materials like FA, slag and other ashes produced from various agricultural wastes such as POFA, RHA, groundnut husk ash, millet husk ash and corn-cob ash have been tried as pozzolanic or secondary cementitious materials [1–6]. These supplementary cementing materials (SCMs) play a significant role when incorporated in the OPC at a certain proportion. Usually SCMs in concrete minimize the permeability of concrete by altering the pore structure and the resulting concrete shows a significant resistance against reinforcement corrosion, acid attack and sulfate attack [7]. Shiathas et al. [8] also reported that these Pozzolanic materials such as ground granulated blast furnace slag (GGBS), RHA, pulverised fuel ash (PFA), SF, FA, POFA generally improve durability properties, reduce adverse environmental effects and also cost of concrete.

Hale et al. [9] reported that cement with a replacement amount of 25% by slag and 15% by FA improved long-term properties of concrete with significant early age properties. An improvement in strength, reduction in permeability as well as reduction in chloride penetration were observed by Thomas and Mathews [10] after adding PFA with OPC in concrete. Authors [10] also observed an improved strength and porosity values for ternary (three-component) blended OPC, RHA and PFA concrete in which strength at a lower replacement level and porosity at a higher replacement level was a significant factor for OPC concrete. Another observation was also reported that the inclusion of PFA and SF in concrete as a partial replacement of cement reduces chloride permeability of concrete [11]. According to Dhir and Byars [12], the construction industry has been steadily regulated to use SCMs with OPC recently as reflected in several standards worldwide. Therefore, durability properties of concrete and mortar by using pozzolanic materials could be established. This paper summarizes the latest advances regarding the durability properties of sustainable binder by using these SCMs as replacement of OPC.

2. Historical background

Investigation of durability properties of mortar and concrete by using pozzolans as a partial replacement of cement was one of the vital issues for researchers over the past few decades. Table 1 presents some recent investigations on durability properties by using SCMs in singular, binary (two-component) and ternary (three-component) blended concrete. The development of using SCMs was a major achievement led by the work of Purdon in 1940s [13]. But the durability studies are the recent issues as they showed a superior compressive strength, splitting tensile strength as well as modulus of elasticity at various ages.

Collepardi et al. [14] showed the influence of mineral additives in the form of FA, slag and ground limestone incorporated as a partial replacement of Portland cement on the CO_2 penetration rate of concrete. The results indicated that there was an increasing trend in the carbonation rate in concretes with increasing mineral additives, except when the amount of OPC replacement was relatively low (15%). On the other hand, when the comparison of the carbonation rate was made on concrete specimens at the same strength level, no significant difference was found between specimens with Portland cement and those with replacement by mineral additives up to 50%. Al-Akhras [15] investigated sulfate resistance of concrete produced from blended MK with OPC to observe the effect of MK where MK was mixed at the replacement levels of 5%, 10%, and 15% by weight of OPC. Concrete specimens were dipped in 5% aqueous solution of sodium sulfate (Na_2SO_4) for 18 months after being moist cured for the desired periods. Sulfate resistance was evaluated in terms of visual observation (for any cracks if initiated), compressive strength reduction and expansion of concrete prisms. The authors [15] reported that replacement of OPC with MK enhanced sulfate resistance of blended concrete specimens in which sulfate resistance increased with increasing MK content in the blend.

In 2007, Ramezanianpour et al. [16] performed chloride permeability/penetration test on concrete incorporated with RHA as a partial replacement of OPC. OPC concrete specimens and specimens by replacing OPC with RHA by the amount of 7%, 10% and 15% (by weight) were prepared. A very low chloride permeability was observed for the specimens prepared using 15% RHA with

Table 1
Some recent studies on durability properties of mortar and concrete containing pozzolans.

Durability properties	Pozzolans used as partial replacement of cement	Author
Carbonation	FA, slag and ground limestone	Collepardi et al. [14]
Sulfate resistance	MK	Al-Akhras et al [15]
Chloride permeability	RHA	Ramezanianpour et al. [16]
Water absorption, drying shrinkage and porosity	MK	Guneyisi et al. [17]
Acid resistance	FA and SF	Murthi et al. [18]
Chloride permeability and Corrosion resistance	RHA and POFA	Rukzon et al. [2]
Sulfate resistance	Black RHA	Chatveera et al. [19]
Modulus of elasticity and Shrinkage	POFA	Awal et al. [5]
Acid resistance	POFA	Budiea et al. [20]
Sorptivity and Carbonation	Slag	Adam et al. [21]
Chloride permeability	RHA, Slag and FA	Gastaldini et al. [22]
Chloride permeability	Slag	Fapohunda et al. [23]
Water permeability, water absorption & chloride ion penetration	RHA	Kartini [24]
Water permeability and porosity	RHA	Jaya et al. [25]
Modulus of elasticity	FA and SF	Turk [26]
Drying shrinkage	FA	Kate et al. [27]
Water absorption and Sorptivity	FA	Pitroda et al. [28]
Carbonation and Chloride permeability	Slag and MK	Duan et al. [29]
Corrosion resistance	POFA	Yahaya et al. [30]
Sulfate resistance	Slag and FA	Nie et al. [31]

FA: Fly ash; MK: Metakaolin; RHA: Rice husk ash; SF: Silica fume; POFA: Palm oil fuel ash.

OPC. On the other hand, moderate, low and low chloride permeability were recorded for the specimens prepared with 0%, 7%, and 10% RHA replacement respectively. In the same year, Guneyisi et al. [17] used MK as a SCMs to enhance the performance of concrete. MK was incorporated by amount of 10% and 20% by weight of OPC, and water-cement (w/c) ratios were taken as 0.35 and 0.55. Durability properties of concrete specimens were observed by measuring water absorption, drying shrinkage and porosity at different ages until 120 days. The authors [17] reported that incorporation of MK content greatly reduced the drying shrinkage strain which mainly relies on the replacement level, w/c ratios and testing ages of the concrete specimens. Incorporation of MK also enhanced pore structures of the concrete specimens by reducing extensive pores. The authors [17] observed that the most impervious concrete specimens were the ones made up of 20% MK replacement. On the other hand, a decreasing trend of water absorption was recorded with increasing MK content.

In 2008, Murthi and Sivakumar [18] investigated the acid resistance of ternary blended concrete by immersing concrete specimens into hydrochloric acid (HCl) and sulfuric acid (H_2SO_4) solutions for 32 weeks. ASTM class F FA was incorporated at an amount of 20% by weight with cement to produce blended concrete. On the other hand, SF was used by 8% replacement level of total powder content by weight to produce ternary blended concrete. Time (in days) was recorded to observe 10% mass loss and strength deterioration of the concrete specimens in 5% H_2SO_4 and 5% HCl solutions. The authors [18] reported that the ternary blended concrete produced from 20% FA and 8% SF showed a significant acid resistance compared with the binary blended concrete and OPC concrete. In the same year, Rukzon and Chindaprasirt [2] performed corrosion resistance and chloride ion penetration tests on mortar specimens made up of binary blends of OPC and ground POFA or ground RHA. The test results revealed that the blended RHA or POFA with OPC can significantly improve corrosion and chloride resistance. Therefore, RHA and POFA have high potentials to be used in concrete industry by a significant amount as a replacement of OPC.

Chatveera and Lertwattanaruk [19] used black rice husk ashes (BRHA) at 0%, 10%, 30% and 50% replacement of OPC (by weight of OPC). Durability properties of prepared mortar specimens were evaluated by immersing the specimens into 5% sodium sulfate (Na_2SO_4) and 5% magnesium sulfate ($MgSO_4$) solutions. The authors [19] observed a reduction trend in compressive strength loss on increasing BRHA replacement level with OPC when the mortar specimens were immersed into Na_2SO_4 solution. On the other hand, compressive strength loss was found to increase with increasing the replacement level of BRHA from 0% to 50% compared to OPC mortar specimens under $MgSO_4$ attack. The authors [19] concluded that the ground BRHA can be used as a replacement with OPC to enhance the resistance against Na_2SO_4 attack, but it may impair resistance against $MgSO_4$ attack. At the same time, Awal and Hussin [5] prepared POFA concrete where OPC was replaced by 30% (by mass) POFA. A slightly lower modulus of elasticity of POFA concrete was recorded in comparison with OPC concrete. However, the authors [5] reported a higher shrinkage strain of POFA concrete compared to OPC concrete.

In 2010, Budiea et al. [20] studied acid resistance (HCl) of the high strength concrete specimens prepared by using POFA with different fineness. OPC was replaced with POFA by 20% (by weight) to prepare two different POFA concrete mixes with different fineness. Reference OPC concrete specimens were also prepared using OPC only. Before immersing in the HCl solution, all the prepared concrete specimens were immersed in water for curing for 28 days. Deterioration was observed in terms of mass changes, visual observations and compressive strength changes. The authors [20] observed that on increasing fineness of POFA enhances resistance of the high strength POFA concrete against acid (HCl) attack. Adam et al. [21] studied durability properties of blended concrete produced by replacing OPC with slag at an amount of 30%, 50%, and 70% by weight of OPC. The authors [21] observed a reduction trend in sorptivity values for the blended concrete specimens while an increasing trend in carbonation values was found with increasing replacement level of slag.

Gastaldini et al. [22] assessed chloride penetration at the age of 91 days according to ASTM C1202 for 10%, 20% and 30% replacement of OPC with RHA. Entire test results were compared with control OPC mixes and with two different binary mixes made up of 35% FA and 50% slag alongside OPC. The authors [22] observed that an increase in RHA content enhances lower charge passed values (Coulomb) and long-term curing reduced charge passed values (Coulomb) for all the prepared mixes. Fapohunda [23] studied chloride permeability of concrete specimens made of 30% replacement of OPC with slag in which all the specimens were cured at elevated temperatures. An increased resistance to chloride penetration was observed for the blended (OPC and slag) concrete specimens. Kartini [24] showed that the concrete incorporated with RHA offers better resistance against chloride ion penetration, water permeability and water absorption when RHA was used up to 30% replacement levels with OPC. Jaya et al. [25] partially replaced OPC (15% by weight) by RHA and observed that the incorporation of RHA produced the concrete with a significant higher compressive strength and low porosity. Moreover, the authors [25] investigated water permeability which was significantly affected by the curing age. Therefore, the authors [25] concluded that permeability coefficient decreases with increase in curing age for blended concrete specimens.

Turk [26] studied binary as well as ternary blended mortar specimens by replacing OPC with FA and SF. The author [26] concluded that increase in SF and FA contents resulted in a decreasing trend in dynamic modulus of elasticity at 28 days for both the binary and ternary blended mortar specimens. Kate and Murnal [27] tested high strength concrete made of 10–70% FA as partial replacement of OPC. The authors [27] observed an increasing trend in shrinkage strain of blended concrete specimens with an increase in FA content. Although the rate of increment of shrinkage over time was uniform for the lower FA concrete specimens, there was a significant increase in shrinkage for high volume FA concrete specimens after 28 days. Moreover, the high volume FA concrete showed a slow strength development rate at an early age of curing. Pitroda et al. [28] also made attempt to study the properties of FA concrete at different percentage of replacement levels of OPC. They [28] found that the water absorption and sorptivity of FA concrete have lower values for 10% replacement of FA. Then, they [28] found an increasing trend of water absorption and sorptivity with increasing percentage replacement of OPC by FA.

Duan et al. [29] also showed that slag and MK have positive impact on pore refinement and interfacial transition zone enhancement of concrete. Yahaya et al. [30] studied corrosion resistance test of a high strength cement concrete mix containing 20% POFA. Reinforcement bar was buried in the middle of prepared cylindrical specimen. The observation leads him to conclude that incorporation of POFA as a partial cement replacement had contributed to the densification of microstructure rendering the concrete denser. This densification that results from the incorporation of POFA allows the concrete to exhibit a higher resistance to corrosion as compared to plain concrete. Nie et al. [31] investigated quality concrete mixtures produced by using slag and FA as a partial replacement of OPC in significant quantities to observe the resistance against an aggressive chemical environment. Sulfate resistance of concrete specimens was found to have significantly improved due to the addition of FA and slag.

3. Durability of mortar and concrete containing pozzolans as replacement of OPC

Durability of concrete means the resistance against deterioration, a prime issue that indicates whether a concrete is durable or does not possess minimum porosity, significant resistance to alkali-silica reaction and sulfate, better corrosion protection ability, reduced heat of hydration, improved resistance to chloride attack and greater resistance against harmful environmental attack. Thomas et al. [32] and Thomas [33] reported that the utilization of those abovementioned pozzolanic materials is extremely advantageous not only to minimize the environmental pollution, but also to enhance the durability of concrete. When pozzolans are added to concrete, they usually alter the pores existing in concrete and minimize water permeability. Therefore, an addition of pozzolans to concrete improves resistance to water penetration and water-induced erosions such as reinforcement corrosion, frost damage, acid and sulfate attack [34–36]. Several durability aspects of mortar and concrete produced by using abovementioned pozzolanic materials have been discussed in the following sections.

3.1. Sorptivity, water absorption and water permeability

The behaviour of pore specimens is assessed by measuring sorptivity, water absorption and water permeability rate of unsaturated specimens by immersing in water with or without water head. Folagbade and Olufemi [37] observed that the sorptivity values decreased on increasing compressive strength and the blended concretes showed lower sorptivity values compared with reference OPC concrete at the similar strength values (Table 2). The authors [37] used OPC as well as several binary and ternary blended concretes containing FA and MK with OPC at equivalent w/c ratios and compressive strengths. They [37] reported that the addition of pozzolanic materials to OPC significantly reduced the sorptivity values of the concrete specimens. Sorptivity values of the FA binary blended cement concrete specimens were found to decrease with the addition of FA content up to 55%. On the other hand, sorptivity values of the MK binary blended cement concretes were found to decrease with the addition of MK content up to only 10%. Authors [37] also reported that the ternary blended concrete shows a better performance compared with the FA binary blended cement concretes when the total replacement level was kept less than 55% at the strength of 50 MPa.

Pitroda et al. [28] also concluded that the water absorption and sorptivity of concrete have lower values at 10% replacement of FA with OPC tested for two different grades of concrete. They [28] also found an increasing trend of water absorption and sorptivity with increasing replacement level of OPC with FA by more than 10%. However, the water absorption and sorptivity of FA incorporated concrete were found to have higher values than traditional OPC concrete. Finally, the results lead them to conclude that the FA can be used as a supplementary cementitious construction material provided some judicious decisions should be made by the engineers. On the contrary, Kakhuntodd et al. [38] have different observations in terms of water permeability as they found that high volume fine FA and fine ground POFA concretes can be produced with relatively low permeability. The permeability values of FA incorporated concretes were found lower than those of the control concretes for all replacement levels. The lowest permeability was obtained with the replacement level of 40%. This result can be attributed to the pozzolanic reaction of FA and the lower amount of mixing water; both of them influenced the reduction in volume and the size of pores in cement paste [39]. Moreover, researchers highlighted the filler effect of the smaller particles of FA which also contributed to produce a denser cement matrix [40].

POFA incorporated concretes also showed the same characteristic of permeability like FA incorporated concretes when the replacement levels were up to 40% by weight of binder [38]. Filler effect was reasonably high up to the replacement level of 40% by POFA and contributed to the low permeability of the concretes. At a higher replacement level of 55% and 70% of OPC by POFA, the permeability increased significantly. The authors [38] concluded that FA is a more effective pozzolan for use in high volume because it produces a good pozzolanic reaction and filler effect through the small particle size. It showed low water demand through the ball bearing effect of the spherical particles. The authors [38] also concluded that the POFA is slightly less effective pozzolan compared to FA and use in high volume resulted in higher permeability.

Assas [41] observed a higher water penetration depth in OPC concrete specimens compared with the concrete specimens containing SF and FA. For all the concrete mixes, it is clear from Fig. 1 that decreasing the w/c ratios has a significant impact on water penetration depth with the increase in OPC content in the mix. Water penetration depth of blended SF concrete showed much lower values compared to blended FA concrete and OPC concrete. The author [41] reported that the addition of SF and FA with OPC to concrete significantly reduces water permeability by improving the pore structure in the transition zone. Similar observations were reported by Menadi et al. [42]. The authors [42] also observed a reduced trend in water penetration depth by using several pozzolans as partial replacement of OPC.

Mahmud [43] observed that at 20% and 30% incorporation of RHA in concrete without and with superplasticizer (SP) respectively showed lower sorptivity values in comparison with OPC concrete specimens (Fig. 2). Therefore, the author [43] concluded that those blended concrete specimens are less porous in comparison with reference OPC concrete specimens. The researcher illustrated the possible reason in such way that the average pore radius of concrete is reduced due to the addition of RHA in which RHA block the extensive voids through the pozzolanic reaction and the finer particles of RHA can easily settle between OPC particles. The results obtained from the study are in line with that obtained by Speare et al. [44]. Mahmud [43] also observed that concrete specimens containing 20% RHA without SP showed a higher percentage of water absorption in comparison with reference OPC concrete specimens. On the other hand, 30% RHA concrete containing SP showed lower water absorption values. The possible reason the author [43] offered was the higher w/c ratio of the RHA20 mix (20% RHA), where water molecules occupy the volume in the concrete specimens and upon evaporation of water from the concrete specimens, leaves voids which are mainly liable for this higher

Table 2
Sorptivity values of concrete specimens at the similar strength values of 30 MPa, 40 MPa and 50 MPa at 28 days curing period [37].

Mix combination	Sorptivity × 10^{-4} (m/$\sqrt{s}$)		
	30 MPa	40 MPa	50 MPa
100% OPC	380	330	275
80% OPC + 20% FA	345	295	255
80% OPC + 15% FA + 5% MK	330	300	255
65% OPC + 35% FA	295	255	230
65% OPC + 30% FA + 5% MK	310	260	225
65% OPC + 25% FA + 10% MK	305	250	220
45% OPC + 55% FA	250	215	180
45% OPC + 45% FA + 10% MK	240	160	100
45% OPC + 40% FA + 15% MK	200	150	110
95% OPC + 5% MK	365	310	260
90% OPC + 10% MK	355	300	235
85% OPC + 15% MK	400	320	235

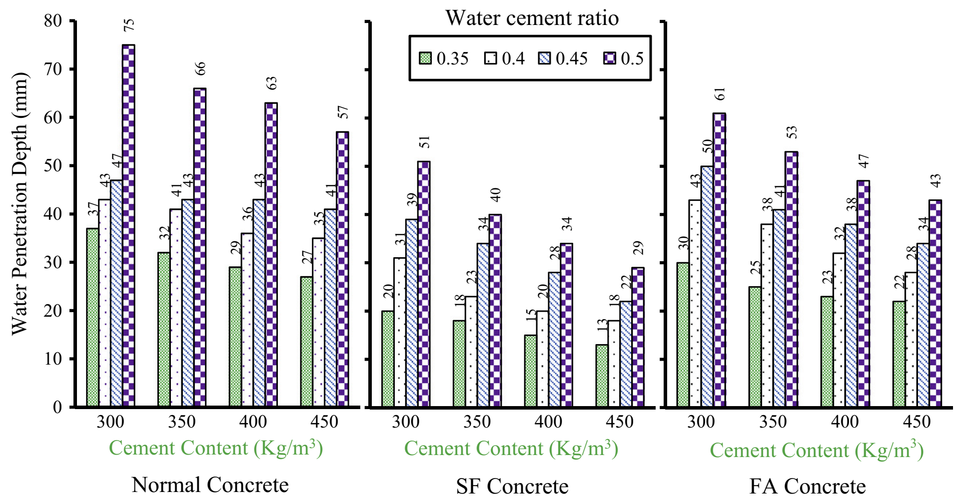

Fig. 1. Water penetration depth of concrete specimens for different w/c ratios at 90 days curing period [41].

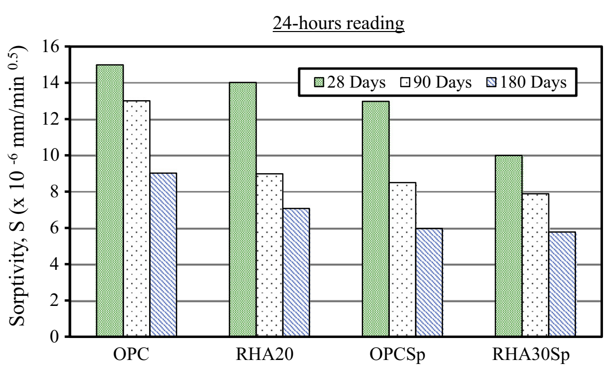

Fig. 2. Sorptivity of concrete mixtures after 24 h immersion period [43].

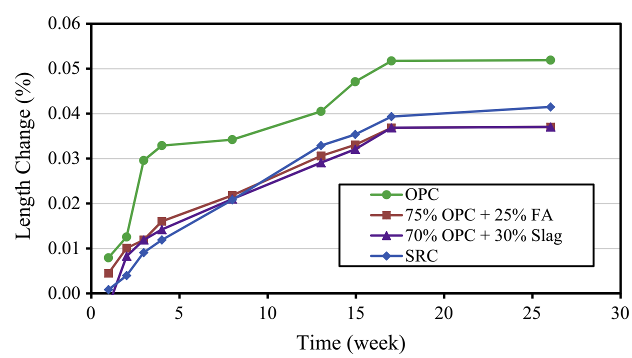

Fig. 3. Effect of SCMs on sulfate resistance of mortar specimens [31].

water absorption value. Therefore, the author [43] concluded that the SP plays a vital role to enhance the liquidity of RHA concrete mixes and maximize the compaction which is mostly responsible for these high impermeable RHA concrete specimens.

Cheng et al. [45] investigated the effect of 0%, 40% and 60% replacement of OPC with GGBS for concrete specimens where they found the permeability values to be 2.56×10^{-13}, 1.52×10^{-13}, and 1.32×10^{-13} m/s respectively. Therefore, the investigation showed that the utilization of higher GGBS content causes more dense structure concrete and minimizes water penetration values of the concrete specimens. Newman and Choo [46] reported that the dense structure concrete (being little permeable to impermeable) can be exhibited by adding the SF to GGBS because of any virtual absence of weak layer that usually surrounds the aggregates.

3.2. Sulfate resistance

The mortar and concrete fabricated with pozzolans alongside OPC improved resistance against sulfate attack than plain OPC mortar and concrete as revealed by several past studies.

According to Nie et al. [31], corrosion of concrete due to sulfate attack commonly appears in terms of cracking, spalling and expansion. The authors [31] evaluated cracking, spalling and expansion by observing length change of the prepared mortars specimens by immersing them in the sulfate solutions. All the mortar specimens were immersed in the sulfate solutions after measuring original length of mortar specimens. Fig. 3 shows the effect of FA and slag on sulfate resistance of mortar specimens in which w/c ratios were kept at 0.4 for all the specimens. It is obvious from the Fig. 3 that the use of SCMs or sulfate resisting cement (SRC) reduces the expansion of the mortar specimens in the sulfate solution in comparison with reference OPC mortar specimens. It is to be noted that the long-term permanence of the mortar specimens with SCMs is better compared with SRC mortar specimens as well as OPC mortar specimens.

Cements evaluated by Bhatty and Taylor [47] for sulfate resistance were: ASTM Type I, Type V, Type I + 7% SF and Type I + 20% FA. Mortar specimens (50 mm cube) were prepared by using w/c ratios of 0.50. The prepared mortar specimens were immersed into different concentration of Na_2SO_4 solutions for two years to observe the physical deterioration of the mortar specimens. The authors [47] observed that the deterioration was significantly affected by the concentration of sulfate solutions, cement type as well as the immersion periods. Type I + 20% FA showed the best sulfate resistance among the all mixtures. Selected data illustrated by the authors [47] on deterioration of specimens caused by the immersion in Na_2SO_4 solution is given in the Table 3.

Chatveera and Lertwattanaruk [19] used black rice husk ash (BRHA) at replacement levels of 0%, 10%, 30%, and 50% of OPC by total weight of the binder. Sulfate resistance of mortar specimens was evaluated in terms of expansion and compressive strength loss. Water to binder ratio was kept at 0.55 and 0.65 for the prepared mortar specimens. The mortar specimens were immersed into 5% Na_2SO_4 and 5% $MgSO_4$ solutions for 180 days curing period. The test results indicated that the expansion and compressive strength loss of mortar specimens decreased with the increase in

Table 3
Deterioration rating of the mortar specimens due to immersion in Na_2SO_4 solution [47].

Cement type	Sulfate solution (%)	Deterioration rating in exposure time			
		4 Months	8 Months	15 Months	24 Months
Type I	1	0	1	2	3
	2	2	2	3	4
	4	3	3	3	3
Type V	1	0	0	0	1
	2	0	0	0	2
	4	1	1	1	3
Type I + 7% SF	1	0	0	1	1
	2	0	0	1	2
	4	1	2	2	3
Type I + 20% FA	1	0	0	0	1
	2	0	0	0	1
	4	0	1	2	2

0 – No deterioration; 1,2,3 – Increasing rate of deterioration.

percentage replacement of BRHA. Expansion of the mortar specimens prepared using 30% and 50% replacement of OPC by BRHA was found to be lower than those of specimens prepared by mixing with SRC. Notably, the expansion of mortar specimens immersed into Na_2SO_4 solution was found higher compared with the specimens which were immersed into $MgSO_4$ solution. However, an increase in the replacement level of BRHA resulted in minimizing the compressive strength loss of the mortar specimens due to Na_2SO_4 attack. On the other hand, an increase in the replacement level of OPC by BRHA resulted in an increase in compressive strength loss from 0% to 50% compared with OPC mortar specimens due to $MgSO_4$ attack (Figs. 4–7). Therefore, the authors [19] concluded that the BRHA can be utilized as a SCMs in concrete technology to enhance resistance against Na_2SO_4 attack; however, it may show less resistance against $MgSO_4$ attack.

Formation of expansive gypsum and ettringite is most likely to cause deterioration, cracking, spalling and expansion in the OPC concrete due to sulfate attack. Sulfate affords to react with different products of OPC paste which results in the formation of gypsum and ettringite [48,49]. Mehta [50] also reported that the OPC paste when immersed in sulfate solutions decreases stiffness and increases the water absorption values of the ettringite. Another issue is that the expansion and cracking due to sulfate attack increases the compressive strength loss of concrete specimens by reducing cohesion in the hydrated OPC paste as well as by reducing adhesion among the aggregate particles [48]. Several previous researchers have been reported the role of FA as a SCMs in OPC concrete in improving its sulfate resistance [51–53].

Concrete produced by using GGBS with OPC also exhibits superior resistance against sulfate attack in comparison with OPC concrete due to the reduction in the C_3A content in the blended OPC concrete as GGBS does not contain significant C_3A. It is commonly considered that the Al_2O_3 content in the GGBS is lower by 15% than that in OPC and cement containing minimum 70% GGBS is accepted as a sulfate resisting OPC [46]. Higgins and Uren [54] also observed an increase in sulfate resistance of the concrete specimens prepared by partially replaced OPC with GGBS. Utilization of MK and RHA also improves sulfate resistance of the concrete specimens. Utilization of MK up to 15% with OPC showed a significant sulfate resistance in a Na_2SO_4 solution [55]. In the same way, concrete prepared by using RHA with OPC has also served as an excellent sulfate resistant compared with OPC and blended SF concrete [56]. Therefore, it can be finally concluded that the sulfate resistance

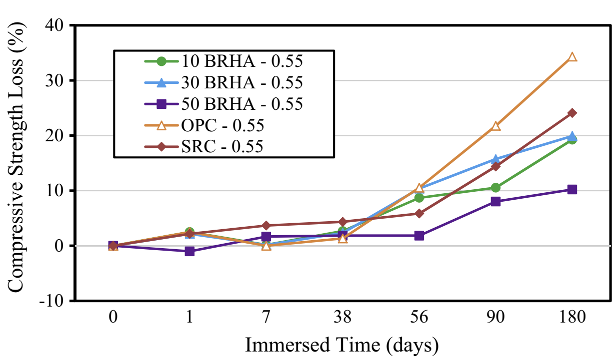

Fig. 4. Compressive strength loss of mortar specimens immersed into Na_2SO_4 solution (water to binder ratio of 0.55) [19].

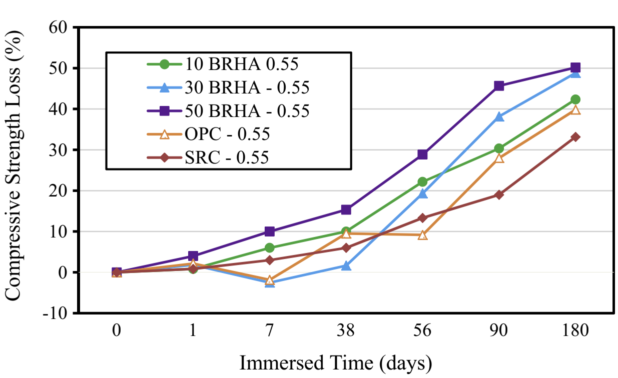

Fig. 5. Compressive strength loss of mortar specimens immersed into $MgSO_4$ solution (water to binder ratio of 0.55) [19].

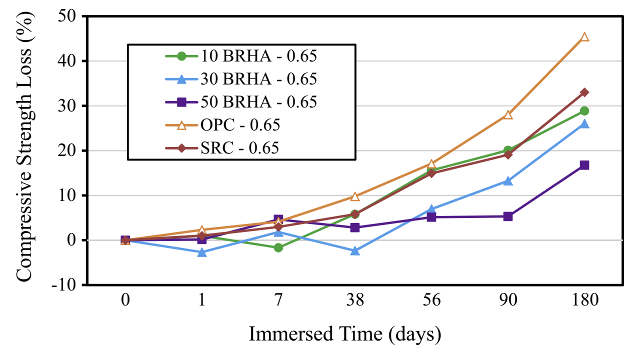

Fig. 6. Compressive strength loss of mortar specimens immersed into Na_2SO_4 solution (water to binder ratio of 0.65) [19].

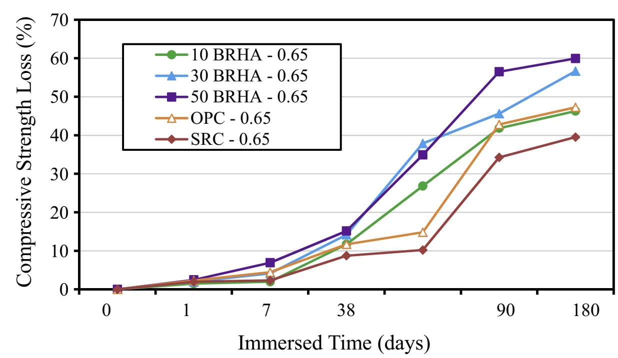

Fig. 7. Compressive strength loss of mortar specimens immersed into $MgSO_4$ solution (water to binder ratio of 0.65) [19].

of concrete can be significantly improved by using pozzolanic materials with OPC which will be advantageous also for long-term strength and durability properties of the concrete.

3.3. Chloride ion penetration

Porous structure allows absorption of salts in reinforced concrete is mainly liable for transportation of chloride ions which resulted in anodic as well as cathodic region. Thus, corrosion of the steel and rupture of concrete can occur due to electrolytic action. Divsholi et al. [57] showed that partial replacement of GGBS with Portland cement (PC) significantly reduces chloride ion penetration. Rapid chloride permeability test (RCPT) was performed to measure the total Coulombs passed during 6 h for the samples with 42 days of water curing. Fig. 8 revealed that 50% GGBS replacement level resulted in a significant reduction in the total charge passing through the concrete. Duan et al. [29] observed minimum chloride migration coefficient (Fig. 9) for long-term curing periods. The authors [29] reported the lowest chloride ions migration coefficient for the concrete specimens containing GGBS and MK for all the curing periods. In addition, 10% MK and 10% GGBS replacement level with OPC in concrete specimens demonstrates a significant resistance against chloride ions penetration.

Kartini [24] showed the results of charge passed values (Coulomb) for concrete specimens at ages up to 365 days curing age which are represented in Fig. 10. The results indicated that the charge passed (Coulomb) values for the OPC concrete specimens with and without super plasticizer (SP) were higher in comparison with RHA concrete specimens. The author [24] reported a moderate to low chloride penetrability for blended RHA concrete specimens. The author [24] cited the possible reason in such way that the RHA in the concrete mixes gave a pore refining effect which

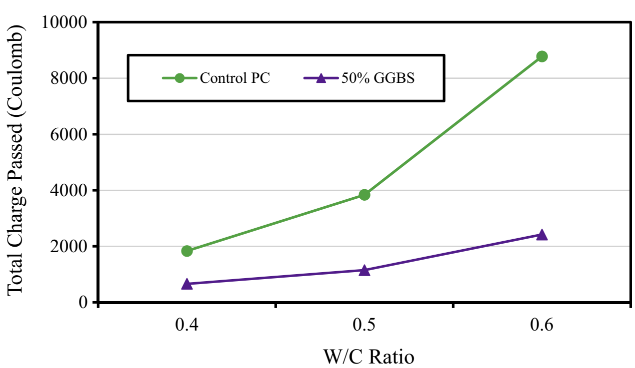

Fig. 8. Effect of slag replacement with different w/c ratio on RCPT results (42 days water curing) [57].

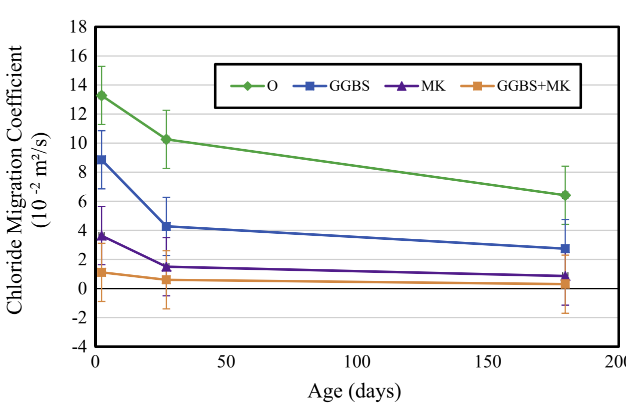

Fig. 9. Effects of GGBS and MK on chloride ions migration coefficient [29].

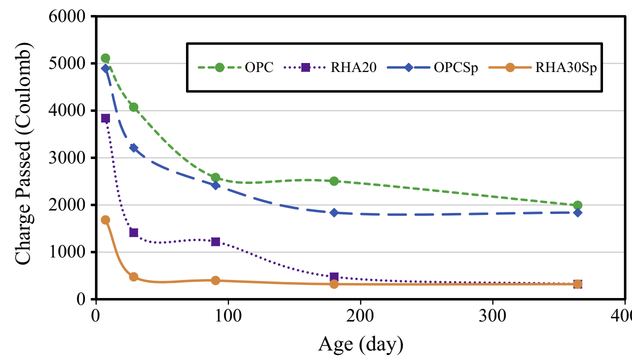

Fig. 10. Charge passed values (Coulomb) for RHA concrete specimens with and without SP [24].

further reduced charge passed values. The author [24] also suggested that the reduction in charge passed values can be improved by adding a significant amount of SP.

Assas [41] observed that the blended SF with OPC concrete specimens showed a better performance in terms of chloride ion permeability in comparison with OPC concrete as well as blended FA with OPC concrete specimens (Figs. 11–13). The author [41] concluded that the 20% FA or 10% SF replacement of OPC significantly improves resistance against chloride ion penetration. The concrete specimens produced by replacing 20% OPC by FA showed a slightly lower chloride diffusivity compared with OPC concrete specimens after 28 days curing periods. The influence of FA was more significant at the later ages as shown in Figs. 12 and 13. The figures also illustrated that the SF was more effective to resist chloride ion diffusion in comparison with FA. The concrete specimens produced by replacing 10% SF enhances lower chloride diffusivities in comparison with FA concrete specimens for all levels of OPC content as well as w/c ratios. The author [41] ascribed this to the fact that 10% SF replacement alter the pores significantly of the prepared specimens. The author [41] concluded that the chloride ion penetration resistance of FA concrete specimens increased significantly as the degree of pozzolanic reaction increased after long-term curing periods.

3.4. Carbonation

Carbonation rate of mortar and concrete mainly depends on physical properties of the solid binder, chemistry of the binder phase, porosity and permeability of the binder. Collepardi et al. [14] showed the influence of mineral additives (in the form of FA, slag and ground limestone) incorporated in OPC on the CO_2 penetration rate of concretes manufactured with a given water-cementitious material ratio (w/c). They [14] reported that when the comparison of the carbonation rate is made on concretes at the same strength level, there is no significant difference between concretes with OPC and those with pozzolans up to 50% replacement level (Table 4).

Duan et al. [29] measured the depth of carbonation (Fig. 14) of concrete specimens where OPC was replaced by MK and GGBS. The carbonation depth of concrete was significantly reduced due to the addition of MK and GGBS with OPC. The authors [29] reported that the phenomenon was predominantly because of the pozzolanic reaction of MK and GGBS as the amount of hydration product $Ca(OH)_2$ decreases by the replacement of OPC with GGBS and MK. In addition, fine MK particles fill up the gaps among the OPC particles which densify the concrete specimens and results in lower CO_2 intake into the pores of concrete specimens.

Yu et al. [58] reported that the $Ca(OH)_2$ content in the RHA paste (produced by replacing 30% RHA with OPC) started to

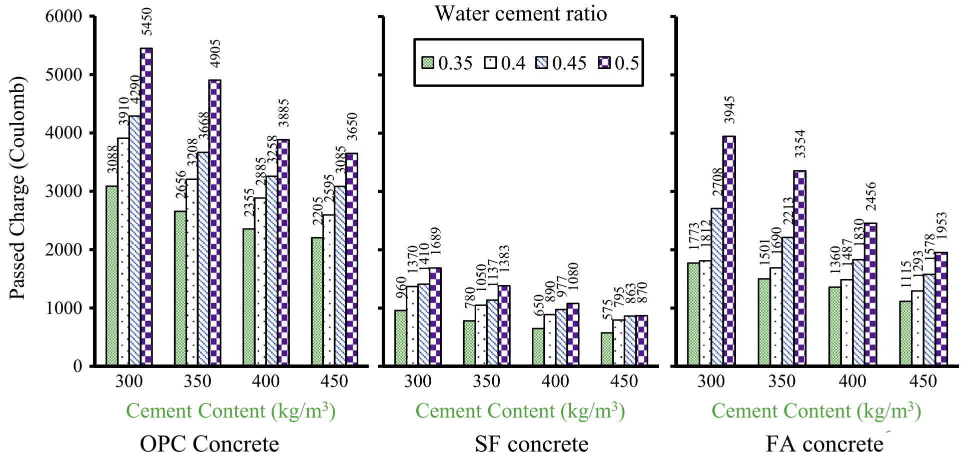

Fig. 11. Charge passed values (Coulomb) for different concrete types and w/c ratios after 28 days [41].

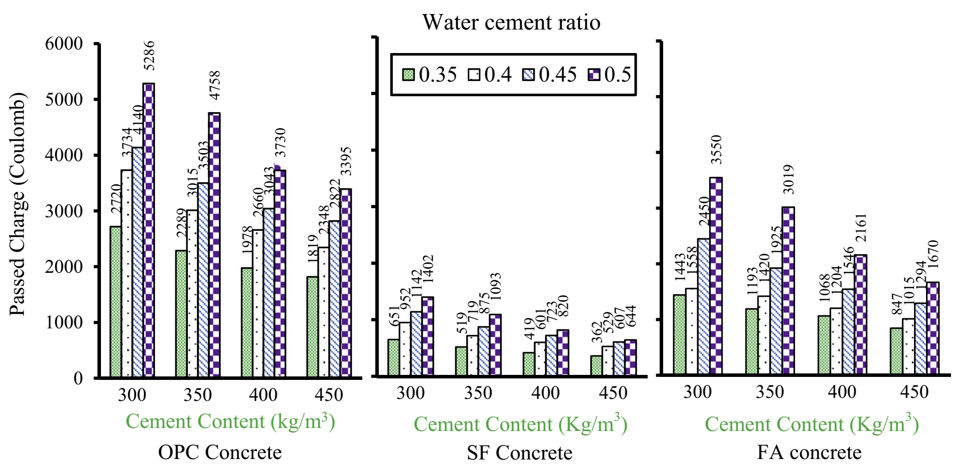

Fig. 12. Charge passed values (Coulomb) for different concrete types and w/c ratios after 90 days [41].

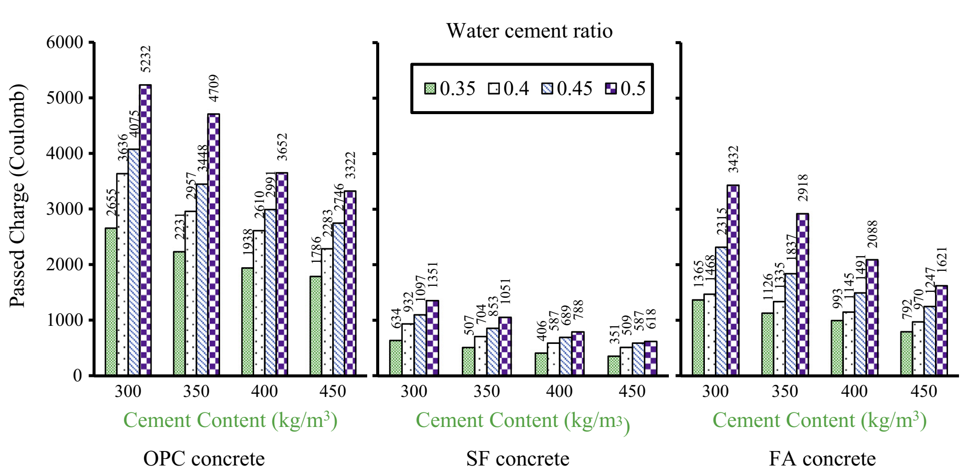

Fig. 13. Charge passed values (Coulomb) for different concrete types and w/c ratios after 360 days [41].

decrease after 3 days curing age, and it was around zero after 90 days curing age. Based on the experimental observation, the authors [58] reported that the RHA concrete contains more C-S-H gel and less portlandite in comparison with OPC concrete which mainly accounts for the improved resistance against carbonation. This is also echoed by Horsakulthai and Paopongpaiboon [59].

3.5. Corrosion resistance

In reinforced concrete structures, superior corrosion resistance of reinforcing bars is a vital durability issue. Therefore, several techniques have been applied so far to measure corrosion affinity of reinforcing steel in the concrete. Yahaya et al. [30] reported cor-

Table 4
Carbonation rate of concrete with and without pozzolans at a given 28 days compressive strength in the range of 40-45 MPa [14].

Composition of cementitious materials (cm)				Cement content (kg/m^3)	w/c ratio	Strength (MPa)	Carbonation depth (mm)					
PC (%)	Lime-stone (%)	FA (%)	Slag (%)				30 days	45 days	60 days	90 days	180 days	360 days
100	–	–	–	300	0.6	43.0	0.5	2.0	2.5	3.5	4.0	4.8
85	–	–	15	300	0.6	40.3	0.5	2.5	3.0	3.5	4.8	5.9
50	–	–	50	350	0.5	42.2	0.5	1.5	2.0	3.0	4.0	5.5
85	15	–	–	350	0.5	45.0	0.0	2.0	2.5	3.0	3.5	4.7
75	25	–	–	350	0.5	40.3	0.5	2.0	3.0	4.5	6.0	6.9
75	–	25	–	350	0.5	44.0	0.0	1.0	2.0	3.5	5.0	5.7
					Average	42.5	0.3	1.8	2.5	3.5	4.5	5.5

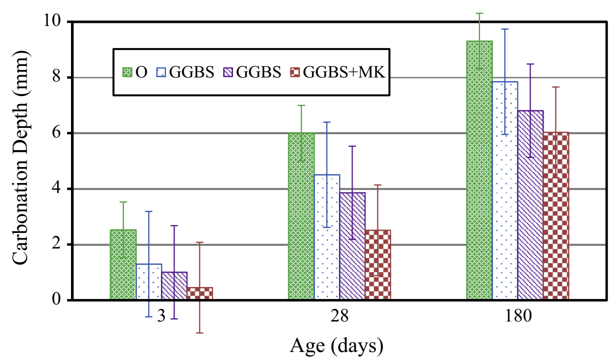

Fig. 14. Carbonation depth for GGBS and MK based concrete specimens [29].

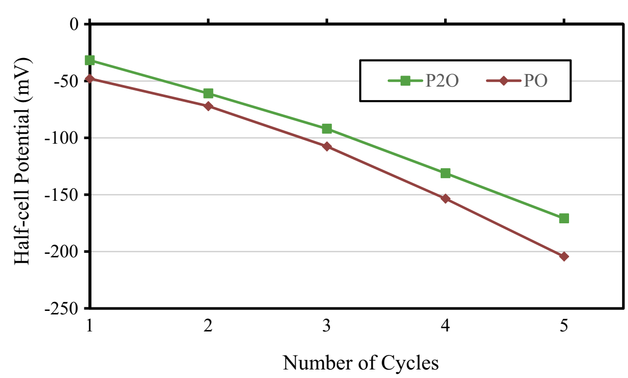

Fig. 15. Potential vs. number of cycles of exposure of P0 and P20 concrete in 5% NaCl solution [30].

rosion resistance of both plain concrete (P0) and POFA high strength concrete (P20) which was obtained in the form of half-cell potential values as shown in Fig. 15. The half-cell potential values of concrete with POFA was higher than that of plain concrete indicates a better resistance of the blended cement concrete against corrosion. Incorporation of POFA increases the amount of C-S-H gel which contributes to concrete pore refinement and makes the concrete denser. Furthermore, the filler effect of fine POFA that strengthens the transition zone between the paste and the aggregate also improves the concrete internal structure resulting in a higher strength and durability. The densification of POFA high strength blended cement concrete microstructure makes this concrete more corrosion resistant in comparison to plain concrete [60].

Saraswathy and Song [61] cast cylindrical concrete specimens (50 mm diameter and 100 mm height) to study corrosion performance of concrete where OPC was replaced by RHA at 5%, 10%, 15%, 20%, 25% and 30% to prepare those specimens. They [61] embedded rebar of 12 mm diameter and 100 mm height into the cylindrical specimens. After 28 days of curing periods, cylindrical concrete specimens were subjected to impressed voltage test. The authors [61] reported that no cracks were formed even after 144 h of exposure by higher replacement percentages (15%, 20%, 25% and 30%) of RHA with OPC, whereas OPC concrete specimens showed cracks upon 42 h of exposure in 5% NaCl solution. They [61] concluded that the replacement of OPC by RHA filled the pores into the microstructure and as a result the permeability and corrosion decreased.

Polder [36] studied concrete structures in marine environment up to 60 years. Based on the several decades laboratory works, the author [36] reported that the concrete specimens produced by 70% GGBS replacement with OPC exhibits an excellent behaviour with respect to reinforcement corrosion. The researcher stated that the blended GGBS concrete specimens greatly decrease apparent diffusion coefficients over time in comparison with OPC concrete specimens. Therefore, blended GGBS concrete showed a superior electrical resistivity as well as minimum corrosion rate. On the other hand, moderate FA replacement with OPC showed minimum diffusion coefficients and superior resistivity in comparison with OPC after several months of hydration periods. The author [36] also observed that the composite produced by FA and slag at 25% OPC replacement behaves in a similar manner. He [36] concluded that replacement of Portland clinker by slag at high levels (50–70%) and FA at intermediate levels (20–30%) decreases the risk of corrosion in chloride rich environments.

3.6. Drying shrinkage

Drying shrinkage is an important characteristic of concrete that affects the eternal structural properties and durability properties of structures. Awal and Hussin [5] measured shrinkage values over a period of 28 days (Fig. 16) which showed that POFA concrete achieved a higher shrinkage strain compared with OPC concrete. The magnitude of shrinkage strain of OPC concrete at 28 days, for

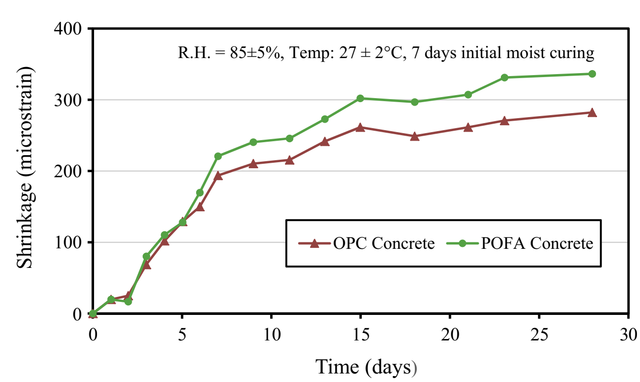

Fig. 16. Shrinkage of OPC concrete and POFA concrete [5].

example, was 275.2×10^{-6}. At the same time about 19% higher value of shrinkage i.e. 328.8×10^{-6} was recorded for the concrete with 30% POFA. The authors [5] stated that the difference in the amount and nature of paste in the POFA concrete could be responsible for the higher shrinkage value in this concrete. A similar observation has been made by Brooks and Neville [62] who have demonstrated that at a certain w/c ratio, a higher rate of FA leads to higher shrinkage by 20%.

Kate and Murnal [27] observed shrinkage values of various concrete mixes with the cement replacement level of 0%, 10%, 25%, 40%, 55% and 70% by FA. The drying shrinkage of high strength OPC concrete and blended FA high strength concrete were obtained from rectangular specimens prepared and tested under specified conditions. The test results of shrinkage and shrinkage strain of concrete Mix-1 (1:1.05:3.08) and Mix-2 (1:0.65:1.91) containing different quantities of FA are represented in Tables 5 and 6. The specimens were made for each concrete mix separately and tested at 7, 28 and 56 days. The effect of 10–70% replacement of cement with FA on shrinkage strains of 7 days cured rectangular concrete specimens was studied under the air dried condition. The results of shrinkage strain were compared among different types of concrete at specific days (7, 28 and 56 days) under the same experimental condition. The strain calculated at each age was the average of three measurements. One specimen was taken from each of the three batches of the concrete mixtures. The authors [27] concluded that the rate of increase of shrinkage strain with the increase in FA content is relatively higher at 56 days than 7 and 28 days. So, shrinkage strains of high strength concrete increases with the increase in FA content.

Guneyisi et al. [17] reported the strain development versus time (Fig. 17) for blended MK with OPC concrete as well as OPC concrete at two w/c ratios of 0.35 and 0.55. The authors [17] observed that the difference of drying shrinkage between OPC and blended MK concretes was insignificant, particularly for the lower w/c ratios. Difference of drying shrinkage became more pronounced and the drying shrinkage of blended MK concrete decreased with increasing MK replacement levels after 2 weeks. The authors [17] observed that the blended MK concrete showed a comparatively lower shrinkage strain than OPC concrete at 60 days. It was concluded that an increase in replacement levels of OPC with MK resulted in reduction in drying shrinkage at intermediate w/c ratios. However, at 10% and 20% MK replacement showed 13% and 18% lower drying shrinkage compared with OPC concrete respectively at higher w/c ratios. Brooks and Megat-Johari [63] also reported similar observations. The authors [63] observed that the total drying shrinkage was significantly lower for the blended MK concretes in comparison with OPC concrete measured after 24 h. The effect of MK was observed to minimize the shrinkage value of OPC concrete by 50%. A similar observation was made by Al-Khaja [64] as well as Jainyong and Yan [65] on drying shrinkage for the blended SF concretes.

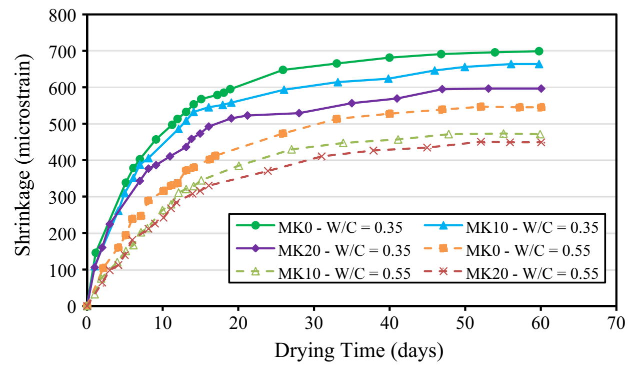

Fig. 17. Drying shrinkage of blended MK concretes and OPC concretes with drying time [17].

Table 5
Test results of shrinkage of concrete Mix-1, length of specimen: L = 275 mm [27].

Mix designation	FA (%)	Change in length (ΔL) in mm			Shrinkage strain (ΔL/L) × 10^{-4}		
		7 days	28 days	56 days	7 days	28 days	56 days
Mix 1-1	0	0.035	0.077	0.141	1.27	2.80	5.12
Mix 1-2	10	0.040	0.102	0.135	1.45	3.70	4.90
Mix 1-3	25	0.040	0.104	0.191	1.45	3.78	6.94
Mix 1-4	40	0.047	0.111	0.200	1.70	4.03	7.27
Mix 1-5	55	0.057	0.076	0.232	2.07	2.76	8.43
Mix 1-6	70	0.097	0.140	0.260	3.52	5.09	9.45

Table 6
Test results of shrinkage of concrete Mix-2, length of specimen: L = 275 mm [27].

Mix designation	FA (%)	Change in length (ΔL) in mm			Shrinkage strain (ΔL/L) × 10^{-4}		
		7 days	28 days	56 days	7 days	28 days	56 days
Mix 2-1	0	0.031	0.219	0.310	1.12	7.96	11.2
Mix 2-2	10	0.079	0.170	0.308	2.87	6.18	10.9
Mix 2-3	25	0.069	0.190	0.330	2.50	6.90	12.0
Mix 2-4	40	0.066	0.251	0.280	2.40	9.12	10.1
Mix 2-5	55	0.087	0.104	0.295	3.16	3.78	10.2
Mix 2-6	70	0.094	0.236	0.325	3.41	8.58	11.8

Al-Khaja [64] observed that the shrinkage of OPC concrete specimens was noticeably reduced by the addition of SF. After one-month of curing period, concrete specimens showed a reduction in strain by 34.9% due to the shrinkage. Jainyong and Yan [65] showed that the GGBS and SF enhance the hydration of OPC which results in increase in C-S-H gel that exerts a superior resistance against deformation for any applied forces. The authors [65] also stated that the incorporation of SF and GGBS in concrete fills miniature pores and voids which mainly contribute to minimization of drying shrinkage of blended concrete specimens.

Habeeb and Fayyadh [66] reported that drying shrinkage of RHA mixed concrete was greater than OPC concrete where 20% cement was replaced by RHA. Mahmud et al. [67] cast 150 mm × 300 mm cylindrical concrete specimens to measure drying shrinkage according to ASTM C(531-85). The authors [67] reported that a higher amount of RHA in concrete showed a lower drying shrinkage value. Similarly, Wu and Peng [68] reported that at normal temperature, drying shrinkage of RHA mixed concrete is lower than that of OPC concrete. Zhang and Malhotra [69] found a similar drying shrinkage for control concrete and 10% RHA concrete after 448 days. It can be concluded that drying shrinkage performance is not so good in case of high percentages RHA blended concrete due to the reduction of cement and pore structure.

3.7. Acid resistance

Acid resistance of mortar and concrete specimens was evaluated so far in terms of visual observation, change in weight and change in compressive strength by immersing specimens in acid solutions. Fineness of POFA improved the resistance against HCl attack for a high strength blended POFA concrete when POFA possessed a median particle size of 45 μm (POFA45) and 10 μm (POFA10) at 20% replacement with OPC (by weight) [20]. It can be observed (Fig. 18) that the concrete specimens prepared with POFA10 showed a comparatively lower mass change in comparison with reference OPC (P0) and POFA45 concrete. Disintegration of all concrete specimens increased on increasing the immersion period. A significant compressive strength reduction was also observed for POFA45 and POFA10 concrete specimens (Fig. 19) in comparison

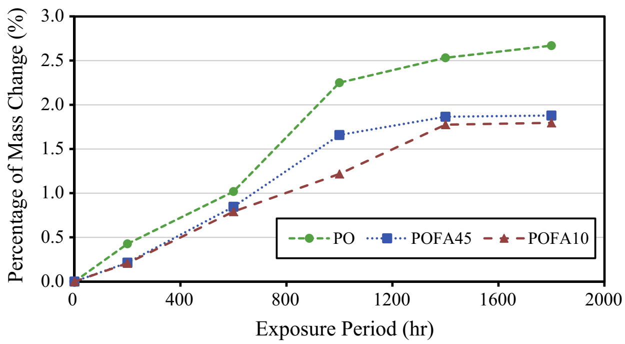

Fig. 18. Mass changes in concrete specimens due to immersion in HCl solution [20].

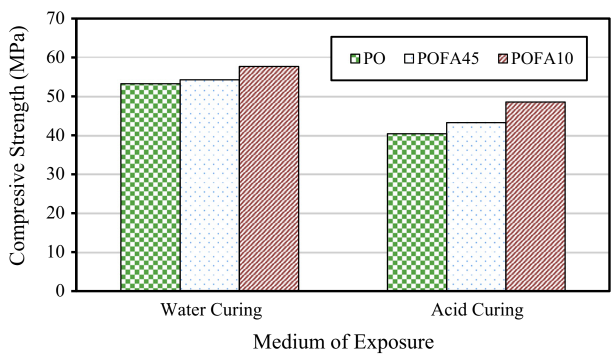

Fig. 19. Compressive strength of water cured and HCl cured specimens [20].

with reference OPC (P0) concrete specimens when immersed in 2% HCl solution. This is mainly due to the attack of acid medium on $Ca(OH)_2$ (hydration products in cement matrix) which promotes hydrolytic decomposition initiated by erosion of mechanical properties of OPC based specimens [70].

Murthi and Sivakumar [18] studied ternary blended concrete produced by 8% SF and 20% FA alongside OPC which showed a significant acid resistance compared with OPC concrete and binary blended concrete. Mortar and concrete have superior durability in acidic environments as illustrated by Mehta also [71]. The author [71] made concrete cylinders by using both Type II Portland cement and Portland-RHA cement containing 35% RHA by weight. Prepared specimens were submerged continuously for a period of 1500 h in 5% HCl and 5% H_2SO_4 solution. The total weight loss for Portland cement and Portland-RHA was recorded by 35% and 8% respectively in the 5% HCl solution and he [71] also found 27% weight loss for the Portland cement and 13% for the Portland-RHA concrete in 5% H_2SO_4 solution. The author [71] concluded that the OPC contains 60–65% CaO and their hydration products contain about 25% $Ca(OH)_2$ which is mainly responsible for the poor resistance of OPC concretes against acidic environment, where in Portland-RHA may have 20–40% CaO and practically no $Ca(OH)_2$ as hydration products.

FA, SF and Slag produce more strengthening gels with minimum amount of $Ca(OH)_2$, thus the addition of pozzolans to OPC confers much more tolerance to concrete in acidic environment. On the other hand, melting ice and condensation of pure water containing CO_2 dissolves $Ca(OH)_2$ present in concrete which leads to erosion [46]. A partial replacement of MK with OPC may prolong the service life of concrete against acid attack [47]. The authors [46] reported that the concrete produced by replacing 10% MK with OPC significantly resists acid attack in comparison with OPC concrete. Therefore, it may be concluded that mortar and concrete incorporated with pozzolans have a higher resistant against acidic environment.

4. Conclusion

Based on the survey of the published literatures, the following conclusions can be drawn:

- Extensive research works have already been carried out to explore the use of the pozzolanic materials such as slag, palm oil fuel ash (POFA), fly ash (FA), silica fume (SF), metakaolin (MK) and rice husk ash (RHA) etc. at high levels of volume replacement with OPC in search of better durability properties (carbonation, chloride penetration, sulfate resistance, acid resistance, drying shrinkage, corrosion resistance, water absorption, water permeability and sorptivity) of mortar and concrete.
- Though there is some debate among the researchers, still a majority of the researchers definitely are in the same platform regarding the advantageous use of the abovementioned pozzolans in mortar and concrete in respect of durability.
- Some researchers already reported some superior durability properties of concrete containing pozzolans with different level of volume replacement with OPC as compared to the plain concrete.
- It is worth mentioning here that the reuse of the mentioned pozzolans will have double advantages: firstly, it leads to reduction in the cost of construction material and secondly, helps minimization of its disposal problem.
- Furthermore, an effective consumption of these pozzolanic materials as a replacement of cement will be a valuable step toward the improvement of durability properties of mortar and concrete.

5. Recommendations for the future research

Based on the existing gaps in the previous studies, the following recommendations are proposed for the future research:

- A comparative study may be conducted using different pozzolans in mortar and concrete to decide the better one in respect of durability.
- Different environmental conditions and exposure may be considered for further study of different durability properties of mortar and concrete containing pozzolans.
- Durability properties of pozzolan incorporated mortar and concrete of different strength values may be investigated.
- Durability of pozzolan incorporated mortar and concrete can be investigated for their probable use in industrial effluent, water and sewerage treatment plant.
- Durability of mortar or concrete using pozzolans, cement and steel fiber with or without coarse aggregate can be examined.
- Durability of ternary or quaternary blended concrete or mortar could be studied to find out the best mix proportion among pozzolans with OPC.
- Based on durability, an optimum mix design (water to binder ratio) of mortar and concrete containing pozzolans with OPC could be established.
- Durability properties of mortar or concrete containing pozzolans could be investigated for the samples on the variation in curing temperatures.

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References

[1] K.Y. Ann, H.Y. Moon, Y.B. Kim, J. Ryou, Durability of recycled aggregate concrete using pozzolanic materials, Waste Manage. 28 (2008) 993–999.

[2] S. Rukzon, P. Chindaprasirt, Use of waste ash from various by-product materials in increasing the durability of mortar, Songklanakarin J. Sci. Technol. 30 (2008) 485–489.

[3] S. Rukzon, P. Chindaprasirt, Use of rice husk-bark ash in producing self-compacting concrete, Adv. Civ. Eng. (2014) 429727.

[4] M.C. Chi, J.J. Chang, R. Huang, Strength and drying shrinkage of alkali-activated slag paste and mortar, Adv. Civ. Eng. (2012) 579732.

[5] A.A. Awal, M.W. Hussin, Strength, modulus of elasticity and shrinkage behaviour of POFA concrete, Malays. J. Civ. Eng. 21 (2009) 125–134.

[6] T.R. Naik, S.S. Singh, Use of high-calcium fly ash in cement-based construction materials, in: Proceedings of the Fifth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Milwaukee, USA, 1995.

[7] M.A. Adole, W.E. Dzasu, A. Umar, O.M. Oraegbune, Effects of groundnut husk ash-blended cement on chemical resistance of concrete, ATBU J. Environ. Technol. 4 (2012) 23–32.

[8] C. Shiathas, T.Z. Muntasser, S.O. Nwaubani, A comparative study of the properties and durability of binary and ternary cementitious systems, ACI Spec. Publ. 212 (2003).

[9] W.M. Hale, S.F. Freyne, T.D. Bush Jr., B.W. Russell, Properties of concrete mixtures containing slag cement and fly ash for use in transportation structures, Constr. Build. Mater. 22 (2008) 1990–2000.

[10] M.D.A. Thomas, J.D. Mathews, Performance of fly ash concrete in UK structures, ACI Mater. J. 90 (1993) 586–593.

[11] M.I. Khan, S. Alsayed, Prediction of chloride permeability of high performance concrete. International association for bridge and structural engineering, in: IABSE symposium report 86 (2002) 77–83.

[12] R.K. Dhir, E.A. Byars, PFA concrete: permeation properties of cover to steel reinforcement, Cem. Concr. Res. 23 (1993) 554–566.

[13] F. Pacheco-Torgal, J. Castro-Gomes, S. Jalali, Alkali-activated binders: A review: Part 1. Historical background, terminology, reaction mechanisms and hydration products, Constr. Build. Mater. 22 (2008) 1305–1314.

[14] M. Collepardi, S. Collepardi, J.O. Olagot, E. Simonelli, The influence of slag and fly ash on the carbonation of concrete, ACI Spec. Publ. 221 (2004).

[15] N.M. Al-Akhras, Durability of metakaolin concrete to sulphate attack, Cem. Concr. Res. 36 (2006) 1727–1734.

[16] A Ramezanianpour, M Mahdikhani, G. Ahmadibeni, The effect of rice husk ash on mechanical properties and durability of sustainable concretes, Int. J. Civ. Eng. 7 (2009).

[17] E. Guneyisi, M. Gesoglu, K. Mermerdaş, Improving strength, drying shrinkage, and pore structure of concrete using metakaolin, Mater. Struct. 41 (2008) 937–949.

[18] P. Murthi, V. Sivakumar, Studies on acid resistance of ternary blended concrete, Asian J. Civ. Eng. 9 (2008) 473–486.

[19] B. Chatveera, P. Lertwattanaruk, Evaluation of sulfate resistance of cement mortars containing black rice husk ash, J. Environ. Manage. 90 (2009) 1435–1441.

[20] A. Budiea, M. Hussin, K. Muthusamy, M. Ismail, Performance of high strength POFA concrete in acidic environment, Concr. Res. Lett. 1 (2010) 14–18.

[21] A.A. Adam, T.C.K. Molyneaux, I. Patnaikuni, D.W. Law, Strength, sorptivity and carbonation of geopolymer concrete, Chall. Oppor. Solut. Struct. Eng. Constr. (2010) 563–568.

[22] A.L.G. Gastaldini, G.C. Isaia, A.P. Saciloto, F. Missau, T.F. Hoppe, Influence of curing time on the chloride penetration resistance of concrete containing rice husk ash: A technical and economical feasibility study, Cem. Concr. Comp. 32 (2010) 783–793.

[23] C.A. Fapohunda, Effects of blast furnace slag on chloride permeability of concrete cured at elevated temperatures, J. Life Phys. Sci. 3 (2010) 119–123.

[24] K. Kartini, Rice husk ash-pozzolanic material for sustainability, Int. J. Appl. Sci. Technol. 1 (2011) 169–178.

[25] R.P. Jaya, B.H.A. Bakar, M.A.M. Johari, M.H.W. Ibrahim, Strength and permeability properties of concrete containing rice husk ash with different grinding time, Cent. Eur. J. Eng. 1 (2011) 103–112.

[26] K. Turk, Viscosity and hardened properties of self-compacting mortars with binary and ternary cementitious blends of fly ash and silica fume, Constr. Build. Mater. 37 (2012) 326–334.

[27] G.K. Kate, P.B. Murnal, Effect of addition of fly ash on shrinkage characteristics in high strength concrete, Int. J. Adv. Technol. Civ. Eng. 2 (2013) 2231–5721.

[28] J. Pitroda, D.F. Umrigar, B.V.M. Principal, V. Vidyanagar, G.I. Anand, Evaluation of sorptivity and water absorption of concrete with partial replacement of cement by thermal industry waste (fly ash), Int. J. Eng. Innov. Technol. (IJEIT) 2 (2013) 245–249.

[29] P. Duan, Z. Shui, W. Chen, C. Shen, Enhancing microstructure and durability of concrete from ground granulated blast furnace slag and metakaolin as cement replacement materials, J. Mater. Res. Technol. 2 (2013) 52–59.

[30] F.M. Yahaya, K. Muthusamy, N. Sulaiman, Corrosion resistance of high strength concrete containing palm oil fuel ash as partial cement replacement, Res. J. Appl. Sci. Eng. Technol. 7 (2014) 4720–4722.

[31] Q. Nie, C. Zhou, X. Shu, Q. He, B. Huang, Chemical, mechanical, and durability properties of concrete with local mineral admixtures under sulfate environment in northwest China, Materials 7 (2014) 3772–3785.

[32] M. Thomas, R.D. Hooton, C. Rogers, B. Fournier, 50 years old and still going strong, Concr. Int. 34 (2012) 35–40.

[33] M. Thomas, Field studies of fly ash concrete structures containing reactive aggregates, Mag. Concr. Res. 48 (1996) 265–279.

[34] S.E. Wallah, B.V. Rangan, Low-Calcium Fly Ash-Based Geopolymer Concrete: Long-Term Properties. Res. Report-GC2, Curtin University, Australia, 2006, pp. 76–80.

[35] A. Meena, R. Singh, Comparative study of waste glass powder as pozzolanic material in concrete (Doctoral dissertation), National Institute of Technology, Rourkela, India, 2012.

[36] R.B. Polder, Effects of slag and fly ash on reinforcement corrosion in concrete in chloride environment-Research from the Netherlands, Heron 57 (2012) 197.

[37] Olufemi.S. Folagbade, Sorptivity of cement combination concretes containing Portland cement, fly ash and metakaolin, Int. J. Eng. Res. Appl. 2 (2012) 1953–1959.

[38] N. Kakhuntodd, P. Chindaprasirt, C. Jaturapitakkul, S. Homwuttiwong, The investigation of water permeability of high volume pozzolan concrete, J. Sci. Technol. MSU 31 (2012) 563–570.

[39] C.S. Poon, S. Azhar, M. Anson, Y.L. Wong, Comparison of the strength and durability performance of normal and high-strength pozzolanic concretes at elevated temperatures, Cem. Concr. Res. 31 (2001) 1291.

[40] D. Govindarajan, R. Gopalakrishnan, Magnetic susceptibility measurements on metakaolin admixtured cement hydrated with ground water and sea water, Int. J. Miner. Metal. Mater. 16 (2009) 349.

[41] M.M. Assas, Assessment of the transport properties and strength of concretes having different mix proportions, silica fume and fly ash additions, Jordan J. Civ. Eng. 6 (2012) 340–352.

[42] B. Menadi, S. Kenai, J. Khatib, A. Al-Mokhtar, Strength and durability of concrete incorporating crushed limestone sand, Constr. Build. Mater. 23 (2009) 625–633.

[43] H. Mahmud, Absorption and permeability performance of Selangor rice husk ash blended grade 30 concrete, J. Eng. Sci. Technol. 5 (2010) 1–16.

[44] P.R.S. Speare, K. Eleftheriou, S. Siludom, Durability of concrete containing rice husk ash as an additive, exploiting wastes in concrete, in: R.K. Dhir, T.G. Jappy (Eds.), Proceeding of International Seminar on Creating Waste in Concrete, Thomas Telford Publication, Dundee, United Kingdom, 1999, pp. 283–290.

[45] A. Cheng, R. Huang, J.K. Wu, C.H. Chen, Influence of GGBS on durability and corrosion behavior of reinforced concrete, Mater. Chem. Phys. 93 (2005) 404–411.

[46] J.B. Newman, B.S. Choo, Advanced Concrete Technology, Butterworth-Heinemann, 2003.

[47] J. Bhatty, P. Taylor, Sulfate Resistance of Concrete Using Blended Cements or Supplementary Cementitious Materials. No. PCA R&D Serial No. 2916a, 2006.

[48] F.M. Lea, The Chemistry of Cement and Concrete, Edward Arnold, London, 1970.

[49] A.M. Neville, Properties of Concrete (fourth and final ed.), Longman Group, Essex, England, 2000. Pearson Education.

[50] P.K. Mehta, Mechanism of sulfate attack on Portland cement concrete-Another look, Cem. Concr. Res. 13 (1983) 401–406.

[51] V.M. Malhotra, P.K. Mehta, High Performance, High-Volume Fly Ash Concrete: Materials, Mixture Proportioning, Properties, Construction Practice, and Case Histories, Supplementary Cementing Materials for Sustainable Development Inc., Ottawa, 2002.

[52] P.J. Tikalsky, R.L. Carrasquillo, Influence of fly ash on the sulfate resistance of concrete, ACI Mater. J. 89 (1992) 69–75.

[53] K. Torii, K. Taniguchi, M. Kawamura, Sulfate resistance of high fly ash content concrete, Cem. Concr. Res. 25 (1995) 759–768.

[54] D. Higgins, M. Uren, The Effect of GGBS on the durability of concrete, Concrete 25 (1991) 17–19.

[55] <https://www.metakaolin.info>, 30 September, 2012.

[56] <http://www.silica-fume-concrete.com/newspage-1.html>, 30 September, 2012.

[57] B.S. Divsholi, T.Y.D. Lim, S. Teng, Durability properties and microstructure of ground granulated blast furnace slag cement concrete, Int. J. Concr. Struct. Mater. 8 (2014) 157–164.

[58] Q. Yu, K. Sawayama, S. Sugita, M. Shoya, Y. Isojima, The reaction between rice husk ash and $Ca(OH)_2$ solution and the nature of its product, Cem. Concr. Res. 29 (1999) 37–43.

[59] V. Horsakulthai, K. Paopongpaiboon, Strength, chloride permeability and corrosion of coarse fly ash concrete with bagasse-rice husk-wood ash additive, Am. J. Appl. Sci. 10 (2013) 239–246.

[60] G.C. Isaia, A.L.G. Gastaldini, R. Moraes, Physical and pozzolanic action of mineral addition on the mechanical strength of high performance concrete, Cem. Concr. Comp. 25 (2003) 69–76.

[61] V. Saraswathy, H. Song, Corrosion performance of rice husk ash blended concrete, Constr. Build. Mater. 21 (2007) 1779–1784.

[62] J.J. Brooks, A.M. Neville, Creep and shrinkage of concrete as affected by admixtures and cement replacement materials, creep and shrinkage of concrete: effect of materials and environment, ACI Spec. Publ. 135 (1992) 19–36.

[63] J.J. Brooks, M.A. Megat Johari, Effect of metakaolin on creep and shrinkage of concrete, Cem. Concr. Comp. 23 (2001) 495–502.

[64] W.A. Al-Khaja, Strength and time-depended deformations of silica fume concrete for use in Bahrain, Constr. Build. Mater. 8 (1994) 169–172.

[65] L. Jianyong, Y. Yan, A study on creep and drying shrinkage of high performance concrete, Cem. Concr. Res. 31 (2001) 1203–1206.

[66] G.A. Habeeb, M.M. Fayyadh, Rice Husk ash concrete: the effect of RHA average particle size on mechanical properties and drying shrinkage, Aust. J. Basic Appl. Sci. 3 (2009) 1616–1622.

[67] H.B. Mahmud, M.F.A. Malik, R.A. Kahar, M.F.M. Zain, S.N. Raman, Mechanical properties and durability of normal and water reduced high strength 60 grade concrete containing rice husk ash, J. Adv. Concr. Technol. 7 (2009) 21–30.

[68] D.S. Wu, Y.N. Peng, The macro and micro properties of cement pastes with silica rich materials cured by wet mixed steaming injection, Cem. Concr. Res. 33 (2003) 1331–1345.

[69] M.H. Zhang, V.M. Malhotra, High-performance concrete incorporating rice husk ash as a supplementary cementing material, ACI Mater. J. 93 (1996) 629–636.

[70] V. Zivica, Acidic attack of materials based on the novel use of silica fume in concrete, Constr. Build. Mater. 13 (1999) 263–269.

[71] P.K. Mehta, Properties of blended cements made from rice husk ash, Am. Concr. Inst. 74 (1977) 440–442.