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The durability of concrete produced from pozzolan materials as a partially cement replacement: A comprehensive review

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ABSTRACT

Recently, the construction industry used innovative, cost-ecofriendly, and efficient materials in infrastructure development to mitigate the negative impact on the environment due to manufacturing Ordinary Portland cement (OPC). Many efforts have been conducted to improve sustainable materials to be used as cementitious material in pozzolanic materials such as fly ash (FA), slag, metakaolin (MK), rice husk ash (RHA), palm oil fuel ash (POFA), silica fume (SF), etc. Therefore, this paper introduced to review the results from previous studies that investigated the influence of waste materials with high pozzolanic materials on the numerous durability properties. The results show many advantages due to using those pozzolanic materials as partial cement replacements for the environment, saving energy and cost, and improving durability. Ground quartz and SF have the highest silica oxide (SiO2) content, it was recorded as higher than 90%, producing more pozzolanic activity than other waste materials. The resistance of the concrete containing POFA against acid and sulfate attacks increased when increasing POFA fineness. Besides, sorptivity values were reduced importantly for the blended concrete samples, the addition of 55% FA in binary blended concrete considerably reduced sorptivity of cement concretes. In addition to that, these pozzolanic materials improved other concrete properties. This paper can be a good base for researchers and construction players to adopt waste materials in improving the durability of concrete. Lastly, numerous possible studies were recommended for future studies.

Selection and peer-review under responsibility of the scientific committee of the International Conference on Advances in Construction Materials and Structures.

1. Introduction

Recently several industrial and agriculture waste materials as by-products with a high pozzolanic reaction, such as slag [1], fly ash (FA) [2], and palm oil fuel ash (POFA) [3–5], have been utilized as cementitious materials [4–6]. Typically, these materials significantly reduce the concrete permeability by changing the pore structure, improving resistance against acid and sulfate attacks, and decreasing the reinforcement corrosion. The high-Pozzolan materials such as silica fume (SF), RHA, pulverized fuel ash (PFA), ground granulated blast furnace slag (GGBS), POFA, and FA mainly enhance durability against acid and sulfate environmental. Thomas

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Abbreviations: AAC, Alkali-activated concrete; MgO, Magnisum oxide; Al_2O_3, Alumina oxide; $MgSO_4$, Magnesium sulfate; ASR, Alkali-silica reaction; Na_2O, Sodiume oxide; CaO, Calcium oxide; Na_2SO_4, Sodium sulfate; CO_2, Carbon dioxide; OPC, Ordinary Portland cement; FA, Fly ash; POFA, Palm oil fuel ash; Fe_2O_3, Iron oxide; RHA, Rice husk ash; GGBS, Ground granulated blast furnace slag; SCM, Supplementary cementitious materials; HL, Hydrated lime; SF, Silica fume; HSC, High strength conceret; SiO_2, Silica oxide; LOI, Loss on igntiton; SO_3, Sulfure oxide; MK, Metakaolin; TiO_2, Titanium oxide.

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and Mathews [6] reported that the compressive strength was increased with decreasing chloride ion penetration and permeability owing to using POFA as partial cement replacement. Hamada et al. [7] conducted many studies on the use of POFA as a cement replacement in the production of sustainable concrete [8–16]. They concluded that the use of POFA as sustainable construction materials in fine particle size has numerous advantages on the concrete samples in terms of enhancing the strength and durability properties.

Caneda-Martínez et al. [17] used ichu ash as sustainable and durable material instead of traditional cement with different replacement levels, namely, 6% and 10% under chloride ion and CO_2 environments. They observed that using 6% ichu ash and OPC increases the exposure to carbonation. On the other hand, using 10% ichu ash increases the carbonation through the mortar surface and thus increases the carbonation depth. Alaghebandian et al. [18] used silica fume (SF) and natural zeolite with high pozzolanic as a cement replacement with limestone to evaluate the durability properties of self-consolidating concrete. They observed that using waste materials with high pozzolanic materials significantly improves the concrete's resistance to aggressive environments. Many efforts should be conducted to discover the potential of waste materials such as pozzolanic materials in improving the durability properties of cement mortar and concrete. However, the production of cement still an increase day by day, causing increase in environmental pollution due to increase releasing CO_2 emissions. Therefore, this paper was introduced to review the newest developments related to the durability properties of sustainable materials generated from agro and industrial waste materials to be used as cementitious binder material in different replacement levels [19–22] in order to reduce cement production and use huge quantities of waste materials. As well as, this paper can be a good base for researchers and construction players to adopt waste materials in improving the durability of concrete.

2. Literature

In recent years, many researchers investigated the durability properties of cement mortar and concrete using pozzolanic materials such as SF and FA as cement binders in different replacement levels. Kasaniya et al. [23] used waste materials as high pozzolanic materials to replace Ordinary Portland cement (OPC) in concrete and investigate concrete's durability properties. They observed that these waste materials improved the resistance to alkali-silica reaction (ASR) and chemical sulfate attacks. Pozzolanic materials produced as by-products, such as SF and FA, were used extensively as cement replacement to reduce the influence of sulfate attacks [24,25]. Al-Amoudi et al. [26] used hydrated lime (HL) as a natural pozzolanic material to evaluate concrete durability. Adding HL into concrete mixtures reduces reinforcement corrosion, strength loss owing to sulfate attacks, depth of carbonation, coefficient of chloride diffusion, and depth of water penetration. Table 1 shows some results of the previous studies on durability properties by using waste materials as cementitious materials in concrete production.

Table 1
Effect of pozzolanic materials on the durability properties.

References	Waste by-products as pozzolanic	Durability Properties
Kasaniya et al., [25]	ground glasses bottom ash and FA	Sulfate attacks and alkali-silica reaction
Hamada et al., [27]	POFA	Water absorption
Hamada et al., [10]	POFA	Water absorption
Collepardi et al. [28]	Ground limestone, slag, and FA	Carbonation
Al-Akhras et al [29]	MK	Resistance to sulfate attacks
Ramezanianpour et al. [30]	RHA	Chloride permeability
Guneyisi et al. [31]	MK	Porosity, shrinkage, and water absorption
Murthi et al. [32]	FA and SF	Acid resistance
Chatveera et al. [33]	Black RHA	Sulfate resistance
Adam et al. [34]	Slag	Sorptivity and Carbonation
Gastaldini et al. [35]	FA, slag, and RHA	Chloride permeability
Fapohunda et al. [36]	Slag	Chloride permeability
Kartini [37]	RHA	Water permeability, water absorption & chloride ion penetration
Jaya et al. [38]	RHA	Water permeability and porosity
Turk [39]	FA and SF	Modulus of elasticity
Kate et al. [40]	FA	Drying shrinkage
Pitroda et al. [41]	FA	Water absorption and Sorptivity
Duan et al. [42]	Slag and MK	Carbonation and Chloride permeability
Nie et al. [43]	Slag and FA	Sulfate resistance

Collepardi et al. [44] presented the effect of pozzolan waste materials of ground limestone, slag, and FA as cement replacement partially to find out the rate of carbon oxide penetration in concrete. The outcomes showed growing requirements for using mineral additives in concrete production. Al-Akhras [29] examined the effect of metakaolin (MK) with cement on the sulfate resistance of concrete samples, especially when using MK with 5%, 10%, and 15% of total cement weight. Concrete samples were immersed in 5% Sodium sulfate (Na_2SO_4) for 18 months next completed curing time. The results detected that using MK as partial cement replacement led to improved sulfate resistance of blended concrete samples. In contrast, the increased replacement level results to increase sulfate resistance.

Budiea et al. [45] examined the resistance of acid attack on the high strength concrete (HSC) samples arranged due to the use of POFA as cement material at 20% replacement level to make two various POFA concrete mixtures with various fineness. The results indicated that the resistance of the HSC containing POFA against acid attacks increased when POFA fineness increased. Adam et al. [46] investigated the durability properties of concrete containing slag as a cement in replacement levels of 30%, 50%, and 70% by total cement weight. They reported that a sorptivity value decreased significantly for the composite concrete samples, whereas the carbonation value increased due to increased slag content in the concrete mix. Gastaldini et al. [47] evaluated chloride ion penetration for concrete containing RHA as cement in replacement levels of 10%, 20%, and 30%. The results revealed a significant improvement observed in charge passed values for the concrete mixtures due to increased RHA content in the concrete mix. Fapohunda [36] investigated the chloride permeability of concrete samples containing 30% slag as cement replacement. The results revealed that the slag and cement blended to improve the resistance to chloride penetration of concrete samples. Kasaniya et al. [25] investigated the chemical composition of pozzolanic materials such as bottom ash, fly ash, and ground glasses as partial cement replacement in concrete production to examine the durability properties of alkali-silica reaction and resistance to sulfate attacks as in Table 2.

Turk [48] investigated binary and ternary blended mortar samples using SF and FA as cement replacements. They observed that an increase in FA and SF contents led to a reduced value of the 28-day modulus of elasticity. Kate and Murnal [40] examined

Table 2
Chemical composition of pozzolanic materials [25].

Pozzolanic materials	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	TiO_2	SO_3	Na_2O	LOI
Ground glasses	53.6	13.7	0.4	1.1	21.9	0.1	–	0.9	0.6
Pumices	75.2	11.4	1.4	–	0.5	–	–	1.3	3.4
Coal ashes	35.6	17.9	5.8	6.8	27.4	1.4	1.6	1.6	0
Silica fume	94.4	0.2	0.1	0.1	0.6	–	–	0.4	4.0
Perlite	73.9	12.7	1.1	0.1	0.8	<0.1	<0.1	6.0	3.6
Lassenite	64.2	13.7	5.7	0.8	1.6	0.5	1.0	2.7	8.8
Metakaolin	51.5	44.1	1.4	0.2	0.1	1.9	–	0.2	0.4
Ground quartz	98.5	0.5	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	0.5
Limestone	3.1	0.1	0.1	1.3	52.8	<0.1	<0.1	0.2	42.1

HSC containing 10–70% FA as cement replacement. They reported that the shrinkage rate increased due to increase FA content. Pitroda et al. [49] investigated the properties of concrete containing FA as cement in different replacement levels. The results indicated that the sorptivity and water absorption of FA concrete decreased due to using 10% FA instead of cement. Also, sorptivity and water absorption decreased due to increased replacement levels. Duan et al. [50] indicated that MK and slag positively influence concrete samples' interfacial transition zone and pore refinement. Yahaya et al. [51] investigated the corrosion resistance test of an HSC mixture comprising 20% POFA. They observed that the combination of POFA increased the corrosion resistance compared with the control concrete sample. Nie et al. [52] examined the influence of FA and slag on concrete durability. They detected that the resistance against sulfate attack increased significantly due to slag and FA use.

3. Durability of cement concrete and mortar

Concrete durability can be known as resistance against deterioration, a significant problem that specifies either concrete is durable or not against resistance to sulfate, porosity, the ability of corrosion protection, decreasing hydration heat, better resistance against destructive environmental attacks, and enhanced resistance to chloride attacks. Thomas et al. [53] stated that the use of pozzolan materials is tremendously helpful in enhancing concrete durability and reducing environmental pollution.

3.1. Water absorption and sorptivity

The performance of concrete samples can be evaluated by determining the sorptivity, water permeability, and water absorption values of concrete samples by submerging them in water. Folagbade, [54] reported that the compressive strength increased due to decreased concrete samples' sorptivity values. He used MK and FA with cement in binary and ternary blended concrete samples. The results indicated that using pozzolanic materials (MK and FA) with cement considerably decreased the sorptivity rates of the concrete samples. The addition of 55% FA in binary blended concrete reduced sorptivity rates. Instead, adding 10% MK decreased sorptivity rates in binary blended cement concretes.

Pitroda et al. [41] likewise observed that concrete's sorptivity and water absorption achieved lower rates with 10% FA as cement replacement. They also observed that the increased replacement levels of cement by FA led to increased sorptivity and water absorption. In contrast, Kakhuntodd et al. [55] observed that the increase in cement replacement levels by ground POFA led to decreased water permeability. Soldado et al. [56] used slag and FA as partial cement replacements to get high-performance concrete with low cement content. They reported that the water absorption of concrete samples generally happens usually extremely at the first time of the test. Overall, using slag as partial cement replacement with high compactness leads to reduced water absorption compared to cement concrete without slag.

POFA in concrete mixtures decreased water permeability, such as FA with replacement levels less than 40% of the total weight binder [55]. Assas [57] detected upper water penetration value in cement concrete samples compared to the concrete samples comprising FA and SF. Similar results were stated by Menadi et al. [58]. They detected a reduction in water penetration depth values due to using different pozzolanic materials as partial cement replacement. Cheng et al. [59] examined the influence of GGBS on cement in different percentages of 0%, 40%, and 60% of cement, and they found that the permeability rate decreased significantly. Meddah et al., [60] reported the use of Sarooj as pozzolanic material and artificial cementitious gotten by traditional calcining of the raw clay soil. The use of 25% Sarooj as a cement replacement level% in the concrete mixture increases the water absorption of the blended cement mortar two times compared to the control sample. Nevertheless, an additional 50% decreased the water absorption but still more than that of the control sample.

3.2. Acid resistance

Murthi and Sivakumar [32] studied the effect of concrete made of 20% FA and 8% SF alongside cement, which exhibited an important acid resistance compared to cement concrete. Mehta also [61] investigated the effect of 35% RHA as cement replacement on concrete cylinders. The concrete samples were immersed constantly for 1500 h in 5% H_2SO_4 and 5% HCl solutions. Bisht et al. [62] used waste glass as aggregates in the concrete mixtures in different replacement levels of 18%, 19%, 20%, 21%, 22%, 23%, and 24%. They subjected the concrete samples to sulphuric acid. They observed that the replacement level of 21 has the positive result among other replacement levels. While, the increase waste glass led to increase porosity of concrete.

MK, as a partial cement replacement, may extend and improve the concrete samples submerged in an acid solution [63]. Newman and Choo [64] stated that using 10% MK as cement replacement considerably improves the performance of concrete against acid attacks compared to cement concrete. Thus, it can be seen that cement concrete and mortar combined with pozzolanic materials have a sophisticated resistance against an aggressive environment.

3.3. Sulfate resistance

As reported by numerous investigations, the cement concrete and mortar made of pozzolanic materials enhanced resistance against sulfate attacks more than that of cement concrete and mortar. The authors [63] detected that 20% FA cement type I produced more concrete with the best sulfate resistance than other concrete mixes. Demir et al. [65] used high pozzolanic activity materials such as slag and FA as partial cement replacement without additives and prepared cement mortar samples at different curing ages. The results showed that the length change of samples cured in sodium sulfate solution has better outcomes than those without additives. The lowest expansion was recorded for the samples without additives cured in potable water for 90 days. In contrast, the most extensive length change was recorded for the samples with 20% slag, Bottom ash, and FA replacement cured in sodium sulfate solution for 28 days.

Chatveera and Lertwattanaruk [33] reported using RHA as cement replacement for 0%, 10%, 30%, and 50%. The mortar samples were absorbed into 5% $MgSO_4$ and 5% Na_2SO_4 solutions for six months of curing time. The results showed that the compressive strength loss and expansion of mortar samples were reduced due to increasing the replacement levels of RHA. Remarkably, the expansion of mortar samples submerged in $MgSO_4$ solution was lower than samples submerged in Na_2SO_4. Nevertheless, increasing the use of RHA led to decreased compressive strength loss due to immersing the mortar samples in Na_2SO_4 solution.

Similar results were observed by Mehta [66], stating that when the cement paste is submerged in sulfate solutions, the water absorption increases and stiffness decreases the ettringite values. As well as expansion and cracking increased owing to being immersed in sulfate solution [67]. Numerous studies stated that the FA and supplementary cementitious materials (SCM) in cement significantly enhances the resistance against sulfate attacks [67,68]. Yang et al. [68] used FA as a cement replacement in different quantities and particle sizes. They observed that the high volume of FA as cement replacement improved the capillary water absorption and resistance against sulfate attacks. In addition, using FA reduces the carbonation depth in concrete samples compared to control samples. They observed that the resistance against sulfate attack coefficient of FA with a particle size of 4.29 μm (F2) and FA with a particle size of 2.51 μm (F3) are 26% and 31%, respectively that higher than the concrete samples with a particle size of 19.7 μm as (F1) as shown in Fig. 1,

Higgins and Uren [69] reported that using GGBS as cement in different percentages resulted in increased resistance against sulfate attacks of the concrete samples. Using RHA and MK likewise increases the resistance against sulfate attacks of the concrete samples. Using 15% MK with cement exhibited a substantial sulfate resistance against Na_2SO_4 solution [70]. Similarly, concrete containing cement and RHA has better sulfate resistance than concrete made of SF and cement [70]. The use of GGBS as cement replacement led to better resistance against sulfate attacks in concrete samples because of the decrease in the C3A in the cement mortar [64].

Kartini [37] showed that the 365 days-charge passed values (Coulombs) for concrete samples were higher than concrete made of RHA. They stated that the RHA decreased the chloride ion penetrability for concrete samples. Assas [44] detected that the combined cement and SF in concrete mixtures presented a superior performance related to chloride ion permeability compared to ordinary cement concrete samples. Using 10% SF or 20% FA as cement replacement considerably enhances resistance against chloride ion penetration.

3.4. Carbonation test

The carbonation rate of cement concrete and mortar is mainly affected by the chemistry and physical properties of the binder materials, permeability, and porosity. Collepardi et al. [71] indicated that mineral additives such as slag, FA, and GGBS integrated into cement affect the CO_2 penetration value of concrete produced with the assumed (w/c) ratio. They stated that there is no noteworthy variance between concrete samples made of cement only and the concrete samples with a 50% replacement level of pozzolanic materials [71]. Yu et al. [72] stated that the use of 30% RHA reduced the carbonation rate after 3 curing days. The RHA concrete comprises less portlandite and more calcium-silicate-hydrate (C-S-H) gels than cement concrete, mainly affecting the resistance against carbonation. Yang et al. [68] used FA as a high pozzolanic material to enhance the concrete's resistance against carbonation with different particle sizes and various replacement levels. They concluded that the carbonation depth for all concrete samples was reduced with the decrease of particle sizes of FA. Using FA with different particle sizes decreases the carbonation depth at 28 days of F2 and F3 from 7.69 mm of raw FA (F1) to 2.62 mm and 1.5 mm, respectively, as in Fig. 2.

A recent study by Caneda-Martínez et al. [17] used ichu ash to partially replace cement with 6% and 10% of total cement weight. The results obtained from the carbonation test indicate that the carbonation can be noticed only after 28 days of exposure to the sample surface containing 10% ichu (ICHU10) mortar. The carbonated parts extend quickly. While the samples made of ICHU6 and OPC mortars show better performance, showing slight carbonation signs at 70 days, as shown in Fig. 3. Moreover, the carbonated parts

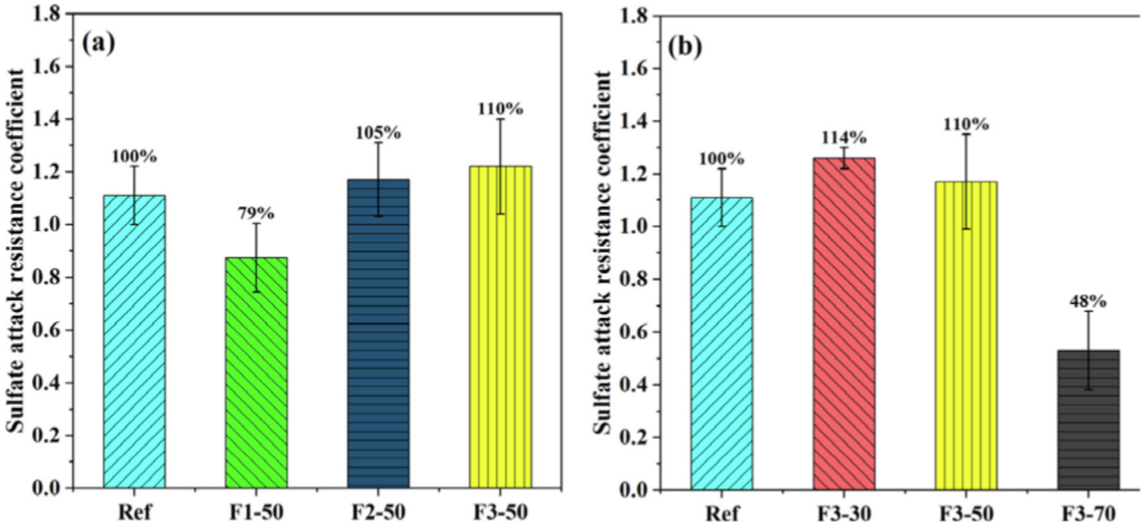

Fig. 1. Effect of FA on the sulfate attacks [68].

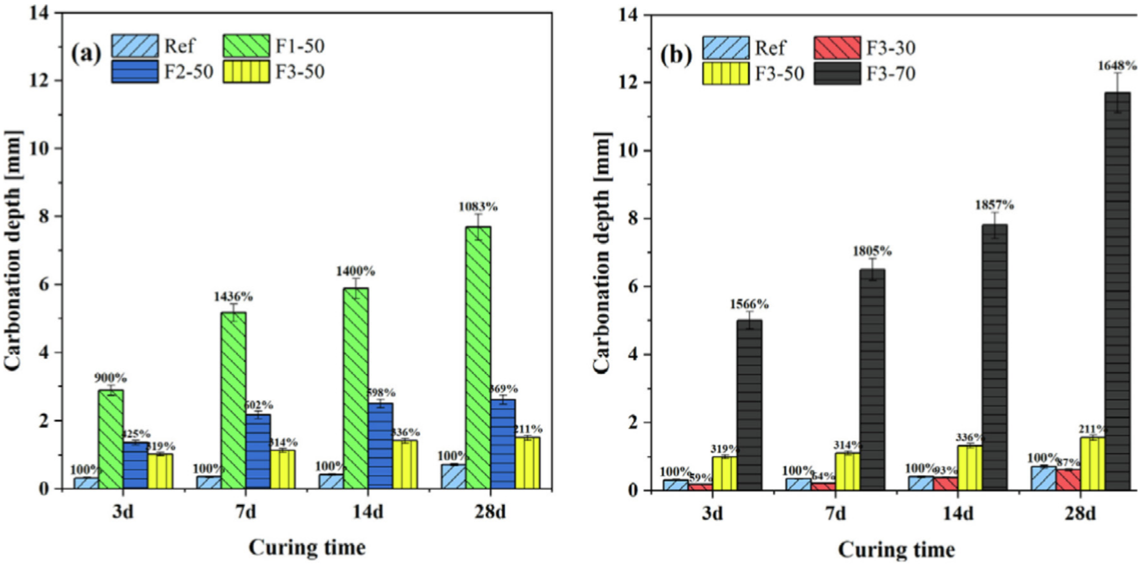

Fig. 2. The carbonation depth after 28 days of accelerated carbonation [68].

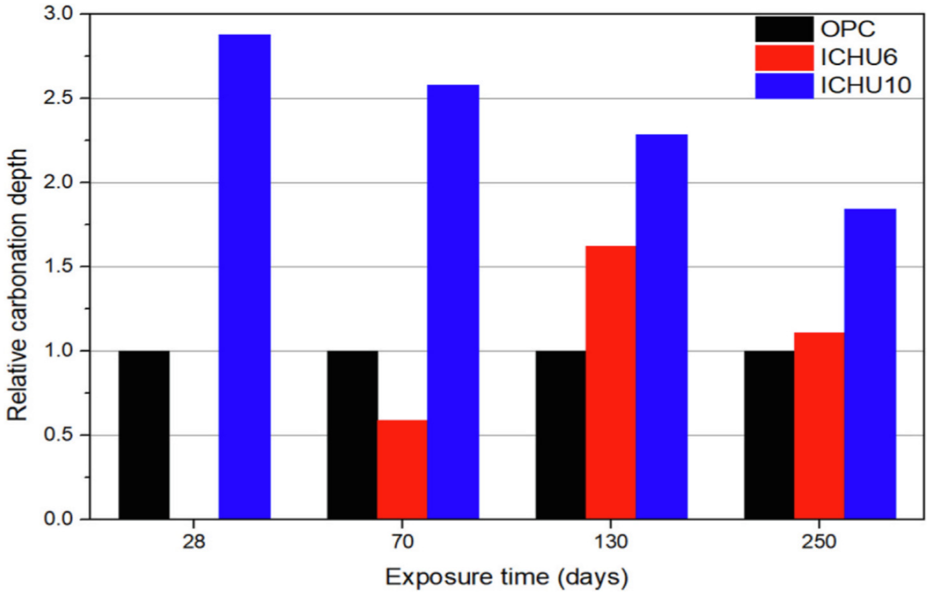

Fig. 3. Carbonation depth vs. exposure time [73].

of OPC and ICHU6 are considerably lesser than that of those recorded for ICHU10 mortars.

3.5. Corrosion resistance

The corrosion of reinforcement steel bars in concrete structures is a significant problem that should be solved [74]. The resistance against corrosion in reinforcement concrete is constantly a significant matter [75]. Corrosion is one of the main issues threatening reinforcement concrete structures [76]. Thus, numerous procedures have been conducted to determine the corrosion rate in reinforcing steel bars. Using POFA increased the quantity of C-S-H gels that donates to produce the concrete denser, as stated by Yahaya et al. [51]. Saraswathy and Song [77] investigated the corrosion resistance of concrete samples when replaced cement by RHA at 5%, 10%, 15%, 20%, 25%, and 30%. The authors inserted steel bars 100 mm in height and 12 mm in diameter into the cylindrical samples. The results indicated no cracks due to using high RHA replacement levels (15%, 20%, 25%, and 30%). Polder [78] investigated concrete samples for long curing age. The author stated that the concrete samples made of 70% GGBS as cement replacement shows a better performance related to reinforcement corrosion. Bastidas et al. [79] stated the resistance against corrosion of cement mortar containing activated FA. Miranda et al. [80] investigated the resistance against corrosion of activated FA-based mortar and stated a similar corrosion resistance to OPC mortar. Kasaniya et al. [23] used pozzolanic materials such as coal bottom ash and ground glasses to test the chloride permeability of concrete. They observed that charge passed, coulombs display an increasing trend with the reducing bulk resistivity of concrete. Aguirre-Guerrero et al. [81] investigated the effect of GBFS with high pozzolanic material as partial cement replacement on the corrosion resistance of alkali-activated concrete (AAC). The results indicate that the use of AAC has a lower corrosion rate than that of OPC concrete, as seen in

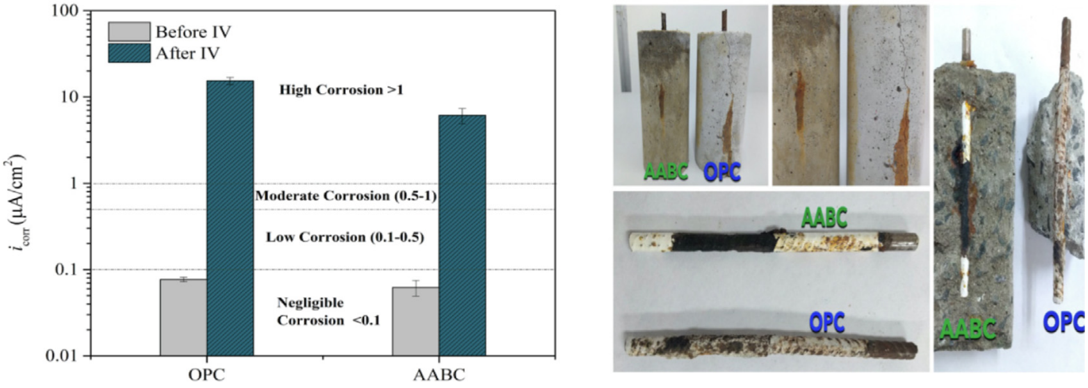

Fig. 4. Effect of AAC on the corrosion of reinforcement concrete [81].

Fig. 4 and the cracks are observed clearly in OPC concrete in contrast to AAC samples.

4. Conclusion

According to the results obtained from the previous studies, the following conclusions have been drawn:

- Numerous studies were conducted to discover the potential use of pozzolanic such as slag, POFA, FA, MK, RHA, and SF at different cement replacement levels to determine the durability properties of cement concrete and mortar.
- The addition of RHA into the concrete mixture led to improve concrete performance against chloride ion penetration.
- The carbonation of concrete samples increases due to the increase of slag content in the concrete mix, while the sorptivity value decreases significantly for the same composite concrete samples.
- Although there is some discussion from academics and scientists, most of the studies mentioned the same benefits acquired from using the aforementioned pozzolanic materials in cement concrete and mortar related to durability properties.
- It is essential to know that recycling those mentioned above pozzolanic has double advantages, firstly assisting in reducing and mitigating landfills and minimizing the final product's construction cost.

CRediT authorship contribution statement

Hussein M. Hamada: Conceptualization, Methodology. **Khamees N. Abdulhaleem:** Software. **Ali Majdi:** Visualization. **Mohammed S. Al Jawahery:** Software, Validation. **Blessen Skariah Thomas:** Supervision. **Salim T. Yousif:** Writing – review & editing.

Data availability

Data will be made available on request.

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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