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Cementitious materials and agricultural wastes as natural fine aggregate replacement in conventional mortar and concrete

Alaa Rashad

Building Materials Research and Quality Control Institute, Housing & Building National Research Center, HBRC, Cairo, Egypt

A R T I C L E I N F O

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A B S T R A C T

In the last 15 years, the worldwide consumption of natural sand as fine aggregate in mortar/concrete production is very high and many developing countries have encountered some problems in the supply of natural sand in order to meet the increasing demands of construction development. In many countries there is a shortage of natural sand that is suitable for construction. On the other hand, disposal of wastes such as fly ash (FA), bottom ash (BA) and agricultural wastes can be considered as the major environmental challenges. This challenge continues to increase with the increase of these wastes. Therefore, studies have been carried out to find suitable solutions of the shortage of natural sand and the huge increasing in the wastes disposal. One logical option to solve this problem is employing these materials as a part of fine aggregate instead of natural one in mortar/concrete. This paper presents an overview of the previous studies carried out on the use of the previous wastes as a partial or full of natural fine aggregate replacement in traditional mortar/concrete mixtures based on Portland cement (PC). Other cementitious material such as ground basaltic pumice and metakaolin (MK), which can replace part or full of natural fine aggregate was also included. Fresh properties, hardened properties and durability of mortar/concrete containing these waste/cementitious materials as natural fine aggregate replacement have been reviewed.

Contents

Abbreviations: FA, fly ash; BA, bottom ash; PC, Portland cement; SS, steel slag; BOF, basic oxygen furnace; EAF, electric arc furnace; SF, silica fume; OPS, oil palm shell; OPBC, oil-palm-boiler clinker; PKS, oil palm kernel shell; RHA, rice husk ash; CA, corncob ash; OA, olive ash; WSA, wheat straw ash; SBA, sugarcane bagasse ash; MK, metakaolin; GBFS, granulate blast-furnace slag; CS, copper slag; SP, superplasticizer; W/c, water/cement; W/b, water/binder; HRWR, high range water reducer; RCPT, rapid chloride permeability test

E-mail addresses: alaarashad@yahoo.com, a.rashad@hbrc.edu.eg

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1. Introduction

The worldwide consumption of natural sand as fine aggregate in mortar/concrete production is very high and several developing countries have met some strain in the supply of natural sand in order to meet the increasing demands of construction development. In many countries there is a shortage of natural fine aggregate which is suitable for construction. Natural sand is most common material which used as natural fine aggregate. In general, in the last 15 years, it has become clear that the availability of good quality of natural sand continues in decreasing [1]. The shortage of the resources of natural sand opened the door for using by-products and cementitious materials as a source of fine aggregate. Reuse of by-products as a partial or full replacement of natural fine aggregate in construction activities not only reduces the demand for extraction of natural raw materials, but also saves landfill space and reduce the consumption of natural resources.

Fly ash (FA) and bottom ash (BA) are residues from the combustion of coal. Coal ash is formed when coal is burned in boilers that generate steam for power generation and industrial applications. FA accounts about 80% of all the coal ash, whilst BA accounts about 20%. FA is captured in the chimney, whilst BA is collected from the bottom of the furnace from the coal fired power plant. The particles of FA are very fine, whereas BA has much larger particle size which is about the size of sand but more porous. The physical and chemical characteristics of FA or BA can vary greatly and will mainly depend on the combustion method and coal properties used at a particular power plant. High quantities of FA were found in the world. Around one billion tonne of FA is produced annually worldwide in coal-fired steam power plants [2]. Although FA can be used in high volume to replace Portland cement (PC) [3–6] or as a source of alkali-activated FA system [7], only a small part of this ash is used (20–30%); the rest is land filled-and surface-impounded, with potential risks of air pollution, contamination of water due to leeching [8]. Therefore, FA should not only be disposed of safely to prevent environmental pollution, but should be treated as a valuable resource.

About 20%, by volume, of the total combustion of coal is BA, depending on the type of boiler, dust collection system, burning temperature and the type of coal. Its particle is porous, irregular and coarser than that of FA, but its chemical composition is not much different [9]. About 45% of BA is used in transportation applications such as asphalt concrete aggregate, road base material, embankment or backfill material and structural fill [10]. Others used BA in concrete production as a part of binder material [11] or as a part of aggregate [12]. The remaining amount of this material is still damped in landfill sites caused environmental problems.

Although the uncertainty of the available references, the world steel industry has produced approximately 1.5 billion tonnes of steel in 2012 [13]. The generated waste slag is calculated between 10% and 20% of the raw materials used (according to oxide content, oxygen supply volume, the quality of metal or furnace efficiency), suggesting a huge amounts of wastes generated by these processes [14]. Steel slag (SS) is a by-product from either the conversion of iron to steel in a basic oxygen furnace (BOF), or the melting of scrap to make in an electric are furnace (EAF). It is the largest by-product from a minimill. The SS wastes are generated daily caused problems and hazardous for both the factories and the environment [15]. In the literatures, most of studies used SS as coarse aggregate in concrete and several of them concluded positive effect of SS on the mechanical properties [16–20]. Others used it in asphalt mixtures [21–25] or as a part of binder material [26–31], whilst there are limited studies which used it as fine aggregate.

Silica fume (SF) is a by-product waste produced by electric arc furnace during the production of metallic silicon or ferrosilicon alloys. The amounts of production of SF as by-product especially in industrial counties have reached alarming proportions. It was estimated that the global output of SF, at almost, between 1 and 1.5 million tonnes annually [32]. SF is also known as silica dust, micro silica, volatilzed silica or condensed silica fume composed primarily of pure silica in non-crystalline form. Its particle size is usually $< 1\ \mu m$, surface area is ranging from 13,000 to 30,000 m^2/kg, specific gravity is around 2.22 and its bulk density (as produced) are in the range of 130–430 kg/m^3 [33]. Although there are several technical advantages of using SF as mineral admixtures in matrix based on PC [34–37] or in matrix based on alkali activation of materials [7,38,39], in most cases most of SF has to be disposed off into landfill. This has significant hazardous environmental impact as it causes air pollution or groundwater pollution. Employing SF as a part of natural sand may help to solve this problem.

Oil palm shell (OPS), oil-palm-boiler clinker (OPBC), oil palm kernel shell (PKS), rice husk ash (RHA), corncob ash (CA), wheat straw ash (WSA), olive ash (OA) and sugarcane bagasse ash (SBA) are agricultural by-products. There are many tonnes of these materials are generated each year. Although some of these materials can be used as animals food or fuel in biomass power plants or in boilers of various industrial sectors to produce steam, a lot of these materials are still disposed off into landfill or burnt caused environmental problems. The utilization of these agriculture waste materials in concrete reduces the environmental problems and conserves existing of natural resources.

Pumice is a natural material of volcanic origin produced by release of gases during the solidification of lava. It is found abundantly in volcanic area in different countries such as Ethiopia, Turkey, Chile, Greece, Span, Iran and USA [40]. Pumice consists mainly of SiO_2, CaO, Al_2O_3, Fe_2O_3 and MgO. Due to the sudden release of gases in the structure of pumice during its formation and sudden cool down, it contains a lot of pores which make it light material. Some studies used this material as aggregates to produces lightweight concrete and as pozzolanic material [41].

Kaolin is one of the most used minerals. The world total output of kaolin exceeds 25 million tonnes [42,43]. Kaolin can be used in many industries such as paper, cement, ceramic, bricks, porcelain, filler for paint, rubber, plastics, medicines, textiles and petroleum [43]. When kaolin thermally activated, it converts to metakaolin (MK) which has pozzolanic activities. The major constituents of MK are SiO_2 and Al_2O_3. Its specific gravity is around 2.6, whilst its bulk density are in the range of 0.3–0.4 (g/cm^3). The particle shape of MK is usually platy with size of 1.5–0.2 μm [43]. MK was used widely in PC system as a pozzolanic material, of which portion of cement was replaced or as cement addition to improve some properties of the matrix or in alkali-activated MK system [43] or as an additive to alkali-activated slag system [39] or alkali-activated FA system [7]. Although in most cases in PC system MK was used as mineral admixtures, it can be used as a part of fine aggregate instead of natural one to solve the scarce of natural sand quarry in some countries.

Although there is a good review on using industrial wastes such as BA, SS, blast-furnace slag, non-ferrous slag, plastic wastes, rubber wastes and ceramic industry wastes as aggregates in concretes [44], this review did not focus on replacing natural fine aggregate with these materials, but focused almost on replacing aggregates (in general coarse and fine) by industrial wastes in concretes only and did not include mortars. On the same line, this review did not include the previous studies which used SF, agricultural wastes, MK and ground basaltic pumice as natural fine aggregate replacement. Anyway, in general, in the literature, there is no research which summarizes the previous studies that carried out on the fresh properties, hardened properties and durability of mortar/concrete containing waste/cementitious materials such as FA, BA, SS, SF, agricultural wastes (such as OPS, OPBC, PKS, RHA, CA, WSA, OA and SBA), MK and ground basaltic pumice, as a partial or full replacement of natural fine aggregate. Therefore, the current article has been written to present the previous findings related to this topic, to act as a primary reference base for future researches. It worth mentioning that the previous studies that recycled granulate blast-furnace slag (GBFS) and copper slag (CS) as a partial or full natural fine aggregate replacement have been and reviewed and published elsewhere [45]. On the same line, the previous studies which focused of employing the other types of ashs such as pond ash, incinerator ash and slags such as welding slag, lead slag, zinc slag, ladle-furnace slag, ferrochrome slag, stainless steel oxidizing slag will be reviewed and published elsewhere.

2. By-products cementitious materials

2.1. Fly ash

FA is typically classified as either Class F or Class C according to ASTM C618-12a. This classification is based on the chemical composition of FA. The major delimiter for this classification is the sum of silica, aluminum and iron oxide percentages in the FA, being a minimum of 70% for a Class F and a minimum 50% for a Class C. The Canadian Standards Association classified FA according to the amount of CaO. FA is generally low-calcium (Class F) when CaO is less than 10%. Most of the FA particles are solid spheres and some are hollow cenospheres. The particle sizes in FA vary from <1 μm up to more than 100 μm with the typical particle size measuring below 20 μm. The surface area is typically 300–500 m^2/kg, although some FA can have surface area as high as 700 m^2/kg and as low as 200 m^2/kg. The mass per unit volume including air between particles can vary from 540 to 860 kg/m^3, whilst the close packed storage or vibration, the range can be from 1120 to 1500 kg/m^3. The specific gravity (relative density) of FA ranging from 1.9 to 2.8. FA is primarily composite of silicate glass mainly containing silica, alumina, iron and calcium. Magnesium, sulfur, sodium, potassium and carbon are minor constituents [6].

2.1.1. Heat of hydration, workability, setting time and bleeding

Dhir et al. [46] partially replaced natural sand with PFA at the PFA/natural sand ratios of 0.05, 0.1 and 0.15, by weight, in concrete mixtures. The results demonstrated that PFA might actively contribute to the reactions in cementitious systems, with increased heat generation and lime consumption, compared to the reference mixture.

Seo et al. [47] reported an increase in the workability of concrete mixture by partially replacing natural sand with 20% FA, at the same water/cement (w/c) ratio. Ravina [48] studied the workability and setting time of concrete mixtures containing FA as natural sand replacement. Natural sand was partially replaced with FA at levels ranging from 15% to 25%, by weight. Various w/c ratios were used. This investigation concluded that the workability of most FA mixtures was better than that for the reference mixture. The initial and final setting time delayed with the inclusion of FA as natural sand replacement. The bleeding in the FA and reference mixtures was the same order. Ravina [49] reported that the inclusion of FA of marginal quality as natural sand replacement improved the workability, cohesiveness and finishability of the concrete mixtures compared to the reference. Pofale and Deo [50] reported that higher workability of concrete mixtures was obtained by replacing natural sand with 12% and 27% FA. The workability increased as the content of FA sand increased. Nambiar and Ramamurthy [51] replaced natural sand with FA at levels of 50% and 100% in foamed concrete mixtures. The results indicated that the foamed concrete mixtures with FA as a filler showed relatively higher flow values. Jones and McCarthy [52] used unprocessed, run-of-station, low-lime FA in foamed concrete mixtures as natural sand replacement. Various w/c ratios were used. They reported that replacement of natural sand with unprocessed run-of-station FA had a significant beneficial effect on fresh foamed concrete properties. The FA mixture enhanced consistence (greater spreadability and flowability out of a modified Marsh cone) and rheology (reduced apparent yield) compared with the natural sand concrete. Hwang et al. [53] investigated the effect FA as partially replacement of natural sand replacement at levels of 25% and 50% on the rheology of mortar mixtures. Test results showed that rheological constants increased with higher content of FA sand.

Dhir et al. [46] partially replaced natural sand with PFA at the PFA/natural sand ratios of 0.05, 0.1 and 0.15, by weight, in concrete mixtures. The workability was not significantly affected at low PFA/natural sand ratio of 0.05, but reduced with the inclusion of higher levels of PFA sand. Pavati and Prakash [54] partially replaced natural sand in concrete mixtures with FA at levels ranging from 10% to 80% with an increment of 10%, by weight. Fixed w/c ratio of 0.45 and various dosages of superplasticizer (SP) were used. The results showed lower workability with the inclusion of FA sand. The workability decreased with increasing FA sand content. Joseph and Ramamurthy [55] investigated the workability of concrete containing FA as natural sand replacement. Natural sand

Table 1
Effect of FA sand on the workability of mortar and concrete.

Reference	FA content (%)	Increased workability
Seo et al. [47]	20	Yes
Ravina [48]	15–25	Yes
Pofale and Deo [50]	12 and 27	Yes
Nambiar and Ramamurthy [51]	50 and 100	Yes
Jones and McCarthy [52]	100	Yes
Hwang et al. [53]	25 and 50	Yes
Dhir et al. [46]	5, 10 and 15	No
Pavati and Prakash [54]	10–80	No
Joseph and Ramamurthy [55]	20–100	No
Bilir et al. [56]	10–100	No

was partially replaced with FA at levels of 20%, 40%, 60%, 80% and 100%, by volume. Fixed w/c ratio and various dosages of SP were used. They reported that the workability of concrete mixtures decreased with the inclusion of FA sand. Bilir et al. [56] replaced natural sand in mortar mixtures at levels ranging from 10% to 100% with an interval of 10%, by weight. They reported a reduction in the workability with the inclusion of FA. This reduction increased with increasing FA content, of which the workability loss reached 13.4% with the inclusion of 100% FA sand. Table 1 summarizes the above mentioned studies about the effect of FA sand on the workability of mortar and concrete.

From the above mentioned studies, it is safe to conclude that the inclusion of FA sand in the mixture increased its workability as reported by several studies (Fig. 1). Pofale and Deo [50] related this improvement in the workability to the more pronounced lubricating effect of FA which led to more workable. The improvement of the workability with the inclusion of FA sand can be considered as one advantage of using this by-product material. It is possible to reduce w/c ratio for FA sand mixture to reach the same workability of the control. This led to improvement in the strength and other properties. However, on the other hand, few studies reported a reduction in the workability with the inclusion of FA as natural sand replacement. Dhir et al. [46] related this reduction to the increase in the fines content. Joseph and Ramamurthy [55] related this reduction to the increase in the specific surface of the mixture containing FA sand.

2.1.2. Density

Pofale and Deo [50] reported 3.39% and 4.94% reduction in the density of concrete specimens by partially replacing natural sand with FA at levels of 12% and 27%, respectively. Roy [57] reported 2.69%, 4.78%, 4.1%, 6.24% and 9.21% reduction in the unit weight of concrete specimens by partially replacing sand with 20%, 30%, 40%,

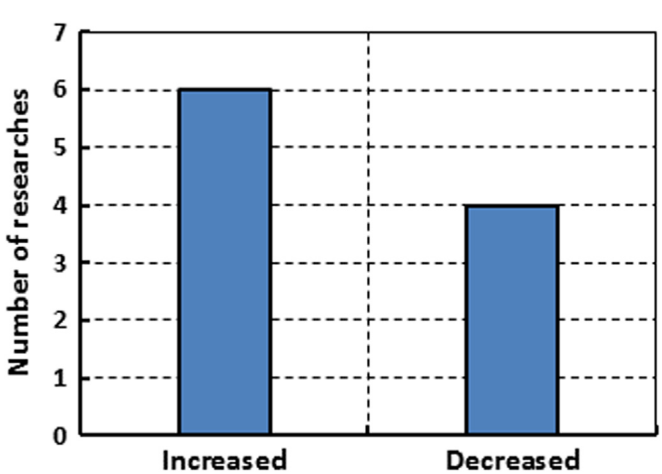


Fig. 1. Research numbers versus the effect of FA sand on the mixture workability.

50% and 60% FA, respectively. Joseph and Ramamurthy [55] reported a reduction in the dry density of concrete specimens by replacing natural sand with FA at levels of 20%, 40%, 60%, 80% and 100%, by volume. The reduction in the dry density increased as the FA sand content increased. Bilir et al. [56] reported a reduction in the unit weight of mortar specimens by replacing natural sand with FA at levels ranging from 10% to 100%, by weight. This reduction increased with increasing FA content. The inclusion of 100% FA caused a reduction of 39.47% and 36.64% at ages of 7 and 28 days, respectively. On the contrary, Siddique [58] reported 0.09%, 0.26%, 0.26%, 0.35% and 0.48% increment in the fresh density of concrete mixtures by partially replacing natural sand with 10%, 20%, 30%, 40% and 50% Class F FA, by weight, respectively. Similar results were obtained when natural sand was partially replaced with FA up to 40% in Siddique [59].

From the above mentioned studies, it is clearly to conclude that the inclusion of FA as natural sand replacement decreased the density of the mixture. This reduction in the density could be related to the lighter weight of FA sand compared to that of natural sand as reported by Pofale and Deo [50]. Roy [57] related this reduction to the lower specific gravity of FA sand. The reduction in the specific gravity of FA led to a reduction of unit weight of FA concrete specimens. The reduction in the concrete density with the inclusion of FA sand is required to reduce the dimensions of structural elements and dead load. Reducing dead load is desired in some special applications of engineering. Subsequently, reducing unit weight using FA sand can be considered as one advantage of using this by-product material.

2.1.3. Strength

Jones and McCarthy [52] reported higher compressive strength of foamed concrete by replacing natural sand with low-lime FA. Rebeiz et al. [60] reported 15% increase in the compressive strength of concrete by partially replacing natural sand with 15% FA, by weight. Ravina [49] reported that FA of marginal quality, as natural sand replacement, had beneficial effects on the properties of hardened concrete. Compressive strength, particularly at later ages and modulus of elasticity were higher than that of the reference mixture. Dhir et al. [46] partially replaced natural sand in concretes with PFA at levels of 5%, 10% and 15%, by weight. The results demonstrated the suitability for using PFA as fine aggregate component in concrete. The strength of concrete specimens increased with the inclusion of PFA sand. Christy and Tensing [61] reported that mortars containing 10% and 20% FA as natural sand replacement yielded higher compressive strength than the reference mixture. Seo et al. [47] reported an enhancement in the compressive strength, splitting strength and Young's modulus of concrete specimens containing 20% FA as natural sand replacement. The enhancement in the compressive strength was 8%, 0%, 9.1%, 14.28% and 13.51% with the inclusion of FA at ages of 7, 14, 21, 28 and 91 days, respectively, whilst the enhancement in the Young's modulus was 3.7%, 0%, 7.69%, 7.69% and 8%, respectively. Pofale and Deo [50] partially replaced natural sand in concretes with FA at levels of 0%, 12% and 27%. The results showed an enhancement in the compressive strength and flexural strength with the inclusion of FA sand. The enhancement in the 28 days compressive strength was 14.64% and 24% with the inclusion of 12% and 27% FA sand, respectively, whilst the enhancement in the flexural strength was 5.13% and 10.26%, respectively.

Papadakis [62] partially replaced natural sand in mortars with FA at levels of 10%, 20% and 30%, by volume. The compressive strength of FA mortars was similar to that of the reference mixture at ages of 3 and 14 days. On the other hand, they showed higher compressive strength from 28 days and beyond. Maslehuddin et al. [63] reported an enhancement in the compressive strength of concretes at ages of 3, 7, 14, 56 and 90 days by partially replacing natural sand with FA at levels of 20% and 30%, by weight. Mangaraj and Krishnamoorthy [64] reported an enhancement in the compressive strength of concretes by partially replacing natural sand with FA at levels 0–30%, when w/c ratio was 0.6. Siddique [59] partially replaced natural sand in concretes with FA at levels of 10%, 20%, 30% and 40%, by weight. Various w/b ratios and various dosages of SP were used. Compressive strength was determined up to 365 days. The results showed an increase in the compressive strength with increasing FA sand content. In another investigation, Siddique [58] partially replaced natural sand with Class F FA in concretes at levels of 0%, 10%, 20%, 30%, 40% and 50% by weight. Various w/c ratios and various dosages of SP were used. Compressive strength, splitting tensile strength, flexural strength and modulus of elasticity were determined at ages of 7, 14, 28, 56, 91 and 365 days. The results indicated significant improvement in the strength properties and the modulus of elasticity with the inclusion of FA as partial replacement of natural sand up to 50%. The enhancement in the 28 days compressive strength was 6.82%, 16.67%, 32.19%, 47.35% and 53.85% with the inclusion of 10%, 20%, 30%, 40% and 50% FA sand, respectively, whilst the enhancement in the 28 days flexural strength was 8.1%, 13.51%, 18.92%, 18.92% and 16.22%, respectively. The enhancement in the 28 days splitting tensile strength was 3.33%, 6.67%, 13.33%, 16.67% and 16.67% with the inclusion of 10%, 20%, 30%, 40% and 50% FA, respectively, whilst the enhancement in the 28 days modulus of elasticity was 5%, 7.5%, 17.5%, 20% and 22.5%, respectively.

Hwang et al. [53] reported an enhancement in the compressive strength of mortars by partially replacing natural sand with FA at levels of 25% and 50%. Roy [57] reported that concrete containing BFS as coarse aggregate and 20%, 30%, 40%, 50% and 60% FA as natural sand replacement increased the compressive strength, flexural strength, splitting tensile strength and modulus of elasticity. The enhancement in the 28 days compressive strength was 17.98%, 38.83%, 38.67%, 12.63% and 3.82% with the inclusion of 20%, 30%, 40%, 50% and 60% FA sand, respectively. Pavati and Prakash [54] reported higher compressive strength, tensile strength and flexural strength of concretes by partially replacing natural sand with FA at levels of 10%, 20%, 30% and 40%, whilst partially replacing natural sand with 50%, 60%, 70% and 80% FA reduced the strength. The optimum FA sand content was 40%. Joseph and Ramamurthy [55] investigated the compressive strength of concretes containing FA as natural sand replacement. Natural sand was partially replaced with FA at levels of 20%, 40%, 60%, 80% and 100%, by volume. Fixed w/c ratio and various dosages of SP were used. They reported that the compressive strength increased with the inclusion of FA sand. 60% FA sand showed the optimum replacement level. Nambiar and Ramamurthy [51] replaced natural sand with FA at levels of 50% and 100% in foamed concrete. The compressive strength increased as FA sand content increased. On the other hand, Bilir et al. [56] reported a reduction in the 7 days compressive strength of mortar specimens by replacing natural sand with FA at levels ranging from 10% to 100%, by weight. At age 28 days, the inclusion of 30% FA enhanced the compressive strength by 4%, whilst the other contents of FA decreased it. Table 2 summarizes the above mentioned studies about the effect of FA sand on the strength of mortar and concrete.

From the above mentioned studies, it is possible to conclude that the inclusion of FA sand in the mixture increased the strength. The enhancement in the strength at early ages could be related to the better packing of mortar/concrete ingredient due to lubricating effect of FA [50]. The enhancement in the strength at latter ages could be related to the pozzolanic action of FA [50]. In the beginning, FA did not react with the calcium hydroxide liberated during the hydration of cement and did not contribute the densification of the mortar/concrete matrix. The reaction between calcium hydroxide and FA cement paste progressed very slowly and enhanced gradually after about 8 to 28 days [63]. Other researchers Joseph and Ramamurthy [55] related the enhancement in strength with the inclusion of FA sand to the combined filler effect and pozzolanic action of FA. Higher amount of CSH was produced with an increase of FA sand content inhibiting large deposits, contributing to early strength gains [65]. The optimum content of FA sand which exhibited the highest compressive strength is still undetermined. Siddique [58]; Pavati and Prakash [54] reported 40% is the optimum, whilst Joseph and Ramamurthy [55] reported 60% is the optimum.

Table 2
Effect of FA sand on the strength of mortar and concrete.

Reference	FA content (%)	Positive effect
Dhir et al. [46]	5, 10 and 15	Yes
Rebeiz et al. [60]	15	Yes
Christy and Tensing [61]	10 and 20	Yes
Seo et al. [47]	20	Yes
Pofale and Deo [50]	12 and 27	Yes
Papadakis [62]	10, 20 and 30	Yes at 28 days and beyond
Maslehuddin et al. [63]	20 and 30	Yes
Mangaraj and Krishnamoorthy [64]	Up to 30	Yes
Siddique [59]	10–40	Yes
Siddique [58]	10–50	Yes
Hwang et al. [53]	25 and 50	Yes
Roy [57]	20–60	Yes
Pavati and Prakash [54]	10–80	Yes (10–40) No (50–80)
Joseph and Ramamurthy [55]	20–100	Yes
Nambiar and Ramamurthy [51]	50 and 100	Yes
Bilir et al. [56]	10–100	Yes (30) No (10, 20, 40–100)

2.1.4. Abrasion, corrosion, carbonation and fire resistance

Siddique [59] studied the abrasion resistance of concretes, of which natural sand was partially replaced with FA at levels of 0%, 10%, 20%, 30%, and 40%. The results revealed that the abrasion resistance of concrete increased with increasing FA sand content. The reduction in the wear depth at age of 28 days was 12.5%, 21.43%, 31.43% and 39.28% with the inclusion of 10%, 20%, 30% and 40% FA sand, respectively, whilst the reduction at age of 365 days was 16.52%, 23.91%, 32.17% and 42.61%, respectively.

Maselehuddin et al. [66] showed that the corrosion rate of reinforcing bars in concrete containing FA as natural sand replacement was lower than that of the reinforcing bars in concrete containing FA as cement replacement. In another investigation, Maslehuddin et al. [63] evaluated the long term corrosion resisting (up to 4 years) characteristics of concretes containing FA as natural sand replacement. Natural sand was partially replaced with FA at levels of 0%, 20% and 30%, by weight. They reported that concretes containing FA sand performed better than the reference concrete in resisting corrosion.

Hwang et al. [53] investigated the carbonation properties of mortars containing FA as natural sand replacement at levels of 0%, 25% and 50%. Test results showed that the carbonation properties improved with the inclusion of FA sand. Pavati and Prakash [54] exposed concrete specimens containing FA as natural sand replacement at levels ranging from 10% to 80% with an increment of 10% to elevated temperatures for 4 h. The results showed high residual strength after exposure to 200, 400, 600 and 800 °C with the inclusion of FA up to 40% and thereafter decreased.

The abrasion resistance, corrosion resistance, carbonation resistance and fire resistance of mortar/concrete increased with the inclusion of suitable content of FA as natural sand replacement. This increase could be attributed to the pozzolanic action of FA, leading to the densification of the matrix. However, these properties still need more investigations.

2.1.5. Drying shrinkage, creep strain and crack width

Ravina [49] reported that FA of marginal quality, as natural sand replacement, had beneficial effects on the drying shrinkage of concrete. Drying shrinkage of the FA mixtures was similar or somewhat lower than that of the reference. Seo et al. [47] investigated the drying shrinkage and creep strain, over 400 days, of concrete containing 20% FA as natural sand replacement. The results indicated that the drying shrinkage and creep strain of concrete containing FA as natural sand replacement was lower than the control. On the contrary, Bilir et al. [56] reported an increase in the drying shrinkage of mortar specimens by replacing natural sand with FA at levels ranging from 10% to 100%, by weight. The drying shrinkage increased with increasing FA sand content. On the other hand, the crack width showed a reduction trend and the crack formation was delayed. Seo et al. [47] investigated the crack width of concrete specimens containing 20% FA as natural sand replacement, by weight. The results showed a reduction in the crack width with the inclusion of FA sand.

It is safe to conclude that drying shrinkage, creep strain and crack width with the inclusion of FA sand still need more investigations. These topics can be used for incoming researches.

2.1.6. Water absorption and sulfate resistance

Ravina [49] reported that FA of marginal quality, as natural sand replacement, had beneficial effects on the penetration depth of concrete mixtures. The results showed that the maximum depth of the water penetration of the FA concrete mixtures was somewhat less than that of the reference mixture. Joseph and Ramamurthy [55] investigated the water absorption of concretes containing FA as natural sand replacement. The replacement of natural sand with FA was done on equal volume basis from 20% onwards. The results showed a reduction in the percentage of water absorption with the inclusion of FA sand. 80% FA sand showed the lowest percentage of water absorption. Roy [57] studied the percentage of water absorption and porosity of concretes containing BFS as coarse aggregate and 20%, 30%, 40%, 50% and 60% FA as partial replacement of natural sand. Fixed w/c ratio of 0.403 and various dosages of SP were used. The results showed that the percentage of water absorption and porosity, at age of 28 days, decreased with increasing FA sand content up to 40%, then increased with higher levels of FA sand. The reduction in the percentage of water absorption was 18.55%, 25.29%, 35.25% with the inclusion of 20%, 30% and 40% FA sand, respectively, whilst the reduction in the porosity was 22.34%, 26.39%, 34.82% and 34.82%, respectively.

Jones and McCarthy [52] used unprocessed, run-of-station, low-lime FA in foamed concrete, as a replacement of natural sand Various w/c ratios were used. They reported that the replacement of natural sand with unprocessed run-of-station FA provided almost complete immunity to sulfate attack.

From the above review of the literature in this section, it can be concluded that the inclusion of FA as natural sand replacement decreased the percentage of water absorption. As the natural sand was replaced with FA, as the improvement in the microstructure of both matrix and matrix–aggregate interface and formation of discontinuous pores (Fig. 2) are attributed for this reduction in the water absorption [55]. In addition, the fine FA particle helps to reduce the inter particle spaces which led to reduce the water absorption and porosity [57]. Subsequently, such properties are inhibiting ingress of harmful chemicals [57]. The reduction in the percentage of water absorption with the inclusion of FA sand is one advantage of using this by-product material as fine aggregate. The reduction in the percentage of water absorption leads to produce high service life and durable matrix. The higher sulfate

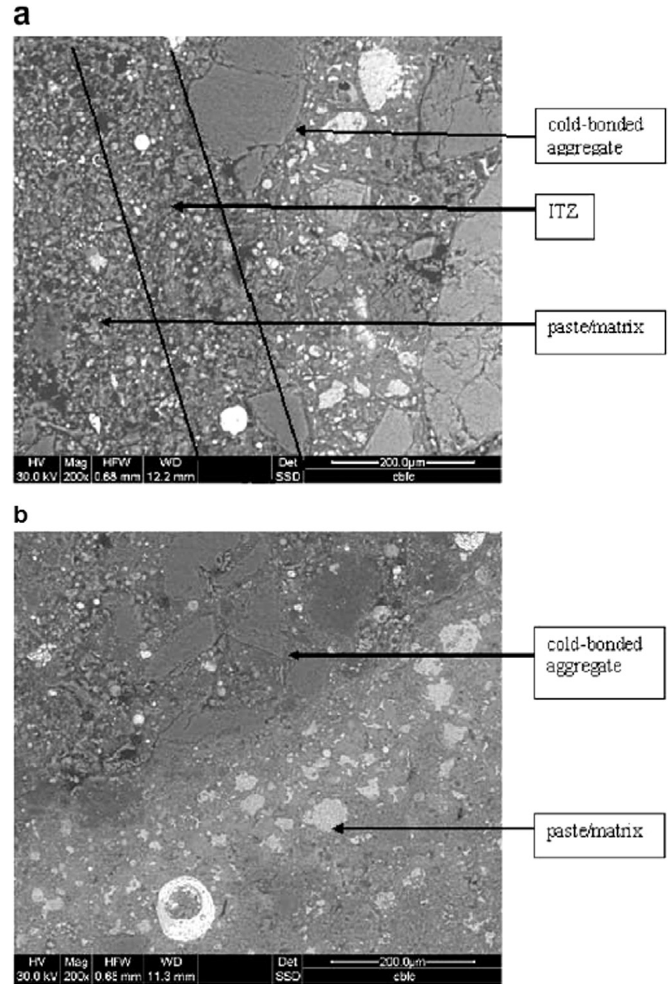


Fig. 2. Microstructure of concrete samples containing FA sand: (a) 0% FA and (b) 80% FA [55].

resistance with the inclusion of FA sand could be related to the pozzolanic reactions of FA that consumed most of or all portlandite coming from cement hydration [52]. However, sulfate resistance of mortar/concrete with the inclusion of FA sand still needs more investigations.

In general view, using FA as fine aggregate in mortar and concrete showed some advantages, of which some properties are improved. The advantages of using FA sand are increasing workability, decreasing density, increasing mechanical strength, abrasion resistance, corrosion resistance, fire resistance, sulfate resistance and decreasing the percentage of water absorption. There are some properties that still need more investigations for better understanding such as the effect of FA sand on drying shrinkage, creep strain and crack width

2.2. Bottom ash

BA particles are irregular, angular, porous and have rough surface texture. The porosity and void content of BA are generally higher than that in natural aggregate, thus BA can accommodate a high amount of water in mixture. The BA is mainly composited primarily of silica, alumina and iron with small amounts of magnesium, calcium, potassium, titanium sodium, phosphorous pentoxide and sulphur trioxide. Its particle size as fine or coarse aggregate. Its specific gravity are in the range of 1.39–2.48 [44].

2.2.1. Workability and setting time

Bai and Basheer [67] replaced natural sand in concrete mixtures with furnace BA at replacement levels of 30%, 50%, 70% and 100%, by weight. Fixed w/c ratio was used for all mixtures. The results indicated that the workability improved with the inclusion of furnace BA sand. The workability increased with increasing furnace BA sand content. The same results were obtained by Basheer and Bai [68] and Bai et al. [69]. Ramadoss and Sundararajan [70] reported higher workability of mortar mixtures by partially replacing natural sand with BA at levels ranging from 20% to 50%, by weight. The workability increased with increasing BA sand content. The flow value increased by 2.68% with the inclusion of 20% BA sand, whilst it increased by 5.26% with the inclusion of 50% BA sand. Yüksel and Genç [71] studied the workability, in term of slump, of concrete mixtures containing furnace BA as natural sand replacement. Natural sand was partially replaced with furnace BA at levels ranging from 10% to 50% with an increment of 10%, by weight. Fixed w/c ratio was used for all mixtures. The results showed an increase in the slump values with the inclusion of 10%, 20% and 30% furnace BA sand by 33.33%, 50% and 33.33%, respectively, related to the control mixture. On the other hand, slump values decreased at furnace BA sand contents higher than 30%. Siddique [72] reported a reduction in the workability of concrete mixtures by partially replacing natural sand with 10%, 20% and 30% BA, by weight.

Aggarwal et al. [73] partially replaced natural sand in concrete mixtures with BA at levels of 20%, 30%, 40% and 50%, by weight. Fixed w/c ratio and various dosages of SP were used. The results showed lower workability with the inclusion of BA sand. The workability decreased with increasing BA sand content. Kin and Lee [74] studied the workability, in term of slump flow, of concrete mixtures containing BA as natural sand replacement. Natural sand was replaced with BA at levels of 25%, 50%, 75% and 100%, by volume. Fixed w/c ratio and fixed dosage of SP were used. The results showed approximately no effect of BA sand on the slump flow. Kasemchaisiri and Tangtermirikul [75] investigated the fresh properties of SCC mixtures incorporating BA as partial replacement of natural sand at levels of 10%, 20%, and 30%, by weight. Fixed water/binder (w/b) ratio was used for all mixtures. Test results revealed that slump flow and L-box passing ability of the SCC mixtures containing BA were reduced as the content of BA sand increased. Topçu and Bilir [76] studied the effect of the non-ground BA as natural sand replacement in mortar mixtures. The replacement levels were ranging from 10-100% with an increment of 10%, by weight. Fixed w/c ratio and fixed dosage of high range water reducer (HRWR) were used. The results showed a reduction in the flow diameter of the mixtures with the inclusion of BA sand. The workability decreased with increasing BA sand content. Singh and Siddique [77,78] reported a reduction in the workability of concrete mixtures by replacing natural sand with BA at levels of 20%, 30%, 40%, 50%, 75% and 100%, by volume, at fixed w/c ratio.

Ghafoori and Bucholc [79] reported an increase in the initial and final setting time by replacing natural sand with BA at level of 100%, by volume. Ghafoori and Bucholc [80] reported an increase in the initial and final setting time by replacing natural sand in concrete mixtures with BA (size <4.75 mm) at levels of 50% and 100%, by volume. The average initial time of setting for the BA mixtures was approximately 6.3% higher than that of the control mixture. An average of 9.4% increase in the final setting time was obtained. Andrade et al. [81] reported higher initial and final setting time of concrete mixtures by replacing natural sand with BA (size <5 mm) at levels of 25%, 50%, 75% and 100%, by volume. This is could regarding to the higher content of water presented in the mixtures containing BA, resulting in the greater workability, subsequently, increasing mixing time in the fresh state, due to a greater distancing of cement hydration products. The reduction of the pH of the media is another factor, which can cause a delay in the hydration activities of cement particles [79]. Table 3 summarizes the above mentioned studies about the effect of BA sand on the workability of mortar and concrete.

Table 3
Effect of BA sand on the workability of mortar and concrete.

Author	BA content (%)	Increased workability
Bai and Basheer [67], Basheer and Bai [68], Bai et al. [69]	30, 50, 70 and 100	Yes
Ramadoss and Sundararajan [70]	20–50	Yes
Yüksel and Genç [71]	10, 20 and 30	Yes
Siddique [72]	10, 20 and 30	No
Yüksel and Genç [71]	40 and 50	No
Aggarwal et al. [73]	20–50	No
Kin and Lee [74]	25, 50, 75 and 100	No effect
Kasemchaisiri and Tangtermirikul [75]	10, 20 and 30	No
Topçu and Bilir [76]	10–100	No
Singh and Siddique [77, 78]	20–100	No

From the previous discussion, it can be noted that some studies reported positive effect of BA sand on the workability, whilst others reported negative effect (Fig. 3). The positive effect of BA sand could be related to its shape. The particles of the natural sand were irregular in shape whereas those of BA sand were spherical. As a consequence, when the BA sand was used to replace the natural sand, there was an increase in the “ball-bearing” effect and a reduction in water demand. This, in turn, increased the slump when the BA sand content was increased [67]. The negative effect of BA sand on the workability could be related to the fineness of its particle. The workability decreased when the BA finesses was higher than that of natural sand [73]. Because BA particles are porous and have higher percentage of water absorption than that of natural sand, the incorporation BA sand in the mixture decreased the workability.

2.2.2. Bleeding

Ghafoori and Bucholc [79] reported an increase in the bleeding of concrete mixtures by replacing natural sand with 100% BA. Andeade et al. [82] studied the bleeding of concrete mixtures containing different contents of BA ranging from 25% to 100%, by weight, as natural sand replacement. The results showed an increase in the bleeding with the inclusion of BA sand. The bleeding increased with increasing BA sand content. Andrade et al. [81] reported that replacing natural sand in concrete mixtures with BA increased the quantity of water loss by bleeding, the bleeding time and the rate of water release. Higher BA sand content led to greater of this effect. Ghafoori and Bucholc [80,83] reported higher

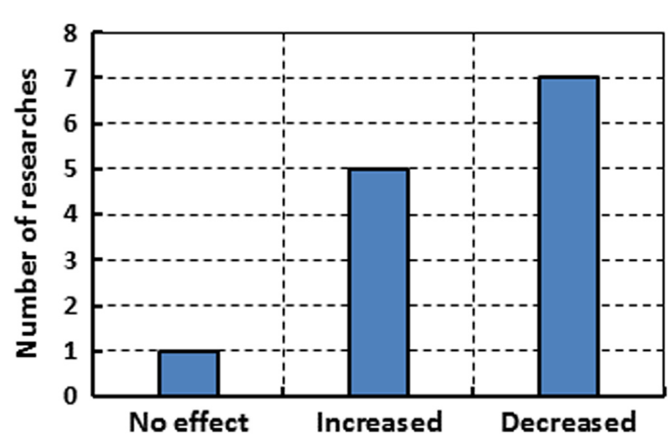


Fig. 3. Research numbers versus the effect of BA sand on the mixture workability.

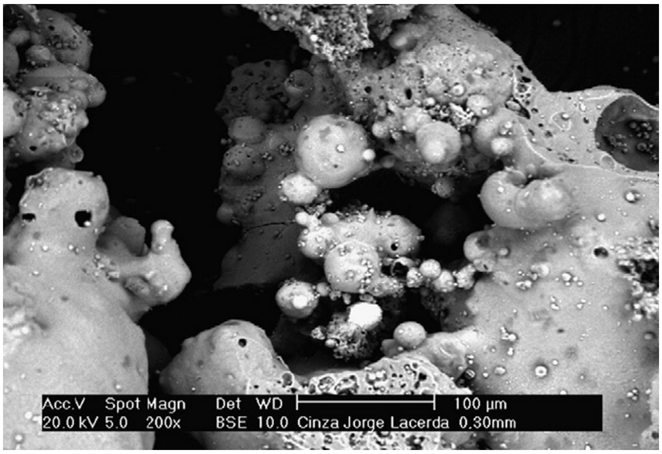


Fig. 4. SEM of bottom ash ($\phi < 250$ µm) [82].

bleeding in concrete mixtures with the inclusion of BA as natural sand replacement. The bleeding rate increased with increasing BA sand content. On the other hand, Singh and Siddique [77,78] reported a reduction in the bleeding percentage of concrete mixtures by replacing natural sand with BA. This reduction increased with increasing BA sand content. The bleeding percentage decreased from 3.14 to 1.66 with the inclusion of 100% BA.

From the above mentioned studies in this section, it can be concluded that the inclusion of BA as natural sand replacement in concrete mixtures increased the bleeding as reported by several studies. The higher bleeding with the inclusion of BA sand could be attributed to its increased demand for mixing water to achieve the required workability [79]. The bleeding can be mitigated by using water reducing admixture [80,83]. On the other hand, other studies reported a reduction of the bleeding of concrete mixtures with the inclusion of BA sand. This reduction could be attributed to less quantity of water available in inter particle voids in the concrete mixtures because the dry and porous particles of BA sand (Fig. 4) which absorbed part of water added internally during the mixing process [77].

2.2.3. Density

Basheer and Bai [68] reported that replacing natural sand with furnace BA at levels of 30%, 50%, 70% and 100%, by weight, in concretes did not affect the density. Bai and Basheer [67] replaced natural sand in concretes with furnace BA at levels of 30%, 50%, 70% and 100%, by weight. The results indicated that the density of concrete decreased with increasing furnace BA sand. Topçu and Bilir [76] reported a reduction of the unit weight of mortar specimens by replacing natural sand with BA at levels ranging from 10% to 100% with an increment of 10%, by weight. The unit weight decreased as the content of BA sand increased. Kin and Lee [74] studied the density of concrete specimens containing BA as natural sand replacement. Natural sand was replaced with BA at levels of 25%, 50%, 75% and 100%, by volume. The density of hardened concrete linearly decreased as the replacement level increased. The reduction in the density reached 9.6% when natural sand was replaced with 100% BA. Andeade et al. [82] studied the unit weight of concrete specimens containing different contents of BA ranging from 25% to 100%, by weight, as natural sand replacement. The results showed a reduction in the unit weight with the inclusion of BA sand. The unit weight decreased with increasing BA sand content. The reduction in the unit weight ranging from 6.4% to 61% with the inclusion of 3.5% and 100% BA sand, respectively. Andrade et al. [84] reported a reduction in the fresh density of concrete mixtures by replacing natural sand with BA at levels of 25%, 50%, 75% and 100%, by volume. The reduction in the fresh density was 2.73%, 6.61%, 12.24% and 16.49% with the inclusion of 25%, 50%, 75% and 100% BA sand, respectively.

Kadam and Patil [85] reported a reduction in the density of hardened concrete specimens with the inclusion of BA as natural sand replacement. The density decreased as the BA sand content increased. Singh and Siddique [77,78] reported a reduction in the density of concrete specimens by replacing natural sand with BA. The reduction in the density increased with increasing BA sand content. Andrade et al. [81] reported a reduction in the fresh density of concrete mixtures by replacing natural sand with BA (size < 5 mm) at levels of 25%, 50%, 75% and 100%, by volume. The reduction in the fresh density was 2.73%, 6.61%, 12.24% and 16.49% with the inclusion of 25%, 50%, 75% and 100% BA, respectively. Ghafoori and Bucholc [80] reported a reduction in the 1 day density of concrete specimens with the inclusion of BA (size < 4.75 mm) as natural sand replacement at levels of 50% and 100%, by volume. Various w/c ratios were used. The reduction in the 1 day density was 3.1% and 3.55% with the inclusion of 50% and 100% BA sand, respectively. Yüksel and Bilir [86] partially replaced natural sand with BA at levels of 20%, 30%, 40% and 50%, by volume, in briquettes. The unit weight of the specimens decreased with increasing BA sand content. The reduction in the unit weight was 12.88%, 21.21%, 25% and 29.55% with the inclusion of 20%, 30%, 40% and 50% BA, respectively. Table 4 summarizes the above mentioned studies about the effect of BA sand on the density of mortar and concrete.

From the mentioned studies of the literature in this section, it can be concluded that the inclusion of BA sand reduced the fresh and hardened density of mortar/concrete. The reduction in the density with the inclusion of BA could be attributed to the lower specific gravity of BA sand compared to that of natural sand. On substitution of natural sand with the BA, heavy particles are replaced with the lighter particles. In addition, increasing voids with the inclusion of BA sand (Fig. 5) resulted lesser density [77].

2.2.4. Strength

Bakoshi et al. [87] used BA in amounts of 10–40% as natural sand replacement. Test results indicated that the compressive strength and tensile strength of BA concretes generally increased with increasing BA content and curing age. Basheer and Bai [68] studied the effect of furnace BA sand on the compressive strength and pull-off tensile strength of concretes. Natural sand was replaced with furnace BA at levels of 30%, 50%, 70% and 100%, by weight. They concluded that at constant slump and cement content, the compressive strength of furnace BA concretes improved, whilst the pull-off tensile strength did not affect by furnace BA sand.

Kasemchaisiri and Tangtermirikul [75] partially replaced natural sand in SCCs with BA at levels of 10%, 20% and 30%, by weight. The results showed that the compressive strength at ages of 3, 7 and 28 days decreased with increasing BA sand content. At age of

Table 4
Effect of BA sand on the density of mortar and concrete.

Author	BA content (%)	Decreased density
Basheer and Bai [68]	30, 50, 70 and 100	No effect
Bai and Basheer [67]	30, 50, 70 and 100	Yes
Topçu and Bilir [76]	10–100	Yes
Kin and Lee [74]	25, 50, 75 and 100	Yes
Singh and Siddique [77,78]	20–200	Yes
Andeade et al. [82]	25–100	Yes
Andrade et al. [84]	25, 50, 75 and 100	Yes
Kadam and Patil [85]	10–100	Yes
Andrade et al. [81]	25, 50, 75 and 100	Yes
Ghafoori and Bucholc [80]	50 and 100	Yes
Yüksel and Bilir [86]	20, 30, 40 and 50	Yes

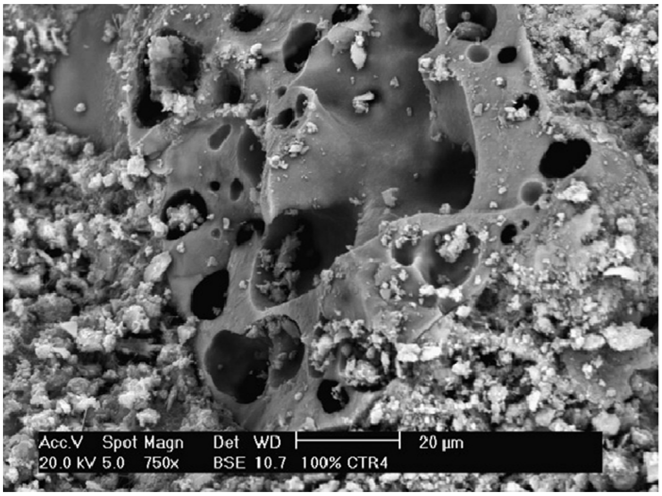


Fig. 5. Micrograph porous surface of concrete containing BA sand [84].

56 days, the inclusion of 10% BA sand slightly increased the compressive strength, whilst 20% and 30% reduced it. Ramadoss and Sundararajan [70] reported 3%, 1.77% and 0.9% enhancement in the 7, 28 and 45 days compressive strength of mortar specimens by partially replacing natural sand with 20% BA, by weight. On the other hand, partially replacing natural sand with 30%, 40% and 50% BA, by weight, decreased the compressive strength at all ages. The reduction in the compressive strength increased with increasing BA sand content. The reduction in the 28 days compressive strength with the inclusion of 30% BA sand was 2%, whilst it reached 8.8% with the inclusion of 50% BA sand. The 28 days flexural strength results showed the same trend. Kadam and Patil [85] reported higher compressive strength of concretes at ages of 7, 28, 56 and 112 days by partially replacing natural sand with 10% and 20% BA, by weight. After that the compressive strength decreased with the inclusion of BA at levels ranging from 30% to 100%. The splitting tensile strength and flexural strength increased with the inclusion of BA up to 30%. Beyond this level, they decreased. On the other hand, the modulus of elasticity decreased with increasing BA sand content. Singh and Siddique [77,78,88] reported a reduction in the early age compressive strength of concretes by replacing natural sand with BA at levels ranging from 20% to 100% At age of 28 days, the compressive strength did not significant affect by BA sand. Beyond age of 28 days, the inclusion of BA sand improved the compressive strength. The splitting tensile strength was improved at all curing ages with the inclusion of BA sand. On the other hand, the modulus of elasticity of concrete decreased with the inclusion of BA sand. Siddique [72] reported a reduction in the 7, 28, 90 and 365 days compressive strength of concretes by partially replacing natural sand with BA. The same trend of the splitting tensile strength was observed at ages of 28, 90 and 365 days. This reduction increased with increasing BA sand content. The reduction in the 28 days compressive strength was 12.84%, 23.31% and 29.73% with the inclusion of 10%, 20% and 30% BA sand, respectively, whilst the reduction in the 28 days splitting tensile strength was 5.83%, 11.67% and 20.83%, respectively.

Sruthee et al. [89] reported higher splitting tensile strength of concretes with the inclusion of BA as natural sand replacement at levels of 10%, 20% and 30%. The enhancement in the tensile strength was 2.96%, 3.7% and 19% with the inclusion of 10%, 20% and 30% BA sand, respectively. On the other hand, the inclusion of 40% reduced it. Mohd Sani et al. [10] partially replaced natural sand in concretes with washed BA at levels of 10%, 20%, 30%, 40% and 50%, by weight. Compressive strength was measured at ages of 3, 7, 28 and 60 days. The results showed a reduction in the compressive strength with the inclusion of BA sand, at all ages. The replacement level of 30% showed the best content. The reduction in the 28 days compressive strength was 45.82%, 39.83%, 37.63%, 49.42% and 46.36% with the inclusion of 10%, 20%, 30%, 40% and 50% BA sand, respectively. Yüksel and Bilir [86] partially replaced natural sand in briquettes with BA at levels of 20%, 30%, 40% and 50%, by volume. They reported that the compressive strength decreased with increasing BA sand content. The reduction in the 28 days compressive strength was 20.77%, 59.38%, 71.98% and 77.72% with the inclusion of 20%, 30%, 40% and 50% BA sand, respectively. Yüksel and Genç [71] reported a reduction in the compressive strength, flexural strength and splitting tensile strength of concretes at age of 28 days with the inclusion of furnace BA as natural sand replacement at levels of 10%, 20%, 30%, 40% and 50%, by weight. The maximum reduction in the compressive strength was 31.8% with the inclusion of 50% BA sand, whilst the maximum reduction in the splitting tensile strength was 58% with the inclusion of 50% BA. The reduction in the flexural strength was 21.44%, 22.29% and 21% with the inclusion of 10%, 30% and 50% BA, respectively. Bilir et al. [90] reported a reduction in the compressive strength of concretes at ages of 28 and 90 days with the inclusion of BA (size 0.045–4 mm) as natural sand replacement at levels ranging from 10% to 50% with an increment of 10%. The reduction in the 28 days compressive strength was 17.97%, 20.51%, 30.24%, 23.19% and 24.69% with the inclusion of 10%, 20%, 30%, 40% and 50% BA sand, respectively. Bilir et al. [91] reported a reduction in the 7 and 28 days compressive strength of concretes by partially replacing natural sand with BA at levels ranging from 10% to 50%, by volume. The reduction in the 28 days compressive strength was 12.5%, 16.7%, 24.4%, 28.5% and 27.6% with the inclusion of 10%, 20%, 30%, 40% and 50% BA sand, respectively. Aggarwal et al. [73] reported a reduction in the mechanical strength at ages of 7, 28, 56 and 90 days by partially replacing natural sand in concretes with BA at levels ranging from 20% to 50%, by weight. This reduction increased with increasing BA sand content. The reduction in the 28 days compressive strength was 8.7%, 11.34%, 16% and 20.88% with the inclusion of 20%, 30%, 40% and 50% BA sand, respectively, whilst the reduction in the 28 days splitting tensile strength was 3.82%, 9.54%, 13.74% and 14.88%, respectively. The reduction in the 28 days flexural strength was 3.61%, 31%, 24.1% and 27.71% with the inclusion of 20%, 30%, 40% and 50% BA sand, respectively.

Ghafoori and Bucholc [79] reported a reduction in the compressive strength, splitting tensile strength, flexural strength and static modulus of elasticity of concretes by replacing natural sand with 100% BA, by volume. The reduction in the flexural strength with the inclusion of BA sand was 25.54%, 19.16% and 16.71% at ages of 7, 28 and 90 days, respectively, when cement content was 297 kg/m^3. Ghafoori and Bucholc [80] replaced natural sand in concretes with BA (size <4.75 mm) at levels of 50% and 100%, by volume. Various w/c ratios were used. The results showed a general reduction in the compressive strength, splitting tensile strength, flexural strength and modulus of elasticity with the inclusion of BA sand. The reduction in the 28 days splitting tensile strength was 16.48% and 14.72% with the inclusion of 50% and 100% BA sand, respectively. Bai and Basheer [67] replaced natural sand in concretes with furnace BA at levels of 30%, 50%, 70% and 100% by weight. They concluded a reduction in the compressive strength with increasing furnace BA sand content at early ages up to 28 days and no adverse influence of the furnace BA on long-term strength at fixed w/c ratio. Bai et al. [69] studied the compressive strength at ages of 3, 7 and 28 days of concretes containing furnace BA as natural sand replacement at levels of 30%, 50%, 70% and 100%, by weight, at two conditions. The first condition when w/c ratio was the same for all mixtures. The second condition when workability was the same for all mixtures. At the same w/c ratio, the compressive strength decreased with

Table 5
Effect of BA sand on the strength of mortar and concrete.

Author	BA content (%)	Positive effect	Notes
Bakoshi et al. [87]	10–40	Yes	For compressive strength and tensile strength
Basheer and Bai [68]	30, 50, 70 and 100	Yes	For compressive strength, at constant slump No effect on bonding strength
Kasemchaisiri and Tangtermirikul [75]	10, 20 and 30	No	For compressive strength at ages of 3, 7 and 28 days
	10	Yes	At age of 56 days
	20 and 30	No	At age of 56 days
Ramadoss and Sundararajan [70]	20	Yes	
	30–50	No	
Kadam and Patil [85]	10 and 20	Yes	
	30–100	No	
Singh and Siddique [77, 78, 88]	20, 30, 40, 50, 75 and 100	No	For compressive strength at early age
	20, 30, 40, 50, 75 and 100	Yes	For compressive strength beyond age of 28 days and for splitting strength at all ages
Siddique [72]	10, 20 and 30	No	Decreased compressive and splitting tensile strength
Sruthee et al. [89]	10–30	Yes	For tensile strength
	40	No	
Mohd Sani et al. [10]	10–50	No	For compressive strength
Yüksel and Bilir [86]	10–50	No	For compressive strength
Yüksel and Genç [71]	10–50	No	For compressive, flexural and splitting strength
Bilir et al. [90]	10–50	No	For compressive strength
Bilir et al. [91]	10–50	No	For compressive strength
Aggarwal et al. [73]	10–50	No	For compressive, flexural and splitting strength
Ghafoori and Bucholc [79]	100	No	For compressive, tensile, flexural strength and static modulus of elasticity
Ghafoori and Bucholc [80]	50 and 100	No	For compressive, splitting, flexural strength and modulus of elasticity
Bai and Basheer [67]	30, 50, 70 and 100	No	For compressive strength at early ages up to 28 days, at fixed w/c ratio
Bai et al. [69]	30, 50, 70 and 100	No	For compressive strength, at the same w/c ratio
Aramraks [92]	50 and 100	No	For compressive strength
Andrade et al. [84]	30, 50, 70 and 100	No	For compressive strength and elastic modulus
Bhuvaneshwari and Murali [93]	30, 40, 50 and 100	No	For compressive and splitting strength
Topçu and Bilir [76]	10–100	No	For compressive and flexural strength and modulus of elasticity
Kin and Lee [74]	25, 50, 75 and 100	No	For flexural strength
	100	No	For modulus of elasticity
Andeade et al. [82]	25, 50, 75 and 100	No	For compressive strength and elastic modulus when BA containing natural water content
Andrade et al. [81]	25, 50, 75 and 100	No	For compressive strength
Singh and Siddique [94]	30–100	No	For compressive strength

increasing furnace BA sand content. At the same workability, the compressive strength was comparable. Aramraks [92] replaced natural sand in concretes with Thailand BA at levels of 50% and 100%. Various w/c ratios were used and 2% of SP was employed for 50% and 100% BA concrete mixtures. The results showed a reduction in the compressive strength with the inclusion of BA sand. The reduction in the compressive strength was about 20% and 40% with the inclusion of 50% and 100% BA sand, respectively. Andrade et al. [84] reported a reduction in the compressive strength and elastic modulus at ages ranging from 3 to 90 days of concrete specimens containing BA as natural fine aggregate replacement, by volume. This reduction increased with increasing BA sand content. The reduction in the 28 days compressive strength was 13.38%, 36.62%, 60.88%, 69.72% with the inclusion of 25%, 50%, 75% and 100% BA sand, respectively, whilst the reduction in the elastic modulus was 14.34%, 25.58%, 51.16% and 65.5%, respectively. Bhuvaneshwari and Murali [93] partially replaced natural sand in concretes with BA at levels of 30%, 40%, 50% and 100%, by volume. The results showed a reduction in the compressive strength and splitting tensile strength at ages of 7 and 28 days with the inclusion of BA. The reduction in the 28 days compressive strength was 4.1%, 5.71%, 1.1% and 68.61% with the inclusion of 30%, 40%, 50% and 100% BA sand, respectively, whilst the reduction in the 28 days splitting tensile strength was 1.86%, 8.95%, 16.79% and 48.51%, respectively. Topçu and Bilir [76] reported that the compressive strength, flexural strength and modulus of elasticity of mortar specimens decreased with the inclusion of non-ground BA as natural sand replacement at levels ranging from 10% to 100% with an increment of 10%, by weight,. The optimum ratios for use of non-ground BA sand were about 40–50% regarding to compressive strength and flexural strength, whilst it was 50% regarding to modulus of elasticity. Kin and Lee [74] studied the compressive strength, flexural strength and modulus of elasticity of concretes containing BA as natural sand replacement. Natural sand was replaced with BA at levels of 25%, 50%, 75% and 100%, by volume. The compressive strength values approximately did not affect with the inclusion of BA sand. On the other hand, the modulus of elasticity reduced by 15.1% with the inclusion of 100% BA sand, whilst the flexural strength decreased with increasing BA sand content. The modulus of rupture decreased by 19.5% with the inclusion 100% BA sand. The modulus of elasticity did not affect with the inclusion of BA sand up to 80%.

Andeade et al. [82] studied the compressive strength and elastic modulus of concretes containing BA as natural sand replacement at ages of 3, 28 and 90 days. Natural sand was replaced with BA at levels of 25%, 50%, 75% and 100%, by weight. Two cases of BA sand were used. The first case the BA sand containing natural water content, whilst the second the BA sand discounting the natural water content. In the case of natural water content, the results showed that both compressive strength and elastic modulus decreased with increasing BA sand content. The reduction in the 28 days compressive strength was 18.3%, 36.62%, 59.51% and 69.71% with the inclusion of 25%, 50%, 75% and 100% BA sand, respectively. In the case of discounting natural water content, both of compressive strength and elastic modulus were affected by the inclusion of BA sand. The inclusion of BA sand sometimes increased the compressive strength and elastic modulus and sometimes decreased them. At age of 28 days, the inclusion of 25% and 75% BA sand decreased the compressive strength, whilst 50% and 100% increased it. The reduction in the compressive strength was

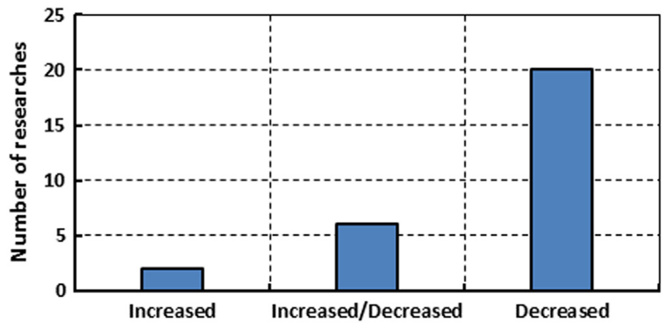


Fig. 6. Research numbers versus the effect of BA sand on the compressive strength.

4.22% and 8.1% with the inclusion of 25% and 75% BA sand, whilst the enhancement was 0.35% and 14.79% with the inclusion of 50% and 100% BA sand, respectively. Andrade et al. [81] replaced natural sand in concretes with BA (size < 5 mm) at levels of 25%, 50%, 75% and 100%, by volume. Different w/c ratios were used. The results showed a reduction in the 3, 28 and 90 days compressive strength with the inclusion of BA sand. The compressive strength decreased with increasing BA sand content. The reduction in the 28 days compressive strength was 18.31%, 36.62%, 59.5% and 69.72% with the inclusion of 25%, 50%, 75% and 100% BA sand, respectively. Singh and Siddique [94] reported that replacing natural sand in concrete specimens with 30%, 50%, 75% and 100% BA, by volume, decreased the 7, 28, 90, 180 and 365 days compressive strength. The compressive strength decreased with increasing BA sand content. Table 5 summarizes the above mentioned researches about the effect of FA sand on the strength of mortar and concrete.

From the above discussion, it can be clearly evident that the inclusion of BA sand, in general, reduced the compressive strength as reported by abundant studies (Fig. 6). The compressive strength decreased with increasing BA sand content. The reduction in the compressive strength with the inclusion of BA sand could be related to the porous matrix which BA sand caused [66,71]. On the other hand, there are few othe studies concluded higher compressive strength with the inclusion of BA sand. The enhancement in the compressive strength could be related to the pore refine effect by pozzolanic reaction of BA sand which dominates over the effect of the increase in the porosity [75].

2.2.5. Abrasion resistance

Bakoshi et al. [87] used BA in amounts of 10–40% as natural sand replacement. Test results indicated that the abrasion resistance of concrete specimens containing BA sand was higher than that of the plain concrete. Basheer and Bai [68] reported an enhancement in the abrasion resistance of concrete specimens by replacing natural sand with furnace BA at levels of 30%, 50%, 70% and 100%, by weight. Yüksel et al. [95] investigated the surface abrasion of concrete specimens containing BA as natural sand replacement. Natural sand was partially replaced with BA at levels of 10%, 20%, 30%, 40% and 50%, by weight. The results showed that 10% BA sand exhibited the highest abrasion resistance followed by 20%, 30%, 40% and 50%, respectively, whilst the control specimen exhibited the lowest abrasion resistance. In another investigation, Bilir et al. [91] found that partially replacing natural sand with 10% BA, by volume, in concretes exhibited the highest abrasion resistance followed by 20% and 30%, respectively, whilst the inclusion of 40% and 50% BA sand reduced it. On the other hand, Ghafoori and Bucholc [79] reported a reduction in the abrasion resistance of concrete specimens by replacing natural sand with 100% BA, by volume. The average depth of wear of BA concrete specimens was 40% higher than that of the control. Aramraks [92] replaced natural sand in concretes with Thailand BA at levels of 50% and 100%. Various w/c ratios were used and 2% of SP was employed for 50% and 100% BA mixtures. The results showed a reduction in the abrasion resistance with the inclusion of BA sand. This reduction increased with increasing BA sand content. Singh and Siddique [78,94] replaced natural sand in concretes with BA at levels of 30%, 50%, 75% and 100%, by volume. The results showed a reduction in the abrasion resistance at ages of 28, 90 and 365 days with the inclusion of BA sand. This reduction increased with increasing BA sand content. Siddique [72] reported a reduction in the abrasion resistance of concretes at ages of 28, 91 and 365 days by partially replacing natural sand with 10%, 20% and 30% BA, by weight. The depth of wear increased by 9.24%, 13.45% and 23.53% at age of 28 days with the inclusion of 10%, 20% and 30% BA sand, respectively.

From the above mentioned studies in this section, it can be noted that there are contradictory reports about the effect of BA sand on the abrasion resistance of concrete. Some studies reported positive effect of BA sand on the abrasion resistance, whilst others reported negative effect. Anyway, this item still needs more investigations.

2.2.6. Carbonation resistance

Bai and Basheer [67] replaced natural sand in concretes with furnace BA at levels of 30%, 50%, 70% and 100%, by weight. The results showed that the carbonation rate of the furnace BA concretes were higher than that of the reference concrete. Similar findings were obtained by Basheer and Bai [68]. Kasemchaisiri and Tangtermirikul [75] investigated the carbonation depth of SCCs incorporating BA as partial replacement of natural sand at levels of 10%, 20%, and 30%, by weight. The results showed an increase in the carbonation depth with increasing BA sand content.

According to the above available studies, it is safe to conclude that the carbonation resistance of concrete decreased with increasing BA sand content. The increase in the BA sand content was associated with an increase in the air permeability, which, in turn, is known to increase the diffusion of CO_2 into concrete [96].

2.2.7. Permeability, water absorption and chloride penetration

Siddique [72] reported an increase in the 7 and 28 days water absorption of concretes with the inclusion of 10%, 20% and 30% BA as natural sand replacement, by weight. As the content of BA increased as the percentage of water absorption increased. Kasemchaisiri and Tangtermirikul [75] investigated the rapid chloride permeability, at ages of 7, 28 and 56 days, of SCCs incorporating BA as partial replacement of natural sand. The replacement levels were 10%, 20%, and 30%, by weight. The results showed that the higher the BA content the higher the chloride permeability at age of 7 days. At ages of 28 and 56 days, all SCC mixtures had not much different Cl^- permeability. The permeability of 10% BA mixture at age of 56 days was about the same as that of the control mixture. Bai and Basheer [67] replaced natural sand in concretes with furnace BA at levels of 30%, 50%, 70% and 100%, by weight. The results showed that the air permeability increased with the inclusion of furnace BA sand. Similar findings were obtained by Basheer and Bai [68]. Andeade et al. [82] studied the water absorption and porosity of concretes containing different contents of BA ranging from 25% to 100%, by weight, as natural sand replacement. The results showed an increase in the water absorption and porosity with increasing BA sand content. The increment in the porosity was 5.65%, 31.1% and 58.59% with the inclusion of 3.8%, 25.9% and 100% BA sand, respectively. Andrade et al. [84] incorporated coal BA as a substitute material for natural sand in the production of concretes. The replacement levels were 25%, 50%, 75% and 100%. The results indicated that the capillary absorption potential with water was higher in the mixtures containing BA sand. Singh and Siddique [77,88] reported an increase in the permeability and water absorption of concretes by replacing natural sand with BA at levels ranging from 20% to 100%, at age of 7 days. The permeability increased with increasing BA sand content. Singh and Siddique [88] reported a reduction in the 28, 90, 180 and 365 days total charge passed in Coulombs of concretes with the inclusion of BA as natural sand replacement at levels ranging from 20% to 100%. Thus, concretes containing BA sand exhibited better resistance to chloride ion penetration. Ghafoori and Bucholc [79] reported higher chloride permeability of concretes containing 100% BA as natural sand replacement, by volume. Adding low dosage of SP decreased drastically the permeation of chloride ions into the BA concretes.

Yüksel and Genç [71] studied the percentage of water absorption of concretes containing furnace BA as natural sand replacement. Natural sand was partially replaced with BA at levels ranging from 10% to 50% with an increment of 10%, by weight. The results showed a significant reduction in the percentage of water absorption with the inclusion of 10% BA sand. The inclusion of 20% BA sand showed higher percentage of water absorption than that of 10% BA, but was still lower than the percentage of water absorption of the reference. The inclusion of 30%, 40% and 50% BA sand showed a significant higher percentage of water absorption compared to the reference. As the content of BA sand increased the percentage of water absorption increased. Ramadoss and Sundararajan [70] reported 5.1%, 12.94% higher percentage of 28 days water absorption of mortars by partially replacing natural sand with 10% and 30% BA, by weight, respectively. On the other hand, partially replacing natural sand with 20%, 40% and 50% BA reduced the percentage of water absorption by 21.37%, 0.2% and 2.35%, respectively. Singh and Siddique [94] reported an increase in the water absorption of concrete specimens at age of 28 days by replacing natural sand with 30%, 50%, 75% and 100% BA, by volume. The inclusion of 50%, 75% and 100% BA displayed 3.9%, 12.2% and 18.8% higher water absorption than the control. Yüksel et al. [95] investigated the capillarity coefficient of concretes containing BA as natural sand replacement. Natural sand was partially replaced with BA at levels of 10%, 20%, 30%, 40% and 50%, by weight. The results showed a reduction in the capillarity coefficient with the inclusion of 10% BA sand, then it increased with increasing BA sand content. Yüksel and Demirtaş [97] studied the rapid chloride permeability test (RCPT) of concretes containing BA (size 0.045–4 mm) as natural sand replacement. Natural sand was partially replaced with BA at levels ranging from 10% to 50% with a step of 10%, by weight. The total charge passed decreased by 13.14%, 10.98%, 7.65% and 4.23% with the inclusion of 10%, 20%, 30%, 40% and 50% BA sand, respectively. On the other hand 50% BA sand led to an increase in the charge passed by 23.31%.

Bilir [98] studied the RCPT of concrete mixtures containing BA as natural sand replacement. Natural sand was partially replaced with BA at levels of 10%, 20%, 30%, 40% and 50%, by weight. The results showed that the chloride diffusion slightly decreased till the inclusion of 20% BA sand. Beyond this level, it increased with increasing BA sand content. Bilir et al. [90] reported a reduction in the chloride ion penetration of concretes containing BA as natural sand replacement at levels ranging from 10% to 50% with an increment of 10%. The total charge passed decreased by 0%, 27%, 29%, 23.94% and 16.77% with the inclusion of 10%, 20%, 30%, 40% and 50% BA sand, respectively. Kadam and Patil [85] reported a reduction in the permeability of concretes containing 10% and 20% BA as natural sand replacement, whilst the inclusion of 30–100% BA sand increased it. Aramraks [92] replaced natural sand in concretes with Thailand BA at levels of 50% and 100%. Various w/c ratios were used and 2% of SP was employed for 50% and 100% BA concretes. They reported that the lowest chloride permeability was obtained with the inclusion of 100% BA sand followed by 50% BA sand. Table 6 summarizes the above mentioned studies about the effect of BA sand on the permeability, water absorption and chloride penetration of concrete.

From the above mentioned studies in this section, it can be noted that some studies reported negative effect of BA sand on the permeability and water absorption of concrete, whilst others reported positive effect of some percentages of BA sand and negative effect of the remaining percentages (Fig. 7). On the other hand, Aramraks [92] reported positive effect. The introduction of BA sand into concrete could produce two different (opposite) effects on the permeability of concrete. The net role of BA sand depends on which of the following two effects dominates. The first effect could be attributed to the reduction in water demand of concrete with increasing BA sand content. The capillary pores could become bigger and the transition zone could become thicker at a given w/c ratio. Thus, the concrete would become more permeable. The second effect is the filling effect of BA sand which resulted a reduction in porosity and the thickness of the interfacial transition zone, which would decrease the permeability [67].

Table 6
Effect of BA sand on the permeability water absorption and chloride penetration of concrete.

Author	BA content (%)	Positive effect	Notes
Siddique [72]	10, 20 and 30	No	Water absorption
Kasemchaisiri and Tangtermirikul [75]	10, 20 and 30	No	Rapid chloride permeability
Bai and Basheer [67] and Basheer and Bai [68]	30, 50, 70 and 100	No	Air permeability
Andeade et al. [82]	3.8–100	No	Water absorption and porosity
Andrade et al. [84]	25–100	No	Capillary absorption
Singh and Siddique [77]	20–100	No	Permeability and water absorption
Ghafoori and Bucholc [79]	100	No	Chloride permeability
Yüksel and Genç [71]	10 and 20	√	Water absorption
	30, 40 and 50	×	
Ramadoss and Sundararajan [70]	20, 40 and 50	Yes	Water absorption
	10 and 30	No	
Singh and Siddique [94]	30–100	No	Water absorption
Singh and Siddique [88]	20–100	Yes	RCPT
Yüksel et al. [95]	10	Yes	Capillarity coefficient
	20–50	No	
Yüksel and Demirtaş [97]	10–40	Yes	RCPT
	50	No	
Bilir [98]	10 and 20	Yes	RCPT
	30, 40 and 50	No	Chloride ion penetration
	10–50	Yes	
Kadam and Patil [85]	10 and 20	Yes	Permeability
	30–100	No	
Aramraks [92]	50 1nd 100	Yes	Chloride permeability

Table 7
Effect of BA sand on the freeze/thaw resistance of concrete.

Author	BA content (%)	Positive effect
Ghafoori and Bucholc [79]	100	Yes
Bilir [98]	10–50	Yes
Yüksel et al. [95]	10–50	Yes
Yüksel and Bilir [86]	20–50	No
Bakoshi et al. [87]	10–40	No

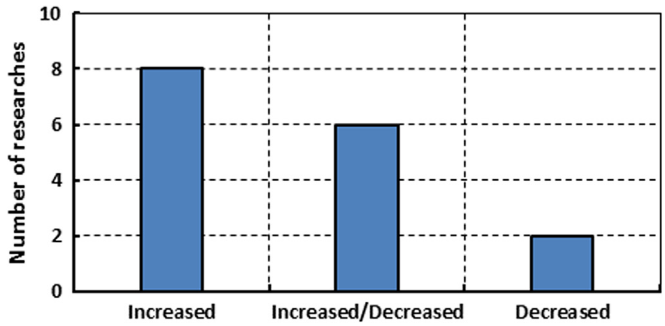


Fig. 7. Effect of BA sand on permeability, water absorption and chloride penetration.

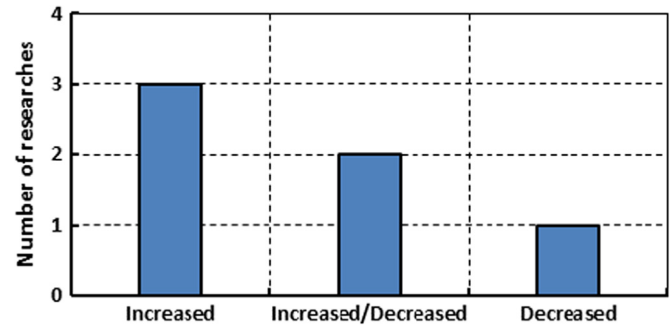


Fig. 8. Effect of BA sand on drying shrinkage.

2.2.8. Drying shrinkage and crack width

Ghafoori and Bucholc [80] replaced natural sand in concretes with BA (size 4.75 mm) at levels of 50% and 100%, by volume. Fixed workability was used. The results showed higher drying shrinkage with the inclusion of BA sand. The drying shrinkage increased with increasing BA sand content. Kasemchaisiri and Tangtermirikul [75] investigated the drying shrinkage, up to 365 days, of SCCs incorporating BA as partial replacement of natural sand at levels of 10%, 20%, and 30%, by weight. The results showed an increase in the drying shrinkage with increasing BA sand content. Bai et al. [69] studied the drying shrinkage, up to 150 days, of concretes containing furnace BA at fixed w/c ratio and fixed workability. Natural sand was replaced with furnace BA at levels of 30%, 50%, 70% and 100%, by weight. The results showed that at fixed w/c ratio, the drying shrinkage decreased with increasing BA sand content. At fixed workability, the drying shrinkage increased with increasing BA sand content beyond 30%. Topçu and Bilir [76] studied the free shrinkage, up to 60 days, of the non-ground BA, as natural fine aggregate in mortars. The replacement levels were ranging from 10% to 100% with an increment of 10%, by weight. The results showed an increase in the free shrinkage with the inclusion of 10%, 20% and 100% BA sand. On the other hand, the inclusion of BA sand at levels ranging from 30% to 50% reduced the free shrinkage compared to the control. They also reported that the occurrence time for shrinkage cracking was delayed by the increment of BA sand content. The crack width decreased with the inclusion of BA sand ratios greater than 40% and lower than 100%. Singh and Siddique [88] reported a reduction in the drying shrinkage of concretes, at ages up to 210 days, with the inclusion of 30%, 40%, 50%, 75% and 100% BA as natural sand replacement, whilst the inclusion of 20% BA sand increased it. At age of 90 days, the reduction in the shrinkage strain was 16.22%, 17.57%, 25.81% and 39.2% with the inclusion of 30%, 40%, 50%, 75% and 100% BA sand, respectively, whilst 20% BA sand cause 5.41% higher drying shrinkage strain. At age of 180 days, the inclusion of 30%, 40%, 50% and 100% BA sand experienced 14.1%, 10.25%, 21.79%, 34.62% and 37.17% less shrinkage strain, respectively, as compared to the control, whilst the inclusion of 20% BA sand experienced 6.4% higher drying shrinkage than the control.

From the above discussion in this section, it is evident that the inclusion of BA sand in concrete increased the drying shrinkage according to the prevalent studies (Fig. 8). This could be attributed to the increase of porosity with increasing BA sand content [75,76]. The effect of BA sand on the drying shrinkage as well as crack width still need more investigation.

2.2.9. Freeze/thaw and dry/wet resistance

Ghafoori and Bucholc [79] exposed concrete specimens to rapid 300 freeze/thaw cycles. Concrete specimens containing 100% BA as natural sand replacement, by volume, showed higher freeze/thaw resistance than the control. Bilir [98] investigated the freeze/thaw resistance of concrete specimens containing BA as natural sand replacement. The loss of strength after 50 cycles of freeze at −20 °C and thaw at 20 °C, in water, was measured. Natural sand was partially replaced with BA at levels of 10%, 20%, 30%, 40% and 50%, by weight. The results showed that the inclusion of 10% and 20% BA sand exhibited the lowest loss in strength after cycles followed by 30%, 40%, and 50%, respectively. Yüksel et al. [95] investigated the freeze/thaw resistance of concrete specimens containing BA as natural sand replacement. The loss in strength after 50 cycles of freeze at −20 °C and thaw at 20 °C in water pool was measured. Natural sand was partially replaced with BA at levels of 10%, 20%, 30%, 40% and 50%, by weight. The results showed that 10% and 20% BA exhibited the lowest loss in strength followed by 30%, 40% and 50%, respectively. On the other hand, Yüksel and Bilir [86] partially replaced natural sand in briquettes with BA at levels of 20%, 30%, 40% and 50%, by volume,. They studied the compressive strength before and after 25 cycles of freeze–thaw. The results showed negative effect of BA on the compressive strength before and after cycles. The loss of strength was 8.86%, 10.55%, 15.7%, 23.71% and 19.61% with the inclusion of 0%, 20%, 30%, 40% and 50% BA sand. Bakoshi et al. [87] used BA in amounts of 10–40% as natural sand replacement. Test results indicated that the freezing/thawing resistance of concrete specimens containing BA sand is lower than that of plain concrete.

Yüksel et al. [95] measured the compressive strength of concretes containing BA sand after 25 cycles of wet and dry. Natural sand was partially replaced with BA at levels ranging from 10% to 50% with an interval of 10%, by weight. The results showed a reduction in the compressive strength after 25 cycles with the inclusion of BA sand. The strength reduction increased with increasing BA sand content. Bilir [98] studied the durability of concrete, containing BA as natural sand replacement, by measuring the loss of strength after 25 cycles of wet at 20 °C and dry at 40 °C. Natural sand was partially replaced with BA at levels of 10%, 20%, 30%, 40% and 50%, by weight. The results showed that the loss in strength increased with increasing BA sand content. Table 7 summarizes the above mentioned studies about the effect of BA sand on the freeze/thaw resistance of concrete.

From the above mentioned studies in this section, it can be noted that there are adverse reports about the effect of BA sand on the freeze/thaw resistance of concrete (Fig. 9). Some studies reported positive effect, whilst others reported negative effect. The freeze/thaw resistance of concrete with the inclusion of BA sand still needs more investigations. Although there are two studies reported that the inclusion of BA sand reduced the resistance of wet/dry cycles, this not enough and more investigates are needed.

2.2.10. Chemical and fire resistance

Kasemchaisiri and Tangtermirikul [75] investigated sodium sulfate resistance of SCCs incorporating BA as partial replacement of natural sand at levels of 10%, 20%, and 30%, by weight. The

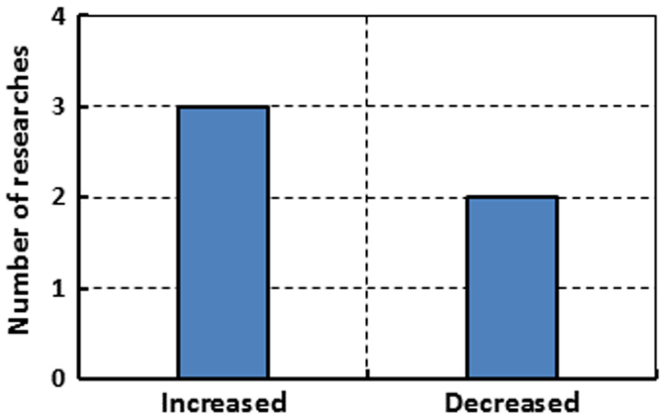


Fig. 9. Effect of BA sand on freezing/thawing resistance of concrete.

results showed that the expansion of concrete specimens decreased with increasing BA sand content. On the contrary, Singh and Siddique [88] reported that concretes containing BA as natural sand replacement at levels ranging from 20% to 100% experienced slightly higher expansion stain when exposed to external sulfate attack. On the other hand, BA concretes performed slightly better under external sulphuric acid attack. The percentage loss of compressive strength and weight after immersion in sulphuric acid solution was lower than the control. After 84 days of immersion, the loss in 28 days compressive strength decreased from 65.72% to 56.4% with the incorporation of 100% BA sand

Yüksel et al. [95] investigated the residual compressive strength of concretes containing BA as natural sand replacement after exposure to 800 °C. Natural sand was partially replaced with BA at levels of 10%, 20%, 30%, 40% and 50%, by weight. The results showed that 20% BA exhibited the highest residual compressive strength followed by 30%, 10%, 40%, 0% and 50%, respectively. In similar investigation Yüksel et al. [99] reported that the ratio of dynamic modulus of elasticity and the compressive strength decreased gradually with increasing BA content, after exposure to 800 °C.

From the above review of the literature in this section, it can be noted that the effect of BA sand on sulfate resistance and fire resistance still need more investigations. However, according to the available literature, it can be concluded that the deterioration effect of sulfate can be mitigated by replacing natural sand with 10–30% BA, by weight. Although the BA concretes containing higher porosity, the pozzolanic reaction of BA reduced the gypsum which produced by the reaction of sodium sulfate with calcium hydroxide resulted from cement hydration [75]. According to fire resistance, the inclusion of 20–30% BA as natural sand replacement exhibited the best fire resistance [95].

In general view, using BA as fine aggregate in mortar and concrete showed some advantages, of which some properties are improved, and some disadvantages, of which some properties are worsen. The advantages of using BA sand are decreasing density and increasing fire resistance. In a different manner, the disadvantages of using BA sand are decreasing workability, increasing bleeding, decreasing mechanical strength, increasing drying shrinkage and decreasing carbonation resistance. There are some properties that still need more investigations for better understanding such as the effect of BA sand on sulfate resistance, abrasion resistance, permeability, freeze/thaw resistance and crack width.

2.3. *Steel slag*

Most of SS consist primary of CaO, MgO, SiO_2 and FeO. Its particle size are in the range of 3–5 mm or 30–50 mm according the cooling conditions of the molten SS [100]. SS is a crushed product having dense, angular, hard and roughly cubical particles. The specific gravity and water absorption capacity of SS are higher than that of conventional aggregates. Its porosity reached about 10.5% [44].

2.3.1. *Workability and density*

Qasrawi et al. [101] replaced natural sand in concrete mixtures with SS (size 0.075–5 mm) at levels of 15%, 30%, 50% and 100%. The workability marginally decreased with the inclusion of SS sand up to 50%. Beyond this level, Increasing SS sand led to a significant reduction in the workability. Pellegrino et al. [102] replaced natural sand in concrete mixtures with EAF slag at levels of 50% and 100%, by weight. W/c ratio of 0.47 was used for the control and 50% EAF slag mixtures, whilst 0.49 was used for 100% EAF slag mixture. The results showed a reduction in the workability with the inclusion of EAF slag sand. The reduction in the slump was 5% and 2.5% with the inclusion of 50% and 100% EAF slag sand, respectively. González-Orteha et al. [103] replaced natural limestone fine aggregate and coarse aggregate with EAF slag fine aggregate (size <4 mm) and EAF slag coarse aggregate (size 4–10 mm and 10–20 mm). The results showed a reduction in the workability with the inclusion of EAF slag aggregate.

Qasrawi et al. [101] reported higher fresh density of concrete mixtures by partially replacing natural sand with SS (size 0.075-5 mm). The density increased with increasing SS sand content. González-Orteha et al. [103] reported higher density of concrete by replacing natural fine aggregate with EAF slag (size <4 mm) and replacing natural coarse aggregate with EAF slag (size 4–10 mm and 10–20 mm). Santamaría-Vicario et al. [104] reported higher fresh density of the mortar mixtures by replacing natural fine aggregate with SS (size <4 mm) at levels of 25%, 50%, 75% and 100%, by weight. The density increased with increasing SS sand content.

From the above review in this section, it is safe to conclude that the inclusion of SS sand in the mixture decreased its workability, but increased its density. The reduction in the workability could be attributed to the angular shape of SS particle and the higher absorption of SS sand compared to natural sand [101]. The increment in the density with the inclusion of SS sand could be related to its higher specific gravity compared to that of natural fine aggregate [103].

2.3.2. *Strength*

Akinmusuru [105] reported an enhancement in the compressive strength of concrete specimens by replacing natural fine aggregate with SS. Faraone et al. [106] employed SS (with different sizes) as fine aggregate in mortars. They reported that SS as aggregate showed good compressive strength at age of 28 days if adequate w/c ratio, cement/SS ratio and suitable SS particle size were used. Qasrawi et al. [101] replaced natural sand in concretes with SS (size 0.075-5 mm) at levels of 15%, 30%, 50% and 100%. The results showed that the inclusion of 15-30% SS sand exhibited the best compressive strength, whilst 30-50% showed the best tensile strength. The SS sand increased the compressive strength by 1.1-1.3 times greater than the control, whilst tensile strength was enhanced by 1.4-2.4 times greater compared to the control. Pellegrino et al. [102] reported that the compressive strength of concrete slightly increased with the inclusion of 50% EAF slag as natural sand replacement, by weight, whilst the inclusion of 100% EAF slag slightly decreased it. The enhancement in the 28 days compressive strength was 1.77% with the inclusion of 50% EAF slag sand, whilst the reduction was 1.41% with the inclusion of 100% EAF slag sand. On the other hand, the tensile strength slightly increased with the inclusion of EAF slag sand at all replacement levels. The enhancement in the tensile strength was 5.37% and 2.26% with the inclusion of 50% and 100% EAF slag sand, respectively. González-Orteha et al. [103] reported similar compressive strength of concrete containing EAF slag (size < 4 mm) as fine aggregate and EAF slag (size 4-10 mm and 10-20 mm) as coarse aggregate compared to the control. On the other hand, the static modulus of elasticity of concrete containing EAF slag was 10% higher than the measured for the control. This related to the higher hardness of EAF slag aggregate. Santamaría-Vicario et al. [104] reported higher 28 and 90 days compressive strength and flexural strength of mortars by replacing natural fine aggregate with 25%, 50%, 75% and 100% SS, by weight. The enhancement increased with increasing SS sand content.

From the above review in this section, it can be noted that the inclusion of SS sand, in general, can increase the compressive strength if adequate w/c ratio, cement/SS ratio and suitable SS particle size were used. The enhancement in the compressive strength could be related to the different cement matrix-aggregate contact surface, which is rougher in concrete specimens containing SS sand and could allow a stronger link between binder and aggregate.

2.3.3. *Durability*

Akinmusuru [105] reported a reduction in the water absorption of concrete specimens by replacing natural fine aggregate with SS. Pellegrino et al. [102] exposed concrete specimens containing 50% and 100% EAF slag as natural sand replacement to 25 freezing/thawing and 30 wetting/drying cycles. The results showed that the compressive strength after cycles of freezing-thawing or wetting-drying exhibited an enhancement with the inclusion of EAF slag sand. The enhancement in the compressive strength after freezing-thawing cycles was 3.19% and 0.44% with the inclusion of 50% and 100% EAF slag sand, respectively, whilst the enhancement in the compressive strength after wetting/drying cycles was 9.07% and 5.38%, respectively.

2.4. *Silica fume*

Ismeil [107] studied the 7, 28 and 56 days compressive strength of concretes in which natural sand was partially replaced with SF at levels of 5%, 10% and 15%, by weight, at various w/c ratios of 0.5, 0.55 and 0.6. The results showed an enhancement in the compressive strength with the inclusion of SF sand. The best level of natural sand replacement with SF was 5% which showed the highest compressive strength at ages of 7 and 28 days at w/b ratios of 0.5 and 0.55, whilst at w/b ratio of 0.6, the inclusion of 10% SF sand showed the highest compressive strength at all ages. Ghafoori and Diawara [108] studied the compressive strength and abrasion resistance of concrete specimens cured under either continuous moist-curing condition or various combinations of wet-dry curing cycles. Natural fine aggregate was partially replaced with SF at levels of 5%, 10%, 15 and 20%, by cement weight. They reported that independent of the curing condition and age, the contribution of SF incorporated in concrete by way of fine aggregate replacement peaked at 10% SF sand content for both compressive strength and wear resistance. When the SF sand was extended beyond 10%, specimens experienced a gradual reduction in both bulk and surface properties.

Ghafoori and Diawara [109] studied the setting time, unit weight, compressive strength and abrasion resistance of concrete containing SF as natural sand replacement. Natural sand was partially replaced with SF at levels of 5%, 10%, 15% and 20%, by cement weight. The results showed that both initial and final setting time increased with increasing SF sand content. The unit weight decreased with the inclusion of SF sand. This reduction increased with increasing SF sand content. The compressive strength was enhanced with the inclusion of SF sand. 10% SF sand showed the highest compressive strength. The abrasion resistance of concrete was improved with the inclusion of SF sand up to 10%, then gradual reduction in both bulk and surface properties was obtained. Table 8 summarizes the above mentioned studies about the effect of SF sand on some properties of concrete.

Table 8
Effect of SF sand on some properties of concrete.

Author	SF content (%)	SF optimum content (%)	Effect
Ismeil [107]	5–15	5–10	Increased compressive strength
Ghafoori and Diawara [108]	5–20	10	Increased compressive strength Increased abrasion resistance
Ghafoori and Diawara [109]	5–20	10	Increased setting time Decreased unit weight Increased compressive strength

From the above mentioned studies of this section, it can be concluded that the inclusion of SF up to 10% in the concrete as natural sand replacement increased the compressive strength and abrasion resistance. This improvement could be attributed to the pozzolanic action of SF and densification of the concrete matrix. The inclusion of SF as natural sand replacement increased setting time, but decreased unit weight of concrete.

2.5. *Agricultural wastes*

Oil palm shell (OPS) is a waste material produced from the extraction of palm oil in South East Asian countries, such as Malaysia, Indonesia and Thailand. The annual production of solid waste from the palm oil industry in these three countries is around 90.5 million tonnes. The excessive dumping of OPS led to pollution in the surrounding environment. Its specific gravity is around 1.3, whilst the bulk density (loose) is around 538 kg/m^3 [110]. Oil palm kernel shell (PKS) is a waste material obtained during the extraction of plain oil by crushing of the palm nut in the palm oil mills. The specific gravity of PKS is ranging from 1.14 [111] to 1.62 [112], whilst its loose bulk density between 500-600 kg/m^3 [113]. PKS has wide range of particles from 3 to 14 mm [114]. Rice husk is one of the agricultural wastes. Globally, approximately 661 million tonnes of rice paddy is produced each year. An average of 20% of the rice paddy is husk, giving an annual total production of approximately 132 million tonnes. Most of the husk produced from processing of rice is either dumped as waste or burnt causing environmental problems. Rice husk ash (RHA) forms the outer covering of rice grain and is removed during the milling process. After suitable treatment, it contains more than 92% of SiO_2. Its specific gravity is around 2.13-2.2 [115,116].

In 2010, the United Nation's Food and Agriculture Organization estimated that sugarcane was cultivated on about 23.8 million hectares of land, in more than 90 countries, with a worldwide harvest of 1.69 billion tonnes [117]. Sugarcane bagasse is a main by-product of sugar industry, which used as an energy source for sugar production. Sugarcane containing 25-30% bagasse, whilst industry recovered sugar is around 10%. Bagasse can be used as a raw material for paper making. The ash produced by burning transforms the silica content of the ash into amorphous phase [118].. Its specific gravity between 1.8 [118] to 2.65 [119]. Wheat in the main food for about 35% of the world's population. The world production increased from 6.16 to 6.92 billion tonnes during the period of 2001 to 2011. Wheat straw is an agricultural by-product, the dry stalks of wheat plants, once the grain and chaff are removed. Wheat straw is abundantly available and can be used as an energy source in gasification and combustion systems. After suitable treatment, the wheat straw ash (WSA) can be used as cementitious material. The majority of wheat straws particles are less than 0.85 mm and the average particle sizes are in the range of 0.38-0.69 mm. The average bulk density is between 97.52-177.23 kg/m^3 [120]. Most of WSA consist primary of SiO_2, CaO, Al_2O_3 and K_2O. Corncob is an agricultural waste product obtained from maize or corn. About 785 million tonnes of maize is produced annually in the world. Corncobs are either thrown out as waste or burnt causing environmental impact [121]. Corncob is known to contain a considerable amount of SiO_2. Once burned in safe manner, it leaves as ash very rich in SiO_2 which is pozzolana in character [122]. Its specific gravity is around 1.15 [123]. Most of corncob ash (CA) consist primary of CaO, K2O, SiO_3 and MgO.

Muthusamy et al. [124] replace natural sand in concretes with OPS at levels of 25%, 50%, 75% and 100%, by weight. The results showed a reduction in the 28 days density of concretes with the inclusion of OPS sand. This reduction increased with increasing OPS sand content. The inclusion of 25% OPS produced hardened density within the range 2000-2400 kg/m^3, whilst the inclusion of 50% OPS produced hardened density less than 1800 kg/m^3. The 7, 14 and 28 days compressive strength decreased with increasing OPS sand content. The reduction in the 28 days compressive strength with the inclusion of 100% OPS was approximately 91%.

Shafigh et al. [125] partially replaced natural sand in concretes containing old OPS as coarse aggregate with oil-palm-boiler clinker (OPBC). The replacement levels were 12.5%, 25%, 37.5% and 50%, by volume. The results showed a reduction in the workability, fresh density and dry density with the inclusion of OPBC sand. This reduction increased with increasing OPBC sand content. The reduction in the dry density of the specimens at age of 28 days was 0.35%, 0.15%, 2.4% and 4.1% with the inclusion of 12.5%, 25%, 37.5% and 50% OPBC sand, respectively. The compressive strength, splitting tensile strength and flexural strength decreased with the inclusion of OPBC sand. This reduction increased as the OPBC sand content increased. The reduction in the 28 days compressive strength was 5%, 1.1%, 11.4% and 17.5% with the inclusion of 12.5%, 25%, 37.5% and 50% OPBC sand, respectively, whilst the reduction in the 28 days flexural strength was 0.7%, 8.1%, 10.8% and 22.97%, respectively. The reduction in the compressive strength could be related to the higher water absorption of OPBC sand compared to natural sand. In addition, the surface texture of OPBC particle is porous. The water absorption increased with the inclusion of OPBC sand, whilst no significant difference between the drying shrinkage of all mixtures.

Muntohar and Rahman [126] used PKS (size 4.75-9.5 mm) as a part of fine aggregate to manufacture light weight blocks. The control mixture was prepared with PC: natural sand ratio of 1: 4. Mixture containing PKS sand prepared with PC: natural sand: PKS sand ratio of 1: 1: 3. Fixed w/c ratio of 0.5 was used for all mixtures. The bulk density and compressive strength of the specimens decreased with the inclusion of PKS sand. The reduction in the bulk density was 22%, whilst the reduction in the compressive strength was approximately 37.5%.

Kunchariyakun et al. [115] replaced natural sand in aerated concretes with RHA after suitable treatment. The replacement levels were 0%, 25%, 50%, 75% and 100%.The specimens were cured at 180 °C for 8 h. The results showed a significant reduction in the unit weight and compressive strength with the inclusion of RHA sand. This reduction increased with increasing RHA sand content. The reduction in the unit weight was 15.83%, 27.64%, 38.15% and 44.95% with the inclusion of 25%, 50%, 75% and 100% RHA sand, respectively. The compressive strength of the control was reduced by 40-80% with the inclusion of RHA sand. The inclusion of 25%, 50%, 75% and 100% RHA sand reduced the thermal conductivity of the control by 7%, 11%, 22% and 28%, respectively. The porous structure (Fig. 10) and low specific gravity of RHA led to a reduction in the thermal conductivity. Sua-iam and Makul [116] replaced natural sand in SCCs with untreated RHA at levels ranging from 10% to 100%, by volume. The results showed a significant reduction in the unit weight, compressive strength and ultrasonic pulse velocity with the inclusion of RHA sand. This reduction increased with increasing RHA sand content. The reduction in the 28 days compressive strength was approximately 16%, 57%, 71%, 84% and 94% with the inclusion of 10%, 20% 40%, 60%, 80% and 100% RHA sand, respectively. The reduction in the ultrasonic pulse velocity at age of 28 days was 5%, 20%, 50%, 59%, 80% and 84% with the inclusion of 10%, 20% 40%, 60%, 80% and 100% RHA sand, respectively. Sua-iam and Mahul [127] replaced natural sand in concrete with 25%, 50%, 75% and 100% RHA, by volume. The inclusion of RHA sand decreased the workability, segregation and fresh unit weight of the mixtures. The workability and fresh unit weight decreased with increasing RHA sand content. The reduction in the fresh unit weight was 4%, 7.8%, 11.6% and 18.61% with the inclusion of 25%, 50%, 75% and 100% RHA sand, respectively.

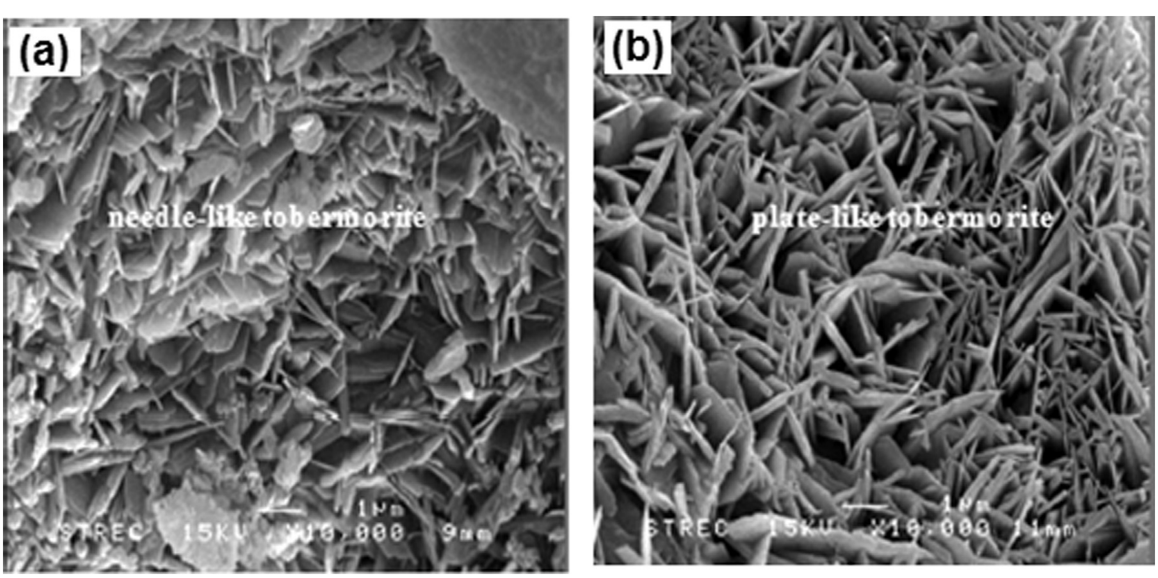


Fig. 10. SEM micrographs of concrete samples: (a) reference and (b) with 50% RHA sand [115].

The 7, 28, 90 and 180 days compressive strength decreased with increasing RHA sand content. The reduction in the 28 days compressive strength was 31.8%, 54.5%, 77.1% and 87.6% with the inclusion of 25%, 50%, 75% and 100% RHA sand, respectively.

Binici et al. [122] used CA and WSA, after treatment at 600 °C for 3 h, as natural sand replacement in concrete mixtures. Natural sand was partially replaced with CA or WSA or PLA at levels of 2%, 4% and 6%, by weight. They studied the compressive strength, at ages of 28 days and 18 months, compressive strength after immersing some specimens in 5% Na_2SO_4 for 18 months and abrasion resistance, They reported that the compressive strength, compressive strength after immersing in Na_2SO_4 and abrasion resistance of concretes improved by replacing part of natural sand with CA and WSA. These improvements increased with increasing replacement level. They also studied the water penetration depth. The results showed a significant reduction in the water penetration depth with the inclusion of CA and WSA as natural sand replacement. This reduction increased as the replacement level increased. The positive effects of these materials could be related to the filling effect in which they can fill the gaps. Thus, less porous matrix produced.

Al-Akhras and Abu-Alfoul [128] partially replaced natural fine aggregate in mortars with WSA at replacement levels of 3.6%, 7.3% and 10.9% by weight. They studied compressive strength and flexural strength of the mortars after autoclaving at pressure of 2 MPa for 2.5 h. The results showed that the inclusion of WSA sand increased the compressive strength and flexural strength of autoclaved mortars. In another investigation, Al-Akhras et al. [129] studied the effect of WSA, after thermal treatment, on the performance of concretes exposed to thermal cycling ranging 30-150 °C. Natural sand was partially replaced with WSA at levels of 5%, 10% and 15% by weight. The results showed positive effect of WSA sand on the performance of concrete specimens under thermal cycling. This positive effect of WSA sand could be related to the filler and pozzolanic activities of this material.

Sales and Lima [119] partially replaced natural sand in mortars with sugarcane bagasse ash (SBA). The replacement levels were 20% and 30%. The compressive strength results showed an enhancement with the inclusion of SBA sand. Modani and Vyawahare [130] partially replaced natural sand in concretes with untreated SBA at levels of 10%, 20%, 30% and 40%, by volume. The results showed a reduction in the workability and tensile strength with the inclusion of SBA sand. This reduction increased with increasing SBA sand content. On the other hand, the sorptivity increased with increasing SBA sand content. Odi [131] replaced sand in concretes with olive ash (OA) at replacement levels of 25%, 50%, 75% and 100%, by weight. They reported that the density of concretes decreased as the content of OA sand content increased. As the content of OA sand increased, concrete specimens became more brittle and better thermal insulation. Table 9 summarizes the above mentioned studies about the effect of agricultural sand on some properties of mortar and concrete.

From the literature review in this part, it is safe to conclude that it is possible to use different agricultural waste types as a partial or full replacement of natural sand. Some of them have positive effect on the compressive strength, abrasion resistance, sulfate resistance and penetration water depth such as CA and WSA sand. The quality of thermal insulation can be enhanced by using OA and RHA sand. Most of agricultural waste types decreased the mechanical strength, unit weight such as OPBS, PKS and RHA sand. The inclusion of these materials as natural sand replacement not only conserve natural rescuers, but also reduce the potential risks of air pollution resulted from burnt them.

3. Natural cementitious materials

3.1. Ground basaltic pumice

Binici et al. [132] investigated some properties of concrete containing ground basaltic pumice as a part of fine aggregate. Natural sand was partially replaced with ground basaltic pumice at levels of 5%, 10% and 15%, by weight. The results showed a reduction in the workability, unit weight and compressive strength with the inclusion of pumice sand. The reduction in the slump value was 50% and 37.5% with the inclusion of 5% or 10% and 15% pumice sand, respectively, whilst the reduction in the unit weight was 0.31%, 0.77% and 1.93%, respectively. The reduction in the 28 days compressive strength was 4.1%, 7.74% and 12.9% with the inclusion of 5% or 10% and 15% pumice sand, respectively. The inclusion of 15% pumice sand increased the coefficient of permeability by 2.21% and 6.91% at ages of 7 and 28 days, respectively, whilst the inclusion of 5% and 10% pumice sand decreased it by 22.76% and 15.45%, respectively, at age of 28 days. The inclusion of pumice sand increased sulfate resistance of the specimens. The reduction in the mass loss was 29.17%, 41.67% and 64.58% with the inclusion of 5%, 10% and 15% pumice sand, respectively, whilst the enhancement in the compressive strength after immersing was 6.23%, 7.9% and 8.5%, respectively. Karakoç et al. [133] studied some properties of concretes containing 10%, 20% and 30% pumice

Table 9
Effect of each type of agricultural sand on some properties of mortar and concrete.

Author	Agricultural type (%)	Effect
Muthusamy et al. [124]	25–100 OPS	Decreased hardened density Decreased compressive strength
Shafigh et al., 2014 [125]	12.5–50 OPBS	Decreased workability, density and mechanical strength Increased water absorption No effect on drying shrinkage
Muntohar and Rahman [126]	75 PKS	Decreased bulk density and compressive strength
Kunchariyakun et al. [115]	25–100 RHA	Decreased unit weight, compressive strength and thermal conductivity
Sua-iam and Makul [116]	10–100 Untreated RHA	Decreased unit weight and compressive strength
Sua-iam and Mahul [127]	25–100	Decreased workability, segregation and fresh unit weight Decreased compressive strength
Binici et al. [122]	2–6 CA or WSA	Increased compressive strength, abrasion resistance and sulfate resistance Decreased water penetration depth
Al-Akhras et al. [129]	5–15 WSA	Positive effect on thermal cycling
Sales and Lima [119]	20–30 SBA	Increased compressive strength
Modani and Vyawahare [130]	10–40 Untreated SBA	Reduced workability and tensile strength Increased sorptivity
Odi [131]	25–100 OA	Decreased density Increased thermal insulation and produce more brittle concrete

as natural sand replacement. At w/b ratio of 0.3, the 28 days compressive strength decreased by 5.29%, 18.49% and 31.48% with the inclusion of 10%, 20% and 30% pumice sand, respectively, whilst the porosity increased by 41.18%, 50% and 97.55%, respectively. Binici [134] reported a reduction in the workability of concrete mixtures with the inclusion of pumice as partially natural sand replacement. The reduction in the slump height was 18.18%, 22.73% and 25.45% with the inclusion of 40%, 50% and 60% pumice sand, whilst the weight of concrete specimens increased by 0.35%, 0.1% and 0.87%, respectively. The 7, 28, 90 and 365 days compressive strength increased with the inclusion of pumice sand content. The chloride penetration depth of concrete specimens after 110 wetting/drying cycles decreased sharply with the inclusion of pumice sand. The abrasion resistance of mortar specimens containing pumice sand was studied. The results showed higher abrasion resistance with the inclusion of pumice sand. The abrasion resistance increased with increasing pumice sand content.

Binici et al. [135] partially replaced natural sand in concrete mixtures with ground basaltic pumice at levels of 40%, 60% and 80%, by weight. The results showed a reduction in the workability with the inclusion of 60% and 80% pumice sand, of which the slump highest decreased by 16.67% and 33.33%, respectively. The fresh density of concrete decreased by 0.83%, 2.07% and 3.32% with the inclusion of 40%, 60% and 80% pumice sand, respectively. The compressive strength at ages up to 365 days decreased with the inclusion of pumice sand. The residual compressive strength after exposure to seawater for 0.25, 1, 2 and 3 years almost decreased with the inclusion of pumice sand. The abrasion resistance decreased with the inclusion of pumice sand. On the other hand, the corrosion resistance increased with the inclusion of pumice sand. In another investigation Binici et al. [136] reported that the inclusion of 40%, 60% and 80% pumice in concrete as natural sand replacement, by weight, decreased the slump height by 10.42%, 6.25% and 8.33%, respectively. The fresh concrete density decreased by 1%, 2.5% and 2.7% with the inclusion of 40%, 60% and 80% pumice sand, respectively. The compressive strength and the hydro-abrasive erosion increased with the inclusion of pumice sand. Degirmenci and Yilmaz [137] replaced natural sand with granulated pumice in production of lightweight cement mortar. The cement/pumice ratio was 1:3. The results showed a reduction in compressive strength and flexural strength with the inclusion of pumice as natural sand replacement. On the other hand, the pumice mortar exhibited higher frost resistance, higher residual strength at high temperatures, higher resistance of freeze-thaw cycles and higher resistance to sulfate attack than natural sand mortar. Hossain et al. [41] reported a reduction in the workability of concrete mixture by replacing natural sand with 100% pumice, by volume. The reduction in the slump height was 16.67%. The 28 days unit weight of concrete decreased by 19.66% with the inclusion of 100% pumice sand. The 28 days compressive strength, tensile strength and modulus of elasticity decreased by 29.63%, 26.67% and 26.67%, respectively. The 12 weeks water permeability decreased by 13.33% with the inclusion of 100% pumice sand, whilst drying shrinkage increased by 5.96%. Table 10 summarizes the above mentioned studies about the effect of pumice sand on some properties of mortar and concrete.

In general view of the above mentioned studies, it can be noted that the inclusion of pumice as natural sand replacement experienced some advantages, of which some properties are advanced, and some disadvantages, of which some properties are worsen. The advantages of using pumice sand are decreasing unit weight, increasing sulfate resistance, freeze/thaw resistance and corrosion resistance. In a different manner, the disadvantages of using pumice sand are increasing drying shrinkage, decreasing workability and mechanical strength. Really, more investigations are still required to completely understanding the effect of pumice sand on the above mentioned properties as well as the effect of pumice sand on water permeability, resistance of chloride ion penetration, abrasion resistance, fire resistance and severe chemical resistance.

3.2. Metakaolin

Badogiannis et al. [138] reported that there was an enhancement in the compressive strength of concretes by partially replacing natural sand with MK at levels of 10% and 20%, by weight. Soriano et al. [139] partially replaced natural fine aggregate in mortars with 10% MK. Some mortar specimens were cures at 5 °C and the other at 20 °C. The results showed 139.9%, 101.2%, 104.44% and 33.27% enhancement in the 1, 2, 7 and 28 days compressive strength, respectively, when curing temperature was 5 °C. When curing temperature was 20 °C, the enhancement in the compressive strength was 43.73%, 25.47%, 45% and 54.97%, respectively.

Badogiannis and Tsivilis [140] reported that HPCs containing 10% and 20% MK as natural sand replacement, by cement weight,

Table 10
Effect of pumice sand on some properties of mortar and concrete.

Author	Cementitious type (%)	Effect
Binici et al. [132]	5–15 Pumice	Decreased workability, unit weight and compressive strength Increased sulfate resistance 5% and 10% Decreased coefficient of permeability, whilst 15% increased it
Karakoç et al. [133]	10, 20 and 30	Decreased compressive strength Increased porosity
Binici [134]	40, 50 and 60	Decreased workability Increased unit weight, compressive strength and abrasion resistance Decreased chloride penetration
Binici et al. [135]	40, 60 and 80	Decreased workability Decreased fresh density Decreased compressive strength Decreased compressive strength after exposure to seawater Increased corrosion resistance
Binici et al. [136]	40, 60 and 80	Decreased workability and fresh density Increased compressive strength and hydro-abrasive
Degirmenci and Yilmaz [137]	100	Decreased compressive and flexural strength Increased forest and fire resistance Increased freeze–thaw and sulfate resistance
Hossain et al. [41]	100	Decreased workability and unit weight Decreased compressive strength, tensile strength and modulus of elasticity Decreased water permeability Increased drying shrinkage

Table 11
Effect of MK sand on some properties of mortar and concrete.

Author	MK content (%)	Effect
Badogiannis et al. [138]	10 and 20	Increased compressive strength
Soriano et al. [139]	10	Increased compressive strength
Badogiannis and Tsivilis [140]	10 and 20	Reduced chloride permeability, gas permeability and sorpitivity
Batis et al. [141]	10-30	Increased compressive strength
		Up to 20% increased corrosion resistance
		30% Reduced corrosion resistance
Rashad [1]	10-40	Increased compressive strength, splitting strength and abrasion resistance
	50	Decreased compressive strength, splitting strength and abrasion resistance

exhibited significant lower chloride permeability, gas permeability and sorpitivity. Batis et al. [141] partially replaced natural sand in mortars with MK at levels of 10% 20% and 30%, by weight. The results showed an enhancement in the compressive strength with the inclusion of MK as natural sand replacement. The corrosion resistance increased with the inclusion of MK up to 20%, whilst it decreased with the inclusion of 30% MK.

Rashad [1] partially replaced natural sand in concretes with MK at levels ranging from 10% to 50% with an interval of 10%, by weight. The results showed an enhancement in the compressive strength, splitting tensile strength and abrasion resistance with the inclusion of MK at levels up to 40%. The enhancement gradually increased with increasing MK sand content up to 40%. 40% showed the optimum MK sand content. On the other hand, the inclusion of 50% MK sand reduced the compressive strength, splitting tensile strength and abrasion resistance. Table 11 summarizes the above mentioned studies about the effect of MK sand on some properties of mortar and concrete.

From the above review in this section, it can be concluded that the inclusion of MK as a part of natural sand up to 40% increased the compressive strength, splitting tensile strength and abrasion resistance. This could be related to the consumption of CH liberated from hydration of cement by the pozolanic reaction of MK, led to formation additional amount of CSH and CASH products as shown in Fig. 11. In addition, the microstructure of the hardened concrete containing 40% MK as natural sand replacement displayed denser structure than the control (Fig. 12). It is worth mentioning that the inclusion of MK up to 20% decreased the corrosion resistance, whilst higher content of MK as a part of fine aggregate increased it.

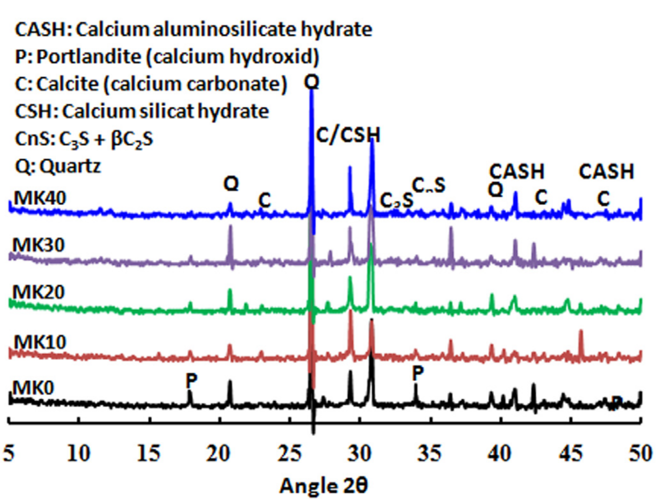
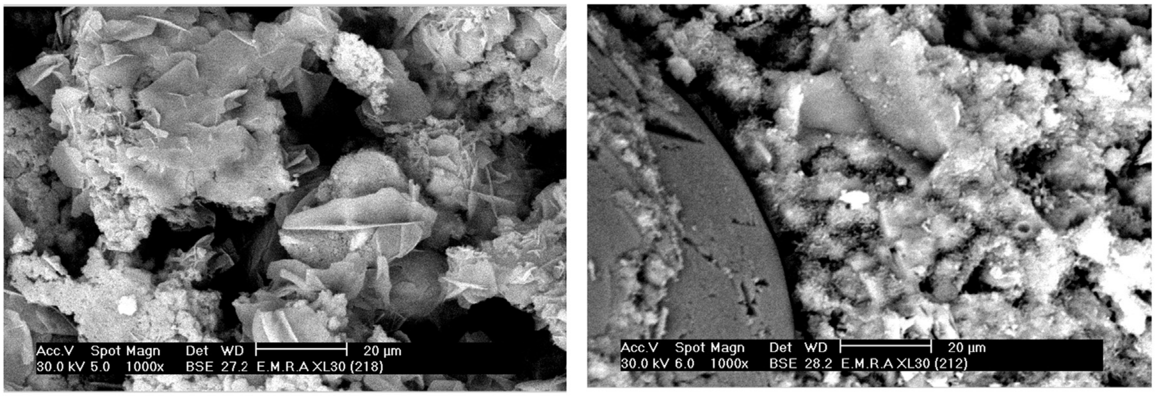


Fig. 11. X-ray patterns of concretes at 500 days hydration [1].

4. Comparison between fine aggregate

Yüksel and Genç [71] compared the workability, in term of slump, of concrete mixtures containing GBFS versus that containing furnace BA as natural sand replacement. Natural sand was partially replaced with GBFS or BA at levels ranging from 10% to 50% with an increment of 10%, by weight. The results showed similar workability of GBFS and BA mixtures at levels of 10% and 20%, whilst GBFS mixtures showed higher workability than BA mixtures at levels of 30%, 40% and 50%. They also compared the mechanical strength and water absorption of these mixtures. The results showed superior mechanical strength values of GBFS specimens. The specimens containing 10%, 20% and 40% BA sand exhibited lower percentage of water absorption than that containing GBFS sand. On the other hand, specimens containing 30% and 50% BA sand exhibited higher percentage of water absorption compared to their related that containing GBFS sand. Yüksel et al. [99] compared the ratio of dynamic modulus of elasticity and the compressive strength, after exposure to 800 °C, of concretes containing GBFS versus that containing BA as natural sand replacement. Natural sand was partially replaced with BA or GBFS at levels of 10%, 20%, 30%, 40% and 50%, by weight. The BA concretes showed higher ratio of dynamic modulus of elasticity and compressive strength than that of GBFS concretes. Yüksel and Demirtaş [97] compared RCPT of concretes containing GBFS (size 0.045-4 mm) versus that containing BA (size 0.045-4 mm) as natural sand replacement. Natural sand was partially replaced with GBFS or BA at levels ranging from 10% to 50% with an increment of 10%, by weight. The total charge passed decreased by 13.14%, 10.98%, 7.65% and 4.23% with the inclusion of 10%, 20%, 30%, 40% and 50% BA sand, respectively. On the other hand 50% BA led to an increase in the charge passed by 23.31%. The total charge passed decreased by 7.92%, 17.55%, 27.72% and 13.23% with the inclusion of 10%, 20%, 30%, 40% and 50% GBFS, respectively, whilst 50% GBFS led to an increase in the total charge passed by 0.63%. Comparing the results, it can conclude that GBFS is more impressive than BA for blocking chloride ion movements.

Bilir et al. [90] compared some properties of concretes containing GBFS versus that containing BA as natural sand replacement. Natural sand was partially replaced with GBFS or BA at levels ranging from 10% to 50% with an increment of 10%, by weight. The results showed higher compressive strength of specimens containing GBFS sand compared to that containing BA sand at ages of 28 and 90 days. The enhancement in the 28 days compressive strength of concretes containing GBFS over that containing BA was 19.45%, 16.26%, 25%, 8.45% and 6.95% at replacement levels of 10%, 20%, 30%, 40% and 50%, respectively. The chloride ion penetration of the specimens containing GBFS sand almost higher than that containing BA sand. Bilir [98] compared the durability of concretes containing GBFS versus that containing BA as natural sand replacement by measuring the loss of strength after 25 cycles of wet at 20 °C and dry at 40 °C; the loss of strength after 25 cycles of wet at 20 °C and dry at 40 °C; as well as the results of RCPT were



a) 0% MK b) 40% MK

Fig. 12. SEM micrographs of fracture surfaces of hardened concrete containing: (a) 0% MK and (b) 40% MK [1].

compared. Natural sand was partially replaced with GBFS or BA at levels of 10%, 20%, 30%, 40% and 50%, by weight. The results showed that the specimens containing GBFS sand exhibited lower loss in strength after freeze–thaw and dry–wet cycles than that containing BA sand. On the same line, specimens containing 20-50% GBFS sand showed lower chloride diffusion than that containing 20-50% BA sand. On the contrary with this, the specimens containing 10% BA sand showed slightly lower chloride diffusion than that containing 10% GBFS sand.

Binici et al. [132] compared some properties of concrete mixtures containing GBFS versus that containing ground basaltic pumice as natural sand replacement. Natural sand was partially replaced with GBFS or pumice at levels of 5%, 10% and 15%, by weight. The GBFS mixtures exhibited higher workability, unit weight and compressive strength than pumice ones. The increment in 5%, 10% and 15% GBFS specimens unit weight over that of pumice specimens was 0.47%, 1.17% and 2.77, respectively. At age of 28 days, the specimens containing 5%, 10% and 15% GBFS sand showed 10.31%, 22.84% and 38.52% higher compressive strength than that containing pumice sand, respectively. The specimens containing 5%, 10% and 15% GBFS sand showed 57.37%, 54.32% and 72.24% lower coefficient of permeability than that containing pumice sand, respectively. The sulfate resistance of GBFS specimens was higher than that of pumice specimens. After immersing specimens in 5% Na_2SO_4 for 180 days, the reduction of mass loss of 5%, 10% and 15% GBFS specimens compared to pumice specimens was 14.7%, 29.76% and 49%, respectively, whilst the enhancement in the residual compressive strength of GBFS specimens over pumice specimens was 5.28%, 13.87% and 22.41%, respectively. Table 12 summarizes the above mentioned studies about comparison one type of cementitious material to another when used as a part of fine aggregate in concrete

5. Remarks

The current review paper carried out on reviewing the previous works that investigated the effect of some cementitious materials such as FA, BA, SS, SF, OPS, OPBC, PKS, RHA, CA, WSA, OA, SBA, pumice and MK which were used as partial or full natural fine aggregate replacement in traditional mortar/concrete based on PC. Fresh properties, hardened properties and durability of mortar/concrete containing different types of these materials have been reviewed. The remarks of this literature review can be summarized as following:

(1) The inclusion of FA sand in the matrix increased its workability, delayed setting time, decreased fresh and hardened density and increased mechanical strength.
(2) The abrasion resistance, corrosion resistance, carbonation resistance and fire resistance of mortar/concrete increased with the inclusion of suitable content of FA sand. 20% FA sand decreased the drying shrinkage and crack width.
(3) The inclusion of FA sand in the matrix decreased the percentage of water absorption and sulfate resistance.
(4) The inclusion of BA sand in the matrix decreases its workability, delayed setting time, decreased the fresh and hardened density and decreased mechanical strength and carbonation resistance, but increased the drying shrinkage. 20–30% BA sand exhibited higher fire resistance.
(5) There are contradictory reports about the effect of BA sand on abrasion resistance, freeze/thaw resistance and water

Table 12
Comparison one type of cementitious material to another when used as a part of fine aggregate in concrete.

Author	Comparing aggregate	Content (%)	Comparing results
Yüksel and Genç [71]	GBFS versus BA	10–50	30–50% Workability of GBFS > BA Mechanical strength of GBFS > BA 10%, 20%, 40% Water absorption of GBFS > BA
Yüksel et al. [99]	GBFS versus BA	10–50	Compressive strength and modulus of elasticity at 800 °C of GBFS < BA
Yüksel and Demirtaş [97]	GBFS versus BA	10–50	Chloride ion penetration GBFS < BA
Bilir et al. [90]	GBFS versus BA	10–50	Compressive strength of GBFS > BA Chloride ion penetration GBFS > BA
Bilir [98]	GBFS versus BA	10–50	Wet/dry and freeze/thaw resistance GBFS > BA 20–50% Chloride diffusion of GBFS < BA 10% Chloride diffusion of GBFS > BA
Binici et al. [132]	GBFS versus pumice	5–15	Workability, unit weight, compressive strength of GBFS > pumice

absorption and sulfate resistance. Some reported positive effect, whilst the others reported negative effect.

(6) The inclusion of pumice sand in the matrix decreased workability, unit weight and compressive strength. 5% and 10% pumice sand decreased coefficient of permeability, whilst 15% increased it.

(7) The inclusion of SF sand, up to 10%, in the matrix decreased unit weigh, increased setting time, compressive strength and abrasion resistance.

(8) The inclusion of MK sand, up to 40%, in concrete increased compressive strength, tensile splitting strength and abrasion resistance, whilst 50% decreased them. 10-20% MK sand reduced permeability and increased corrosion resistance. On the other hand 30% MK sand decreased corrosion resistance.

(9) The inclusion of SS sand in the matrix decreased workability, but increased density, compressive strength, freeze/thaw resistance and wet/dry resistance.

(10) The inclusion of LS, ZS or SSOS sand in the mixture decreased its workability, whilst LFS sand increased it. The inclusion of WS, SSOS or FeCrS sand in the mixture increased the compressive strength, whilst ZS sand decreased it. The inclusion of LS or LFS sand decreased the compressive strength at ages of 7 and 28 days, but increased it at ages of 90 days and beyond. LFS increased the durability of concrete.

(11) Some of the agricultural wastes that used as natural fine aggregate replacement have positive effect on the compressive strength, abrasion resistance, sulfate resistance and penetration water depth such as CA, WSA and PLA. The quality of thermal insulation can be enhanced by using OA and RHA. Most of agricultural waste types decreased mechanical strength, unit weight such as OPBS, PKS and RHA.

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