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A BRIEF REVIEW ON BLAST-FURNACE SLAG AND COPPER SLAG AS FINE AGGREGATE IN MORTAR AND CONCRETE BASED ON PORTLAND CEMENT

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Abstract. In the last 15 years, it has become clear that the availability of good quality natural sand is decreasing. The shortage of the resources of natural sand opened the door for using by-products as fine aggregate. Reuse of by-products as a partial or full replacement of fine aggregate in construction activities not only reduces the demand for extraction of natural raw materials, but also saves landfill space. There are many studies reused granulate blast-furnace slag (GBFS) and copper slag (CS) as a part of fine aggregate. Others recycled them as a part of binder material (after suitable grinding). In this article, an overview of the previous studies carried out on the use of GBFS and CS as a partial or complete replacement of natural fine aggregate in traditional mortars and concretes based on Portland cement (PC). Fresh properties, hardened properties and durability of these mortars and concretes are reviewed.

1. INTRODUCTION

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

Granulated slag originates from the production of pig iron blast-furnaces as a by-product of metallurgical processes. It drives from a combination, under specific conditions, of the minerals contained in iron ore and in foundry coke and flux ashes. During the smelting process (~ 1500 °C) the metals in the liquid state are separated from the non-metallic fraction that forms the slag which contains all the undesirable impurities and solidifies upon cooling. The worldwide production of iron slag was estimated to be around 270-320 million tonnes [2]. The vast majority of this slag is still disposed in landfills [3]. One option to eliminate the disposed slag in an ecologically sensitive manner is to reuse it in concrete production after suitable grinding. A significant part of slag is utilized for the production of aggregate. The use of slags, by-products of the iron industry (blast furnace slag), as an aggregate for concrete is well-known in Europe for more than 30 years.

CS is an industrial by-product obtained during the matte smelting and refining of copper. The density of copper slag is relatively higher since it has a

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higher composition of iron oxide. When one tonne of copper is produced, 2.2-3 tonnes of CS are generated [4]. In Oman approximately 60,000 tonnes of copper slag is produced every year [5]. The production approximately 0.36, 0.244, 2.0, and 4.0 million tonnes of CS is reported in Iran, Brazil, Japan and the United States, respectively [6]. Currently, about 2 million tonnes of waste copper slag is produced each year in Korea [7]. It has been estimated that approximately 24.6 million tonnes of slag are generated from the world CS industry [8]. CS is widely used for sand blasting, rail road ballast, cement and concrete industries [9]. In spite of these different uses of CS, high quantities of slag are still disposed in landfills.

Waste reduction and recycling are very important elements in a waste management framework because they help to conserve natural resources and reduce demand for valuable landfill space. Many studies recycled GBFS and CS as a part of cement and clinker. Others recycled them as a partial or full replacement of natural fine or coarse aggregate.

Already the literate has abundant of review papers related to employing slag as a component of building materials. The previous review papers summarized the use of CS in cement clinker production and blended cement [6]; the use of CS aggregates in hot mix asphalt pavements [8]; the use of CS in production of tile [8].

Song and Sarawathy [10] reviewed the chloride, corrosion resistance and long term durability of concrete containing ground GBFS as a part of binder material. Indeed, there is no published literature review paper that reviewed the previous works carried out on the fresh properties, hardened properties and durability of mortar/concrete mixtures containing GBFS or CS as a partial or full fine aggregate replacement. In this paper, an effort has been made to review the past studies made of utilizing the GBFS and CS as fine aggregate in the preparation of mortar/concrete. This study could help other researchers for better understanding what has already been done and what needs to be done in this field.

2. BLAST-FURNACE SLAG (GBFS)

2.1. Workability

Topçu and Bilir [11] studied the workability of mortar mixtures containing non-ground granulated blast furnace slag GBFS (size 0.125-4 mm) as fine aggregate. Natural sand (size 0.08-2 mm) was replaced with GBFS at levels ranging from 0% to 100% with an increment of 10%, by weight. Fixed w/c ratio was used. The mortar flow diameter decreased with increasing slag content, this means that the workability decreased with increasing slag content. Binici et al. [12] studied the workability, in terms of slump, of concrete mixtures containing GBFS (size <5 mm) as natural sand replacement. Natural sand (size < 5 mm) was partially replaced with GBFS at levels of 5%, 10%, and 15%, by weight. The results showed a reduction in the slump values with the inclusion of GBFS sand. This reduction increased as the content of GBFS sand increased. The reduction in the slump value was 12.5%, 25%, and 37.5% with the inclusion of 5%, 10%, and 15% GBFS sand, respectively. Mosavinezhad and Nabavi [13] reported a reduction in the workability of concrete mixture by partially replacing natural sand with 30% GBFS (size <5 mm), by weight, at fixed w/c ratio and fixed dosage of superplasticizer (SP). Nataraja et al. [14] reported lower workability by replacing natural sand in mortar mixtures with GBFS (size <4.75 mm) at levels of 25%, 50%, 75%, and 100%, by weight. The reduction in the workability increased with increasing GBFS content.

On the other hand, Yüksel and Genç [15] studied the workability, in terms of slump, of concrete mixtures containing GBFS as natural sand replacement. Natural sand was partially replaced with GBFS (size ~ 0.08-5 mm) at levels ranging from 10% to 50% with an increment of 10%, by weight. Fixed w/c ratio was used. The results showed an increase in the slump values with the inclusion of GBFS. The slump value almost increased as the GBFS sand content increased. The increment in the slump value was 33.33%, 50%, 83.33%, 66.67%, and 100% with the inclusion of 10%, 20%, 30%, 40%, and 50%

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

Reference	GBFS content (%)	Size (mm)	Positive effect
Topçu and Bilir, 2010 [11]	10-100	0.125-4	×
Binici et al. [12]	5, 10, and 15	<5	×
Mosavinezhad and Nabavi [13]	30	<5	×
Nataraja et al. [14]	25, 50, 75, and 100	<4.75	×
Yüksel and Genç [15]	10-50	~ 0.08-5	√

Table 2. Effect of GBFS sand on the density of mortar and concrete.

Reference	GBFS content (%)	Size (mm)	Decreased density
Topçu and Bilir [11]	0-100	0.125-4	√
Yüsel et al. [16]	25-100	~0.045-4	√
Binici et al.[12]	5, 10, and 15	<5	×
Mosavinezhad and Nabavi [13]	30	<5	×

GBFS sand, respectively. Table 1 summarizes the mentioned studies about the effect of GBFS sand on the workability of mortar and concrete.

It is safe to conclude that the inclusion of GBFS sand in the mixture decreased the workability as reported by many studies. The high water absorption of GBFS particles [16-18] and their angular shape [13] led to this reduction in the workability.

2.2. Unit weight

Topçu and Bilir [11] studied the unit weight of mortars containing GBFS (size 0.125-4 mm) as fine aggregate. Natural sand was replaced with GBFS sand at levels ranging from 0% to 100% with an increment of 10%, by weight. Fixed w/c ratio was used. The results showed a reduction in the unit weight of the mortar with the inclusion of GBFS sand. The unit weight decreased as the GBFS sand content increased. Yüsel et al. [16] studied the saturated unit weight of concrete containing GBFS (size ~ 0.045-4 mm) as natural sand replacement. Natural sand was replaced at levels of 0%, 25%, 50%, 75%, and 100%, by weight. Fixed w/c ratio was used. The results showed a reduction in the concrete unit weight with the inclusion of GBFS sand. The reduction in the saturated unit weight was 2.48%, 7.02%, 9.15%, and 9.5% with the inclusion of 25%, 50%, 75%, and 100% GBFS sand, respectively.

On the other hand, Binici et al. [12] studied the unit weight of concrete mixtures containing GBFS (size <5 mm) as natural sand replacement. Natural sand was partially replaced with GBFS sand at levels of 0%, 5%, 10%, and 15%, by weight. The results showed a slight increase in the unit weight with the inclusion of GBFS sand. The increment in the unit weight was 0.15%, 0.39%, and 0.77% with the inclusion of 5%, 10%, and 15% GBFS sand, respectively. Mosavinezhad and Nabavi [13] reported that both fresh and dry density of concrete increased by partially replacing natural sand with 30% GBFS (size <5 mm), by weight. The increment in the wet and dry density was 7.9% and 4.33%, respectively, with the inclusion of GBFS sand. Table 2 summarizes the mentioned studies about the effect of GBFS sand on the density of mortar and concrete.

From the mentioned studies it can be noted that there are still contradictory results about the effect of GBFS sand on the unit weight of mortar and concrete. This is probably due to the differences in physical properties and chemical composition of the used GBFS. Some studies [11,16] reported that the unit weight decreased with increasing GBFS sand. They related this reduction to the lower unit weight of GBFS sand compared to natural sand. In addition, the GBFS sand exhibited porous structure [11]. On the other hand, other studies [12,13] reported higher unit weight with the inclusion of GBFS sand. Binici et al. [12] reported higher density of GBFS (2.75 t/m^3) compared to natural sand (1.6 t/m^3).

2.3. Strength

Binici et al. [12] studied the ultimate load of concrete pipes when fine aggregate was partially replaced with GBFS (size <5 mm). The replacement levels were 0%, 5%, 10%, and 15%, by weight. The results indicated that the specimens containing GBFS sand exhibited higher ultimate load compared to the control. They also investigated the compressive strength, at ages of 28 and 180 days, of the same mixtures. The results showed an increase in the compressive strength with the inclusion of GBFS sand, at all ages. The enhancement in the 28 days compressive strength was 5.81%, 13.33%, and 20.64% with the inclusion of 5%, 10%, and 15% GBFS, respectively. Ramesh et al. [19] reported higher compressive strength by partially replacing natural sand with furnace slag at levels of 5% and 10%. On the contrary, partially replacing natural sand with 15% furnace slag reduced it. The inclusion of 10% furnace slag showed the optimum content, of which the 28 days compressive strength was enhanced by 23.29%, whilst the inclusion of 15% was decreased it by 16.77%. Mosavinezhad and Nabavi [13] reported an increase in the compressive strength of concrete by partially replacing natural sand with 30% GBFS (size <5mm), by weight, when fixed w/c ratio and fixed dosage of SP were used. The enhancement in the compressive strength was 55%, 67%, and 66% at ages of 14, 28, and 56 days, respectively. Escalante-Garía et al. [20] partially replaced silica sand in mortars by GBFS at levels of 0%, 30%, 40%, and 50%. 90% retained in the 0.42 mm mesh and 28% was retained in the 1.0 mm mesh. The mortar systems were prepared of which the ratios of aggregate: binder were 2.3:1, 3:1, and 4:1.They concluded that the GBFS sand was more effective than natural silica sand in terms of strength, good properties and environmentally friendly.

Yüksel and Genç [15] studied the compressive strength, flexural strength and splitting strength of concrete containing GBFS (size ~ 0.08-5 mm) as natural sand replacement. Natural sand was partially replaced with GBFS at levels ranging from 10% to 50% with an increment of 10%, by weight. The results showed a reduction in the compressive strength with increasing GBFS content. The reduction in the 28 days compressive strength ranging from 1% to 10.6% was obtained in 10%, 20%, 30%, and 40% GBFS concretes related to the control, whilst it reached 22.4% in 50% GBFS concrete. They related this reduction to the porosity which increased with increasing GBFS sand content. The inclusion of 10% GBFS sand increased the flexural strength by 10.83%, whilst 20% and 50% GBFS sand showed flexural strength values closed to the value obtained for the reference specimen. The splitting tensile strength decreased with increasing GBFS sand content. Valcuende et al., [21] partially replaced natural sand (limestone sand) in SCCs with GBFS (size ≤4 mm) at levels ranging from 0% to 60% with an interval of 10%, by weight. The results showed that the 7, 28, 90, and 365 compressive strength of concretes containing GGBFS as natural sand replacement are very similar to the control, but at 7 days the highest GBFS content led to lower compressive strength. The 28 days elastic modulus slightly decreased with the inclusion of GBFS sand. The reduction in the elastic modulus was 4.98%, 3.72%, 5.86%, 6.86%, 5.68%, and 6.18% with the inclusion of 10%, 20%, 30%, 40%, 50%, and 60% GBFS sand, respectively. Zeghichi [22] studied the compressive strength, at ages of 3, 7, 28, 60 days and 5 months, of concrete containing GBFS (size <5 mm) as natural sand replacement. Natural sand was replaced with GBFS at levels of 30%, 50%, and 100%, by weight. The results showed an increase in the compressive strength with the inclusion of 30% GBFS sand, at all ages. At 50% GBFS sand, the compressive strength was higher at age of 3 and 60 days and 6 months, compared to the control concrete. On the contrary, the inclusion of 100% GBFS sand showed a reduction in the compressive strength, at all ages. Nataraja et al. [14] reported a slight increase in the 28 days compressive strength by partially replacing natural sand in mortars with GBFS (size <4.75 mm) at levels of 25%, 50%, and 75%, by weight. On the other hand, replacing natural sand with 100% GBFS reduced the compressive strength by 6.68%. Topçu and Bilir [11] studied the compressive strength, flexural strength and modulus of elasticity of mortars containing GBFS (size 0.125-4 mm) as fine aggregate. Natural sand was partially replaced with GBFS at levels ranging from 0% to 100% with an increment of 10%, by weight. The results showed a general reduction in the compressive strength, flexural strength and modulus of elasticity, but the optimum content for the use of GBFS as fine aggregate in mortars was 40% regarding to the improvement of compressive strength and flexural strength, whilst it was 10% regarding to modulus of elasticity.

Yüsel et al. [16] studied the compressive strength, at ages of 7, 28, and 360 days, and flexural strength, at age of 28 days, of concrete containing GBFS (size ~ 0.045-4 mm) as natural sand replacement. Natural sand was replaced with GBFS at levels of 25%, 50%, 75%, and 100%, by weight. The results showed a reduction in the both compressive strength and flexural strength with the inclusion of GBFS sand. The strength decreased as the content of GBFS increased. The reduction in the 28 days compressive strength was 4.97%, 19.07%, 27.65%, and 38.38% with the inclusion of 25%, 50%, 75%, and 100%, respectively, whilst the reduction in the 28 days flexural strength was 8.54%, 16.7%, 22.72%, and 30.87%, respectively. Shoaib et al. [23] studied the compressive strength, at age of 7 months, of mortars containing water-quenched slag (size 0.15-5 mm) as fine aggregate. The results showed a reduction in the compressive strength with the inclusion of water-quenched slag sand compared to the control. Yüksel and Bilir [24] replaced natural sand with GBFS (size ~ 0.045-4 mm) at levels ranging from 20% to 100% with an increment of 10%, by volume, in concrete pavement block specimens. The compressive strength decreased with the inclusion of 20% and 30% GBFS sand. On the other hand, between 60% and 80% replacement ratio intervals, the compressive strength showed comparable values to that of the control. They also partially replaced natural sand with GBFS at levels of 20%, 30%, 40%, and 50% in concrete kerb specimens. The results showed that the flexural strength decreased gradually as GBFS sand

Table 3. Effect of GBFS sand on the strength of mortar and concrete.

Reference	GBFS content (%)	Positive effect	Remarks
Binici et al. [12]	5, 10, and 15	√	
Ramesh et al. [19]	5, 10, and 15	√	-For 5% and 10% only
Mosavinezhad and Nabavi [13]	30	√	
Escalante -Garía et al. [20]	30, 40, and 50	√	
Yüksel and Genç [15]	10-50	√	-At 10% GBFS (flexural strength)
Yüksel and Genç [15]	10-50	×	-For compressive and splitting strength
Valcuende et al. [21]	10-60	×	-For high content of GBFS at 7 days-28 days elastic modulus
Zeghichi [22]	30, 50, and 100	√	-For 30% GBFS at all ages-For 50% GBFS at 3, 60 days and 6 months
Zeghichi [22]	30, 50, and 100	×	-For 100% GBFS at all ages
Nataraja et al. [14]	25, 50, and 75	√	
Nataraja et al. [14]	100	×	
Topçu and Bilir [11]	0-100	×	
Yüsel et al. [16]	25, 50, 75 and 100	×	
Shoaib et al. [23]	100	×	
Yüksel and Bilir [24]	20-100	×	

content increased. Table 3 summarizes the mentioned studies about the effect of GBFS sand on the strength of mortar and concrete.

It is safe to conclude that there are still conflicting results about the effect of GBFS sand on the strength of mortar and concrete. Some studies reported positive effect of specified percentages of GBFS on the compressive strength as 5%, 10%, and 15%. On the other hand, other studies reported negative effect. They related this negative effect to the porous GBFS particles that led to increase the porosity which led to decrease the compressive strength. These differences in the results may be related to the differences in physical properties and chemical composition of the used GBFS. However, the inclusion of GBFS up to 30% as natural sand replacement may be suitable, of which the SEM of concrete specimen containing 30% GBFS sand is similar to the control [25].

2.4. Abrasion resistance

Yüksel et al. [18] investigated the surface abrasion of concrete containing GBFS as partial natural sand replacement. Natural sand was partially replaced with GBFS at levels of 10%, 20%, 30% 40%, and 50%, by weight. The results showed that the inclusion of 10% GBFS sand exhibited the highest abrasion resistance followed by 20% and 40%, respectively. Yüksel and Bilir [24] partially replaced natural sand with GBFS (size ~ 0.045-4 mm) at levels of 20%, 30%, 40%, and 50%, by volume, in concrete pavement block specimens. They studied the surface abrasion of different mixtures. They reported that as GBFS sand content increased, the surface abrasion caused by the friction on paving block decreased gradually. The surface abrasion of the specimens containing 20%, 30%, 40%, and 50% GBFS sand was lower than the reference by 19.68%, 23.93%, 26.84%, and 28.63%, respectively. This result is a positive one for the sake of paving blocks endurance. They also partially replaced natural sand with GBFS (size ~ 0.045-4 mm) at levels of 20%, 30%, and 40%, by volume, in concrete kerb specimens. They studied the surface abrasion of different mixtures. They reported that as GBFS sand content increased, the surface abrasion caused by the friction on kerb specimens decreased gradually. The surface abrasion of the specimens containing 20%, 30%, and 40% GBFS sand was lower than the reference by 23.84%, 40.48%, and 41.28%, respectively. This result is a positive one for the sake of paving blocks endurance. It is safe to conclude that the inclusion of GBFS sand increased the abrasion resistance of concrete.

2.5. Shrinkage

Topçu and Bilir [11] studied the free shrinkage of mortars containing GBFS (size 0.125-4 mm) as fine aggregate. Natural sand was partially replaced with GBFS at levels ranging from 0% to 100% with an increment of 10%, by weight. The results showed an increase in the free shrinkage with the inclusion of 10%, 20%, 70%, 80%, 90%, and 100% GBFS sand. On the contrary, the free shrinkage was lesser for 30%, 40%, and 50% GBFS sand content compared to the control. Valcuende et al., [21] reported higher autogenous shrinkage, drying shrinkage and total shrinkage up to 365 days of concretes with the inclusion of GBFS as natural (limestone) sand replacement. The replacement levels were 10%, 20%, 30%, 40%, 50%, and 60%, by weight. The shrinkage increased with increasing GBFS sand content. The control specimens exhibited 11%, 14%, 21%, 26%, 28%, and 33% less autogenous shrinkage at 12 months than that containing 10%, 20%, 30%, 40%, 50%, and 60% GBFS sand, respectively. On the same line, at one year, the drying shrinkage increased by 4%, 11%, 15%, 19%, 24%, and 36% with the inclusion of 10%, 20%, 30%, 40%, 50%, and 60% GBFS sand compared to the control. The higher autogenous shrinkage with the inclusion of GBFS sand may be related to the higher paste volume of GBFS specimens. In addition, the GBFS sand containing higher porous than natural sand. Therefore, probably less stiff and less likely to hinder the deformation of the specimens. The higher drying shrinkage with the inclusion of GBFS sand may be related to the porous of slag, of which water lost faster. As water evaporates the internal pressure in the capillary network increases and promotes drying shrinkage. In addition, since the porous structure is also finer in the concretes with the highest GBFS sand content, the attraction exerted by the capillary walls is greater and therefore shrinkage is higher.

From the available studies about the effect of GBFS sand on the shrinkage, it can noted that there are still incompatible. One study reported lesser free shrinkage with the inclusion 30-50% GBFS sand, whilst other reported higher shrinkage. Indeed, the effect of GBFS sand on the drying shrinkage, autogenous shrinkage and total shrinkage still need a lot of investigations.

2.6. Water absorption and permeability

Binici et al. [12] studied the permeability coefficient of concrete pipes when natural fine aggregate was partially replaced with GBFS (size <5 mm). The replacement levels were 5%, 10%, and 15%, by weight. The amount of water passing through the cylindrical specimens at ages of 7 and 28 days was measured to determine the permeability coefficient of the concrete. The results showed a reduction in the coefficient of permeability with the inclusion of GBFS sand, at all ages. The reduction in the coefficient of permeability, at age of 28 days, was 67.07%, 61.38%, and 70.33% with the inclusion of 5%, 10% and 15% GBFS sand, respectively. Mosavinezhad and Nabavi [13] reported a reduction in the water absorption by partially replacing natural sand in concrete with 30% GBFS (size <5 mm), by weight, when fixed w/b ratio and fixed dosage of SP were used. The reduction in the water absorption was 38.97% and 49.33% at ages of 28 and 56 days, respectively.

Yüksel and Genç [15] studied the percentage of water absorption of concrete containing GBFS as natural sand replacement. Natural sand was partially replaced with GBFS at levels ranging from 10% to 50% with an increment of 10%, by weight. The results showed that the inclusion of 50% GBFS sand exhibited the highest percentage of water absorption followed by 40%, 10%, 30%, and 20%, respectively. Yüksel and Bilir [24] partially replaced sand with GBFS (size ~ 0.045-4 mm) at levels of 0%, 20%, 30%, 40%, and 50%, by volume, in concrete pavement block specimens. They studied the percentage of water absorption of different mixtures. The results showed 6.47% reduction in the percentage of water absorption with the inclusion of 20% GBFS sand. On the contrary, the other replacement levels showed an increase in the percentage of water absorption. The percentage of water absorption increased by 1.34%, 15.18%, and 16.29% with the inclusion of 30%, 40%, and 50% GBFS sand, respectively. Bilir [25] studied the RCPT of concrete mixtures containing GBFS as natural sand replacement. Natural sand was partially replaced with GBFS at levels of 0%, 10%, 20%, 30%, 40%, and 50%, by weight. The results showed a reduction in the chloride diffusion till 30% GBFS sand. 40% GBFS sand increased it, but it was still lower than the control. 50% GBFS sand showed comparable chloride diffusion to the control.

Yüksel et al. [18] investigated the capillarity coefficient of concrete containing GBFS as natural

Table 4. Effect of GBFS sand on the water absorption and permeability of mortar and concrete.

Reference	GBFS content (%)	Positive effect
Binici et al. [12]	5, 10, and 15	√
Mosavinezhad and Nabavi [13]	30	√
Yüksel and Genç [15]	10-50	√
Yüksel and Bilir [24]	20	√
	30, 40, and 50	×
Bilir [25]	10-50	√
Yüksel et al. [18]	10	√
	20, 30, 40, and 50	×
Yüsel et al. [16]	25, 50, 75, and 100	×

sand replacement. Natural sand was partially replaced with GBFS at levels of 0%, 10%, 20%, 30%, 40%, and 50%, by weight. The results showed a reduction in the capillarity coefficient with the inclusion of 10% GBFS sand, then it increased with increasing GBFS sand content. Yüsel et al. [16] studied the percentage of water absorption of concrete containing GBFS (size ~ 0.045-4 mm) as natural sand replacement. Natural sand was replaced with GBFS at levels of 0%, 25%, 50%, 75%, and 100%, by weight. The results showed an increase in the percentage of water absorption with increasing GBFS sand content. The increment in the percentage of water absorption was 7.57%, 18.42%, 31.67%, and 57.49% with the inclusion of 25%, 50%, 75%, and 100% GBFS sand, respectively. They also studied the chloride permeability of concrete specimens containing 0%, 25%, and 50% GBFS sand. The results showed a reduction in the chloride permeability with the inclusion of GBFS sand. Table 4 summarizes the previous researches about the effect of GBFS sand on the waster absorption of mortar and concrete.

It is safe to conclude that there are still conflicting results about the effect of GBFS sand on the water absorption of mortar and concrete (Fig. 1). Some studies reported positive effect, whilst others reported negative effect. The increment in the water absorption of the matrix with the inclusion of GBFS sand was related to the high water absorption of GBFS sand compared to natural sand. The water absorption increased with increasing GBFS sand content due to the more porous.

2.7. Freeze-thaw and wet/dry resistance

Yüksel and Bilir [24] partially replaced natural sand with GBFS (size ~ 0.045-4 mm) at levels of 0%, 20%, 30%, 40%, and 50%, by volume, in concrete pavement block specimens. They studied the compressive strength before and after 25 cycles of freeze-thaw. The results showed a reduction in the compressive strength after 25 cycles with the inclusion of 20% and 30% GBFS sand. Beyond that, the compressive strength started to increase, but it was still lower than the control. The inclusion of 50% GBFS sand showed better freeze-thaw resistance compared to the other replacement levels. In similar investigation, Yüksel et al. [18] studied the durability of concrete containing GBFS as natural sand replacement by measuring the loss in strength after 50 cycles of freeze at – 20 °C and thaw at 20 °C in water pool. Natural sand was partially replaced with GBFS at levels of 0%, 10%, 20%, 30%, 40%, and 50%, by weight. The results showed that the 20% GBFS sand exhibited the lowest loss in strength followed by 30%, 40%, 10%, 50%, and 0%, respectively. They also studied the durability of the concretes by measuring the compressive strength after 25 cycles of wet and dry. The results showed a reduction in the compressive strength with the inclusion of GBFS sand. The strength reduction increased with increasing GBFS sand content. Bilir [25] studied the durability of concrete containing GBFS as natural sand replacement by measuring the loss of strength after 50 cycles of freeze at – 20 °C and thaw at 20 °C, in water. Natural sand was partially replaced with GBFS at levels of 0%, 10%, 20%, 30%, 40%, and 50%, by weight. The results showed that the inclusion of 20% and 30% GBFS sand exhibited the lowest strength loss after cycles followed by 40%, 50% and 0%, respectively.

From the mentioned studies it can be noted that the inclusion of GBFS sand in concrete increased the freeze-thaw resistance compared to the reference. Yüksel et al. [18] and Bilir [25] related the high freeze-thaw resistance of concrete containing GBFS sand to the increase in concrete porosity with the inclusion of GBFS sand.

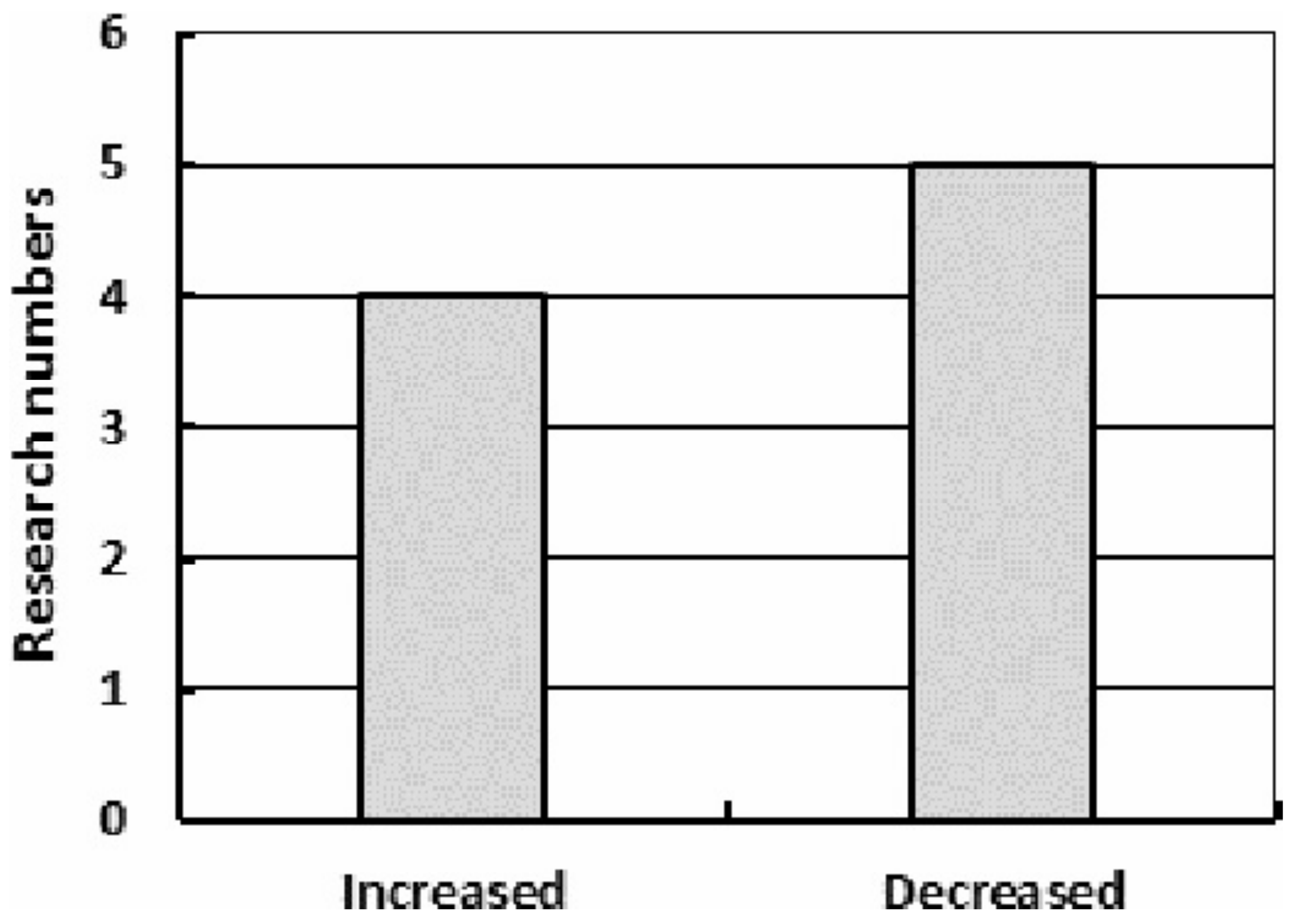

Fig. 1. Research numbers versus the effect of GBFS sand on the water absorption and permeability.

2.8. Fire resistance

Yüksel et al. [18] studied the effects of elevated temperature on the residual compressive strength, after exposure to 800 °C, of concrete containing GBFS as natural sand replacement. Natural sand was partially replaced with GBFS at levels of 10%, 20%, 30% 40%, and 50%, by weight. The results showed that 20% GBFS sand exhibited the highest residual compressive strength followed by 10%, 30%, 40%, 0%, and 50%, respectively. In similar investigation Yüksel et al. [26] reported that the ratio of dynamic modulus of elasticity and the compressive strength decreased gradually with increasing GBFS sand (size ~ 0.07-4 mm) content, after exposure to 800 °C. Shoaib et al. [23] studied the compressive strength of mortars containing GBFS (size 0.15-5 mm) as fine aggregate after exposure to 600 °C for 2 h. Various w/c ratios of 0.4, 0.5, and 0.6 were used. After exposure to elevated temperature, there were three types of cooling named water cooling, air cooling and furnace cooling. The results showed that specimens containing GBFS sand showed lower residual compressive strength compared to the control when water cooling was applied, at w/c ratios of 0.4 and 0.6. On the contrary, GBFS specimens exhibited higher residual strength when furnace and air cooling were applied. At w/c ratio of 0.5, specimens containing GBFS sand exhibited lower residual strength at all cooling conditions.

In general view of the mentioned studies, it can be concluded that the inclusion of GBFS sand up to 40% as natural sand replacement increased the fire resistance of concrete compared to the control, but this mainly depending on w/b ratio and cooling condition.

2.9. Sulfate resistance

Binici et al. [12] studied sulfate resistance of concrete containing GBFS (size <5 mm) as fine aggregate. The replacement levels were 0%, 5%, 10%, and 15%, by weight. The specimens were kept in 5% Na_2SO_4 for 180 days. The results showed higher sulfate resistance of GBFS specimens compared to the control. The sulfate resistance increased as the content of GBFS sand increased (Fig. 2). The reduction in weight loss was 1.44%, 0.87%, 0.59% and 0.26% with the inclusion of 0%, 5%, 10%, and 15% GBFS sand, respectively. Compared to the control, the enhancement in the compressive strength which measured after immersing in sulfate was 11.85%, 22.87%, and 32.85% with the inclusion of 5%, 10%, and 15% GBFS sand, respectively.

2.10. Leachability

Saikia et al. [27] investigated the leachabilities of some toxic elements from mortar containing lead GBFS (size <4.75 mm) as natural sand replacement. Natural sand was partially replaced with Pb GBFS at levels of 25% and 35%, by weight. The results showed that the concentrations of some toxic elements in the leachates of mortar containing slag were considerably higher than that mortar prepared without addition of slag. The toxic element contents in all the leachates obtained after the diffusion-leaching test were far below the standard requirements. The leaching of the majority of elements from mortar containing 35% slag was lower than or similar to that from mortar containing 25% slag.

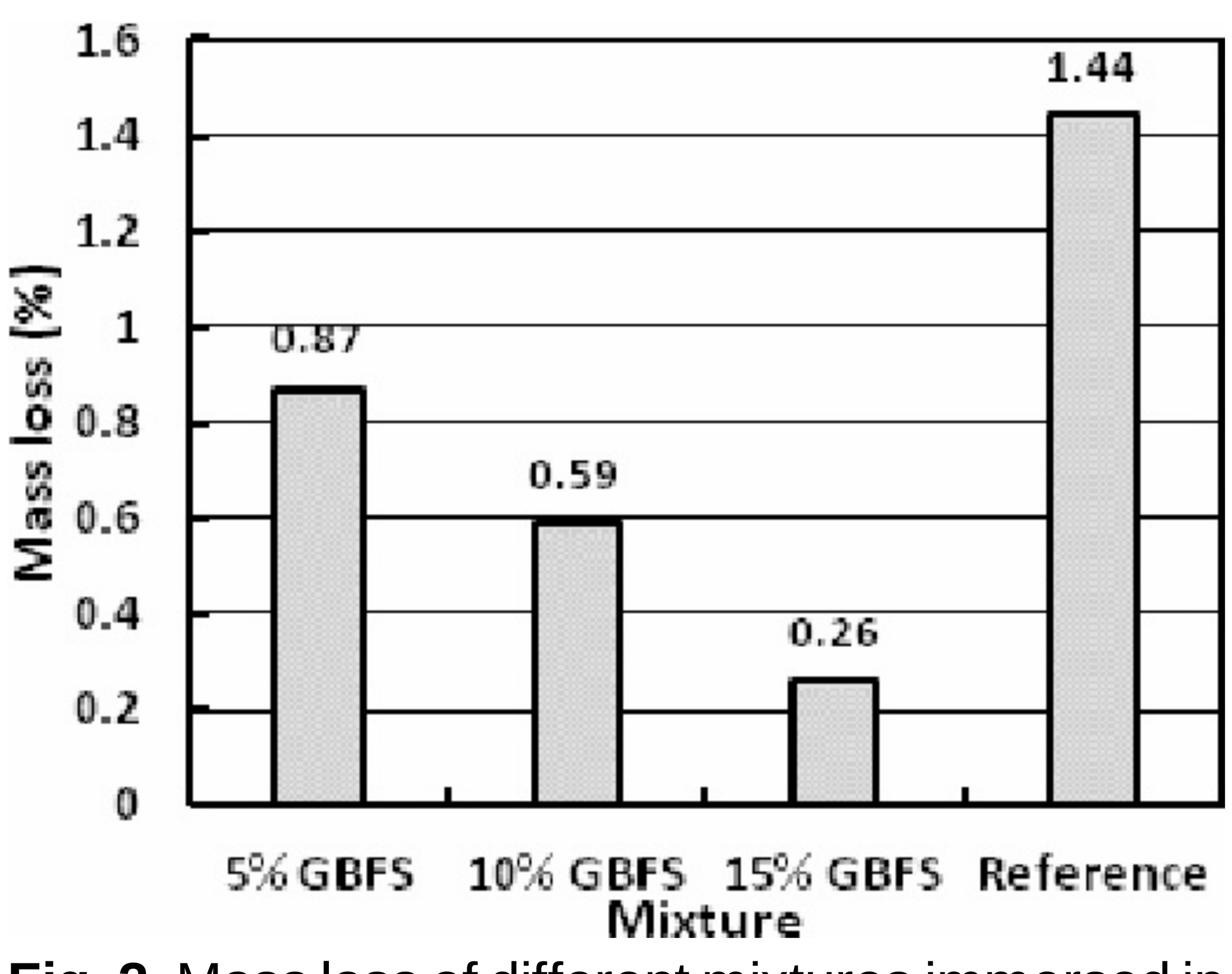

Fig. 2. Mass loss of different mixtures immersed in sulphate solution. Reprinted with permission from: Binici et al. // Scienctia Iranica A 19 (2012) 366. (c) 2012 Elsevier.

Table 5. The advantages and disadvantages of using GBFS sand in mortar and concrete.

Property	Positive effect	Negative effect	Remarks
Compressive strength	√		In most cases, the GBFS content < 30%
Abrasion resistance	√		GBFS up to 40%
Permeability	√		GBFS ≤ 15%
Chloride diffusion	√		GBFS up to 30%
Freeze-thaw resistance	√		
Wet/dry cycles	√		20% GBFS is the optimal
Fire resistance	√		GBFS ≤ 40%
Sulfate resistance	√		GBFS ≤ 15%
Workability		√	
Compressive strength		√	in most cases when GBFS > 30%
Water absorption		√	

In general view, using GBFS as fine aggregate in mortar and concrete showed some advantages, of which some properties are improved, and some disadvantages, of which some properties are defected. The advantages of using GBFS sand are increasing compressive strength (in most cases when GBFS content <30%), increasing abrasion resistance (GBFS up to 40%), reducing concrete permeability (GBFS ≤15%), reducing chloride diffusion (GBFS up to 30%), increasing freeze-thaw resistance, resisting wet/dry cycles, increasing fire resistance (GBFS ≤40%) and increasing sulfate resistance (GBFS ≤15%). On the other hand, the disadvantages of using GBFS sand are decreasing workability, decreasing compressive strength (in most cases when GBFS >30%) and increasing water absorption. Other properties such as the effect of GBFS sand on drying shrinkage, autogenous shrinkage and total shrinkage still need more investigations. Table 5 summarizes the advantages and disadvantages of using GBFS sand in mortar and concrete.

3. COPPER SLAG (CS)

3.1. Workability and bleeding

Hwang and Laiw [28] reported that the amount of bleeding of mortar made with CS sand comparatively is less than that containing natural sand. However, the heavy specific weight and the glass-like smooth surface properties of irregular grain shape of CS aggregate are effective on characteristics of bleeding. Shoya et al. [29] reported that the bleeding rate increased by using CS fine aggregate. This rate was depending on the w/c ratio, the volume fraction of CS and air content. They recommended using less than 40% of CS to control the amount of bleeding to less than 5 l/m^2. Al-Jabri et al. [30] studied the workability of HPC mixtures containing CS (size 0.075-5 mm) as natural sand replacement. Natural sand was replaced with CS at levels of 0%, 10%, 20%, 40%, 50%, 60%, 80%, and 100%. Fixed w/b ratio and fixed dosage of SP were employed. The results showed higher workability with increasing CS sand content. The slump height increased by 78.57% with the inclusion of 20% CS sand, whilst it increased by 435.71% with the inclusion of 100% CS sand. The mixtures containing 80% and 100% CS sand showed higher bleeding and segregation that can have detrimental effects on the concrete performance.

Al-Jabri et al. [31] studied the workability, in term of slump, of concrete mixtures containing CS as natural sand replacement. Natural sand was replaced with CS (size 0.075-5 mm) at levels of 0%, 10%, 20%, 40%, 60%, 80%, and 100%, by weight. Fixed w/c ratio was used. The results showed a significant increase in the workability with increasing CS sand content. The increment in the slump value with the inclusion of 20% CS sand was 22.14%, whilst it was 205.34% with the inclusion of 100% CS sand. Wu et al. [32] employed fixed w/b ratio and fixed dosage of SP in HSC mixtures. They reported higher workability of HSC mixtures by replacing natural sand with CS (size 0.1-1 mm) at levels of 0%, 20%, 40%, 60%, 80%, and 100%, by weight. The workability increased as the CS sand content increased. Pazhani and Jeyaraj [33] reported higher workability of concrete mixtures by replacing natural sand with CS at levels ranging from 20% to 100% with an increment of 20%, by weight, at fixed w/c ratio. The workability increased as the CS sand content increased. The slump value with the inclusion of 40% CS sand was 8.33% higher than that of the control mixture, whilst it reached 41.67%

Table 6. Effect of CS sand on the workability of concrete.

Reference	CS content (%)	Size (mm)	Positive effect
Al-Jabri et al. [30]	10, 20, 40, 50, 60, 80, and 100	0.075-5	√
Al-Jabri et al. [31]	10, 20, 40, 60, 80, and 100	0.075-5	√
Wu et al. [32]	20-100	0.1-1	√
Pazhani and Jeyaraj [33]	20-100	—	√
Arivalagan [34]	20-100	< 4.75	√

Table 7. Effect of CS sand on the density of concrete.

Reference	CS content (%)	Size (mm)	Increased density
Al-Jabri et al. [30]	10, 20, 40, 50, 60, 80, and 100	0.075-5	√
Al-Jabri et al. [36]	30, 50, 70, 80, and 100	0.075-5	√
Al-Jabri et al. [31]	20, 40, 60, 80, and 100	0.075-5	√

with the inclusion of 100% CS sand, related to the control. Arivalagan [34] studied the workability of concrete mixtures containing CS (size <4.75 mm) as natural sand replacement. Natural sand was replaced with CS at levels ranging from 0% to 100% with an increment of 20%. The results showed a slight reduction in the workability with the inclusion of 20% CS sand, whilst other levels showed higher workability. Table 6 summarizes the mentioned studies about the effect of CS sand on the workability of concrete.

From the mentioned studies it can be noted that less than 40% CS sand is recommended to control the amount of bleeding and segregation. The inclusion of CS sand increased the workability. The workability increased as the CS sand content increased. This considerable increase in the workability with increasing CS is attributed to the low water absorption characteristics of CS sand and its glass surface [35] compared to the natural sand which caused surplus quantity of free water to remain after the absorption and hydration processes have completed.

3.2. Density

Al-Jabri et al. [30] reported an increase in the concrete density by replacing natural sand with CS (size 0.075-5 mm) at levels of 10%, 20%, 40%, 50%, 60%, 80%, and 100%. The increment in the density with the inclusion of 20% CS sand was 0.78%, whilst it was 5.14% with the inclusion of 100% CS sand. Al-Jabri et al. [36] investigated the density of HSC mixtures containing CS (size 0.075-5 mm) as natural sand replacement. Natural sand was replaced with CS at levels of 30%, 50%, 70%, 80%, and 100%. Constant workability was employed. The results showed an increase in the density with the inclusion of CS sand. The increment in the density was 0.35%, 1.74%, 6.75%, 5.23%, and 7.84% with the inclusion of 30%, 50%, 70%, 80%, and 100% CS sand, respectively. Al-Jabri et al. [31] reported an increase in the concrete density by replacing natural sand with CS (size 0.075-5 mm) at levels of 20%, 40%, 60%, 80%, and 100%, by weight, whilst the inclusion of 10% CS sand slightly decreased it. The increment in the density was 0.63%, 1%, 1.43%, 3.1%, 2.9%, and 5.11% with the inclusion of 20%, 40%, 60%, 80%, and 100% CS, respectively. Table 7 summarizes the mentioned studies about the effect of CS sand on the density of concrete.

It is safe to conclude that the inclusion of CS sand increased the density. The density increased with increasing CS sand content. This is mainly due to the higher gravity of CS sand compared to the natural sand.

3.3. Strength

Several works reported that the compressive strength and tensile strength of concrete specimens made with CS fine aggregate are almost the same to the normal concrete or even significantly higher [37,38]. Al-Jabri et al. [36] reported an increase in the compressive strength, tensile strength and flexural strength with the inclusion of CS (size 0.075-5 mm) as natural sand replacement in HSC mixtures designed with the same workability. Natural sand was replaced with CS at levels of 0%, 30%, 50%, 70%, 80%, and 100%. The enhancement in the 28 days compressive strength was 14.98%, 14.89%, 13.18%, and 18.33% with the inclusion of 50%, 70%, 80%, and 100% CS sand, respectively. The enhancement in the 28 days tensile strength was 10.64%, 17%, 12.77%, 17%, and 19.15% with the inclusion of 30%, 50%, 70%, 80%, and 100% CS sand, respectively, whilst the enhancement in the 28 days flexural strength was 15.79%, 26.31%, 29.82%, 21.93%, and 27.19%, respectively. The inclusion of 100% CS sand showed the highest compressive strength and tensile strength, whilst the inclusion of 70% CS sand showed the highest flexural strength. Al-Jabri et al. [31] studied the compressive strength, at ages of 3, 7, 28, 56, and 90 days, of mortars containing CS (size 0.075-5 mm) as natural sand replacement. Natural sand was replaced with CS at levels ranging from 20% to 100% with an increment 20%, by weight. Fixed w/c ratio was used. The results showed that all mixtures containing different contents of CS sand yielded comparable or higher compressive strength than the control mixture. The enhancement in the 28 days compressive strength was 26%, 61.79%, 73.58%, 59.35%, 42.28%, and 6.1% with the inclusion of 20%, 40%, 60%, 80%, and 100% CS sand, respectively. They also studied the compressive strength, tensile strength and flexural strength of concrete containing CS (size 0.075-5 mm) as natural sand replacement at levels of 10%, 20%, 40%, 60%, 80%, and 100%, by weight. Fixed w/c ratio was used. The results showed that substitution of natural sand with CS up to 40-50% yielded comparable strength to the control mixture. The addition of more CS sand reduced it. The enhancement in the 28 days compressive strength was 2.22%, 4.44%, 4.67%, 4.44%, and 2.22% with the inclusion of 10%, 20%, 40%, 50%, and 60% CS sand, respectively, whilst the inclusion of 80% and 100% CS sand reduced it by 22.67% and 22%, respectively. Nazer et al. [39] replaced natural sand in mortar mixtures with CS (size <5 mm) at levels of 0% and 100%. The results showed higher compressive strength with the inclusion of CS sand. The enhancement in the compressive strength was 113.67%, 65.54%, and 43.93% at ages of 3, 7, and 28 days, respectively. Brindha and Nagan [40] reported higher compressive strength and splitting tensile strength of concretes by partially replacing natural sand with CS (size <4.75 mm) at levels of 20%, 40%, and 60%, by weight. The enhancement in the 28 days compressive strength was 23.61%, 32.93%, and 13.1% with the inclusion of 20%, 40%, and 60% CS sand, respectively, whilst the enhancement in the splitting tensile strength was 18.1%, 36.43%, and 17%, respectively. The inclusion of 40% CS sand showed the highest strength.

Al-Jabri et al. [30] reported that the compressive strength of concrete specimens, at age of 28 days, increased with the inclusion of CS (size 0.075-5 mm) content up to 50% as natural sand replacement, then decreased beyond this level (Fig. 3). The enhancement in the compressive strength was 6.28%, 1.49%, 1.38% and 3.1% with the inclusion of 10%, 20%, 40%, and 50% CS sand, respectively, whilst the reduction was 10.27%, 17%, and 17.55% with the inclusion of 60%, 80% and 100% CS sand, respectively. The tensile strength showed approximately the same trend. On the contrary, the flexural strength decreased with the inclusion of CS sand. The reduction in the 28 days flexural strength was 10.96%, 15.1%, 14.38%, 11.64%, 23.97%, 29.45%, and 30.82% with the inclusion of 10%, 20%, 40%, 50%, 60%, 80%, and 100% CS sand, respectively. Suresh and Kishore [41] partially replaced natural sand in concretes with CS at levels 0%, 10%, 20%, 30%, 40%, and 50%, by weight. The results showed an enhancement in the compressive strength, splitting tensile strength and flexural strength with the inclusion of CS sand up to 40%, then a reduction in strength was obtained with the inclusion of 50% CS sand. Chavan and Kulkarni [42] replaced natural sand in concretes with CS (size <5 mm) at levels of 10%, 20%, 30%, 40%, 50%, 60%, 75%, and 100%, by weight. Fixed w/b ratio of 0.52 was used. The results showed an enhancement in the 28 days compressive strength by partially replacing natural sand with CS sand up to 60%. Beyond this level, the compressive strength decreased. The flexural strength increased with the inclusion of CS sand at all levels. The enhancement in the 28 days compressive strength was 15.84%, 25.88%, 41.67%, and 18.21% with the inclusion of 10%, 20%, 30%, 40%, 50%, 60%, 75%, and 100% CS sand, respectively, whilst the reduction was 10.9% and 16.67% with the inclusion of 75% and 100% CS sand, respectively. The enhancement in the 28 days flexural strength was 3.15%, 14.61%, 4%, 5.15%, 7.44%, 2.29%, 0.86%, and 9.74% with the inclusion of 10%, 20%, 30%, 40%, 50%, 60%, 75%, and 100% CS sand, respectively. Arivalagan [34] replaced natural sand in concretes with CS (size <4.75 mm) at levels ranging from 0% to 100% with an interval of 20%, by weight. The 28 days compressive strength showed 8.6% and 16.25% enhancement with the inclusion of 20% and 40% CS sand, respectively. A reduction of 30%, 33%, and 33.33% was obtained with the inclusion of 60%, 80%, and 100% CS sand, respectively. They also

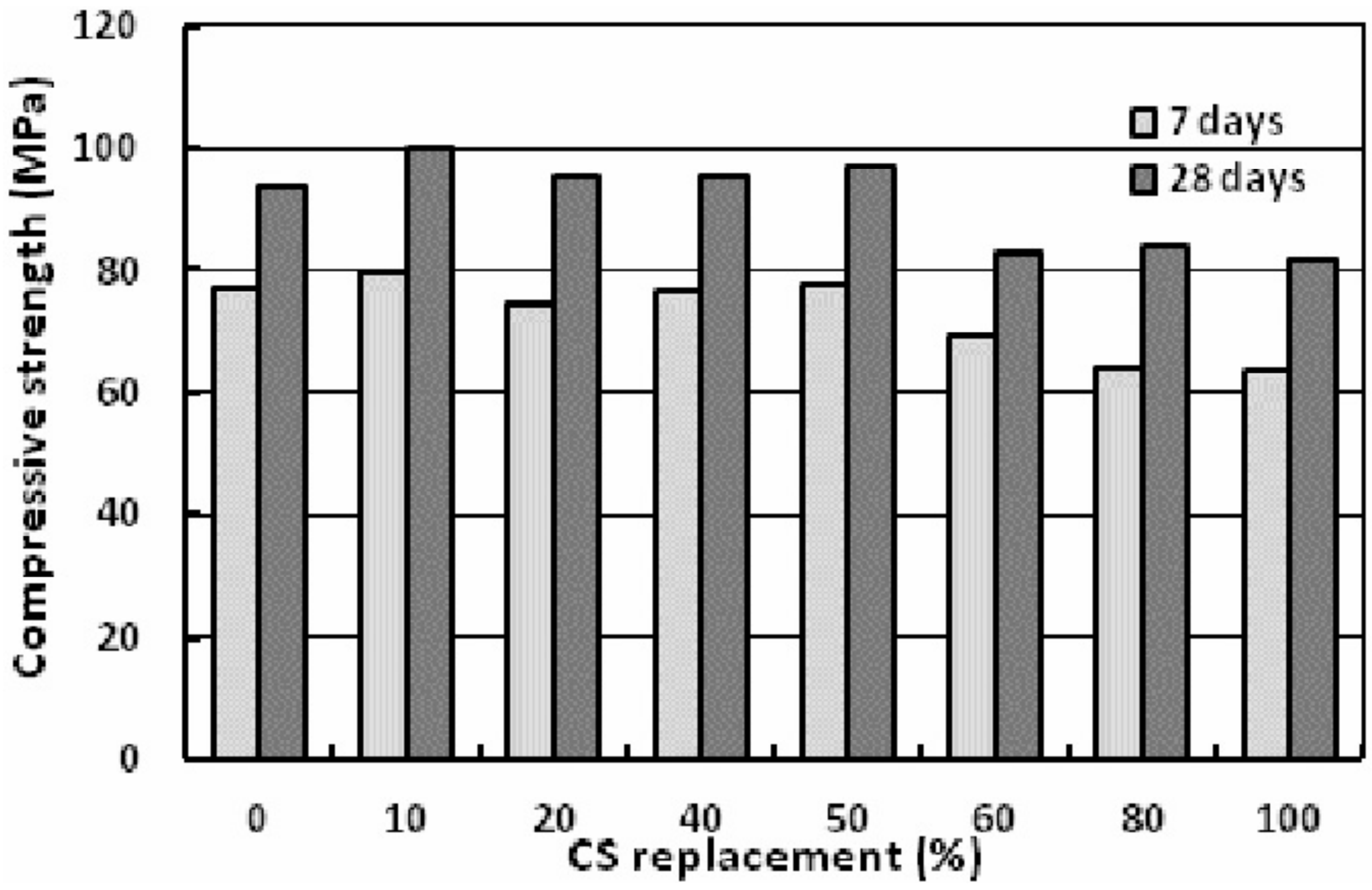

Fig. 3. Average cube compressive strength of HSC containing CS sand at 7 and 28 days of curing. Reprinted with permission from: Al-Jabri et al. // *Cement & Concrete Composites* 31 (2009) 483. © 2009 Elsevier.

found an increase in the splitting tensile strength and flexural strength with the inclusion of CS sand. The enhancement in the 28 days splitting tensile strength was 44.52%, 84.52%, 58.06%, 12%, and 3.22% with the inclusion of 20%, 40%, 60%, 80%, and 100% CS sand, respectively, whilst in the enhancement in the 28 days flexural strength was 21.58%, 33.1%, 47.6%, 51.35%, and 51.97%, respectively.

On the other hand, Alnuaimi [43] reported that substitution natural sand with CS (size ~ 0.075-5 mm) up to 40% in concrete did not cause a major change in strength. Further increasing in the CS sand content up to 100%, decreased the strength. Wu et al. [32] reported that the compressive strength, tensile strength and flexural strength of HSC strength containing less than 40% CS sand (size 0.1-1 mm) showed, at almost cases, slightly reduction, whilst beyond this level the reduction in strength increased. The reduction in the 28 days compressive strength was 2%, 3.45%, 10.96%, 29.44%, and 34% with the inclusion of 20%, 40%, 60%, 80%, and 100% CS as natural sand replacement, respectively, whilst the reduction in the 28 days tensile strength was 3.57%, 3.57, 5.36%, 26.78%, and 25%, respectively. The reduction in the 28 days flexural strength was 1.1%, 9.68%, 7.53%, and 11.83% with the inclusion of 20%, 60%, 80%, and 100% CS sand, respectively. Hassan and Al-Jabri [5] investigated the effect of using CS (size ~ 0.075-4.75 mm), up to 40%, as fine aggregate on the dynamic modulus and indirect tensile strength of hot-mix asphalt concrete. The results showed a reduction in the strength with increasing CS sand content compared to the control. On the contrary, the tensile strength ratios for CS sand mixtures were higher than that of the control mixture. Table 8 summarizes the mentioned studies about the effect of CS sand on the strength of mortar and concrete.

From the mentioned studies it can be noted that there are still contradictory results about the effect of CS sand on the strength of mortar and concrete. This is probably due to the differences in physical properties and chemical composition of the used CS sand. Some studies reported higher compressive strength with the inclusion of CS sand. Others reported higher compressive strength with the inclusion of CS up to 50%, then a significant reduction was obtained when CS content exceeds 50%. At higher replacement level than 50%, the compressive strength decreased due to the significant increase in the free water remained in the mixture in excess than that required for hydration of cement paste and for proper compaction of fresh concrete. The excessive free water content in the mixtures with high CS sand content caused the particles of the constituents to separate leaving pores in the hardened concrete which consequently caused a reduction in the compressive strength [30]. On the other hand, some studies reported lower compressive strength with the inclusion of CS sand. The compressive strength decreased with increasing CS sand content. This reduction could be attributed to the presence of excess water which improves the workability. The trapped excess water, which is not involved in the hydration process, forms internal voids especially the water pockets at the transition zone between the cement paste and the coarse aggregate in the concrete matrix. The increased porosity of the concrete weakens the bond between the concrete components, which is one of determining factors for the strength [32]. With the inclusion of CS

Table 8. Effect of CS sand on the compressive strength of concrete.

Reference	CS content (%)	Size (mm)	Positive effect
Al-Jabri et al. [36]	30, 50, 70, 80, and 100	0.075-5	√
Al-Jabri et al. [31]	20-100	0.075-5	√
Nazer et al. [39]	100	< 5	√
Brindha and Nagan [40]	20, 40, and 60	< 4.75	√
Al-Jabri et al. [30]	10, 20, 40, and 50	0.075-5	√
Al-Jabri et al. [30]	60, 80, and 100	0.075-5	×
Suresh and Kishore [41]	Up to 40	Not available	√
Chavan and Kulkarni [40]	Up to 60	<5	√
Chavan and Kulkarni [40]	75 and 100	<5	×
Arivalagan [34]	20 and 40	<4.75	√
Arivalagan [34]	60, 80, and 100	<4.75	×
Alnuaimi [43]	20-100	~ 0.075-5	×
Wu et al. [32]	20-100	0.1-1	×

sand there are more voids and microcracks (Fig. 4) that reduced the compressive strength. Anyway, partially replacement natural sand with CS up to 50% is recommended.

3.4. Durability

Al-Jabri et al. [36] reported that the water absorption of HSC mixtures slightly decreased with the inclusion of CS (size 0.075-10 mm) up to 50% as natural sand replacement. Beyond this level, the water absorption slightly increased as CS sand content increased. These mixtures were designed with the same slump. Al-Jabri et al. [31] studied durability of concrete mixtures containing CS (size 0.075-10 mm) as natural sand replacement at levels of 10%, 20%, 40%, 50%, 60%, 80%, and 100%,

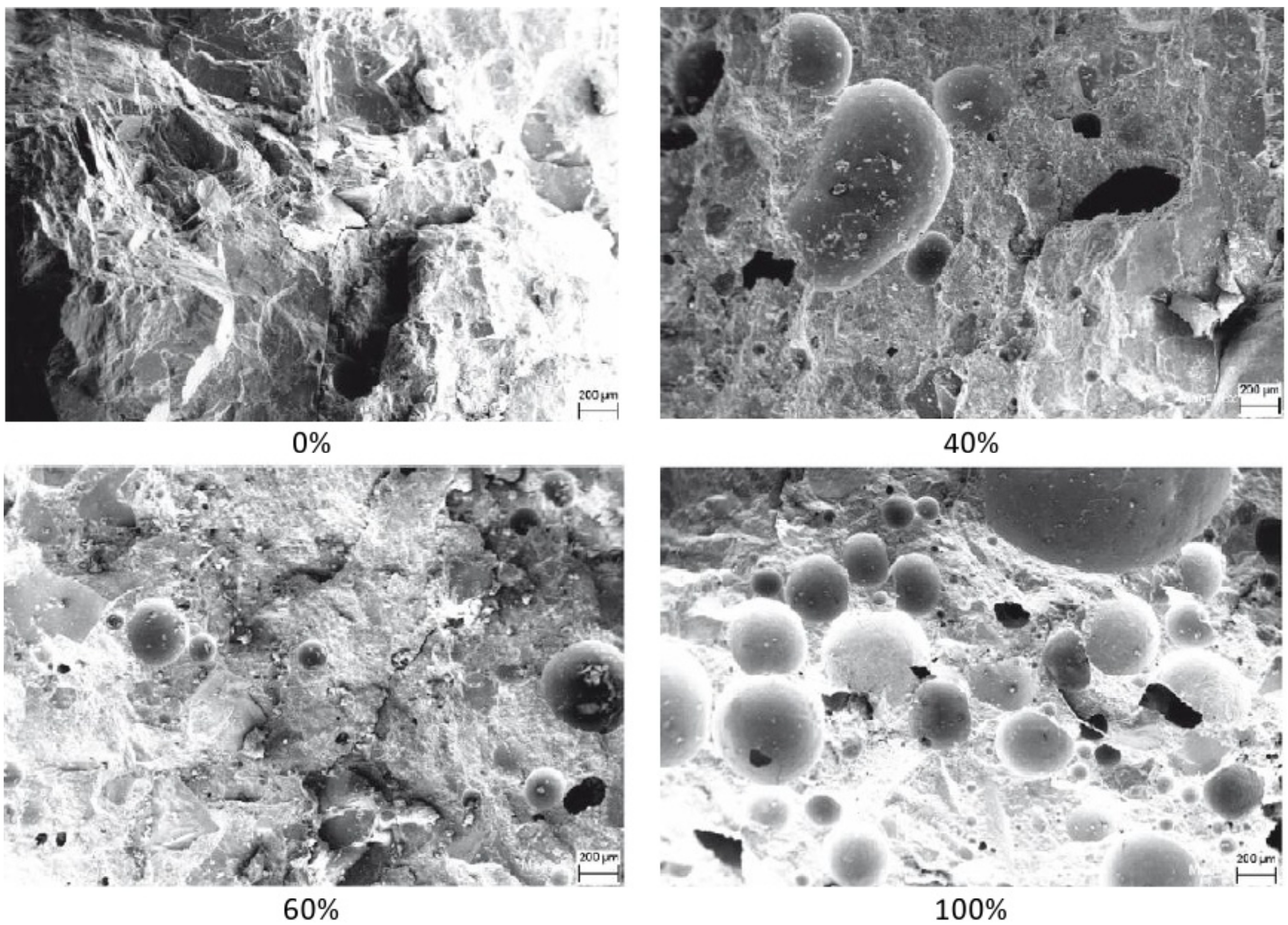

Fig. 4. Microscopic view of concrete specimens at different CS proportions. Reprinted with permission from: Wei Wu, Weide Zhang and Guowei Ma // *Materials and design* **31** (2010) 2878, (c) 2010 Elsevier.

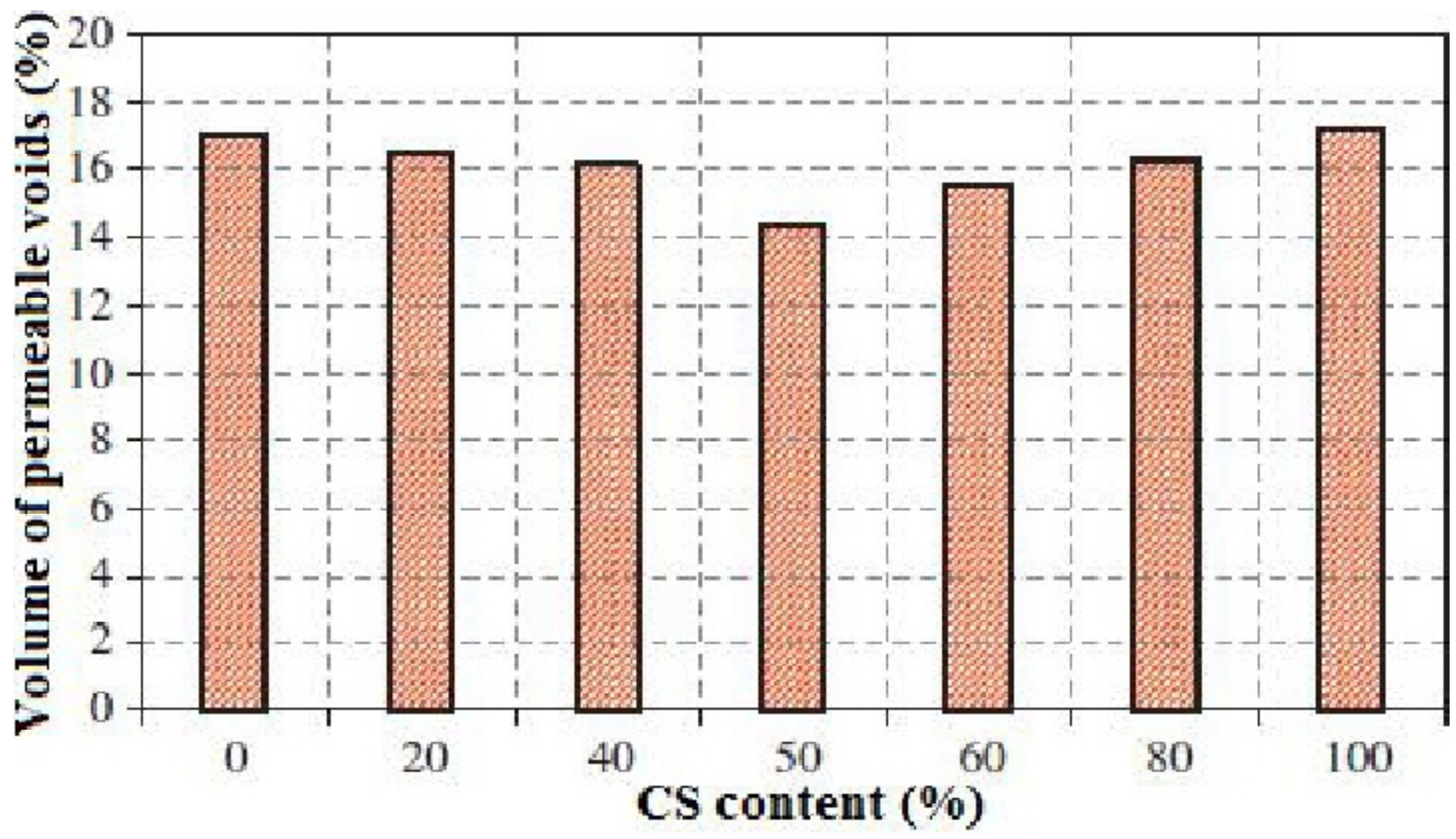

Fig. 5. Water permeable void contents for different concrete mixtures at 28 days curing. Reprinted with permission from: Khalifa S. Al-Jabri, Abdullah H. Al-Saidy and Ramzi Taha // *Construction and Building Materials* **25** (2011) 933. © 2011 Elsevier.

by weight, by measuring the surface water absorption and the percentage of volume of permeable voids, at age of 28 days. The surface water absorption results showed that the inclusion of 40% CS sand exhibited the lowest surface water absorption followed by 20%, 50%, 0% 60%, 80%, and 100%, respectively. The volume of water permeability void results showed a slight reduction with increasing CS sand content up to 50%. Beyond this level, the volume of voids increased to become comparable to the control mixture (Fig. 5).

Al-Jabri et al. [30] studied the durability by measuring the initial surface absorption of HPC mixtures containing CS (size 0.075-10 mm) as natural sand replacement at levels ranging from 10% to 100%. The results showed that the inclusion of 40% CS sand exhibited the lowest initial surface absorption followed by 20%, 50%, 0%, 80%, 60%, and 100% CS sand, respectively, (Fig. 6). Pazhani and Jeyaraj [33] reported that the chloride ion penetration of concretes decreased by replacing natural sand with CS sand. This reduction increased with increasing CS sand content. The reduction in the chloride ion penetration was 19.12%, 29.41%, 52.94%, 58.82%, and 67.65% with the inclusion of 20%, 40%, 60%, 80%, and 100% CS sand, respectively. The pH value slightly decreased with increasing CS sand content. The reduction in the pH value was 0.39% with the inclusion of 20% CS sand, whilst it reached 2.66% with the inclusion of 100% CS sand. Brindha and Nagan [40] reported that concrete containing 20% CS sand (size <4.75 mm) showed lower chloride penetration rate than the control, whilst concretes containing 40% and 60% CS sand showed higher chloride penetration rate. All replacement levels showed very low chloride penetration rate as per ASTM C1202.

One study [44] reported that the freezing-thawing resistance of concrete containing CS sand was lower than the control, whilst another [45] reported higher resistance of specimens made with CS sand. Hwang and Laiw [28] reported that the evaluation of the effects of CS aggregate on the sulfate attack resistance and the depth of carbonation shows no significant attack and slower rate carbonation by using CS sand. Brindha and Nagan [40] exposed concrete specimens containing 0%, 20%, 40%, and 60% CS sand to 5% dilute sulphuric acid (H_2SO_4) for 60 days. The results showed lesser resistance of concrete specimens containing CS sand to acid attack. The degradation increased with increasing CS sand content. Some studies [28,29] reported that the shrinkage of specimens containing CS fine aggregate is similar or even lesser than that of specimens without CS fine aggregate.

It is safe to conclude that the inclusion of CS up to 40% reduced the water absorption and the volume water permeability. On the other hand, the chloride ion penetration of concrete decreased with increasing CS sand content. Also, it is safe to conclude that sulfate resistance, acid resistance, carbonation resistance and freeze-thaw resistance still need more investigations.

In general view, using CS as fine aggregate in mortar and concrete showed some advantages, of which some properties are improved, and some disadvantages, of which some properties are defected. The advantages of using CS sand are increasing workability, reducing water absorption (CS ≤40%), decreasing chloride ion penetration, decreasing shrinkage and increasing compressive strength (in most cases when CS content ≤50%). On the other hand, the disadvantages of using CS sand are increasing bleeding (CS content >40%), decreasing

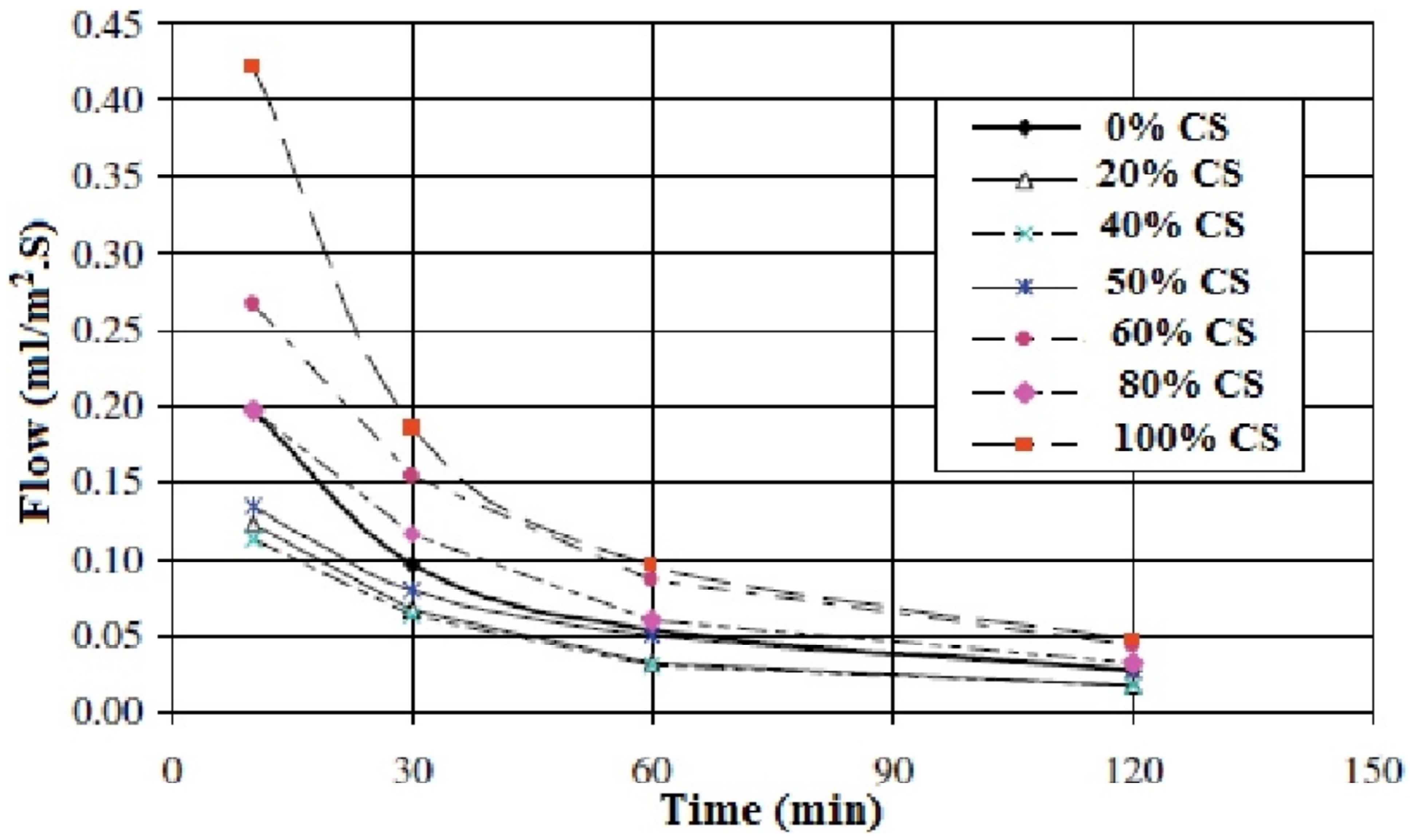

Fig. 6. Flow versus time for mixtures containing different contents of CS. Reprinted with permission from: S. Al-Jabri Khalifa, Makoto Hisada, Salem K.Al-Oraimi and Abdullah H.Al-Saidy // *Cement & Concrete Composites* **31** (2009) 483. © 2009 Elsevier.

compressive strength (in most cases when CS content >50%), increasing water absorption (CS content >40%), decreasing acid resistance and increasing density which led to increasing dead load. Table 9 summarizes the advantages and disadvantages of using CS sand in mortar and concrete.

The electronic library still needs more investigations about the effect of CS on setting time, ASR expansion, chemical resistance, abrasion resistance, freeze-thaw resistance, dry/wet resistance, carbonation resistance and fire resistance.

4. REMARKS AND SCOPE FOR FUTURE RESEARCHES

Both GBFS and CS recycled wastes are candidates to be more popular and widely used in the next few years in the field of building materials after suitable crushing and grinding. The current article reviewed the previous studies that investigated the effects of GBFS and CS fine aggregate on some properties of mortar and concrete based on PC. The remarks of this literature review and the scope for future researches can be summarized as following:

1. Reuse of by-product as a partial or full replacement of fine aggregate in construction activities not only reduces the demand for extraction of natural raw materials, but also saves landfill space.
2. Workability of the mixture decreased with increasing GBFS sand.
3. There are contradictory reports about the effect of GBFS sand on unit weight and compressive strength, of which some reported positive effect and the others reported negative effect. However, the inclusion of GBFS sand up to 30% may be suitable for good strength.
4. The inclusion of GBFS sand up to 40% increased abrasion resistance of concrete.

Table 9. The advantages and disadvantages of using CS sand in mortar and concrete.

Property	Positive effect	Negative effect	Remarks
Workability	√		
Water absorption	√		The CS content up to 40%
Chloride ion penetration	√		
Shrinkage	√		
Compressive strength	√		In most cases, the CS content ≤ 50%
Bleeding			The CS content > 40%
Compressive strength		√	In most cases, the CS content > 50%
Water absorption		√	In most cases, the CS content > 40%
Acid resistance		√	
Density		√	According the application that it used for

5. One study reported that the inclusion of 30-50% GBFS sand reduced free shrinkage, whilst another study reported higher shrinkage. Shrinkage still needs more investigations. The inclusion of GBFS sand up to 30% reduced the chloride diffusion, whilst ≤ 15% GBFS sand reduced the permeability.
6. The inclusion of suitable content of GBFS sand can increase fire resistance, sulfate resistance, freeze-thaw resistance and wet/dry resistance. On the contrary, in most cases, the inclusion of GBFS sand increased the water absorption.
7. Workability of the mixture increased with increasing CS sand content, whilst bleeding increased if the CS sand content exceeds 40%.
8. The wet and dry densities increased with increasing CS sand content.
9. In most cases, the compressive strength increased with the inclusion d"50% CS sand, otherwise the reduction was obtained.
10. The inclusion of CS sand has positive effect on chloride ion penetration and shrinkage.
11. The inclusion of CS sand up to 40% has positive effect on water absorption, whilst higher content than 40% showed negative effect.
12. The inclusion of CS sand reduced the acid resistance of concrete. The acid resistance decreased with increasing CS sand content.

Based on the current review, it is possible to used GBFS and CS as a part/full of natural fine aggregate in mortar and concrete. With the inclusion of these materials, some properties are enhanced and others are defected. The electronic library still needs more investigations about the effect of GBFS sand on heat of hydration, setting time, ASR expansion, chemical resistance, drying shrinkage and carbonation resistance. On the same line, the electronic library still needs more investigations about the effect of CS sand on heat of hydration, setting tine, ASR expansion, chemical resistance, abrasion resistance, freeze-thaw resistance, dry/wet resistance, carbonation resistance and fire resistance.

REFERENCES

[1] Alaa M. Rashad // *Construction and Building Materials* **44** (2013) 487.

[2] Alaa M. Rashad // *Journal of Cleaner Production* **93** (2015) 47.

[3] D. M. Roy // *Cement and Concrete Research* **29** (1999) 249.

[4] D. Brindha, T. Baskaran and S. Nagan // *Int. J. Civil Struct. Eng. Res.* **1** (2010) 192.

[5] Hossam F. Hassan and Khalifa Al-Jabri // *Journal of Materials in Civil Engineering (ASCE)* (June 2011) 879.

[6] C. Shi, C. Meyer and A. Behnood // *Resources, Conservation and Recycling* **52** (2008) 1115.

[7] Byung-Su Kim, Seul-Ki Jo, Doyun Shin, Jae-Chun Lee and Soo-Bock Jeong // *International Journal of Mineral Processing* **124** (2013) 124.

[8] B. Gorai, R. K. Jana and Premchand // *Resources, Conservation and Recycling* **39** (2003) 299.

[9] L.Teik-Thye // *Waste Manage. Res.* **24** (2005) 67.

[10] Ha-Won Song and Velu Saraswathy // *Journal of Hazardous Materials* **B138** (2006) 226.

[11] Llker Bekir Topçu and Turhan Bilir // *ACI Materials Journal* **107-M61** (2010) 545.

[12] H. Binici, M. Y. Durgun, T. Rizaoglu and M. Koluçolak // *Scienctia Iranica A* **19** (2012) 366.

[13] S. H. G. Mosavinezhad and S. E. Nabavi // *KSCE Journal of Civil Engineering* **16** (2012) 989.

[14] M.C. Nataraja, P.G. Dileep Kumar, A.S. Manuand and M.C. Sanjay // *International Journal of Structural and Civil Engineering Research* **2** (2013) 59.

[15] İsa Yüksel and Ayten Genç // *ACT Materials journal* **104-M44** (2007) 39.

[16] İ. Yüksel, O. Ozkan and T. Bilir // *ACI Materials Journal* **103** (2006) 203.

[17] İ. Yüksel and T. Bilir // *Construction and Building Materials* **21** (2007) 686.

[18] İ. Yüksel, T. Bilir and O. Ozkan // *Building and Environment* **42** (2007) 2651.

[19] S.T. Ramesh, R. Gandhimathi, P.V. Nidheesh and S. Rajakumar // *International Journal of Energy and Environmental Engineering* **4** (2013) 1.

[20] J. I. Escalante-Garía, R. X. Magallanes-Rivera and A. Gorokhovsky // *Construction and Building Materials* **23** (2009) 2851.

[21] M. Valuende, F. Benito, C. Parra and I. Miñano // *Construction and Building Materials* **76** (2015) 1.

[22] L. Zeghichi // *Asian Journal of Civil Engineering (Building and Housing)* **7** (2006) 27.

[23] M.M. Shoaib, S.A. Ahmed and M.M. Balahk // *Cement and Concrete Research* **31** (2001) 1533.

[24] İsa Yüksel and Turhan Bilir // *Construction and Building Materials* **21** (2007) 686.

[25] Turhan Bilir // *Construction and Building Materials* **26** (2012) 730.

[26] İsa Yüksel, Rafat Siddique and Ömer Özkan // *Construction and Building Materials* **25** (2011) 967.

[27] Nabajyoti Saikia, Geert Cornelis, Özlem Cizer, Carlo Vandecasteele and Dionys Van Gemert // *J Mater Cycles Waste Manag* **14** (2012) 102.

[28] C. Hwang and J. Laiw // *ACI* **SP-114** (1989) 1677.

[29] M. Shoya, S. Nagataki, F. Tomosawa, S. Sugita and Y. Tsukinaga // *ACI* **SP-170-45** (1997) 879.

[30] S. Al-Jabri Khalifa, Makoto Hisada, Salem K.Al-Oraimi and Abdullah H.Al-Saidy // *Cement & Concrete Composites* **31** (2009) 483.

[31] Khalifa S. Al-Jabri, Abdullah H. Al-Saidy and Ramzi Taha // *Construction and Building Materials* **25** (2011) 933.

[32] Wei Wu, Weide Zhang and Guowei Ma // *Materials and design* **31** (2010) 2878.

[33] K. Pazhani and R. Jeyaraj // *ATI-Applied Technologies & Innovations* **2** (2010) 19.

[34] S. Arivalagan // *Journal of Civil Engineering and Urbanism* **3** (2013) 176.

[35] T. Ayano, O. Kuramoto and K. Sakata // *J. Soc. Mater. Sci. Jpn.* **49** (2000) 1097.

[36] S. Al-Jabri Khalifa, Makoto Hisada, Abdullah H. Al-Saidy and S. K. Al-Oraimi // *Construction and Building Materials* **23** (2009) 2132.

[37] A. Behnood, In: *Proceeding of Seventh International Symposium on high-performance concrete* (ACI, YEAR?????), p. 228.

[38] S. Caliskan and A. Behnood, In: *Proceedings of seventh International Conference on concrete technology in developing in developing countries* (Malaysia, 2004), p. 91.

[39] Amin Salvador Nazer, Osvaldo Pavez and Feddy Rojas // *REM: R. Esc. Minas, Ouro Preto* **65** (2012) 87.

[40] D. Brindha and S. Nagan // *Asian Journal of Civil Engineering (Building and Housing)* **12** (2011) 562.

[41] Reddy S. Suresh and Kumar M. Kishore // *International Journal of Mechanical Engineering and Computer Applications* **1** (2013) 140.

[42] R. R. Chava and D. B. Kulkarni // *International Journal of Advanced Engineering Research and Studies* **II** (2013) 95.

[43] As. Alnuaimi // *TJER* **9** (2012) 90.

[44] M.Shoya, M. Aba, Y. Tsukinaga and K. Tokuhashi // *ACI* **SP 212-67** (2003) 1093.

[45] T. Ayano and K. Sakata // *ACI* **SP-192** (2000) 141.