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The Highs and Lows of Incorporating Pozzolans into Concrete and Mortar: A Review on Strength and Durability

R. C. Arum[1, *], C. Arum, S. A. Alabi

[1,2,3]*Department of Civil Engineering, Federal University of Technology, Akure, Ondo State, NIGERIA*

Abstract

It has been established that the construction industry, especially with regards to the production and use of cement generates lots of toxic gases, as well as consumes large quantities of natural resources. Cement itself is an expensive constituent of concrete. In order to reduce environmental pollution, improve cost-savings in production, achieve carbon neutrality and sustainability, the focus should be directed at using alternative waste materials such as ceramic waste, waste glass, palm oil waste, and rice husk, among others. This paper presents a widescale review of the incorporation of pozzolans into concrete and mortar, highlighting the effects on its strength and durability. The review revealed that while the existing literature agrees that the incorporation of pozzolans into mortar and concrete generally improves their durability, there is an apparent contradiction in various research findings on the effect of pozzolans on their strength. The review has shown however that whether the inclusion of pozzolan will increase or decrease strength depends on a number of factors such as Portland cement replacement level, fineness of the pozzolan (particle size of the ash), the reactivity of the pozzolan, concrete/mortar age, type of pozzolan, water-cement ratio, burning temperature, the microstructure of the pozzolan (weakly or strongly amorphous).

Keywords: Concrete, Cement, OPC, Rice Husk Ash (RHA), Ceramic Waste, Waste Ceramic Powder (WCP), Waste Glass Powder (WGP), Palm Oil Fuel Ash (POFA), Strength, Durability, Natural Zeolite, Fly ash, Silica Fume (SF).

1.0 INTRODUCTION

There have been growing concerns about the environmental impact and sustainability of granite aggregate deposit exploitation, and the processes involved in many building constructions. Continuous blasting of rocks for granite production has a telling negative environmental impact [1]. River sand, erosion, and dune sands which are used as fine aggregate in concrete production have not been readily available for concrete production [2]. For this reason, recent studies have begun to look into materials that are environmentally friendly, readily available, cheap, and durable as substitutes for the conventional materials used in construction [3]. Although a lot of research has gone into sourcing alternatives to the more conventional constituents of concrete, it is cement replacement that has been the focus of most of these studies. The manufacturing process of cement results in a significant increase in the levels of carbon dioxide present in the atmosphere, consumption of excess energy, and depletion of natural resources that are hitherto limited [4]. Different studies have highlighted some solid wastes as alternatives to cement and other concrete constituents [5]-[7].

In the processing, these solid wastes can be used as supplementary cementitious materials. They may also be used alternatively as aggregates depending on the particle size they are pulverized into. These solid wastes may be grouped into industrial, municipal, and agricultural wastes categories [8]. Some of these wastes include rice husk, waste sheet glass, cow bone, sawdust, recycled concrete aggregate, and waste ceramic tiles [9]-[11]. When processed into very fine forms and for the purpose of cement replacement owing to their cement-like properties, they are known as pozzolans [12]. The use of these pozzolans as cement replacements in mortar and concrete has been found to be beneficial in terms of ecology, energy efficiency, and cost [13].

Studies carried out on pozzolanic concrete have been aimed at investigating the improvement in strength and durability properties. Other properties examined include sorptivity, water absorption, water permeability, resistance to sulfate attack, drying shrinkage, corrosion resistance, carbonation, and chloride permeability[14]-[17].

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*Corresponding author **(Tel:** +234 (0)8160839272**)**

Email addresses: arumrc@futa.edu.ng (R.C. Arum), carum@futa.edu.ng (C. Arum), saalabi@futa.edu.ng (S.A. Alabi)

2.0 STRENGTH PROPERTIES

Ordinary Portland Cement (OPC) which is the costliest constituent of concrete for normal construction works and of serious environmental concern has seen an exponential increase in demand which must be met with some form of replacement to reduce the resultant environmental pollution from its production and improve cost savings in construction [18]. OPC production contributes about 7.4% of the carbondioxide emissions produced across the world [19]. The carbondioxide emission problem has necessitated countries across the world to deliberate on what industries must do to achieve the goal of carbon neutrality [20]. The European community submits that carbon neutrality can be achieved by reducing the number of wastes disposed into landfills and refuse dumps. In fact, in Europe, the goal is zero waste [20].

The use of agricultural wastes and industrial by-products in producing structural concrete is a good route to achieving carbon neutrality in our world [21]. This submission resonates with the ideologies of Sanjuan et al [19] who suggested that the use of industrial wastes and by-products as supplementary cementitious materials (SCMs) in producing concrete and blended cement was a lever to achieving net-zero carbon dioxide emissions.

Consequently, studies have been conducted on multiple abundant agricultural residues with some pozzolanic characteristics. Some of these are rice husk ash [22]; oil palm residue ash [23]; groundnut husk ash [24]; fly ash [18]; palm kernel shell ash [25], cassava peel ash [26], plantain peel ash [27], date palm seed ash [28], and bagasse ash [29]-[31].

2.1 Rice Husk Ash

Rice Husk is a major by-product of rice milling industries. For this reason, it is mostly found in rice-producing countries including Nigeria and in particular, the Northern Nigerian states of Nasarawa, Kogi, Kaduna, Kano, Kwara, Benue, and Niger. Since rice husk is indigestible and of no real use to humans, it is usually disposed arbitrarily in the environment, burnt down [30] [32], or disposed into landfills and rivers [33].

Partially burnt husk obtained from milling plants when used as fuel contributes greatly to global warming and environmental pollution. In order to reduce this environmental problem, studies have been carried out on using this Rice Husk Ash (RHA) as supplementary cementitious material [34]. Rice husk is composed of 50% cellulose, about 25-30% lignin, and 15-20% silica and the quality of RHA generally depends on the production method [35].

Most rice husk ash studies have focused on partially replacing cement with RHA. A replacement of up to 10% of cement with RHA gives a significant improvement in concrete strength (about 30.8% more than the control mix) [36]. The study asserts that 20% replacement of cement with rice husk ash is also viable and gave a compressive strength result comparable with that of the control concrete. The authors also stated that concrete containing fine RHA is of higher strength than the control OPC mix or a concrete mix containing coarser RHA. Another study revealed that RHA can have an adverse effect on concrete's strength if the ash to water ratio is uneven or too much of the ash is added to the concrete batch [37]. It was also concluded in this study that beyond 10%, there is a decrease in the concrete's workability with the RHA demanding more water.

Muthadhi and Kothandaraman [38] carried out a wholesome study on the characteristics of rice husk-ash blended concrete. In their study, RHA was added as a partial replacement for OPC from 10 to 30%. The results show that 20% is the optimum replacement level for rice husk ash-blended concrete. The resultant compressive strength at a 20% RHA replacement level was higher than that of the control mixture. The authors attribute the improvement in the compressive strength of the mix to the high pozzolanic activity of RHA, increase in hydration process in the wet phase which provides more nucleation sites for the hydration process to occur, and the pore-filling effect which improves the packing characteristics of the solid particles in the concrete matrix.

According to Gautam *et al.* [39], there is a continuous increase in the compressive strength of a concrete batch with the addition of rice husk ash up to a certain level and a dip in the compressive strength afterward. The compressive strength of concrete is maximum at 7.5% replacement level of RHA, beyond which the compressive strength starts reducing. In other words, 7.5% is the optimum a replacement level [39]. These results corroborate the findings of Kumar and Malleswara [40] who report 7.5% replacement of OPC by RHA as the ideal RHA replacement level in concrete. In the study, the mix design was prepared according to standard and OPC was replaced by RHA in replacement levels of 5%, 7.5%, 10%, 12.5% and 15%. At 3 and 7 days, the strength of the RHA-concrete was considerably lower than the OPC concrete (control). However, at 28 and 56 days of curing, the RHA-concrete mix produced performed better in compressive strength than the control. The compressive strength at 7.5% RHA (37.62 N/mm^2 after 56 days of curing was higher than the control concrete at 56 days (36.36 N/mm^2).

Zareei *et al.* [41] in an independent study carried out on high strength concrete (HSC) containing microsilica found out that incorporation of RHA into HSC increased its compressive strength. Thus, at a 25% replacement level, the compressive strength increases by 6.9% at 7 days, and 6.8% at 28 days. Beyond 25% replacement level which the authors deemed as the optimum, it was inferred that there would be a dip in the compressive strength of the RHA concrete.

Padhi *et al.* [42] investigated the compressive strength of concrete containing coarse recycled concrete aggregate (RCA) and RHA. It was concluded that a concrete mix containing 100% coarse recycled concrete aggregate and 10-15% RHA satisfies the design requirements of the construction industry. However, workability reduced with increasing RHA percentages, especially in concrete containing both RCA and RHA. Also, the pozzolanic activity of RHA was more obvious between 28 and 90 curing days. At 7 days, the concrete's compressive strength decreased with the increasing quantity of RHA owing to RHA's slow pozzolanic activity during the early days of curing.

Sathawane *et al.* [43] assessed the replacement of 30% OPC (weight) in concrete by rice husk ash (RHA) and fly ash (FA). The experimental program started with 30% FA and 0% RHA in the concrete mix, after which there was a gradual decrease in FA cement replacement by 2.5% and a corresponding increase in RHA cement replacement simultaneously. The maximum compressive strength was recorded at 22.5% FA and 7.5% RHA replacement of OPC in the concrete mix. However, this compressive strength was lower than that of the control.

Adesina [44] however identified RHA as a more suitable supplementary cementitious material (SCM) than any fly ash and silica fume. This was attributed to the higher silica content and reactivity present in RHA. The reactivity is associated with its large surface area and the high silica content because of the high amount of amorphous silica present in it. According to the author, concrete containing RHA as an SCM typically has high early strength. This is because the incorporation of RHA in the concrete creates a less permeable matrix. However, the said RHA must meet the relevant requirements of ASTM C618-17a. One such requirement is that the loss on ignition must not be more than 12% and the sum total composition of iron oxide, silicon dioxide and aluminum dioxide must be at least 70%.

Results of the investigation carried out by Amin and Abdelsalam [45] agree with an earlier claim by Adesina [44] about the suitability of RHA compared to FA for SCM purposes. From the study, it can be seen that concrete containing 10 and 30% RHA showed better mechanical properties than concrete containing the same percentage of fly ash (FA). However, it should be noted that superplasticizer was also introduced into the concrete mix.

When RHA was used in a ternary cementitious concrete matrix with OPC and coconut husk ash, it produced a concrete mix with 16.1% higher compressive strength than the control at 10% replacement [46]. The authors arrived at this conclusion following compressive strength tests on eighty-four (84) cubes of 150mm x 150mm x 150mm which were cured for 7, 14, 28, 35, 42, 49, and 56 days. A total of twenty-one (21) cubes were cast as control while RHA and CHA were introduced into the concrete at percentage replacement levels of 5%, 10%, 15%, and 20%.

Studies by Mehta [47] and Nehdi *et al.* [48]however do not go in this direction. According to the authors, the addition of RHA as an SCM causes a reduction in the concrete mixture's compressive strength. Anwar and Gaweesh [49] also postulate that the compressive strength of concrete decreases with an increasing RHA composition up to 28 days of curing. However, after that, RHA-concrete exhibit higher strength or the same strength as OPC-concrete (control mix).

A more recent study by Zaid *et al.* [50] also accedes to earlier reports by Mehta [47] and Nehdi *et al.* [48] in regards to RHA reducing the compressive strength of concrete relative to the control. According to the analysis by Zaid *et al.* [50], the incorporation of RHA causes a reduction in concrete's workability due to its porous nature and fineness. At 5% replacement of OPC by RHA, there was a reduction in compressive strength by 5.4%, 3.6%, and 3.9% compared to the control mix after 7, 21, and 28 days respectively of curing. At 10% replacement of OPC by RHA, strength reduced by 12.1, 13.2, and 13.5% after 7, 21, and 28 days respectively of curing relative to the control while at 15%, strength reduced by 20.3, 21.7, and 23.4% compared to the control samples after 7, 21, and 28 days of curing respectively. The trend continued at the 20% replacement level, where compressive strength reduced by 25.4, 26.1, and 28.5% after 7, 21, and 28 days of curing respectively. It was concluded that an increasing amount of OPC replacement with RHA results in a corresponding reduction in the concrete's compressive strength. Up to 10% of RHA was then recommended as the ideal replacement level, the level at which incorporation of RHA into a concrete mix does not considerably affect the concrete's compressive strength [50].

It is important to note that the authors also produced a control concrete mix containing steel fibers and a superplasticizer and compared it with RHA-concrete containing steel fibers and a superplasticizer. The RHA-concrete containing superplasticizer and steel fibers also showed reduced compressive strength compared to the control containing steel fibers and a superplasticizer [50].

Kamaruddin *et al.* [51] also attempted using RHA as an SCM in high-strength concrete. From the results of their investigation, it can be seen that RHA-concrete showed lower compressive strength compared to the control after 28 days of curing. It was also concluded that with an increasing RHA content in the concrete mix comes a reduction in the concrete's compressive strength.

Praveenkumar *et al.* [52] looked into the use of rice husk ash and bagasse ash as suitable cement replacements in producing concrete. The bagasse waste was collected from a sugarcane mill dumping yard while the rice husk waste was collected from a rice mill. From the results of the test carried out, it was found that rice husk ash was a more suitable material than bagasse ash in making pozzolanic concrete.

Previous studies have attempted using RHA as a supplementary cementitious material in regular concrete [53], concrete blocks [54], geopolymer concrete [55]-[57], and self-compacting concrete [58]. In these studies, the rice husk ash used was usually pre-processed by mechanical, chemical, or thermal treatments [54]-[58].

Generally, the quality of the rice husk ash depends on a number of factors including its source, incineration method, time, duration, and burning temperature. The optimal temperature is usually between 500-700°C. The most reactive silica is usually produced within this range [56]. Also, RHA's pozzolanic properties are influenced by the percentage replacement of cement in the concrete mix, the particle size of the ash, specific surface area, and water-cement ratio [59]. The type of fertilizer used during cultivation may also influence the properties of the RHA produced [60].

RHA is added to concrete for the following reasons – an improvement in the concrete mix microstructure, increase in early age strength, reformation of void structure, and reduction of interfacial transition zone (ITZ) width between paste and aggregate [61][62].

2.2 Waste Ceramic Powder

There have been a lot of experimental and analytical investigations into the possibility of using ceramic waste in concrete production as supplementary cementitious material in recent years [63]-[68].

In general, materials containing thermally treated clay materials are known to have high pozzolanic activity. A good example is waste ceramic. The authors note that of all ceramic types, brick ware ceramics is the most commonly used, which is obtainable from two main sources – processing of construction/demolition waste and brick block calibration by grinding technology [69].

Lavat *et al.* [70] crushed roof tile wastes into powder and sieved them through 44µm to be used as a pozzolanic admixture in the production of concrete. Blended cement was prepared with replacement levels of 20, 25, 30, 35, and 40% of non-glazed, natural-glazed, and black-glazed tiles. Based on findings from their experimental investigations, it was concluded that the partial substitution of 20-30% cement by weight with calcined clay ceramic wastes produced concrete with strengths comparable with that of the control mix.

Vejmelková *et al.* [71] studied the properties of high-performance concrete containing ceramics as an SCM (material, fracture, thermal, hydric, and durability properties). In this study, 10, 20, 40, and 60% of OPC by mass was replaced with ceramic waste powder (CWP). Following results from the compressive strength tests conducted on the CWP-concrete, it was revealed that 20% is the optimum replacement level of OPC by CWP.

El-Dieb and Kanaan [72] reiterated the suitability of CWP in the partial replacement of cement in concrete and mortar. The authors developed a Performance Index (PI) approach to determine the most suitable CWP replacement levels needed to achieve the desired performance criteria. The developed PI took into consideration performance criteria like durability, workability retention, and compressive strength. Concrete with 25 MPa, 50 MPa, and 75 MPa strength grades was produced and cured for up to 90 days, then the compressive strength values were determined. El-Dieb and Kanaan [72] note that the incorporation of CWP did not bring about any significant improvement in compressive strength of the concrete mix (25 MPa) at 7 days of curing age. The study attributes this slight improvement to zero hydraulic action. However, there was an improvement at 28 days of age. The compressive strength values of the CWP mixtures up to 20% replacement were slightly higher than that of the control (up to 4%), and a dip in the compressive strength value for replacement levels higher than 20%. This slight improvement the study attributes to the dilution effect (replacing hydraulic binding material with a non-hydraulic one). At 90 days of curing age, the concrete mix showed even better compressive strength results, and the highest compressive strength value was recorded at a 10% replacement level (33.6 MPa). The authors conclude that this further increase in compressive strength values is due to the pozzolanic characteristics of the CWP material.

Mohit and Sharifi [73] replaced OPC with 5, 10, 15, 20, and 25% of CWP in cement blends to produce mortar. The mortar mixes were cured for 7, 14, 28 and 56 days and their compressive strengths determined. The results of the experimental program show that the mix containing 10% CWP as cement replacement yielded the highest compressive strength. The 5% CWP-OPC mortar mix also showed better strength than the control. For instance, at 56 days, the strength values of the mortar mixes containing 5% (52 N/mm^2) and 10% 56 N/mm^2 CWP replacement levels were higher than that of the control (52 N/mm^2). However, at 7 days, the mortar mix with 10% CWP substitution recorded lower strength relative to the OPC mix. The authors attribute this to the delayed pozzolanic activity of CWP which makes its influence less significant in the early age of the mortar mix. Lasseuguette *et al.* [74] assert that the optimum replacement level for mortar mixes is 15%. Glazed white ceramic wall tiles were obtained from a demolition site, manually broken down into smaller pieces, then fed through a Retch jam crusher, before finally milling in a Tema orbital mill.

Mohammadhosseini *et al.* [75] studied the compressive strength of green mortar containing ceramic waste as an SCM and as fine aggregate. It was observed in the study that with an increasing number of curing days comes an increase in the compressive strength of ceramic mortar compared to the control. For instance, mortar containing 40% ceramic powder and 100% fine ceramic powder had a compressive strength that was about 7% higher than that of the control mix. The authors explained that the increase in the cement mortar's compressive strength may be due to the pozzolanic reactivity between silicon oxide and OPC-hydration products such as calcium hydroxide.

El-Dieb *et al.* [76] in a book on the applications of ceramic materials highlights a reduction in concrete strength values of some CWP-concrete cubes at 7 and 28 days of concrete age – compared to the target strength - like the ceramic waste powder (CWP) content increases. The study attributes this trend to the fact that CWP has no hydraulic reaction. However, at a later stage (90 days), the compressive strength of the concrete containing CWP was higher than that of the control. This eventual increase in compressive strength compared to the control can be justified by the delayed pozzolanic reaction of CWP [76].

According to Samadi *et al.* [77], the optimum replacement level of CWP in OPC mortar mix is 40%. The authors assessed the feasibility of using waste ceramic in partial replacement of both cement and fine aggregate and carried out compressive strength results in mortar mixes containing CWP in partial replacement of cement (sample 1) and another containing ceramic waste in partial replacement of both cement and fine aggregate (sample 2). In the early days of curing, the mortar mix' compressive strength value was low relative to the control mix (sample 1). Due to the pozzolanic activity of CWP the compressive strength value was higher than that of the OPC mix in the latter stages of the curing process. For instance at 20% replacement level and 7 days curing age, the compressive strength was 38 MPa compared to the control (41 MPa) at the same curing age. The compressive strength value then increased to 57 MPa at 90days curing age, slightly higher than OPC-mortar at the same curing age (55 MPa).

A study by Juan-Valdés *et al.* [78] focuses on the use of recycled concrete aggregate, ceramic waste mix, ceramic powder and blast furnace slag cement. It was asserted that the incorporation of ceramic waste (up to 50% substitution) into an RCA concrete gave comparable performance results with the conventional concrete mix at 28 days. The study attributed this great performance to the low effective water/cement (w/c) ratio of the mix.

De Matos *et al.* [79] investigated the early-age influence of ceramic tile demolition waste as a SCM in concrete. Following findings from the experimental study, it was concluded that CWP produced from ceramic title demolition waste showed no significant pozzolanic reaction.

Jafari and Rajabipour [80] noted that although the use of impure calcined clay (CC) as a pozzolan in concrete gave desirable durability properties, the compressive strength properties obtained from this mix is not as impressive. In this case, the compressive strength of the cubes containing CC gave results slightly lower than the control.

2.3 Waste Glass Powder

Glass has lots of applications in today's world. Poor disposal of glass materials and their non-biodegradability has made it a serious source of concern for green environment enthusiasts [81]. Different researchers have therefore sought to use waste glass in a number of construction applications [82]-[84]. There is a huge potential for the use of waste glass, especially in the production of high performance pozzolanic concrete [85][86].

Al-Zubaidi *et al.* [87] states that the glass color has a significant effect on the compressive strength of WGP concrete. The study reveals that concrete produced from green colored glass powder up to 15% replacement level showed significantly lower values of compressive strength compared to the control. Strength was however improved by about 13% in concrete containing neon glass powder. This improved strength is so because of the high calcium carbonate content of neon glass [87].

Waste glass with high silica and calcium content is also known as amorphous glass. It is this type of glass that is considered pozzolanic or cementitious in nature and hence, can be used as a SCM [88][89].

According to Jani and Hogland [90], the pozzolanic properties of glass waste powder increases significantly when the particle sizes below 100 µm is used. Shao *et al.* [91] further stressed the importance of the waste glass powder particle size. The authors added that 30% replacement of glass particles of 38 µm exhibited about 14.3% and 33.3% higher compressive strength compared to concrete containing the same 30% replacement of glass particles, but this time, particle sizes of 75 µm and 150 µm respectively. Lu *et al.* [92] confirms the importance of the particle size of the WGP used as a SCM in an independent study where the compressive strengths of mortar containing ground glass with particle sizes of 28.3 µm, 47.9 µm, 88.5 µm and 204 µm were compared against each other. From the results of the compressive strength tests, it can be seen that mortar containing ground glass of 28.3 µm had about 40% higher compressive strength than the mortar mix with a ground glass particle size of 204 µm.

Anwar [93] produced M-40 grade concrete containing WGP in percentages of 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50% and compared their compressive strengths to concrete containing 0% WGP (control). The compressive strength of concrete containing WGP in replacement levels of 5%, 10%, and 15% were higher than that of the control. However, the highest compressive strength was recorded at 10% replacement level (55.39 MPa) compared to the control (47.52 MPa). The results of this study corroborate the results obtained from an independent study by Abdulazeez *et al.* [94] which show that 10% is the optimum replacement level for WGP in concrete.

Khan *et al.* [95] substituted OPC in concrete in proportions of 0-35% by weight with WGP, in increments of 5%. Concrete cubes made from these concrete mixtures were cured for 28, 56, and 84 days. Results from the experimental program show a reduction in compressive strength as the replacement level increased. Also, for the first 28 days of testing, there was a loss in compressive strength of concrete (10% relative to the control mix) up to 25% partial replacement of OPC with WGP. However, an increase in curing age (up to 84days) reduced the strength reduction gap to about 5%. The optimum replacement level is noted as 20% within which the concrete mix does not lose considerable strength.

However, a decrease in the compressive strength of concrete containing recycled glass waste relative to the control mix has been variously reported [96]-[98].

Olutoge [98] investigated the mechanical properties of concrete incorporating WGP as SCM. The glass powder was sieved to particle sizes less than 300 µm and was used to produce concrete with a nominal mix design of 1:2:4 and water/cementitious material ratio of 0.6. In the study, WGP was used to partially replace cement in replacement levels of 10, 20, and 30%. For all replacement levels, the research recorded lower compressive strength values compared to the control mix; with the highest being at 10% replacement level. However, the compressive strength values at these replacement values were lower than that of the control mix. For instance, at 28 days and 10% replacement level, the average compressive strength was 24.47 N/mm^2 for the WGP-concrete and 33.28 N/mm^2 for the control. The paper however posited that the concrete could show even higher strength beyond 28 days as has been pointed out by other researchers but these latter concrete ages (56 and 90 days) were beyond the scope of the study.

Lee *et al.* [99] on comparison betweenWGP and waste glass sludge (WGS) as a SCM inferred that concrete containing WGS showed about 10% higher compressive strength than concrete containing 20% replacement level of WGP. This is attributed to the greater pozzolanic reactivity and finer granulometry of WGS.

2.4 Palm Oil Fuel Ash (POFA)

POFA, a by-product of the palm oil industry, can be obtained from the combustion of palm oil plant residues [100]. These plant residues include empty fruit bunches, palm oil fiber and shells in the powerplant [101]. Typically, these palm residues/wastes are burnt in palm oil mills as a major source of energy. The by-product of this combustion process is what is known as POFA and makes up about 5% of the entire waste load in these palm oil mills [102]. The increase in the production of palm oil in tropical countries and a corresponding increase in POFA creates a large environmental load whch must be disposed properly [103]. However, they are mostly dumped in open fields creating huge environmental pollution and health hazard problems [104]. In a bid to resolve these environmental problems, several studies have been conducted to evaluate the feasibility of using POFA as a supplementary cementitious material in the production of mortar and concrete. The production process of POFA is environmentally-friendly and consumes less amount of energy [105]. Abdullah *et al.* [103] highlights burning temperature as the major burning condition influencing the physical properties of POFA. These properties include its color, specific gravity, median particle size, soundness, strength activity index, and fineness.

Tangchirapat *et al.* [106] argues that the particle size of POFA in cement blends has a huge influence on the compressive strength of concrete. In the study, it was reported that concrete made from OPC and POFA with its original size (from the milling plant) is of lower compressive strength than the control mix. On the other hand, POFA with fine particles gave a better compressive strength value than OPC-concrete. Johari *et al.* [107] accedes to this conclusion, stating that the finer POFA the particles are, the better their microstructure and the higher their reactivity; properties which make them highly effective as pozzolans. The authors state that ultrafine POFA with a a specific surface area of 1.775 m^2/g could improve the compressive strength of concrete, even with replacement levels as high as 60%. The median particle size used in this study was 2 µm. With a median particle size less than 11µm, Sujivorakul *et al.* [108] and Sinsiri *et al.* [109] report that the optimum POFA replacement level in concrete is 10%. In terms of workability, the high carbon content present in POFA puts it at a disadvantage for SCM use in concrete compared to fly ash (FA) and ground, granulated blast-furnace slag (GGBS). Beyond 30% replacement level, further addition of POFA in concrete reduces its workability, necessitating the addition of a superplasticizer [110] [111].

Islam *et al.* [110] reports that POFA can be used to partially replace cement in concrete (up to 25%) without dealing a significant blow to the concrete's compressive strength. Putting things in perspective, at 25% replacement level and full water curing, the compressive strength was 35 MPa compared to that of the control mix (42 MPa). At 10% and 15% replacement levels, the compressive strength values were 43 MPa and 42 MPa respectively; which were slightly higher than the control's (42 MPa). The authors conclude that 10-15% replacement levels are the ideal replacement percentage for POFA in concrete. The curing age for the experimental program was 28 days. Muthusamy and Zamri [112] take an exception to this. In an independent study carried out by Muthusamy and Zamri [112], it is reported that 20% is the optimum replacement level for POFA in concrete for 28 days of curing age. At the 20% replacement level, the compressive strength value of the POFA-concrete mix was 35 MPa compared to 31 MPa of the control mix. The strength increased even further with an increase in curing age.

Hamada *et al.* [113] wrote a review paper on the present state of the use of POFA in concrete. In this 2018 desktop study, the authors presented a summary of research studies on the partial replacement of OPC with POFA in concrete as presented in Fig. 1.

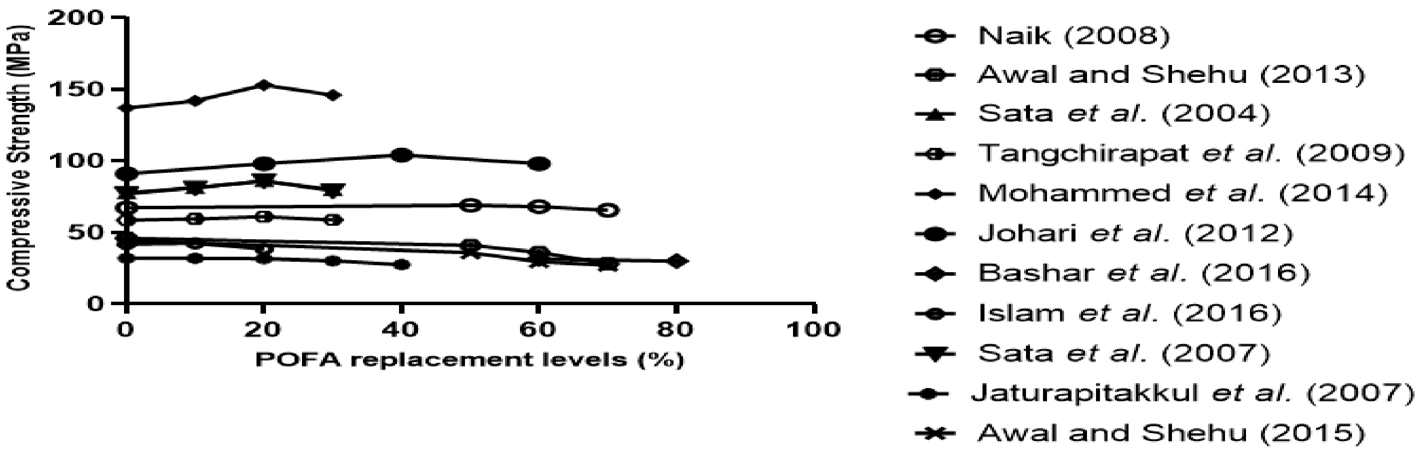

Figure 1: Summary of compressive strength values of POFA-OPC concrete mixes reported by different studies for a curing age of 28 days; adapted from [113].

3.0 DURABILITY

The idea of infusing pozzolans into concrete to improve its durability stems from the knowledge that concrete made from Ordinary Portland Cement (OPC) has poor resistance against chemicals present in an aggressive environment because it contains up to 25% calcium hydroxide which can be reactive in an acidic environment. An introduction of these pozzolans strengthen the concrete's binding gel and by extension, improves its durability [114].

There have been lots of investigations into the durability properties of mortar and concrete where there was a partial replacement of cement with pozzolans [115]-[118]. The pozzolans discussed in many of these studies include palm oil fuel ash (POFA), metakaolin (MK), rice husk ash (RHA), fly ash (FA), glass, calcined ceramics, and slag. It was reported in these studies that the durability of mortar and cement produced from these pozzolanic materials with alkali-activated binder (AAB) were significantly better than the traditional mortar and concrete. A few others however could not conclusively state that this was the case and therefore recommended further research into the suitability of pozzolans for improvement in durability performance in mortar and concrete [80].

In the construction industry, durability refers to the resistance of the non-homogenous composition to sulfate and chlorine attack, corrosion, and improvement of porosity. The permeability of the concrete to water is reduced by reducing the existing pores [119][120].

Malviya and Goliya [117] submits that fly ash concrete activated by NaOH and $NaSiO_3$ showed less deterioration in acid and sulphate solution compared to OPC concrete. The study concluded by saying that fly ash based concrete was more durable than OPC concrete. In an earlier report conducted by Thokchom *et al.* [121] on mortar, a similar conclusion was reached. In the experimental study to evaluate the resistance to acid of fly ash based mortar specimens activated by NaOH and $NaSiO_3$, the specimens were immersed in 10% H_2SO_4 and 10% $HN0_3$ for a 6-month period. The resistance of the concrete to acid was then evaluated in terms of residual alkalinity, mass change, and change in compressive strength. There were no noticeable changes in color. It was concluded that mortar activated by NaOH and $NaSiO_3$ is highly resistant to the deteriorating effects of H_2SO_4 and $HN0_3$.

Adam [122] following a series of experiments concluded that fly-ash based alkali-activated concrete outperformed OPC concrete in chloride penetration and sorptivity. It also did better than alkali-activated slag concrete.

Al-Akhras [115] investigated the response of concrete infused with metakaolin instead. Metakaolin was used to partially replace cement in levels of 5%, 10% and 15% by OPC weight. The concrete samples were cured in water for the desired periods before they were fully immersed in a 5% aqueous solution of sodium sulfate for 18 months. The samples were then evaluated through visual inspection for concrete prisms expansion and reduction in compressive strength. Following the results of this evalution, it was concluded that replacement of OPC with metakolin improves the sulfate resistance of blended concrete. It was further established that there is a positive correlation betweeen increasing metakaolin content and the sulfate resistance. In other words, the higher the metakaolin content, the greater the concrete's resistance to sulfate attack.

It has been shown that 30% replacement of OPC by rice husk ash (RHA) can bring about a reduction in concrete's absorption, porosity and water penetration [118][123]. According to Venkatanarayanan and Rangaraju [124], the water absorption may remain the same or slightly different with only 0-15% RHA replacement. Their study also stressed the significance of the fineness of the rice husk ash and its pozzolanic reactivity in reducing the porosity of concrete. Praveenkumar and Vikayalakshmi [125] explains that beyond 20% replacement of OPC with RHA, the concrete experiences a reduction in its porosity and increase in density. Mosaberpanah and Umar [126] attempts to explain why and how this happens. In their study, it was reported that the penetration of CO_2 through the permeable pores of OPC concrete mass leads to its carbonation. Addition of $Ca(OH)_2$ further leads to the precipitation of carbonate. In RHA-blended concrete however there is a lesser volume of $Ca(OH)_2$ present due to the high pozzolanicity of RHA.

Setina *et al.* [116] investigated the effect of pozzolanic additives on the structure and chemical durabilty of concrete. From their conclusion, it can be inferred that pozzolans act both as cementitious admixture and fine filler in concrete. This conclusion was arrived at based on results from extensive tests like X-ray diffraction, porosimetry, optical microscopy and Hg absorption. The pozzolanic additives used include wood ashes and mikro/nanosilica.

Hwang *et al.* [127] carried out an interesting study on concrete containing recycled aggregate. The study showed that concrete made from recycled aggregate was of lower compressive strength and durability compared to concrete made from Ordinary Portland Cement and traditional concrete constituents. To compensate for this reduction in its properties, pozzolanic materials were introduced. 30% Pulverised Fuel Ash (PFA) and 60% Ground Granulated Blast furnace Slag (GGBS) were used in the partial replacement of OPC in the concrete. It was discovered following results of the tests carried out that the rate of chloride transport in concrete containing RCA, PFA and GGBS was lower than concrete containing only RCA after 91 days of curing. The authors ascribe the reduction in the rate of chloride transport to more formation of hydration products and the refinement of pore structure. It should however be noted that the concrete containing OPC (control) did better than the RCA-concrete containing PFA and GGBS in the early stages of curing. This, the authors attribute to delayed hydration. Also, the RCA-concrete containing PFA and GGBS proved to be slightly more resistant to sulfate attack than the control concrete.

Another study on recycled aggregates with natural pozzolan showed similar results. Thus, Omrane *et al.* [128] produced self compacting concrete using RCA and natural pozzolans. Following observations from their tests, they concluded that replacing natural aggregate with recycled coarse and fine aggreagtes by as much as 50% increases the workabilty of the concrete. It was also stressed in their study that introduction of natural pozzolans into this concrete mix decreased the concrete's slump, improves its mechanical properties and chloride diffusivity as well. The study also agrees with earlier reports on the premise that the chloride penetration of a concrete mix can be improved upon by adding natural pozzolans.

Since most research studies peg the optimum replacement level of OPC by natural pozzolans at 30 to 40%, Uzal *et al.* [129] decided to take it a bit further by looking into the possibility of replacing OPC in concrete by 50% of natural pozzolans. Preliminary results from the tests carried out show that 50% replacement of OPC by natural pozzolans was viable and would produce more durable concrete for construction. Concrete mixes made from 50% replacement of OPC by concrete also produced concrete with compressive strengths of 29 MPa and 38 MPa for 3 and 28 days respectively, highlighting their suitability for structural concrete applications.

Celik *et al.* [130] looked into the use of natural volcanic pozzolan in concrete. In the study, 45% of OPC was replaced by 15% limestone powder (LS) and 30% finely-ground basaltic ash. Asides from a high 28-day compressive strength (39 MPa), it also showed very high resistance to chloride penetration. This concrete blend can also potentially reduce 48% of Carbon emissions that would have been released from the control containing OPC and no pozzolans. The petrographic and scanning electron microscopy (SEM) tests conducted on the volcanic pozzolans showed better hydration and cement reactions than is obtainable with regular natural pozzolans such as fly ash and calcined ceramics, etc.

Natural zeolite has shown potential pozzolanic activity and can be used as a natural pozzolan in producing structural concrete [131]. The authors posited that as mineral deposits, zeolites are distributed across many mineral deposits in the world. According to Agosto [132], zeolites are potentially non-viable for concrete production in large scale since they are general mineral admixtures and the zeolite phase is only a variable mineral constituent. Raggioti *et al.* [131] however pointed out that in deposits of higher purity, it was possoble to see the zeolite phase in a ratio of 80% and more. Following their experiment, it was concluded that introduction of zeolite into concrete improved the resistance of concrete to chemical attack in the latter stages of curing (28 days).

Menéndez *et al.* [21] attributes the improvement in durability of concrete containing pozzolans to reduction in the Alkali-Silica Reaction (ASR) going on in the concrete mix. ASR is a highly deleterious process that occurs in mortar and concrete. For the purpose of inhibiting ASR, silica fume and fly ash were noted as the best pozzolan additions to concrete.

Silica fume (SF), also referred to as micro silica, condensed silica fume, or volatilized silica, is a byproduct of the silicon and ferrosilicon industry. Quartz reduced at a temperature of 2000°C produces silicon dioxide vapors that condense into spherical particles of amorphous silica, which is collected and used as a supplementary cementitious material (SCM) in Portland cement concrete. The mean particle size of silica fume is typically around 0.1 micron with most (95%) particles under 1 µm [133]. It has been reported that the replacement of PC with modest amounts (5%) of SF dramatically decreased permeability of concrete. Several sources have noted that the inclusion of SF into PC mixes will also increase the resistance to corrosion and sulfate attack, which is mainly due to the reduced permeability [134][135]. Boddy *et al.* [136] reported that SF replacement also reduced alkali-silica reactivity to the acceptable 0.10% expansion limit prescribed by ASTM C1260 [137]; in which expansion of less than 0.10 % at 16 days after casting is indicative of innocuous behavior in most cases. The inclusion of SF has also been shown to reduce the workability and increase water demand of concrete [138].

Studies show that cement replacement levels, fineness of POFA and concrete age are major influencers of the permeability of PFA concrete. A number of research works have revealed that that the permeability of POFA-OPC concrete to water reduces as curing age increases This is attributed to the formation of additional gel from the pozzolanic reactivity of POFA. The water permeabilty of POFA-OPC concrete mix at 7days was compared to a similar mix at 360 days [139].

4.0 CONCLUSION

A widescale review of current literature was undertaken on the effects of some commonly used pozzolanic materials on the compressive strength and durability of concrete. The review also gave an insight into the properties of the various pozzolans which are responsible for their influences on the strength and durability of the product pozzolanic cement concretes. The findings from various research works confirm that partial replacement of Portland cement in concrete by pozzolans improves the durability of the concrete by reducing its permeability as a result of reduction or refinement of pore structures of the concrete. In addition, pozzolans have been established to retard the process of alkali-silica reaction, a fact which improves concrete durability. It would also established that depending on the percentage level of replacement of cement with pozzolan, the microstructure, particle size, reactivity, burning temperature, and type of pozzolan as well as water-cement ratio and concrete/mortar age addition of pozzolans to mortar or concrete can have positive effect on the strength.

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REFERENCES

[1] G. Assefa, and A. Gebregziabher, “Environmental Impact and Sustainability of Aggregate Production in Ethiopia,” *Sandy Materials in Civil Engineering - Usage and Management*, 2020 pp. 1-9,.

[2] J. O. Ukpata, M. E. Ephraim, and G. A. Akeke, “Compressive strength of concrete using lateritic sand and quarry dust as fine aggregate,” *ARPN Journal of Engineering and Applied Sciences,* 7(1), 2012.

[3] K. O. Olusola, “Factors Affecting Compressive Strength and Elastic Properties of Laterized Concrete,” *Unpublished Ph.D. Thesis, Department of Building, Obafemi Awolowo University, Ile- Ife,* 2005.

[4] P. G. Quedou, “A review on the sustainability of sugarcane bagasse ash as a supplementary cementitious material,” *International Journal of Progressive Sciences and Technologies,* 23(1), 2020, pp: 49-52.

[5] T. Sathanadam, P. O. Awoyera, V. Vijayan, and K. Sathishkumar, “Low carbon building: Experimental insight on the use of fly ash and glass fibre for making geopolymer concrete,” *Sustainable Environment Research,* 27(3), 2016, pp: 146-153.

[6] A. Formisano, F. Fabbrocino, E. Dessì, and G. Chiumiento, “Experimental shear tests on tuff blocks triplets with hemp fibres reinforced lime mortar,” *Proceedings of the 23rd Conference of the Italian Association of Theoretical and Applied Mechanics.* AIMETA, 2017.

[7] F. O. Okafor, and E. A. Egbe, “Models For Predicting Compressive Strength and Water Absorption of Laterite-Quarry Dust Cement Block Using Mixture Experiment,” *Nigerian Journal of Technology,* 6, 2017.

[8] K. M. Liew, A. O. Sojobi, and L. W. Zhang, “Green concrete: Prospects and challenges,” (Elsevier, Ed.) *Construction and Building Materials*, 2017, pp: 1063-1095.

[9] M. B. Ogundiran, and S. Kumar, “Synthesis of fly ash-calcined clay geopolymers: Reactivity, mechanical strength, structural and microstructural characteristics,” *Construction and Building Materials*, 2016, pp: 450-457.

[10] A. Sojobi, S. Nwobodo, and O. Aladegboye, “Recycling of polyethylene terephthalate (PET) plastic bottle wastes in bituminous asphaltic concrete,” *Cogent Engineering*, 2016.

[11] T. F. Awolusi, A. O. Sojobi, and J. O. Afolayan, “SDA and laterite applications in concrete: Prospects and effects of elevated temperature,” *Cogent Engineering*, 2017.

[12] E. Soldado, A. Antunes, H. Costa, R. do Carmo, E. Júlio, “Influence of pozzolan, slag and recycled aggregates on the mechanical and durability properties of low cement concrete,” 2021.

[13] M. M. Hossain, M. R. Karim, M. Hasan, M. K. Hossain, and M. F. Zain, “Durability of mortar and concrete made up of pozzolans as a partial replacement of cement: A review” *Construction and Building Materials,* 116, 2016, pp: 128-140.

[14] N. Kakhuntodd, P. Chindaprasirt, C. Jaturapitakkul, and S. Homwuttiwong, “ The invesitigation of water permeability of high volume pozzolanic concretes at elevated temperatures,” *Journal of Science and Technology*, 2012, pp: 563-570.

[15] M. M. Assas, “Assessment of the transport properties and strength of concretes having different mix proportions, silica fume and fly ash additions,” *Jordan Journal of Civil Engineering,* 6, 2012, pp: 340-352.

[16] C. Arum, and G. O. Mark, “Partial replacement of portland cement by granulated cupola slag - sustainable option for concrete of low permeability,” *Civil and Environmental Research*, 2014.

[17] S. Rukzon, and P. Chindaprasirt, “Use of rice husk ash in producing self-compacting concrete,’ *Advanced Civil Engineering*, 2014.

[18] E. B. Ogunbode, E. I. Egba, O. A. Olaiju, C. A. Johnson, D. J. Amusuk, and Y. A. Dodo, “Determining the Properties of Green Laterized Concrete with Fly Ash for Sustainable Solid Waste Management,” *Chemical Engineering Transactions*, 2018, pp: 649-654.

[19] M. Á. Sanjuán, C. Andrade, P. Mora, and A. Zaragoza, “Carbondioxide uptake by cement-based materials: A Spanish Case Study,” *Applied Science,* 10, 2020.

[20] U. European Commission, *The European Green Deal.* Brussels, Belgium: Communication from the Commission to the European Parliament, The European Council, the Council, The European Economic, Social Committee and The Committee of the Regions; European Commission, 2019.

[21] E. Menéndez, M. A. Sanjuán, R. García-Roves, C. Argiz, H. and Recino, “ Sustainable and Durable performance of pozzolanic additions to prevent akali-silica reaction (ASR) promoted by aggregates with different reaction rates,” *Applied Sciences*, 2020.

[22] H. Moayedi, B. Aghel, H. Nguyen, and A. S. Rashid, “Applications of rice husk ash as green and sustainable biomass,” *Journal of Cleaner Production*, 2019

[23] N. Altwair, M. A. Johari, S.F. Hashim, “Influence of treated palm oil fuel ash on compressive properties and chloride resistance of engineered cementitious composites,” *Materials and Structures.* pp:47, 2014.

[24] A. U. Elinwa, and A. A Awari, "Groundnut-husk ash concrete," *Nigerian Journal of Engineering Management,* 2(1), 2001, pp. 8-15.

[25] E. Fanijo, A. J. Babafemi, and O. Arowoloju, "Performance of Laterized Concrete Made with Palm Kernel Shell as Replacement for Coarse Aggregate," *Construction and Building Materials,* 250, 2020.

[26] M. T. Abdulwahab, and O. A. U. Uche, "Durability Properties of Self-Compacting Concrete (SCC) Incorporating Cassava Peel Ash (CPA)," *Nigerian Journal of Technology,* 40(4), 2021, pp: 584 –590.

[27] O. O. Aderinola, Y. Yusuf and O. O. Omotayo, "Assessment of cement concrete partially replaced with polystyrene and plantain peel ash," *Nigerian Journal of Technology,* vol. 39(3), 2020, p: 690-700.

[28] A. S. J. Smith, G. Xu, M. J. Garba, and M. Y. Aliyu, "Pozzolanic and mechanical properties of date palm seed ash (dpsa) concrete," *Nigerian Journal of Technology,* 39(3), 2020, p: 680-686.

[29] N. B. Singh, and V. D. Singh, "Hydration of Bagasse Ash blended Portland Cement," *Cement and Concrete Research, 30,* 2000, pp: 1485-1488.

[30] A.A. Raheem, M. Kareem, "Optimal raw material mix for the production of rice husk ash blended cement," *International Journal of Sustainable Construction Engineering and Technology,* 7(2), 2017.

[31] C. M. Ikumapayi, and C. N. Arum, "Pozzolanic influence of bagasse ash on the compressive strength and dry shrinkage of concrete," *FUTA Journal of Engineering and Engineering Technology,* 13(2), 2019.

[32] G. L. Oyekan, and O. M. Kamiyo, "Effect of Nigerian Rice Husk Ash on Some Properties of Sandcrete Blocks and Concrete," *Research Journal of Applied Sciences, 3(*5), 2008, pp: 345-351.

[33] V. Jittin, A. Bahurudeen, and S. D. Ajinkya, "Utilisation of rice husk ash for cleaner production of different construction products," *Journal of Cleaner Production, 263,* 2020.

[34] S. Chandrasekhar, K. Satyanarayana, P. Pramada, and J. Majeed, "Effect of calcinations temperature and heating rate on the optical properties and reactivity of rice husk ash," *Journal of Materials Science,* 41(1), 2006, pp: 7926-7933.

[35] A. Choobbasti, M. Samakoosh, and S. Kutanaei, "Mechanical properties of soil stabilized with nano calcium carbonate and reinforced with carpet waste fibers," *Construction Building Materials,* 2019, pp: 1094-1104.

[36] G. A. Habeeb, and H. B. Mahmud, "Study on properties of rice husk ash and its use as cement replacement material," *Materials Research,* vol. 13, pp: 185-190, 2010.

[37] B. S. Thomas, "Green concrete partially comprised of rice husk ash as a supplementary cementitious material - A comprehensive review," *Renewable and Sustainable Energy Reviews,* 2017.

[38] A. Muthadhi, and S. Kothandaraman, ''Experimental investigations of performance characteristics of rice husk-ash blended concrete'', *Journal of Materials in Civil Engineering,* ''vol. 25, no. 8'' pp: 1115-1118 , 2013.

[39] A. Gautam, R. Batra, and N. Singh, ''A study on the use of rice husk ash in concrete'',*Engineering Heritage Journal (GWK),* pp: 01-04, 2019.

[40] C. P. Kumar, P.R. Malleswara ,"A study on reuse of rice husk ash in concrete*", EM International,* Vol. 29, no. 1, 2020.

[41] S.A. Zareei, F. Ameri, F. Dorostkar, and M. Ahamdi, ''Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: Evaluating durability and mechanical properties'', *Case Studies in Construction Materials*, vol. 7, pp: 73-81. 2017.

[42] R.S. Padhi, R.K, Patra, B.B Mukharjee, and T.Dey, ''Influence of incorporation of rice husk ash and coarse recycled concrete aggregates on properties of concrete''. Construction and Building Materials, vol. 173, pp: 289–297, 2018 .

[43] S.H. Sathawane, V.S. Vairagade, and K.S. Kene, ''Combine effect of rice husk ash and fly ash on concrete by 30% cement replacement'', *Procedia Engineering,*vol. 51, pp: 35-44, 2013.

[44] A. Adesina, ''Use of rice husk ash in concrete: Review of mechanical properties''. *Concordia University*. 2013.

[45] M. Amin, and B.A. Abdelsalam, ''Efficiency of rice husk ash and fly ash as reactivity materials in sustainable concrete'', *Sutainable Environment Research.* 2019.

[46] I.S. Obokparo, and C.N. Arum, ''Properties of ternary cementitious concrete matrix containing rice husk ash and coconut husk ash'', *International Journal of Engineering Research and Technology (IJERT),* vol.9, no.2, 2020.

[47] P.K.Mehta,''Rice husk ash - a unique supplementary cementing material''. *154,* 1992, pp: 531-542.

[48] M. Nehdi, J. Duquette, and A. El Damatty, ''Performance of rice husk ash produced using a new technology as a mineral admixture in concrete'', *Cement and Concrete Research,* pp: 1203-1210, 2003.

[49] M. Anwar, and M. Gaweesh,''Using rice husk ash as a cement replacement material in concrete'',*Waste Management In Construction*. 2000.

[50] O. Zaid, J. Ahmad, M.S. Siddique, and F. Aslam, ''Effect of incorporation of rice husk ash instead of cement on the performance of streel fibers reinforced concrete'', *Frontiers in Materials, vol.8,* 2021.

[51] K. Kamaruddin, M.Y. Nazierah, S. Aisyah, and Z.M. Zahib, ‘’Effects of silica in rice husk ash (RHA) in producing High Strength Concrete’’, *International Journal of Engineering and Technology*, pp: 1952-1956. , 2012.

[52] S. Praveenkumar, G. Sankarasubramanian, and S. Sindhu, ‘’Evaluation of pozzolanic performance of bagasse ash and rice husk ash’’, *Recent Trends in Civil Engineering. Lecture Notes in Civil Engineering*, vol. 105, pp: 189-196, 2021.

[53] J. Alex, J. Dhanalakshmi, and B. Ambedkar, ‘’Experimental investigation on rice husk ash as cement replacement on concrete production’’, *Construction and Building Materials, vol. 127*, pp: 353–362, 2016.

[54] S. Mayooran, S. Ragavan, S. Navaratnarajah, ‘’Comparative study on open air burnt low-and high-carbon rice husk ash as partial cement replacement in cement block production’’. *Journal of Building Engineering*, vol. 13, 2017.

[55] A. Mehta, R. Siddique, ‘’Strength, permeability and micro-structural characteristics of low-calcium fly ash based geopolymers’’. *Construction and Building Materials*, vol. 141, pp: 325-334, 2018.

[56] S. Yaseri, Y.M. Verki, and M. Mahdikhani, ‘’Utilization of high volume cement kiln dust and rice husk ash in the production of sustainable geopolymer’’. *Journal of Cleaner Production*, pp: 592–602, 2019.

[57] S. Gambo, K. Ibrahim, A. Aliyu, A. G. Ibrahim and H. Abdulsalam, “Performance of metakaolin based geopolymer concrete at elevated temperature.” *Nigerian Journal of Technology,* vol 39(3), p: 732-737, (2020).

[58] R.K.Sandhu, R. Siddique, Influence of rice husk ash (RHA) on the properties of self-compacting concrete: A review. *Construction and Building Materials*, vol.153, pp: 751-764. 2017.

[59] F. Zunino, and M. Lopez, ‘’A methodology for assessing the chemical and physical potential of industrially sourced rice husk ash on strength, water permeability and workability of binary blended concrete’’. *Construction Building Materials*, pp: 869-881, 2017.

[60] A. Muthadhi, R. Anitha, and S. Kothandaraman, ‘’*Rice husk ash - Properties and its users: A review.* Puducherry’’. I.E.I Journal. 2007.

[61] F. Zunino, and M. Lopez,‘’Decoupling the physical and chemical effects of supplementary cementitious materials on strength and permeability: A multi-level approach’’, *Cement and Concrete Composites*, pp: 19-28, 2016.

[62] E. Mohseni, F. Naseri, R. Amjadi, M.M. Khotbehsara, and M.M. Ranjbar, ‘’ Microstructure and durability properties of cement mortars containing nano-TiO2 and rice husk ash’’. *Construction and Building Materials*, pp: 656-664, 2016.

[63] J.R. Correia, J. De Brito, and A.S Pereira, ‘’Effects on concrete durability of using recycled *Materials and Structures’’, vol.39 , no.*2, pp: 169-177, 2006.

[64] S. Seitl, V. Viszlay, J. Domski, and J. Katzer, ‘’Fracture Mechanical Properties of Cement Based Composites with Various Amount of Waste Aggregates’’ *Procedia Engineering, vol. 190*, pp: 345-351, 2017.

[65] K. Rashid, A. Razzaq, M. Ahmad, T. Rashid, S. Tariq, ‘’Experimental and analytical selection of sustainable recycled concrete with ceramic waste aggregate’’. *Construction and Building Materials*, vol. 154, pp: 829-840, 2017.

[66] D. M. Kanaan, S. Aboubakr, A.S. El-Dieb, "High performance concrete incorporating ceramic waste powder as large partial replacement of Portland cement," *Construction and Building Materials,* vol. 144, pp: 35-41.

[67] O. Babatola, and C. Arum, ‘’Determination of the compressive strength of concrete from binary cement and ternary aggregates’’. *Open Journal of Civil Engineering*, vol. 10, pp: 385-402, 2020.

[68] J.H. Filho, C.A. Pires O.D. Leite, M.R.Garcez, and M.H. Medeiros, ‘’Red ceramic waste as supplementary cementitious material: Microstructure and mechanical properties’’, *Construction and Building Materials*, vol. 296, pp: 1-11, 2021.

[69] M. Keppert, M.Čáchová, M. Pavlíková, T.J. Žumár , and R. Černý, ‘’Waste ceramics as supplementary cementitious material: characterization and utilization’’, *WIT Transactions on Ecology on the Built Environment*, vol. 142, 2014.

[70] A.E.Lavat, M.A. Trezza, and M. Poggi, ‘’Characterization of ceramic roof tile wastes as pozzolanic admixture’’,*Waste Management,vol. 96, no.4*, pp: 1666-1674, 2009.

[71] E. Vejmelková, M. Keppert, P. Rovnaniková, M. Ondráček, Z. Keršner, and R. Cerný, ‘’Properties of high performance concrete containing fineground ceramics as supplementary cementitious material’’. *Cement and Concrete Composites*, vol.34, no.1, pp: 55-61, 2012.

[72] S. El-Dieb, and D.M. Kanaan, ‘’Ceramic waste powder an alternative cement replacement - Characterization and evaluation’’. *Sustainable Materials and Technologies,* vol. 17, 2018.

[73] M. Mohit, and Y. Sharifi, ‘’Ceramic waste powder as alternative mortar-based cementitious material’’. *ACI Materials Journal*. 2019.

[74] E. Lasseuguette, S. Burns, D. Simmons, E. Francis, H.K. Chai, V. Koutsos, and Y. Huang, ‘’Chemical, microstructural and mechanical properties of ceramic waste blended cementitious systems’’. *Journal of Cleaner Production, vol. 211*, pp: 1228-1238, 2019.

[75] H. Mohammadhosseini, N.H. Lim, and M.M. Tahir, ‘’Performance evaluation of green mortar comprising ceramic waste as cement and fine aggregates replacement’’. *SN Applied Science*,vol. 1, no. 557, 2019.

[76] S. El-Dieb, M.R.Taha, and S.I. Abu-Eishah, S. I. ‘’The use of ceramic waste powder in making eco-friendly concretes’’. In D. Eliche Quesada, L. Perez Villarejo, and P. Sánchez Soto, *Ceramic Materials - Synthesis, Characterization, Applications and Recycling.* IntechOpen. 2019.

[77] M. Samadi, G. Huseien, H. Mohammadhosseini, H.S. Lee, N.H. Abdul Shukor Lim, M.M.Tahir, and R. Alyousef, ‘’Waste ceramic as low cost and eco-friendly materials in the production of sustainable mortars’’. *Journal of Cleaner Production*. 2020.

[78] A. Juan-Valdés D. Rodríguez-Robles D. García-González, M. Gomez, M.I. Guerra-Romero, N.D. Belie, and J.M. Morán-del Pozo, ‘’Mechanical and microstructural properties of recycled concretes mixed with ceramic recycled cement and secondary recycled aggregates’’, A viable option for future concrete. *Construction and Building Materials*. 2020.

[79] de Matos, Paulo Ricardo et al. “Utilization of ceramic tile demolition waste as supplementary cementitious material: An early-age investigation.” *Journal of building engineering,* vol. 38, pp: 102-187, 2021.

[80] K. Jafari, and F. Rajabipour, ‘’Performance of impure calcined clay as a pozzolan in concrete’’. *Transportation Research Record: Journal of the Transportation Research Board*. 2020.

[81] S.P. Gautam, V. Srivastava, "Use of glass wastes as fine aggregate in concrete," *Journal of Academia and Industrial Research,* Vol. 1, no. 16, 2012.

[82] D. Bisikirske, D. Blumberga, S.Vasarevicius, and G. Skripkiunas, ‘’Multicriteria analysis of glass waste application’’. *Environmental and Climate Technologies, vol.23, no.*1, pp: 152-167, 2019.

[83] D. Kazmi, D.J. Williams, and M. Serati, ‘’Waste glass in civil engineering applications’’—A review. *International Journal of Applied Ceramic Technology, vol.17, no.* 2, pp: 529-544, 2019.

[84] Q. Deng, Z. Lai, R. Xiao, J. Wu, M. Liu, Z. Lu, and S. Lv, ‘’Effect of waste glass on the properties and microstructure of magnesium potassium phosphate cement’’. *Materials (Basel), vol.14, no.8,* 2021.

[85] A. M. Auwal, and M. O. A. Mtallib, “Recycling of waste glass powder and tyre fiber in the development of eco-efficient concrete for high-performance structural application,” *Nigerian Journal of Technology,* vol. 40(6), pp: pp.1039 –1047, (2021)

[86] T.O. Ogundairo, D.D. Adegoke, I.I. Akinwumi, and O.M.Olofinnade, O. M. ‘’Sustainable use of recycled waste glass as an alternative material for building construction’’ - A review. *IOP Conference Series: Materials Science and Engineering.* Vol. *640.* IOP Publishing. 2019.

[87] A.B. Al-Zubaidi, K.M. Shabeeb, and A.I. Jan, ‘’A study of the effect of recycled mixglass on the mechanical properties of green concrete’’. *Journal of the University of Babylon, vol.26, no.*2 , pp: 265-272, 2018.

[88] G.S. Islam, M.H. Rahman, and N. Kazi, ‘’Waste glass powder as partial replacement of cement for sustainable concrete practice’’. *International Journal of Sustainable Built Environment,vol. 6, no.1,* pp: 37-44. 2017.

[89] S. Patnaik, and P.K.Parhi, ‘’Experimental investigation of the strength of concrete by partial replacement of cement with industrial wastes’’. 2018.

[90] Y.Jani, and W. Hogland, ‘’Waste glass in the production of cement and concrete - A review. *Journal of Environmental Chemical Engineering’’vol. 2, no.*3, pp: 1767-1775, 2018.

[91] Y. Shao, T. Lefort, S. Moras, and D. Rodriguez, “Studies on concrete containing ground waste glass,” *Cement and Concrete Research*, pp: 91-100, 2000.

[92] J. Lu, Z. Duan, and C. S. Poon, “Combined use of waste glass powder and cullet in architectural mortar,” *Cement Concrete and Composites,* vol. 82, pp: 34-44, 2017.

[93] A. Anwar, “The influence of waste glass powder as a pozzolanic material in concrete,” *International Journal of Civil Engineering and Technology (IJCIET),* vol. 7, no. 6, 131-148, 2016

[94] A.S. Abdulazeez, A. I. Kolawole, M.A. Hamza "Effect of waste glass powder as a pozzolanic material in concrete production," *International Journal of Engineering and Technical Research,* vol. 9, (2020).

[95] F. A. Khan, K. Shahzada, Q. S. Ullah, M. Fahim, S. W. Khan, and Y. I. Badrashi, “Development of environment-friendly concrete through partial addition of waste glass powder as cement replacement,” *Civil Engineering Journal,* vol. 6, no. 12, 2020.

[96] S. de Castro, and J. de Brito, "Evaluation of the durablity of concrete made with aggregates. *Journal of Cleaner Production*, vol. 41, pp: 7-14, 2013.

[97] K. Afshinnia, and P. R. Rangaraju, "Impact of combined use of ground glass powder and crushed glass aggregate on selected properties of Portland cement concrete," *Construction and Building Materials*, vol. 117, pp: 263-272, 2016.

[98] F. A. Olutoge, "Effect of waste glass powder (WGP) on the mechanical properties of concrete," *American Journal of Engineering Research (AJER)*, vol. 5, no. 11, pp: 213-220, 2016.

[99] H. Lee, A. Hanif, J. Sim, and H. Oh, "Performance evaluation of concrete incorporating glass powder and glass sludge wastes as supplementary cementing material," *Journal of Cleaner Production*, vol. 170, pp: 638-693, 2018.

[100] M. Safiuddin, M. A. Salam, and M. Z. Jumaat, "Utilization of palm oil fuel ash in concrete: a review," *Journal of Civil Engineering and Management*, vol. 17, no.2, pp: 234-237, 2011.

[101] E. Khankhaje, M. W. Hussin, J. Mirza, M. Rafieizonooz, M. R. Salim, H. C. Siong, and M. N. Mohd Warrid, "On blended cement and geopolymer concretes containing palm oil fuel ash," *Materials and Design*, vol. 89, 385-398, 2018.

[102] H. Noorvand, A. A. Ali, R. Demirboga, H. Noorvand, and N. Farzadnia, "Physical and chemical characteristics of unground palm oil fuel ash cement mortars with nanosilica," *Construction and Building Materials*, pp: 1104-1113, 2013.

[103] K. Abdullah, M.W. Hussin, F. Zakaria, R. Muhamad, and Z.A. Hamid, "POFA: A potential cement replacement material in aerated concrete," *Proceedings of the 6th Asia-Pacific Conference on Structural Engineering and Construction*, Kuala Lumpur, 2006.

[104] D. Tonnayopas, F. Nilrat, K. Putto, and J. Tantiwitayawanich, "Effect of oil palm fiber fuel ash on compressive strength of hardening concrete," *Proceedings of the 4th Thailand Materials Science and Technology Conference*, (pp. 1-3`). Pathumthani, Thailand, 2006.

[105] N. Ranjbar, M. Mehrali, U. J. Alengaram, H. S. Metselaar, and M. Z. Jumaat, "Compressive strength and microstructural analysis of fly ash/palm oil fuel ash based geopolymer mortar under elevated temperatures," *Construction and Building Materials*, pp: 114-121, 2014.

[106] W. Tangchirapat, T. Saeting, C. Jaturapitakkul, K. Kiattikomol, and A. Siripanichgorn, "Use of waste ash from palm oil industry in concrete," *Waste Management*, vol. 27, *no.*1, pp: 81-88, 2007.

[107] M. A. Johari, A. M. Zeyad, N. M. Bunnori, and K. S. Ariffin, "Engineering and transport properties of high-strength green concrete containing high volume of ultrafine palm oil fuel ash," *Construction and Building Materials*, vol. 30, pp: 281-288, 2012.

[108] C. Sujivorakul, C. Jaturapitakkul, A. M. ASCE, and A. Taotip, "Utilization of fly ash, rice husk ash and palm oil fuel ash in glass fiber-reinforced concrete," *Journal of Materials in Civil Engineering*, vol. 23, pp: 1281-1288, 2011.

[109] T. Sinsiri, W. Kroehong, C. Jaturapitakkul, and P. Chindaprasirt, "Assessing the effect of biomass ashes with different finenesses on the compressive strength of blended cement paste," *Materials and Design*, vol. 42, 424-433, 2012.

[110] M. M. Islam, K. H. Mo, U. J. Alengaram, and M. Z. Jumaat, "Mechanical and fresh properties of sustainable oil palm shell lightweight concrete incorporating palm oil fuel ash," *Journal of Cleaner Production*, vol. 115, pp: 307-314, 2016.

[111] C. Jaturapitakkul, K. Kiattikomol, W. Tangchirapat, and T. Saeting, "Evaluation of sulfate resistance of concrete containing palm oil fuel ash," *Construction and Building Materials*, vol. 21, no. 7, pp: 1399-1405, 2007.

[112] K. Muthusamy, and N. Zamri, "Mechanical properties of palm oil shell lightweight aggregate concrete containing palm oil fuel ash as partial cement replacement," *KSCE Journal of Civil Engineering*, vol. 20, no. 4, pp: 1473-1481, 2016.

[113] H. M. Hamada, G. A. Jokhio, F. M. Yahaya, A. M. Humada, and Y. Gul, "The present state of the use of palm oil fuel ash (POFA) in concrete," *Construction and Building Materials*, vol. 175, pp: 26-40, 2018.

[114] J. B. Newman, and B. S. Choo, *Advanced Concrete Technology*. United Kingdom: Butterworth-Heinemann, 2003.

[115] N. M. Al-Akhras, "Durability of metakaolin concrete to sulfate attack," *Cement and Concrete Research, vol. 36, no.* 9, pp: 1727-1734, 2006.

[116] J. Setina, A. Gabrene, and I. Juhnevica, "Effect of pozzolanic additives on structure and chemical durability of concrete," *Procedia Engineering*, vol. 57, pp: 1005-1012, 2013.

[117] M. Malviya, and H. S. Goliya, "Durability of fly ash based geopolymer concrete using alkaline solutions (NaOH)," pp: 18-33, 2014.

[118] A. Siddika, M. A. Al Mamun, R. Alyousef, and H. Mohammadhossein, "State-of-the-art-review on rice husk ash: A supplementary cementitious material in

concrete," *Journal of King Saud University-Engineering Sciences*, 2021.

[119] A. Meena, and R. Singh, "Comparative study of waste glass powder as pozzolanic material in concrete," *Doctoral Dissertation, National Institute of Technology*, 2012.

[120] R. B. Polder, "Effects of slag and fly ash on reinforcement corrosion in concrete in chloride environment - Research from the Netherlands," *Heron*, vol. 197, 2012.

[121] S. Thokchom, P. Ghosh, and S. Ghosh, "Effect of water absorption, porosity and sorptivity on durability of geopolymer mortars," *ARPN Journal of Engineering and Applied Sciences*, vol. 4, no. 7, pp: 28-32, 2009.

[122] A. A. Adam, "Strength and durability properties of alkali-activated slag and fly ash-based geopolymer concrete," *Doctoral Dissertation, RMIT University Melbourne, Australia*, 2009.

[123] Y. Hamzeh, K. P Ziabari, J. Torkaman, A. Ashori, and M. Jafari, "Study on the effects of white rice husk ash and fibrous materials additions on some properties of fiber–cement composites," *Journal of Environmental Management*, vol. 117, pp: 263-267, 2013.

[124] H. K. Venkatanarayanan, and P. R. Rangaraju, "Effect of grinding of low-carbon rice husk ash on the microstructure and performance properties of blended cement concrete," *Cement and Concrete Composites*, vol. 55, pp: 348-363, 2015.

[125] T. R Praveenkumar, and M. M. Vikayalakshmi, "Microstructural properties of nano-rice husk ash concrete," *Nanotechnology for Environmental Engineering*, vol. 9, 2019.

[126] M. A. Mosaberpanah, and S. A. Umar, "Using rice husk ash as supplement to cementitious materials on performance of ultrahigh-performance concrete: a review," *Materials Today Sustainability*, pp: 7-8, 2020.

[127] J. P. Hwang, H. B. Shim, S. Lim, and K. Y. Ann, "Enhancing the durability properties of concrete containing recycled aggregate by the use of pozzolanic materials," *KSCE Journal of Civil Engineering*, pp: 155-163, 2013.

[128] M. Omrane, S. Kenai, E. Kadri, and A. Aït-Mokhtard, "Performance and durability of self compacting concrete using recycled concrete aggregates and natural pozzolan," *Journal of Cleaner Production*, vol. 165, pp: 415-430, 2017.

[129] B. Uzal, L. Turanli, and P. Mehta, "High-volume natural pozzolan concrete for structural applications" *ACI Materials Journal*, vol. 104, no. 5, pp: 535-538, (n.d.).

[130] K. Celik, M. D. Jackson, M. Mancio, C. Meral, A. Emwas, P. K. Mehta, and P. J. Monteiro,. "High-volume natural volcanic pozzolan and limestone powder as partial replacements for portland cement in self-compacting and sustainable concrete," *Cement and Concrete Composites*, vol. 45, 136-147, 2014.

[131] B. B. Raggioti, M. J. Positieri, and A. Oshiro, "Natural zeolite, a pozzolan for structural concrete," *Procedia Structural Integrity*, vol. 11, pp: 36-43, 2018.

[132] M. F. Agosto, "Estudio de zeolitas procedentes de depósitos Argentinos. Aspectos tecnológicos que posibiliten su aplicación en agroindustriay contralor ambiental," *Doctoral Thesis*, vol. 185, 2002.

[133] C. C. Ferraro, J. M. Paris, T. G. Townsend, and M. Tia, "Evaluation of alternative pozzolanic materials for partial replacement of Portland cement in concrete," *Thesis Dissertation: The Florida Department of Transportation Research Center* , 2017.

[134] J. G. Cabrera, and P. A. Claisse,. "Measurement of chloride penetration into silica fume concrete," *Cement and Concrete Composites*, 1990.

[135] S. F. Association, "Silica fume User's manual," *Silica Fume Association*, 2005.

[136] A. M. Boddy, R. D. Hooton, and M. D. Thomas, "The effect of the silica content of silica fume on its ability to control alkali-silica reaction'" *Cement and Concrete Research*, 2003.

[137] ASTM-C1260, "Standard test method for potential alkali reactivity of aggregates (Mortar-Bar Method)", *ASTM International, 2021*

[138] H. S. Wong, and H. A. Razak,. "Efficiency of calcined kaolin and silica fume as cement replacement material for strenght performance," *Cement and Concrete Research*, pp: 696-702, 2005

[139] P. Chindaprasirt, S. Homwuttiwong, and C. Jaturapitakkul, "Strength and water permeability of concrete containing palm oil fuel ash and rice husk-bark ash," *Construction and Building Materials*, vol. 21, pp: 1492-1499, (2007).