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Utilization of waste glass in the improvement of concrete performance: A mini review

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Abstract

Every year, millions of tonnes of glass waste pose terrible problems related to the environmental condition all over the world. The glass is mainly composed of silica. Its use in concrete could be a beneficial solution for the environment and also economic problems. In this mini review, the different possibilities of the valorization of glass waste by substitution of aggregates and cement in concrete have been explored. Its effects on the physicochemical and mechanical characteristics were examined in the main research in this direction. The use of waste glass in concrete can offer an improvement in concrete performance and an asset for participation in sustainable development by reducing this waste.

Keywords

Utilization, waste glass, recycling, concrete performance, waste management

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Introduction

Concrete is the most widely used material in structures and buildings. It is a mixture of cement paste with aggregates, and it is well known that the dosing and mixing of concrete components are important steps in its manufacture (Donadkar and Solanke, 2016).

It is obvious that cement is a key ingredient of concrete matrix, because it is the binder of all the other components of the composition, constituting 7% to 15% of it (Olutoge, 2016).

Glass is considered one of the oldest materials fashioned by man. The origin of glass manufacturing remains, today, an enigma. According to specialists, the oldest glass objects that have been discovered, such as glazes of ceramics, date from the 7th century BC. We can speak of a real production activity from 3500 BC, in the form of glass beads, then rings and small figurines with the help of molds. The sand technique was developed around 1500 BC (Glas Trösch Holding AG, 2013).

The main raw materials used in the manufacture of glass are sand (providing silicon dioxide), soda ash and limestone, which generally constitute more than 85% of the mixture.

In 2016, world glass production was 140 million tonnes, of which 72 million tonnes were flat glass, 50% produced in China, 15% in Europe, 10% in North America, 7% in South East Asia, 5% in Japan and 4% in South America, and in 2010, out of a world production of 56 million tonnes, low-quality flat glass (mainly in China) constituted 20 million tonnes, drawn glass represented 1 million tonnes and laminated glass 2 million tonnes (French Chemical Company, 2017).

The environmental and economic interest in recycling glass waste is interesting. The use of cullet as additives to raw materials, which allows glass producers to reduce their energy consumption and reduce greenhouse gas emissions, and the increase in glass recycling, also helps to address the major environmental problems associated with solid waste management (Sibelco Green Solutions, 2019).

Glass waste from different origins can be collected and recycled in the sector of cement production and concrete. Several recycling options are envisaged, by the replacement of aggregates or cement and cement additives, which can offer the construction industry real solutions to participation in sustainable development.

This paper examined the different ways of using waste glass in concrete by replacing aggregates and cement or as a cementitious addition, and also investigated the effect of the replacement ratio and particle size of this waste on the performance and durability of concrete. Its objective is to provide an environmentally friendly solution by eliminating this waste and an economical solution through reducing the cost of concrete.

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Valorization of glass waste as aggregates

The use of glass waste as aggregate in concrete offers an opportunity for the elimination of this waste and to reduce the consumption of mineral aggregate used in construction, including an economic gain in the costs of transporting glass waste to recycling facilities and construction sites (Afshinnia, 2015).

The low thermal conductivity of glass compared to limestone aggregates is a technical advantage, which gives concrete a better thermal insulation. The glass aggregates also improve the abrasion resistance of concrete (Polley et al., 1998).

However, the use of glass waste as aggregates can cause alkali–silica reactions (ASR) that produce expansive materials, which can deteriorate the mechanical properties of concrete (Lee et al., 2011). Many research studies have been carried out, with the objective of the use of glass waste as a partial replacement of fine and coarse aggregates in concrete. Ismail and AL-Hashmi (2009) examined the use of glass waste as a partial replacement of fine aggregate in concrete at percentages of 5%, 10% and 20%. The results indicated that the partial replacement of fine aggregate by glass powders decreases ASR expansion, and finely crushed glass waste reduced the expansion compared to the control mixture. This decrease is related to the reduction in available alkali due to the consumption of lime by reaction with waste glass and the expected reduction in the alkalinity of the system. In their work on the determination of the replacement percentages of fine aggregates by glass waste in order to have an optimal value of compressive strength, Kumar and Nagar (2017) found that the optimal percentage is 25%, at which the compressive strength of concrete increased at 28 days by up to 11.56%.

Liaqat et al. (2018) conducted experiments on the mechanical strength of concrete made with the use of glass waste as coarse aggregate with a particle size of 4.75 to 12.5 mm and percentages of 10, 20, 30 and 40% by weight. They concluded that the ideal replacement level of glass waste is 10%. On the other hand, Nwofor and Ukpaka (2017) studied the replacement of fine and coarse aggregates by waste glass at percentages of 20%, 40%, 60% and 80%. They found that the optimal replacement in both cases (fine and coarse) was 20% compared to the other percentages. On the contrary, Rajitha et al. (2017) found that the optimal replacement as fine and coarse aggregate was 5%.

The compressive strength of concretes produced by the substitution of fine and coarse aggregates is related to many parameters of glass waste, such as the percentage of replacement and the particle size of the latter. Previous research agrees on the possibility of using glass waste in the form of aggregates in concrete.

The effect of the replacement of aggregates by glass waste on the fresh and hardened properties of concrete

For the slump test, the research carried out proved to be contradictory in results. The work of Ismail and AL-Hashmi (2009) showed that the slump of concrete samples decreased with the increase of the glass waste rate. This decrease can be explained by the angular form of the glass waste aggregates, which reduces the fluidity of the mixture. On the other hand, Liaqat et al. (2018) found that the workability of concrete mix increases with increasing glass waste content.

Adaway and Wang (2015) found that the compressive strength increases with the addition of glass waste to the mixture by up to 30%. This can be attributed to the angular shape of the glass particles facilitating increased liaison with the cement paste. The same result is found by (Park et al., 2004). Mageswari and Vidivelli (2010) showed that the compressive strength of concrete cubes and cylinders for all mixtures increased with the increase in the percentage of glass powder; nevertheless, a decrease was found with the increase in the age, explained by the alkali–silica reaction.

Saand et al. (2017) found that the compressive strength of concrete increases with the replacement of fine aggregate by waste glass (4–12%); beyond 12%, the strength decreases. The substitution of 12% of fine aggregate with glass waste aggregate with a particle size between 1.19 mm and 1.71 mm gave the best results in mechanical compressive tests. Keryou and Ibrahim (2014) concluded that the best variant giving the best mechanical strength was observed when replacing coarse aggregate at 25% by weight, as shown in the Table 1. Ibrahim (2017) showed that it was possible to use glass waste as a partial substitute of sand up to 40% by weight without reducing the tensile and compressive strengths compared to the control concrete, and the best replacement dose was 15%. Rahim et al. (2015) found that the best value of the compressive strength is obtained in the mixture containing 10% of glass waste as a replacement of fine aggregate, which represents an increase of 13.6% compared to the control concrete, as shown in the Table 1. Abdallah and Fan (2014) showed a continuous increase in flexural strength with age when replacing fine aggregate by glass waste. At 28 days, strength increased by 3.54%, 5.03% and 8.92% when the glass content increased by 5%, 15% and 20%. This could be attributed to the pozzolanic reaction that seems to be accelerating over time.

For the water absorption test, Liaqat et al. (2018) concluded that the water absorption decreases with increasing glass waste content as a replacement of coarse aggregate. Saand et al. (2017) showed that the water absorption of concrete decreases as the used glass dosage increases, and the maximum decrease was observed with 40% sand replacement.

Lam et al. (2007) found that the incorporation of 25% or less of recycled crushed glass as a partial replacement for natural aggregates induced negligible ASR expansion after a 28-day test period, but ASR expansion results must be confirmed by other test methods such as the concrete prism test.

Romero et al. (2013) showed that the use of more than 10% cathode ray tube glass as a partial replacement of fine aggregates in concrete can lead to deleterious expansions throughout its lifetime.

Saccani and Bignozzi (2010) concluded that the chemical composition of glass strongly influences the expansion behavior of concrete samples containing cullet as an aggregate. In view of glass recycle broadening, it is necessary to determine the expansion compositions and to introduce selective procedures for the

Table 1. Summary of research using glass waste as an aggregate.

Type of glass waste	Percentage studied	Size of particles studied (mm)	Optimum percentage of waste glass	Rate of increase in compressive strength at 28 days (%)	Rate of increase in flexural strength at 28 days (%)	Optimal size (mm)	Reference
Bottles, pots, windows	0–20	Fine (0.15–4.75)	20	66.30	55.21	0.15–4.75	Ismail and AL-Hashmi (2009)
Recycled glass wastes	0–45	Fine (<4.75)	25	11.56	/	NI	Kumar and Nagar (2017)
Glass of broken windows	0–40	Coarse (4.75–12.5)	20	6.56	/	4.75–12.5	Liaqat et al. (2018)
Glass waste from windows	0–80	Fine (⩽4.75) Coarse (⩽25)	20	3.01	/	NI	Nwofor and Ukpaka (2017)
Recycled glass wastes	0–15	NI	5	/	1.28	NI	Rajitha et al. (2017)
Recycled glass wastes	0–40	Fine (<4.75)	30	6	/	NI	Adaway and Wang (2015)
Soda–lime glass waste	0–70	Coarse (6–20)	30	/	/	NI	Park et al. (2004)
Glass sheet waste	0–50	Fine (⩽4.75)	10	/	/	NI	Mageswari and Vidivelli (2010)
Recycled glass wastes	0–40	Fine (1.19–1.71; 0.5–1.19)	12	36.85	/	1.19–1.71	Saand et al. (2017)
Glass waste from windows	0–30	Coarse (0.15–20)	25	30.03	30.64	NI	Keryou and Ibrahim (2014)
Recycled glass wastes	0–40	Fine (<4.75)	15	25	/	NI	Ibrahim (2017)
Bottles (soda–lime glass)	0–50	Fine (<4.75)	10	13.6	/	Less than 4.75	Rahim et al. (2015)
Glass waste from windows	0–20	Fine (<4.75)	20	5.28	8.92	NI	Abdallah and Fan (2014)

NI: not indicated.

treatment of post-consumer glass. Limbachiya et al. (2012) concluded that the presence of foamed glass aggregate did not affect the carbonation depth of the concrete mixes and the carbonation depth was halved when the water–cement ratio was reduced from 0.76 to 0.62. Previous research has shown that the presence of supplementary cementitious materials reduces the expansion caused by waste glass in concrete.

Lu et al. (2019a) found that the water permeability of concretes was improved, in particular for concretes prepared with glass cullet as coarse aggregate, because the use of the latter was favorable for improving water permeability due to the negligible water absorption nature and the smooth surface of glass cullet.

Aghabaglou et al. (2016a) concluded that the freeze–thaw resistance of mixtures containing glass aggregates was better than that of the control mixture. This was more pronounced by increasing the glass aggregate content of the mixture. Aghabaglou et al. (2016b) concluded that recycled concrete mixes containing more than 50% recycled aggregates showed better performance than the control mix in terms of sulphate resistance. Aghabaglou et al. (2018) concluded that the carbonation depth of the control sample was similar to that of the mixtures with glass aggregates and the latter showed better durability performance than the control mixture.

Table 1 presents the summary of research using glass waste as an aggregate.

Valorization of glass waste as a partial replacement of cement

Much research has been performed on the replacement of Portland cement with waste having pozzolanic effects such as fly ash, silica fume. Glass is mainly composed of silica, and its use in concrete as a partial replacement for cement could constitute a technical-economic solution that respects the environment, provided that it is finely ground. When glass waste is ground into micro-sized particles, pozzolanic reaction with cement hydrates are favored, thus forming a calcium silicate hydrate (CSH).

The effect of particle size of glass waste

The experimental results of Zakir et al. (2016) showed that with the size of glass powder particles decreasing in concrete, the resistance of concrete increases. Grain sizes of less than 75 µm gave greater strength than particle sizes ranging from 90 to 150 µm. Prudhvi et al. (2016) studied the strength of concrete with glass waste as a partial replacement of cement with a particle size of 90 to 150 µm. They concluded that 20% of glass powder of a size less than 100 µm could be included as cement replacement in concrete without any unfavorable effect. Shanmuguanathan et al. (2017) used glass waste with a particle size of less than 90 µm. They found that the flexural strength is higher at 15% and 20% compared to the control concrete at 14 and 28 days. Sreenivasulu and Prudhvi (2016) evaluated the pozzolanic activity of glass powder in concrete with two particle sizes, one ranging between 100 µm and 150 µm, and the other less than 100 µm. They concluded that glass powder with a grain size below 100 µm exhibits pozzolanic behavior, which favors the improvement of the strengths of concrete mixtures. Harish et al. (2016) concluded that the compressive and tensile strength increased in the mixtures containing glass powder with a size less than 150 µm, and they noted a decrease in mixtures containing glass powder with a particle size below 300 µm. Hussain and Verma (2016) found that the finer particle size of used glass waste has more intense activity with the cement, which results in a higher compressive strength in the concrete mix.

The rate of cement replacement by the powder of waste glass

Various research works have been carried to study the optimal percentage of glass waste that can be introduced as a partial replacement of cement in concrete.

Vandhiyan et al. (2013), Gahoi and Kansal (2016) and Olutoge (2016) concluded that 10% of cement replacement by glass powder is the best proportion. On the other hand, Meena et al. (2018), Karde et al. (2018) and Khan et al. (2015) found that 15% of glass powder is the optimum content to keep mechanical strength.

In addition, Prudhvi et al. (2016) and Sakale et al. (2016) concluded that the optimal percentage of waste glass to improve the performance of concrete is 20%.

Kumar and Sood (2017) found that cement can be replaced by glass powder by up to 20% without any loss of flexural and tensile strength in all concrete variants studied. Rahman and Uddin (2018) concluded that 30% of cement replacement achieves maximum tensile strength by splitting compared to the control concrete at 28 days. Olofinnade et al. (2017) showed that it is possible to produce medium-strength durable concrete for structural applications using 20% glass powder as a cement replacement. The study conducted by Aliabdo et al. (2016) shows the effect of the use of glass powder in concrete as a replacement and addition to cement. The test results showed that the use of 15% glass powder as an addition to cement allows an increase in strength of 16%.

Effect of glass powder on the properties of fresh concrete

The workability of concrete is a desired characteristic. There are many tests to measure this property of concrete based on different principles such as slump and flow tests. Vandhiyan et al. (2013) concluded that the workability of concrete was reduced with an increase in the replacement of cement by glass powder. This is due to the increase in the surface area of glass powder and also the angular shape of the glass particles. The same result was observed by Olutoge (2016). In addition, Khan et al. (2015) found that the slump value decreased with the addition of glass powder, so a large amount of water is required to obtain the same workability as the control mix. Aliabdo et al. (2016) showed that the use of glass powder as an addition to cement reduces the slump of concrete. This trend can be explained by an increase in the content of fine materials, which increases the cohesion of the concrete mix

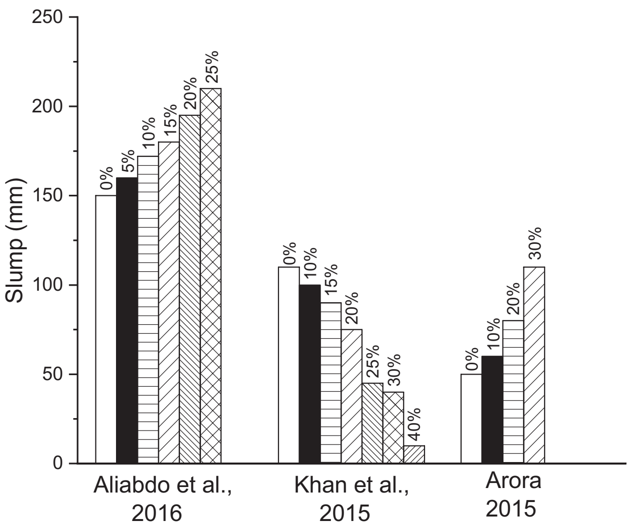

Figure 1. Summary of the results of the effect of glass powder content on concrete slump.

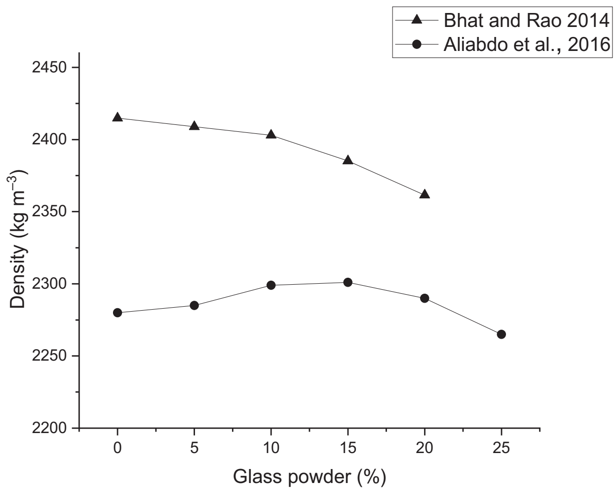

Figure 2. Different results of the effects of glass powder content on the density of hardened concrete.

and thus decreases the concrete slump. The results have shown that increasing the level of replacement of cement by glass powder increases concrete slump. This behavior can be explained by the low water absorption of glass powder or can be attributed to the coarser particles of the glass powder compared to the cement. Arora (2015) showed that the concrete slump increases with increasing glass powder content in the concrete mix. Keerio et al. (2017) found that the workability of concrete increases as the dosage of glass waste increases; the maximum increase in workability was observed at a 25% replacement of cement by glass waste. The different workability results are summarized in Figure 1.

Effect of glass powder on the properties of hardened concrete

Kumar et al. (2014) found that the density of concrete at 28 days decreased with an increase in the percentage of cement replacement by glass powder. This is due to the low-density value of glass used (2.58) compared to cement (3.15). The same result was confirmed by Bhat and Rao (2014). Keerio et al. (2017) observed that the density of hardened concrete increases with the substitution of 5%, 10% and 15% of cement by glass waste; the maximum increase of 1.25% in the control concrete was observed when replacing 10% of cement by glass powder. Aliabdo et al. (2016) concluded that the use of glass powder as partial cement replacement has a significant effect on concrete density. Figure 2 shows the different results of the effect of glass powder content on the density of hardened concrete.

The essential characteristic of hardened concrete is the compressive strength at a given age. Olofinnade et al. (2017) reported that the concrete containing powdered glass has shown a considerable improvement in the development of compressive strength at 28 days compared to the control concrete because of the pozzolanic activity of glass powder. Vandhiyan et al. (2013) concluded that the compressive strength of concrete increases up to 10% of cement replacement. Zakir et al. (2016) found that there is an increase in compressive strength at 28 days, as shown in Table 2. Mounika et al. (2017) found that the optimum compressive strength was obtained in the mixture containing 10% glass powder and increased by 28.3%, 31.1% and 36% at 7, 14 and 28 days, respectively. Gahoi and Kansal (2016) replaced Portland cement by glass powder at percentages from 0% to 25%. They found that there was a significant increase in the compressive strength of concrete when the percentage of glass powder was increased to 10%.

Du and Tan (2014) showed that 30% replacement of cement by glass waste is optimal for the development of compressive strength of concrete after seven days. The results of Khan et al. (2015) show a decrease in compressive strength, but with time. The strength obtained at constant rates and at 84 days of testing of M2 (10%), M3 (15%) and M4 (20%) mixture achieved 88% compressive strength of the control concrete. Bhat and Rao (2014) concluded that the compressive strength of concrete containing 20% of glass powder presents a maximum strength compared to control concrete; this result is consistent with Sakale et al. (2016). Figure 3 shows the different compressive strength results as a function of glass powder content in the concrete.

For tensile strength, Kumar et al. (2014) found that the tensile strength is maximum at 20% replacement cement by glass powder. The same result is observed by Sakale et al. (2016). On the other hand, Shekhawat and Aggarwal (2014) and Aliabdo et al. (2016) concluded that the tensile strength by splitting increases at 10% of the replacement of cement by glass powder compared to control concrete, and then decreases with an increase in glass waste powder. Karde et al. (2018) found that the continuous tensile strength increased by up to 5.05%, 6.52% and 6% at 28, 56 and 90 days, respectively, in the percentages of 5%, 10% and 15%. Kumar and Sood (2017) concluded that the tensile strength by splitting of M20 concrete increased by 39% at seven days, and 38% at 28 days compared to the reference concrete, and in M25 concrete, they noted an increase of 40% at seven days and 28% at 28 days compared to the control concrete. In addition, Zakir et al. (2016) showed that the tensile strength by splitting of glass

Table 2. Summary of research on the use of glass waste as a partial replacement for cement.

Type of glass waste	Percentage of replacement studied (%)	Size of particles studied (µm)	Optimum percentage of waste glass	Rate of increase in compressive strength at 28 days (%)	Rate of increase in flexural strength at 28 days (%)	Optimal particle size (µm)	Reference
Recycled glass waste	0–5–10–15 20–30	<75 90–150	20	16.02	27.30	<75	Zakir et al. (2016)
Waste of glass parts	0–2–4–8–16 20	90–150	16	24.56	/	<100	Prudhvi et al. (2016)
Recycled glass waste	0–10–15–20	<90	20	42.04	16.21	NI	Shanmuguanathan et al. (2017)
Recycled glass waste	0–10–20–30 40–50	(100–150) <100	30	/	31.55	<100	Sreenivasulu and Prudhvi (2016)
Crushed glass waste	0–10–20–30 40	<150 <300	30	14.15	/	<150	Harish et al. (2016)
Crushed glass waste	0–5–10–15–20 25	<75	15	17.15	18.13	<75	Hussain and Verma (2016)
Green glass waste	0–5–10–15	<90	10	8.98	37	NI	Vandhiyan et al. (2013)
Crushed glass waste	0–5–10–15 20–25	<90	10	29.51	17.27	<90	Gahoi and Kansal (2016)
Crushed glass waste	0–10–20–30	<300	10	/	/	NI	Olutoge (2016)
Waste glass bottles	0–10–15–20 25	100	15	24.94	19.11	NI	Meena et al. (2018)
Recycled glass waste	0–5–10–15–20 25–30	<90	15	3.71	/	NI	Karde et al. (2018)
Recycled glass waste	0–10–20–30 40	<90	20	24.61	/	NI	Sakale et al. (2016)
Recycled glass waste	0–5–10–15–20	<75	20	/	25.40	NI	Kumar and Sood (2017)
Waste glass bottles	0–10– 20– 30	<75	20	6.12	/	<75	Rahman and Uddin (2018)
Bottles (soda–lime glass)	0–15–18–21–24 27–30	<75	21	/	/	<75	Olofinnade et al. (2017)
Construction glass waste and bottles	0–5–10–15–20 25	<75	10	4.81	/	<75	Aliabdo et al. (2016)
Recycled glass waste	0–5–10–15–20 25	<45	15	/	/	NI	Khan et al. (2015)
Recycled glass waste	0–5–10–15–20 25	NI	10	12.95	/	NI	Keerio et al. (2017)
Recycled glass waste	0–5–10–15–20 25–30–35–40	<100	20	35.74	/	<100	Kumar et al. (2014)
Crushed glass waste	0–5–10–15–20	<600	20	27.32	/	NI	Bhat and Rao (2014)
Crushed glass waste	0–10–20–30	NI	10	36	9.74	NI	Mounika et al. (2017)
Recycled glass waste	0–10–20–30	<90	20	19.11	15.20	NI	Shekhawat and Aggarwal (2014)
Crushed glass waste	0–10–20–30	NI	20	19.11	15.20	NI	Arora (2015)
Crushed glass waste	0–5–10–15–20 25	<150	15	41.23	40.76	NI	Rokdey et al. (2018)
Green glass waste	0–10–20–30 40	<90	30	22.87	54.42	NI	Mwizerwa and Garg (2017)
Recycled glass waste	0–15–30–45 60	<100	15	/	/	NI	Du and Tan (2014)

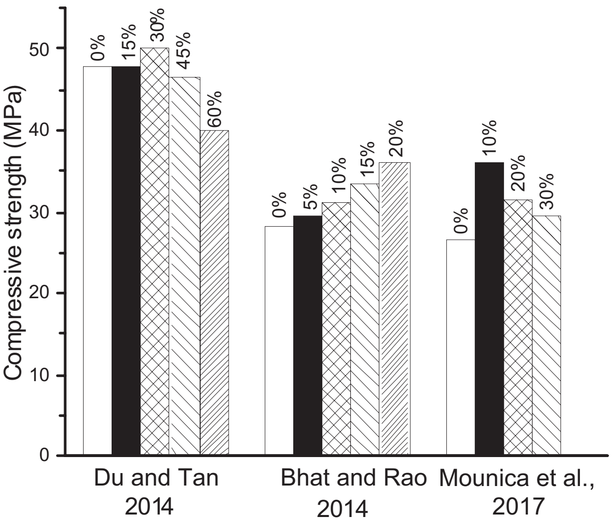

Figure 3. Compressive strength as a function of glass powder content in the concrete at 28 days of curing.

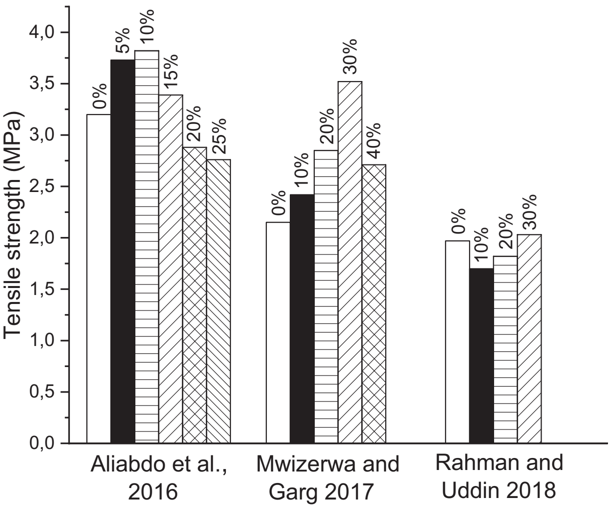

Figure 4. Effect of using glass powder on tensile strength of concrete at 28 days of curing.

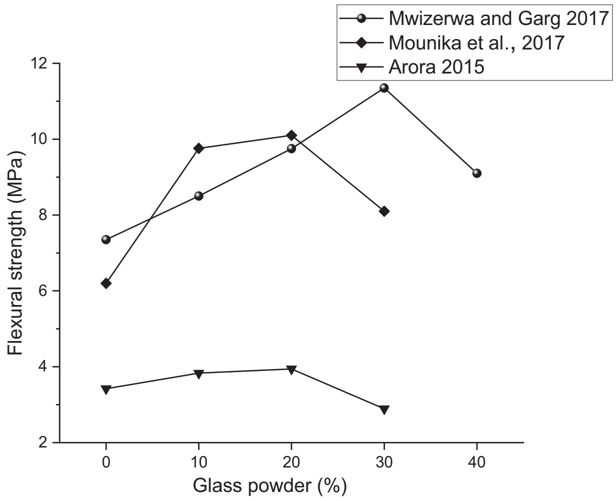

Figure 5. Effect of glass powder content on flexural strength of concrete at 28 days of hardening.

powder concrete increases by about 29% at 28 days. Rahman and Uddin (2018) and Mwizerwa and Garg (2017) found an increase in tensile strength by splitting of 3.04% and 51.16%, respectively, in 30% replacement of cement by glass powder. Figure 4 illustrates the results of the effect of glass powder on the tensile strength for various works.

For flexural strength, Mounika et al. (2017) found that the flexural strength increases when the cement is replaced by ground glass powder by 10% and 20%. The increase in strength observed is 1.46% and 1.66% at seven days, 8.21% and 8.60% at 14 days, then 9.74% and 10.10% at 28 days. Arora (2015) concluded that the flexural strength of concrete containing 10% and 20% glass powder is higher than that of the reference concrete, and the optimal dosage of replacement is 20%, as the maximum strength is achieved at this percentage. In addition, Gahoi and Kansal (2016) concluded that for the class M20 and M30 concrete there was an increase of 22.5% and 7%, respectively. Zakir et al. (2016) found that the flexural strength of glass powder concrete shows an increase at 28 days compared to the control concrete, as indicated in Table 2. Karde et al. (2018) observed a decrease in flexural strength at an initial replacement of 5% and 10%. The resistance is increased at the replacement of 15% and 20% during 28 days and 56 days. For 90 days, they observed that only 15% of glass powder increased the flexural strength compared to the reference mix and other percentages. On the other hand, Rokdey et al. (2018) found that the flexural strength increases by up to 15%. This increase is explained by the pozzolanic reaction of glass powder and the efficient filling of the voids, which result in a dense concrete microstructure. However, beyond 20%, the strength starts to decrease. The work objective of Mwizerwa and Garg (2017) concluded that green glass offers a higher flexural strength than clear glass with the same replacement rate and the optimal replacement percentage in concrete was 30% in both types of glass. Figure 5 shows the results of the effect of glass powder content on the flexural strength of concrete at 28 days of hardening.

Other properties have been studied by different researchers to examine the durability of concrete. Shekhawat and Aggarwal (2014) concluded that with increasing glass powder content, the percentage of water absorption decreases, and the minimum value is found at 10% replacement of cement by glass powder. Bhat and Rao (2016) concluded that the water absorption decreases with an increasing percentage of glass powder in concrete. In addition, Gahoi and Kansal (2016) concluded that the percentage of water absorption decreases compared to the reference concrete for both classes of concrete M20 and M30. Olofinnade et al. (2017) found that an increase in porosity can be observed at an increase of glass powder content. Du and Tan (2014) studied the properties of concrete with the partial replacement of cement by glass powder. They concluded that the resistance to penetration of chloride ions and water was greatly improved by replacing cement with glass powder, and this is due to the refined microstructure of paste. They found that the use of glass powder as a cementitious material can obviously reduce porosity and pore-size distribution. Nassar and Soroushian

(2012) concluded that the use of milled waste glass as a partial replacement for cement in recycled aggregate concrete results in enhanced durability properties such as chloride permeability and freeze–thaw resistance through improvement in the pore system characteristics and the filling effect of glass particles.

Table 2 shows the summary of research on the use of glass waste as a partial replacement for cement.

Valorization of glass waste as a partial replacement of cement and aggregate in the same mixture

The possibility of simultaneous valorization of glass waste in the form of aggregate and powder in the same mixture has been subject to many research studies.

Shaikh et al. (2015) concluded that the replacement of glass powder in cement, as well as crushed glass aggregate in sand by 5%, 10%, 15% and 20%, promotes the increase in compressive strength after 28 days of 9.25%, 38.50%, 70.80% and 33.09%, respectively. The replacement of glass powder in cement and crushed glass aggregate in the sand by 15% increases the tensile strength by splitting after 28 days by 4.25%. In addition, finely ground glass can have effective pozzolanic properties that serve as a partial cement substitute; also, the crushed glass grains that are retained on a 3.36 mm and 1.18 mm sieve also make a good filling material.

Taha and Nounu (2008) observed that there was an average reduction in compressive strength of 16% when 20% of the cement was replaced by glass powder. This can result directly from the modification of the nature of the hydration products and the CSH gel. The tensile strength by splitting of concrete was significantly reduced in the concrete mix containing glass waste as a replacement of cement and aggregates. In addition, they found that there were no observed differences in the results of flexural strength of concrete, even when recycled glass, sand and glass powder were used in the same concrete mixture.

Shayan and Xu (2006) concluded that the compressive strength of concrete with glass waste has been improved compared to concrete without glass. On the other hand, the experimental result showed that 30% of cement replacement by glass powder and 50% replacement of natural aggregate by coarse and fine aggregate could also be replaced in concrete of strength class 32 MPa with acceptable strength development properties. Lu et al. (2019b) concluded that the incorporation of 20% glass powder with particle sizes below 50 μm in the paving blocks could successfully suppress ASR expansion caused by the use of a high content of glass aggregates. The high silica content and fine particle size of the glass powder could play an important role in preventing ASR gel formation.

Valorization of glass waste as a raw material for cement production

In the context of glass waste recovery, the cement industry is also interested in this type of waste because of its similar chemical composition to clay. Chen et al. (2002) found that there was a slight increase in the alkali content. The detailed analysis of the quality of cement shows that there is no significant impact of the glass on the feeding rate tested. In addition, they showed that the physical and chemical properties of the glass cement produced were identical to those of Portland cement without glass.

Xie and Xi (2002) examined the use of glass waste as partial replacement of clay; their tests showed that the addition of glass to the cement paste favors the formation of the liquid phase between 950°C and 1250°C compared to its usual form, decreases the level of silicate tricalcique in the clinker and increases that of NC_8A_3, which results in a rapid setting and a low development of the mechanical strength of cement. In addition, glass as a raw material has the same effects on the clinker combustion process as other raw materials with a high alkali content. It is expected that the properties of cement manufactured with the glass waste will be the same as ordinary alkaline cement. In contrast, X-ray diffraction analysis indicates that the addition of the glass in the raw cement mixture does not result in the formation of new minerals in the clinker. Glass can be added in cement as raw material with a small fraction.

Dvořák et al. (2017) studied the improvement of the pozzolanic properties of recycled glass during the production of mixed Portland cement. The results show that it is possible to improve the pozzolanic properties of recycled glass by using as a base of mixed cement, and that this will positively influence the value of the physical and mechanical parameters of the material. The energy dispersive spectroscopy, analysis confirms the presence of hydration products (CSH gel) in the contact zone between the glass particle and the hydration products cement.

Conclusion

This paper investigated the different ways of using waste glass in concrete by replacing aggregates and cement or as a cementitious addition, which leads to the elimination of this type of waste in nature and the reduction of concrete cost. This study differs from others regarding the possibility of using waste glass in various forms in concrete by the examination of the effect of the replacement rate and particle size of these wastes in the improvement of the properties of fresh and hardened concrete.

The results of the works by the various researchers mentioned above indicate the following:

1. The partial replacement of sand by glass powder reduces ASR expansion if the glass waste is finely ground.
2. The strength of concrete with the addition of glass waste as a partial replacement for fine and coarse aggregate or cement is related to many parameters, such as the percentage of replacement, the particle size and shape of the glass and the type of waste.
3. Compressive strength in concrete with the addition of glass powder as a partial replacement of cement increases with the decrease of the particle size of waste.

4. A particle size of less than 100 µm exhibits a pozzolanic behavior, which favors the improvement of the compressive strength of concrete mixtures.
5. The surface and the angular shape of glass waste affect the workability of concrete.
6. The addition of glass powder in concrete as a partial replacement of the cement fills voids and reduces porosity, which leads to an increase in the flexural strength and the resistance to the penetration of chloride ions.
7. The chemical composition of glass is similar to clay, allowing glass to be used in cement production as a raw material without changing the physical and chemical properties of the cement.

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References

Abdallah S and Fan M (2014) Characteristics of concrete with waste glass as fine aggregate replacement. *International Journal of Engineering and Technical Research* 2: 11–17.

Adaway M and Wang Y (2015) Recycled glass as a partial replacement for fine aggregate in structural concrete – effects on compressive strength. *Electronic Journal of Structural Engineering* 14: 116–122.

Afshinnia K (2015) *Investigation into mechanisms and mitigation of alkali-silica reaction in sustainable Portland cement concrete containing recycled glass materials*. PhD Thesis, Clemson University, USA.

Aghabaglou AM, Beglarigale A, Yazici H, et al. (2016a) Transport properties and freeze-thaw resistance of mortar mixtures containing recycled concrete and glass aggregates. *European Journal of Environmental and Civil Engineering* 23: 53–69.

Aghabaglou AM, Beglarigale A, Yazici H, et al. (2016b) Microstructural analyses of recycled aggregate-bearing mortar mixture. *ACI Materials Journal* 113: 769–780.

Aghabaglou AM, Beglarigale A, Yazici H, et al. (2018) Comparison of recycled glass and recycled concrete aggregates bearing mortar mixtures exposed to high temperature, abrasion and drying. *Journal of Green Building* 13: 39–59.

Aliabdo AA, Abd Elmoaty AE and Aboshama AY (2016) Utilization of waste glass powder in the production of cement and concrete. *Construction and Building Materials* 124: 866–887.

Arora R (2015) Determination of compressive and flexural strength of concrete using waste glass powder. *International Journal of Engineering Trends and Technology* 19: 150–153.

Bhat P and Rao NB (2014) Influence of glass powder on the properties of concrete. *International Journal of Engineering Trends and Technology* 16: 196–199.

Chen G, Lee H, Young KL, et al. (2002) Glass recycling in cement production-an innovative approach. *Waste Management* 22: 747–753.

Donadkar MU and Solanke SS (2016) Review of e-waste material used in making of concrete. *International Journal of Science Technology & Engineering* 2: 66–69.

Du H and Tan KH (2014) Waste glass powder as cement replacement in concrete. *Journal Advanced Concrete Technology* 12: 468–477.

Dvořák K, Dolák D and Dobrovolný P (2017) The improvement of the pozzolanic properties of recycled glass during the production of blended Portland cements. *Procedia Engineering* 180: 1229–1236.

French Chemical Company (2017) Available at: http://www.societechimiquedefrance.fr/extras/Donnees/mater/verre/texver.htm (accessed 20 December 2017).

Gahoi G and Kansal R (2016) Waste glass powder as a partial replacement of PPC. *International Journal of Science and Research* 5: 1414–1418.

Glas Trösch Holding AG (2013) *Glass and its Applications*. Conseil. Bützberg.

Harish BA, Hanumesh BM, Siddesh TM, et al. (2016) An experimental study on partial replacement of cement by glass powder in concrete. *International Research Journal of Engineering and Technology* 3: 1218–1224.

Hussain G and Verma G (2016) Experimental investigation on glass powder as partial replacement of cement for M-30 concrete. *International Journal of Scientific Research in Science, Engineering and Technology* 2: 846–853.

Ibrahim KI (2017) The effect of using Waste Glass [WG] as partial replacement of sand on concrete. *Journal of Mechanical and Civil Engineering* 14: 41–45.

Ismail ZZ and AL-Hashmi EA (2009) Recycling of waste glass as a partial replacement for fine aggregate in concrete. *Waste Management* 29: 655–659.

Karde AD, Bagwan MI, Gowda MR, et al. (2018) To study properties of concrete using waste glass powder replacement to cement. *International Journal for Scientific Research and Development* 6: 992–996.

Keerio MA, Khoso S, Khan JS, et al. (2017) The effect of waste glass as partial replacement of cement on properties of concrete. *Engineering Science and Technology International Research Journal* 1: 59–63.

Keryou AB and Ibrahim GJ (2014) Effect of using windows waste glass as coarse aggregate on some properties of concrete. *Engineering and Technology Journal* 32: 1519–1529.

Khan FA, Fahad M, Shahzada K, et al. (2015) Utilization of waste glass powder as a partial replacement of cement in concrete. *International Journal of Advanced Structures and Geotechnical Engineering* 4: 181–185.

Kumar P, Ananthayya M and Vijay K (2014) Effect of partial replacement of cement with waste glass powder on the properties of concrete. *International Journal of Structural and Civil Engineering Research* 3: 1–6.

Kumar S and Nagar DB (2017) Effects of waste glass powder on compressive strength of concrete. *International Journal of Trend in Scientific Research and Development* 1: 289–298.

Kumar V and Sood H (2017) Effect of waste glass powder in concrete by partial replacement of cement. *International Journal of Civil Engineering* 4: 13–22.

Lam CS, Poon CS and Chan D (2007) Enhancing the performance of pre-cast concrete blocks by incorporating waste glass-ASR consideration. *Cement and Concrete Composites* 29: 616–625.

Lee G, Ling TC, Wong YL, et al. (2011) Effects of crushed glass cullet sizes casting methods and pozzolanic materials on ASR of concrete blocks. *Construction and Building Materials* 25: 2611–2618.

Liaqat M, Shah ML and Baig MA (2018) Effect of waste glass as partial replacement for coarse aggregate in concrete. *International Journal of Technical Innovation in Modern Engineering & Science* 4: 609–619.

Limbachiya M, Meddah MS and Fotiadou S (2012) Performance of granulated foam glass concrete. *Construction and Building Materials* 28: 759–768.

Lu JX, Yan X, He P, et al. (2019a) Sustainable design of pervious concrete using waste glass and recycled concrete aggregate. *Journal of Cleaner Production* 234: 1102–1112.

Lu JX, Zheng H, Yang S, et al. (2019b) Co-utilization of waste glass cullet and glass powder in precast concrete products. *Construction and Building Materials* 223: 210–220.

Mageswari M and Vidivelli DB (2010) The use of sheet glass powder as fine aggregate replacement in concrete. *The Open Civil Engineering Journal* 4: 65–71.

Meena MK, Gupta J and Nagar B (2018) Performance of concrete by using powder- an experimental study. *International Research Journal of Engineering and Technology* 5: 840–844.

Mounika M, Lalith BV, Rao VR, et al. (2017) Experimental study on strength parameters of concrete by partial replacement of cement recycled crushed glass powder. *International Journal of Civil Engineering and Technology* 8: 444–450.

Mwizerwa F and Garg A (2017) Experimental study on effects on properties of concrete with different colours of glass powder as a partial replacement of cement. *International Journal of Civil Engineering and Technology* 8: 1639–1644.

Nassar RUD and Soroushian P (2012) Strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement. *Construction and Building Materials* 29: 368–377.

Nwofor TC and Ukpaka C (2017) Predictive models for compressive strength of concrete produced with waste glass as replacement for aggregates. *International Journal of Civil Engineering* 4: 31–34.

Olofinnade OM, Ndambuki JM, Ede AN, et al. (2017) Application of waste glass powder as a partial cement substitute towards more sustainable concrete production. *International Journal of Engineering Research in Africa* 31: 77–93.

Olutoge FA (2016) Effect of waste glass powder (WGP) on the mechanical properties of concrete. *American Journal of Engineering Research* 11: 213–220.

Park SB, Lee BC and Kim JH (2004) Studies on mechanical properties of concrete containing waste glass aggregate. *Cement and Concrete Research* 34: 2181–2189.

Polley C, Cramer SM and De La Cruz RV (1998) Potential for using waste glass in Portland cement concrete. *Journal of Materials in Civil Engineering* 10: 210–219.

Prudhvi K, Saiprasad K, Reddy KS, et al. (2016) Laboratory study on compressive strength of concrete with glass powder as partial replacement of cement. *Journal of Emerging Technologies and Innovative Research* 3: 272–277.

Rahim NL, Amat RC, Ibrahim NM, et al. (2015) Utilization of recycled glass waste as partial replacement of fine aggregate in concrete production. *Materials Science Forum* 803: 16–20.

Rahman S and Uddin MN (2018) Experimental investigation of concrete with glass powder as partial replacement of cement. *Civil Engineering and Architecture* 6: 149–154.

Rajitha D, Srinivas V and Nawaz MZ (2017) Experimental study on partial replacement of fine and coarse aggregate with waste glass. *International Journal of Civil Engineering and Technology* 8: 1521–1525.

Rokdey MS, Dhawale GD and Wagh MS (2018) Partial replacement of cement by using refused glass powder in concrete for strengthening. *International Journal of Scientific and Engineering Research* 5: 77–82.

Romero D, James J, Mora R, et al. (2013) Study on the mechanical and environmental properties of concrete containing cathode ray tube glass aggregate. *Waste Management* 33: 1659–1666.

Saand A, Keerio MA, Juj R, et al. (2017) Utilization of waste glass as partial replacement of fine aggregate in concrete. *Engineering Science and Technology International Research Journal* 1: 28–31.

Saccani A and Bignozzi MC (2010) ASR expansion behavior of recycled glass fine aggregates in concrete. *Cement and Concrete Research* 40: 531–536.

Sakale R, Jain S and Singh S (2016) Experimental investigation on strength of glass powder replacement by cement in concrete with different dosages. *International Journal of Science Technology and Engineering* 2: 76–86.

Shaikh S, Bachhav SS and Kshirsagar D (2015) Effective utilisation of waste glass in concrete. *International Journal of Engineering Research and Applications* 5: 1–4.

Shanmuguanathan N, Gokila R, Parameshwari T, et al. (2017) Study and experimental investigation of partial replacement of waste glass powder as cement in concrete. *International Journal of Engineering Trends and Technology* 8: 1–9.

Shayan A and Xu A (2006) Performance of glass powder as a pozzolanic material in concrete: A field trial on concrete slabs. *Cement and Concrete Research* 36: 457–468.

Shekhawat BS and Aggarwal V (2014) Investigation of strength and durability parameters of glass powder based concrete. *International Journal of Engineering Research and Technology* 3: 333–338.

Sibelco Green Solutions (2019) Promoting glass: Your future our talent. Available at: https://www.sibelco.com/wp-content/uploads/Sibelco-Green-Solutions-Brochure-FR.pdf?x17555 (accessed 1 September 2019).

Sreenivasulu S and Prudhvi K (2016) Suitability of waste glass powder as pozzolanic material in concrete. *International Journal of Professional Engineering Studies* 7: 131–148.

Taha B and Nounu G (2008) Properties of concrete contains mixed colour waste recycled glass as sand and cement replacement. *Construction and Building Materials* 22: 713–720.

Vandhiyan R, Ramkumar R and Ramya R (2013) Experimental study on replacement of cement by glass powder. *International Journal of Engineering Research and Technology* 2: 234–238.

Xie Z and Xi Y (2002) Use of recycled glass as a raw material in the manufacture of Portland cement. *Materials and Structure* 35: 510–515.

Zakir M, Qadri SI and Siwach ER (2016) Experimental evaluation of waste glass powder as a partial replacement of cement in concrete. *International Journal of Recent Innovation in Engineering and Research* 1: 71–75.