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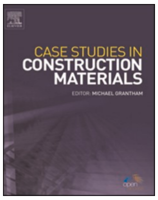

Effect of recycled waste glass on the properties of high-performance concrete: A critical review

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ABSTRACT

Solid waste disposal is one of the major environmental concerns. Disposal of waste glass into open areas and landfills is one of the major threats that pollutes the environment in addition to the cases of health hazards around the world. Recycling the discarded glass as a sustainable construction material have received an increasing attention in the construction industry as it may mitigate the greenhouse emissions and potential environmental risks. This paper presents a brief review on the fresh, mechanical and durability properties of normal and high-performance concrete containing waste glass aggregates (WGA). The size, type, replacement ratio of the WGA, in addition to the mixing and curing methods of concrete significantly affects the mechanical and durability characteristics. The concrete containing powdered glass exhibited superior durability properties on account of the refined pore structure and densified microstructure. The findings exhibited that waste glass can be potentially utilised as coarse and fine aggregates in concrete production, along with the advanced recommendations for further studies.

1. Introduction

To support the earth's sustainability, it is critical that a circular economy be developed in the iconstruction sector by innovation and research [1]. Currently, concrete is considered as the most used construction supply throughout the world [2,3]. However, the process of obtaining aggregates and producing cement has created significant environmental hazards such as high production energy and excessive CO_2 emissions [4–21]. Both in the present and future, modern approaches are being implemented to cut down ienvironmental pollution by valorising, recycling, and eco-establishing iconcrete waste in the set of cement or aggregates to depress disastrous impacts on nature [22,23].

Glass is one of the most essential and commonly used materials around the globe. After the end use, the waste glass can be screened, cleaned and re-melted for the manufacture of new glass products. However, the impurities, multiple type, colour, and lack of screening facilities makes a barrier to this re-use, and they usually end up in stockpiles or landfills [6,24]. Glass wastes (GW) is an environmental hazard in many occupied landfill spaces all over the world [25–33]. This is because of the non-biodegradable nature of glass waste, and the lack of extended areas for the new ↱landfills in highly populated cities. Therefore, using these wastes is a better option to ↱maintain

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natural resources by reducing the area of the landfill and saving money and ↱energy [34]. The need for large amounts, low quality, and wide sites of iconstruction requirements made the concrete industry one of the main methods to solve the ienvironmental ↱effects due to the accumulation of the waste glass↱ [35]. The recent studies showed that the iconcrete industry has become the one of the main consumers of various industrial by-products [36,37]. The iconstruction industry provides one of the most attractive options in the use of recycled imaterials due to its large consumption of raw imaterials and high iconstruction work rates. Also, the debris from construction and demolition is responsible for a high participation rate in the generation of waste, with concrete being a major contributor in this category [38].

Esmaeili and AL-Mwanes [39] investigated the Ultra-High-Performance Glass Concrete (UHPGC) from the glass Powder as a partial cement replacement in different replacement levels [40,41]. They showed that the UHPGC produced has high mechanical properties as compressive, tensile, and bending strength [42–44]. Furthermore, the GP reduces the possibility of chloride-induced steel corrosion and reduces the penetrability of chloride-ion in concrete. Zhang et al. [45] used a nano-SiO2 (NS) particles to produce a high performance concrete (HPC). The results show that the incorporation of Nano SiO2 considerably enhance the durability and mechanical properties of HPC. In this respect, this paper aims to investigate the properties of recycled waste glass (RWG) as aggregate and study the chemical composition and the physical properties of RWG. This study also aims to investigate the fresh and hardened properties of normal an HPC. Moreover, the study aims to highlight several important characteristics such as workability, density, icompressive strength, flexural strength, splitting itensile strength, and the relationship between the properties, which is shown in a variety of tables and figures.

1.1. Waste glass

Various investigations were carried out on the utilisation of glass wastes as aggregates and partial replacement to Portland cement in cementitious composites. It can also be utilised as a precursor in alkali activated composites on account of the high silica content. The use of waste glass in cementitious composites reduces the energy consumption, natural raw materials and CO_2 emission [27,46]. Ali and Al-Tersawy [47] utilised recycled glass waste with fine particle size in white colour, as fine aggregate to obtain the Self-Compacting Concrete (SCC). Poutos et al. [48] examined the influence of high and low temperatures, 60 ^{o}C and 20 ^{o}C, respectively, on concrete with glass aggregates and observed that it had high thermal stability because of having low thermal conductivity and specific heat compared to rock aggregates and concrete. This concrete is perfect for constructing buildings that consider thermal stability as the main important and for casting in the cold climate [49,50]. Table 1 illustrates the results of several the previous studies of different replacement levels of glass waste as concrete materials.

Generally, glass waste can be reused/recycled absolutely and substantially with maintaining its physical properties and chemical composition [64–66]. Nevertheless, the mixed colour of broken WG makes the recycling procedure unfeasible and extremely costly since these materials may result in a deviation in their chemical compositions [67]. Contaminants and impurities that can be establish in the WG combined with the mixed colour may influence the chemical composition of the manufactured new glass [67,68]. The rate of reusing/recycling of WG is very low in the entire world, and it is mostly focused on the packaging and container areas [54]. In the USA alone, 11.5 million tons of WG has been generated with 27% as a recycling rate by 2010 [69]. However, the whole WG in the European countries was expected to be 4.1 million tons in 2008 about 60% as a recycling rate [70]. In Sweden, about 44,000 tons of mixed colour and 195,000 tons of isolated colour WG were generated in 2010 with 93% as a recycle rate for the insulated colour WG [71]. Tables 2 and 3 displays the amount of WG and its recycling rate for some countries.

Thus, the management of waste glass can be considered as one of the main challenges that faced the researchers and scientists over the world because of the lack in open areas and landfills, the low recycling rate, and the absence of sufficient spaces for open area [75,76].

Table 1
Type and optimum replacement level of WG in concrete.

Ref.	Replacement level %	Particle size	Type of glass waste	Optimum glass waste %
[51]	0–60	4–16 mm	Bottles	23
[52]	0–20	≤ 4 mm for fine agg. > 4 mm for coarse agg.	Building and car windows glass	20
[53]	100	Coarse	Quartz, fibreglass, and opal.	Not mentioned
[54]	0–100	0.15–4.75 mm	Bottles	Less than 25
[55]	0–20	0.15–4.75 mm	Container and flat glass	20
[56]	100	≤ 19 mm	Bottles	Not mentioned
[57]	0–100	4.75–0.15 mm	Bottles	20
[58]	0–70	36–100 mm	Container	70
[59]	0–70	Less than 5 mm	Bottles	Less than 30
[60]	0–20	0.15–9.5 mm	Building glass	20
[61]	0–50	≤ 4.75 mm	Sheet glass	10
[62]	0–100	0.125–2.00 mm	Bottles	30
[48]	0–100	0.15–9.5 mm	Cullet glass	Not mentioned
[63]	0–100	≤ 4.75 mm for fine agg. > 4.75 mm for coarse ag.	Bottles	10

Table 2
The amount of WG and its recycling rate in some countries.

Ref.	Country	WG (tons)	% of recycling rate
[72]	USA	11,500,000	27
[51]	Germany	3,200,000	94
[73]	Australia	1,000,000	30
[74]	Taiwan	600, 000	20
[48]	UK	587,000	65
[75]	Portugal	493,000	25
[71]	Sweden	195,000	93
[51]	Turkey	120,000	66
[67]	Canada	116,000	68
[54]	Singapore	72,800	29
[60]	Jordan	35	0

Table 3
Summary of the physical properties of natural and waste glass aggregate [91].

Physical properties	Coarse glass aggregate	Natural aggregate	
		Sand	Gravel
Water absorption %	0.36	0.42	0.25
Specific gravity	1.93	2.62	2.70
Fineness Modulus	2.73	2.69	2.85

1.2. Research significance and economic benefits

Over the past few years, several researchers' scholarly efforts were directed towards the use of glass waste as cement and aggregates to produce concrete in an attempt to address the environmental regulations and the high disposal cost of waste glass [51,77–81]. Ismail and Al-Hashmi, [55] reported that WG generates dangerous environmental problems, mostly owing to the variation of WG streams. The concrete industry used WG to decrease the solid wastes and recycle as much as possible to mitigate environmental problems. Sobolev et al., [82] reported that all materials have a limited life in a certain form and essential to be recycled/reused to another thing to avoid environmental hazards. The reuse of waste glasses in concrete and cement manufacture has many advantages as reported by Shi and Zheng [83]:

1. Reducing the cost related disposal of glass waste into landfills, which are expected to increase because of the landfill tax.
2. Protecting the environment by maintaining a high quantity of main raw materials on earth.
3. Utilising landfill sites for building and construction instead of using them as dumping sites.
4. Reducing the emission of CO_2 and energy consumption.
5. Reducing the air pollution resulting from the production cement clinker when ground glass powder (GP) is used instead of cement.
6. Growing public awareness about the waste problems and advantages of reusing.

The economic benefits from the reused/ recycled WG in concrete and cement manufacture may also be quite important. In the USA, the tipping fee of landfill typically ranged between $40 and 100/ton, cost the supplementary cementing materials (SCM) around $30–80/ton, and the aggregates of concrete cost around $5–15/ton. On the other hand, the grinding cost possibly ranged between $15 and 30/ton. This review paper about using WG in concrete as cement/ sand/ gravel replacement provides significant advantages,

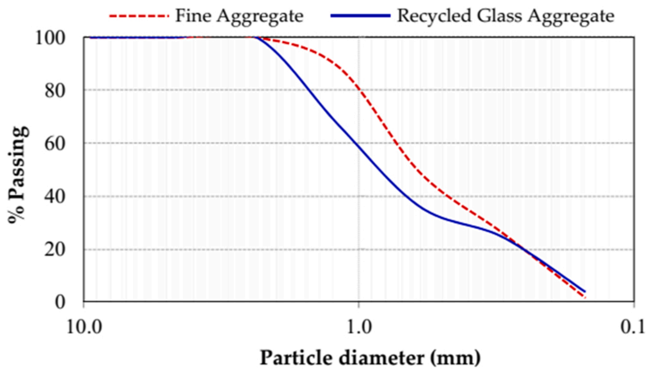


Fig. 1. Particle size distribution of RGA and fine aggregate [85].

economically and environmentally. Recycling of WG constitutes the main problem for municipalities over the world, and this problem can be solved in many beneficial ways such as the re-utilisation of WG as cement/sand/gravel replacement in sustainable concrete. Besides, the re-utilisation WG in the construction industry can reduce the need for natural resources and conserve precious materials for future generations. Therefore, the use of WG in concrete production can be considered a significant factor in improving both ↱economic and environmental aspects.↱

2. Waste glass as construction materials

2.1. Waste glass as fine aggregate

Wang [84] investigated the effect of the incorporation of glass as fine aggregates in three different mixtures to achieve strengths, 21 MPa, 28 MPa, and 35 MPa, at a replacement level ranging from 0% to 80%. The results showed that icompressive istrength decreased significantly for the replacement level of more than 20%. The particle size of glass waste used as fine aggregate by Tuaum et al. [85] was somehow less than the fine aggregate as in Fig. 1.

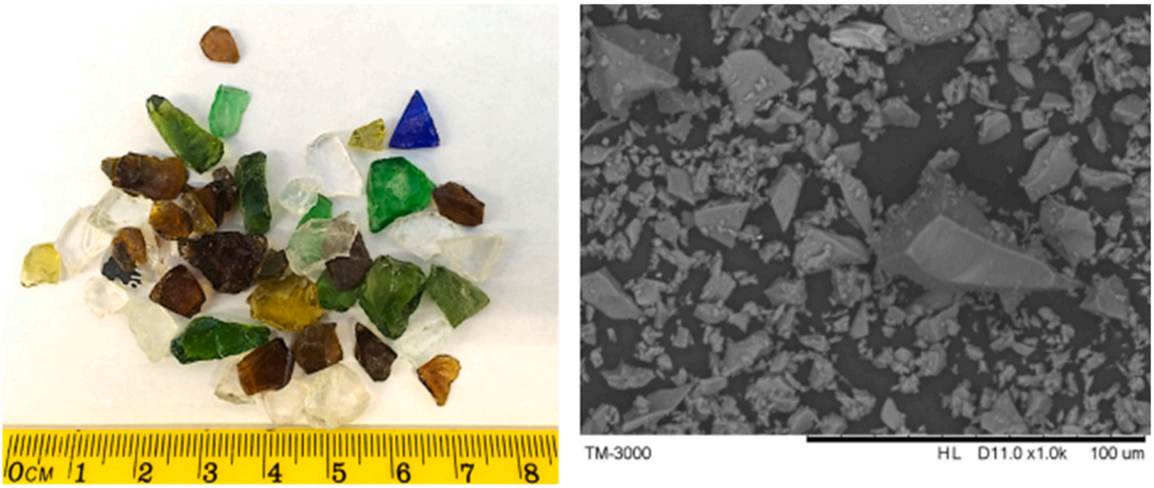
Abdallah and Fan [86] studied the properties of concrete comprising finer crushed glass used as fine aggregate in the best ratio to achieve the highest icompressive istrength of concrete blocks, and the influence of GA replacement level on the expansion rate resulted from the Alkali-silica reaction (ASR). Borhan et al. [87] studied the properties of GA to produce concrete reinforced with chopped basalt fibre. Fine aggregate was replaced by the recycled mixed colour glass at different replacement levels (20%, 40%, and 60% by total weight) with various replacement levels of fibre (0%, 0.1%, 0.3%, and 0.5%). The results showed that there is an insignificant decrease in compressive and tensile strength due to increasing GA to more than 20%. Sikora et al. [88] concluded that waste glass (WG) can be replaced with normal fine aggregate in cement concrete without a decrease in the performance of specimens. Furthermore, the use of WG as fine aggregates resulted in a substantial reduction in thermal conductivity and a reduction in the sorptivity of cement mortars.

2.2. Glass waste as coarse aggregate

Topçu and Canbaz [51] investigated the effect of using GA to replace 4–6 mm coarse aggregates at replacement levels between 0% and 60%. The outcomes showed that the increase in GA content led to reducing the air content, slump value, and density. Afshinnia and Rangaraju [89] used WG as a cement replacement material and as a coarse aggregate at different replacement levels. They concluded that the increased GA content led to a reduction in the concrete strength. The use of WG of sizes 4–16 mm as in Fig. 2 as coarse aggregate replacement in concrete production was investigated with replacement levels between 0% and 60% [51]. The results showed that there was no significant influence on the concrete workability with a small decrease in its strength. Extremely porous particles of WG mixed with fine ground glass (GG) have been utilised also to make LWCs [90].

In general, based on the results, regular weight concrete with further estates in hardened states can be formed with waste glass crushed to coarse aggregate sizes to replace ordinary coarse aggregate in the same concrete blend up to 25% [91].

Alao et al. [92] examined the impact rates of both granite and WG, which are 33.85 and 30.42, respectively that occurred between the fields of 30–35. The best achievement on the concrete properties was achieved due to replace the coarse aggregates by 25% of level of WG.



a) Coarse GA

b) SEM image of glass powder

Fig. 2. Glass waste [89].

3. Physical properties and chemical composition of glass waste

Park et al. [59] carried out an analysis of GW using SEM and EDX to determine the morphology of the grain shape and elemental composition. The results revealed that silica oxide (SiO_2) recorded the highest value in the chemical composition test (71.30–73.04%), followed by Na_2O and K_2O. A small change was observed in the chemical composition of different WG based on their colours. However, the usual grain shape was angular of the WG colour [78]. The chemical composition and physical properties are illustrated in Table 4 and Table 5, respectively.

According to a study by Park et al. [59], they reported that the crushed WG has specific gravity between 2.48% and 2.52%, the fineness modulus between 3.46% and 3.49%, the absolute volume between 60.90% and 62.60%, water absorption between 0.40% and 0.43%, and unit weight more than 1500 kg/m^3. Nevertheless, the crushed waste glass aggregate (CWGA) has an angular and edged grain shape and comprises a substantial amount of particles higher than 0.6 mm, which can affect the workability directly or indirectly.

4. Properties of concrete containing GW

4.1. Properties of fresh concrete

4.1.1. Workability

Previous studies concluded that integrating WG as fine aggregate in concrete led to reducing the slump values owing to the geometry and harsh texture of WG [54,55,89,103]. On the other hand, other researchers [94,104,105] stated that the concrete containing WG has increased the slump value, and this resulted in improving workability. This can be attributed to the influence of the smooth surface of the WG surface, while some researchers [47,106] reported that the slump value stayed similar in both concrete statuses with and without WG. Castro and Brito [52] proved that the workability of concrete with WG has been significantly influenced by the particle size, resulting in an increase in the water-cement ratio for the concrete mix with 20% WG as fine aggregate. Malik et al. [93] stated that the increase of WG in the concrete mix is the main reason for the increase in the workability of concrete.

Afshinnia and Rangaraju [89] investigated the combined influence of crushed GA and ground GP on the workability of cement mortar, they observed that the 20% replacement level of the combined effect has a higher slump value compared to the reference concrete as shown in Fig. 3.

Furthermore, Taha and Nounu [107] detected that the water absorption and smooth surface of WG particles led to a decrease in the cohesive force in the concrete mix, which resulted in bleeding and segregation of the concrete. Instead, the decrease cohesion between the cement paste and WG aggregates was due to their smooth surfaces [47,63] and the nature of WG [63], which led to an increase of the slump value. The slump of concrete containing waste glass particles shows different values. Some researchers noted reduction, a few noted increments, while others noted similar workability for the concrete with and without WG particles. The variation in particle size, water to cement ratios and the percentage of replacements can be the reason for this variation.

4.1.2. Density

The incorporation of WG into concrete resulted in a clear loss in the concrete density. This can be qualified to the lower specific gravity value of WG compared to fine aggregate [52]. The incorporation of fine WGA in concrete mixtures resulted in decreasing unit weight and concrete density [55,60,86,87,107,108]. Nevertheless, Adaway and Wang [109] stated that concrete containing 15% crushed WG acquired a fresh density more than that of the reference concrete, whereas all other crushed WG samples with replacement levels of more than 15% achieved lower density than the reference concrete, the increase replacement fine aggregate by the WG resulted in decreasing the density of concrete. The decrease in concrete density can be qualified to the difference in the specific gravity between WG and natural fine aggregate [52,87,107].

In a study by Afshinnia and Rangaraju [89], they reported that the fresh density of concrete mix containing WG as aggregates or

Table 4
The chemical composition of WG.

Ref.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	P_2O_5	LOI
[85]	81.98	0.86	0.23	10.67	5.63		0.23	0.19	0.12	–
[93]	70.4	1.9	1.2	–	10.3	14.0	0.4	–	–	–
[94]	70.50	2.60	–	5.70	2.90	16.30	1.20	0.20	–	–
[55]	67.72	2.5	0.9	6.90	6	9.6	1.15	0.17	–	–
[59]	71.30	2.18	0.596	8.18	4	12.0	1.07	0.053	–	–
[95]	70.22	1.64	0.52	11.13		15.29	–	–	–	0.80
[96]	72.3	1.04	0.17	8.61	3.89	13.31	0.52	–	0.05	–
[57]	47.5	2.25	1.076	10.63	o.42	12.74	1.15	0.2	0.05	–
[47]	67.72	2.9	0.5	6.90	6	10.1	0.65	0.17	–	–
[54]	71.22	1.63	0.32	10.79	1.57	13.12	0.64	–	–	–
[89]	69.6	2.2	0.9	11.6	0.4	12.3	–	–	–	–
[82]	72.61	1.38	0.48	11.70	0.56	13.12	0.38	0.09	–	0.22
[97]	71.91	–	0.01	14.1	1.50	9.58	0.53	0.22	0.06	–
[98]	68.36	1.67	0.64	10.93	0.7	11.52	0.41	0.11	0.13	5.42

Table 5
Physical properties of glass waste.

Ref.	Specific gravity	Water absorption	Fineness modulus	Bulk density	Density kg/m^3
[85]	2.32	–	2.70	1.545	–
[52]	–	0.03	–	–	2512
[55]	2.19	0.39	2.36	1.672	–
[59]	2.50–2.52	0.40–0.43	3.48–3.49	1.543 – 1.559	–
[95]	2.42	0.4	–	–	2420
[47]	2.2	0.57	–	1.34	–
[99]	–	0.10	3.18	–	2490
[100]	–	0.00	3.34	–	3000
[101]	2.50	0.002	–	–	–
[102]	2.45	0.36	–	1.36	–

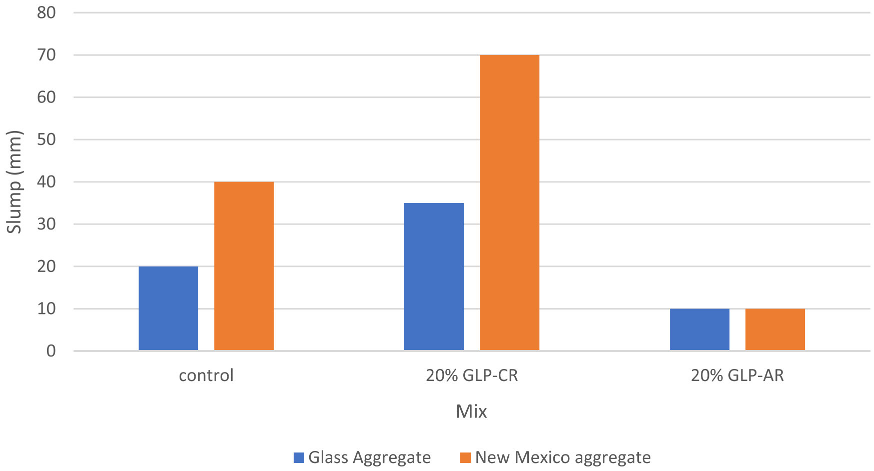


Fig. 3. Slump of the concrete comprising GP as aggregate or cement replacement [89].

glass powder (GP) as replacement of cement as presented in Fig. 4, the unit weight of the concrete comprising GA was lower than the concrete mix comprising natural aggregate. For example, the unit weight of the concrete mixt comprising natural fine aggregate and GA was 2321 and 2286 kg/m^3, respectively. There is a slightly lower density in concrete comprising WA, which was qualified to the specific gravity of GA, which is lower than that of natural fine aggregates. Likewise, as shown in Fig. 6, it is clear that regardless of the aggregate type (natural aggregate or GA), the use of glass powder (GP) as cement replacement resulted in reducing the concrete density, whereas the use of GP as an aggregate replacement didn't show any effect on the unit weight of the concrete mix.

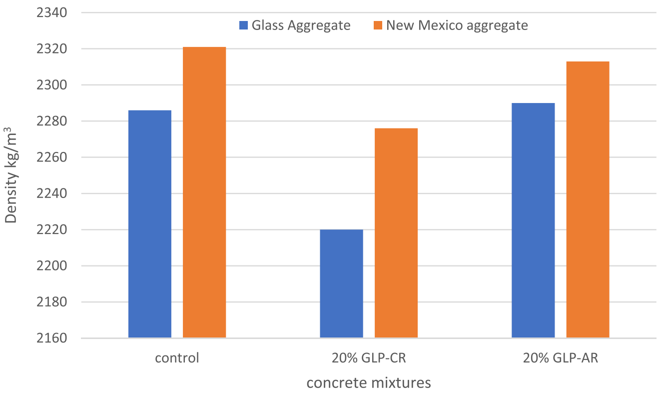


Fig. 4. Density of concrete comprising GP as cement or aggregate replacement [89].

4.2. Mechanical properties

4.2.1. Compressive strength

Many experimental studies were conducted to determine the icompressive istrength of concrete comprising recycle glass aggregates (RGA) as aggregate compared with concrete comprising natural aggregates [47,54,89,103,106,110]. The experimental test results by Tuaum et al. [85] showed the icompressive istrength of SCM mixtures at 3, 7, 14, and 28 curing days as illustrated in Fig. 5.

Based on the results, the combination of recycled glass aggregates (RGA) as a fine aggregate replacement in SCM ordinarily reduced compressive strength comparative to control concrete nevertheless of the age and replacement levels. This decrease might be qualified to the lower toughness strength compared to the smooth grain surface, fracture, as well as the weak interfacial adhesion among the GA and cement paste mix [54,105,106,111].

Tan and Du [54] reported the 7 and 28 day-compressive istrengths of GA mortar as shown in Fig. 6. The utilisation of GA resulted in reducing icompressive istrength because of the sharper edges and smooth surface of GA, which led to a weaker bond strength between the cement matrix and GA at the Interfacial Transition Zone (ITZ).

Guo at al. [112] reported that replacement levels and the particle size of glass illustrated significant effects on the compressive istrength. Most researchers proved that the compressive strength improved when used waste glass as partial cement replacement. A particle size up to 40 mm of glass with soda-lime can be used to get an ultra-high-performance concrete (UHPC). Shao et al. [113] concluded that WG with finer particle size up 38 mm, has a clear pozzolanic reaction. The development of compressive istrength at 3, 7, 28, and 90 days, of the concrete mix containing 30% GP as cement replacement with particle size 38-mm were 91%, 84%, 96%, and 108%, respectively. Fig. 7 shows the compressive istrength of concrete at different replacement levels of GA.

From Fig. 8, it can be concluded that it's better to use GA as fine aggregate with a replacement-level ↱not exceeded to 20% to get better performance concrete↱. Chen et al. [81] investigated the compressive istrength of concrete containing GA as natural fine aggregates replacement, it is observed that the inclusion of GA considerably increased the compressive istrength of concrete. Furthermore, Lee et al. [108] studied the compressive istrength of concrete blocks with WGA in different particle sizes. They observed that the 28 days-compressive istrength of concrete comprising (<0.60 mm) WG achieved ultra-high compressive istrength. Jubeh et al. [114] mentioned that the icompressive istrength of glass mortar increased with the increase replacement levels of cement by the glass powder (GP) and the curing age increasing from 7 to 28 days, it is can be classified as high-performance concrete [115]. An increment in the mechanical properties could be noted when the WG is used to partially replace the binder or as the fine aggregates, while the replacement for coarse aggregates leads to a reduction in the mechanical properties. The higher strength may be attributed to the higher aluminium and silica dissolution resulting to an efficient Pozzolanic reaction and curing age.

4.2.2. Flexural istrength

Many researchers, including Abdallah and Fan [86], Ismail and Al-Hashmi [60], Turgut and Yahlizade [95], and Batayneh et al. [60] stated that the incorporation of finely CWG aggregates resulted to an increase in the **i**flexural **i**strength of concrete; but others stated that the incorporation CWG in the concrete mix led to reducing the flexural and icompressive istrengths. On the other hand, Ali and Al-Tersawy [47] stated that the **i**flexural **i**strength of concrete containing WGA was lower than that of the reference concrete. Taha and Nounu [96], Park et al. [59], Ismail and Al-Hashmi [55] observed that increasing GA as an aggregate replacement resulted in a reduction in the **i**flexural **i**strength of concrete. Tan and Du [54] proved that the decrease in the **i**flexural **i**strength of concrete was evident for GA content above 25%, particularly for the clear glass type. However, other types of GA, the 28 day-flexural **i**strength was reduced by less than 10% if the GA content is lower than 75% as shown in Fig. 8. The 28 day-flexural strengths of cement mortar with 100% green, brown, clear, and mixed GA were 90%, 76%, 70%, 76%, respectively of natural sand mortar.

Yasouj et al. [116] reported that the highest effect on the **i**flexural **i**strength growing at 7 days of age and waste glass powder (WGP), which has the highest effect on the flexural strength, decreased at same age. The mixture of basalt fibre (BF) and carbon nanotube (CNT) in the mix design has too shown the highest **i**flexural **i**strength at 7 days. Fig. 9 displays the relationship between **i**flexural **i**strength and compressive strength compared to the volume of WGA, as well as the relationship equation.

Topcu and Canbaz [51] reported that **i**flexural **i**strength changed inconsistently from 3.00 to 5.27 MPa, and WG increased this

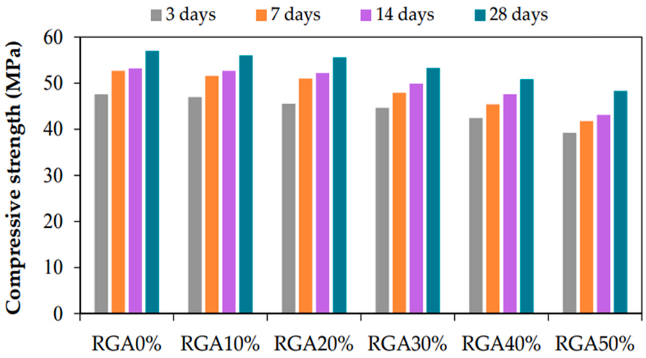


Fig. 5. Compressive strength of concrete comprising RGA [85].

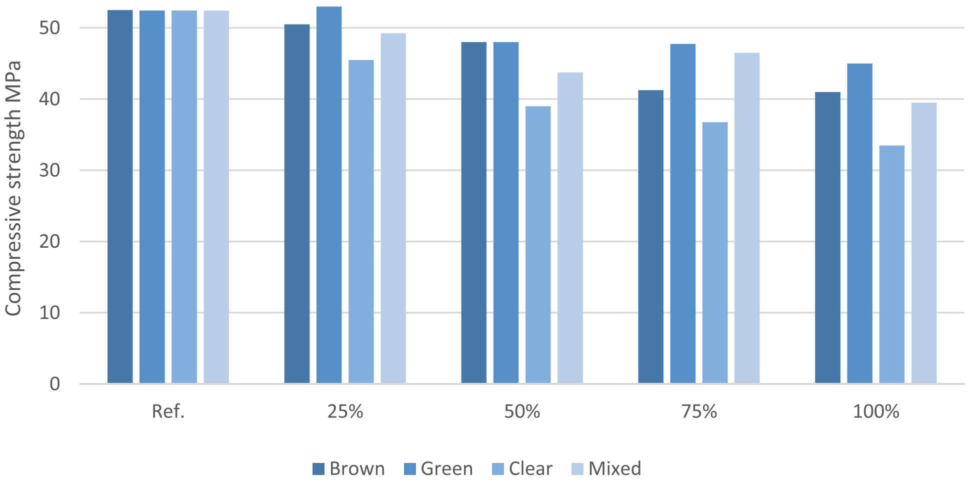


Fig. 6. Compressive istrength of GA and cement mortar [54].

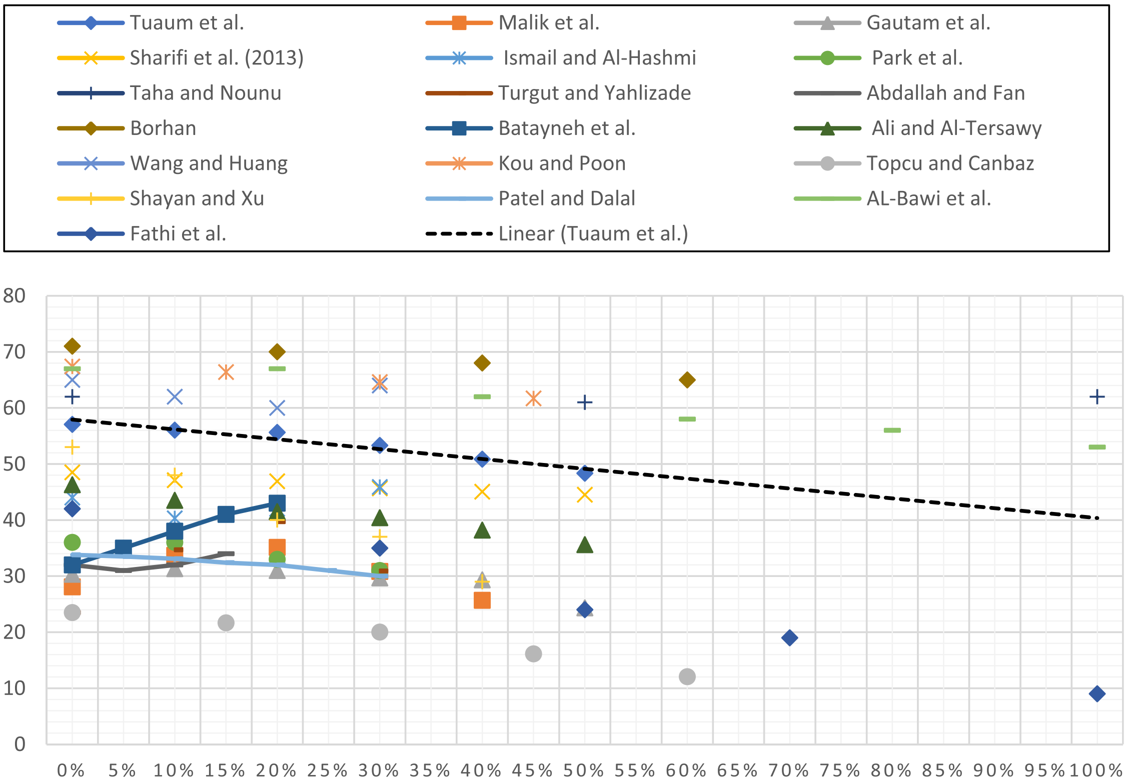


Fig. 7. The compressive strength of concrete at various replacement levels of WG.

level, reduced up to 2%. Sobolev et al. [117] studied the influence of WGA on the concrete properties, it was found that the 28 day-flexural strength of WG in cement mortar was placed in a quite narrow range between (6.9 and 7.3 MPa). Figs. 10 and 11 shows the flexural strength of WGA-reinforced concrete obtained from previous studies.

4.2.3. Splitting tensile strength

The results obtained from the previous studies showed the effect of WGA as a fine aggregate replacement on the splitting tensile istrength of concrete. Malik et al. [93], Ali and Al-Tersawy [47], and Park et al. [59] investigated the splitting tensile istrengths of concrete containing WGA, and they reported that all the concrete samples had a lower flexural istrength than that of the reference sample. However, Batayneh et al. [60], Ali and Al-Tersawy [47], Malik et al. [93], Taha and Nounu [96], and Park et al. [59] observed

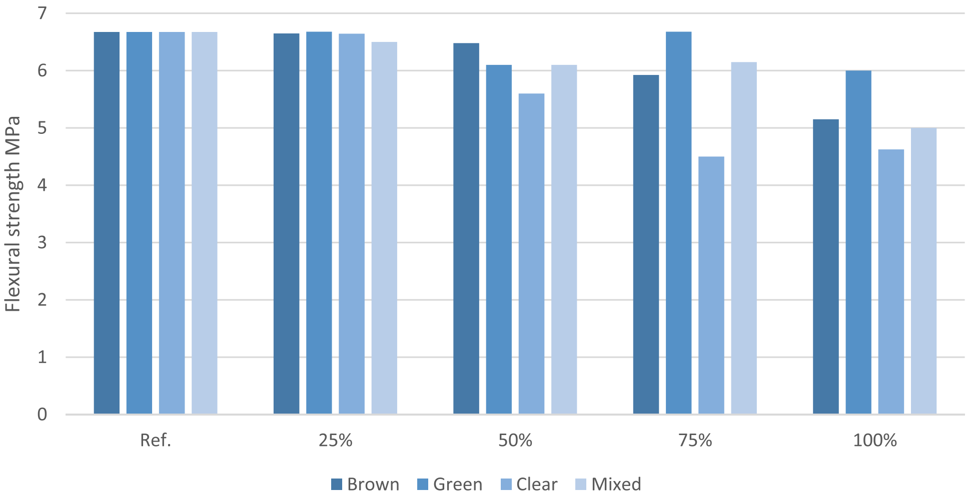


Fig. 8. Flexural istrength of glass sand mortar at 28 days [54].

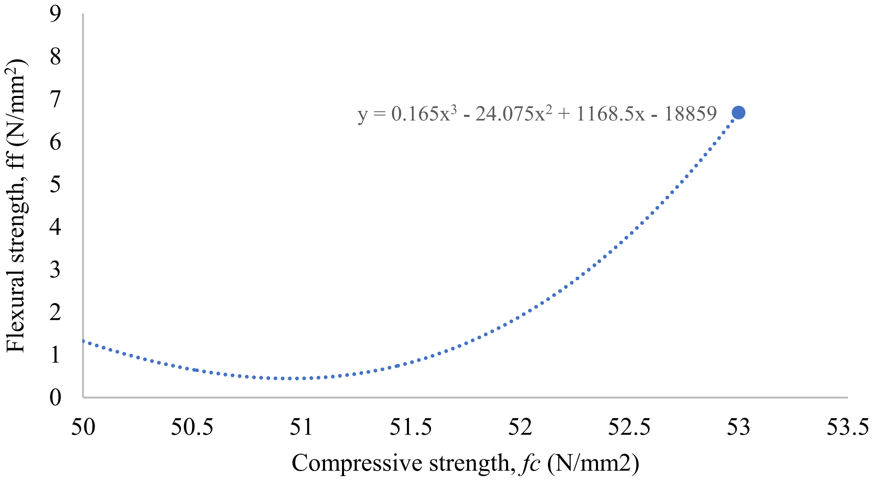


Fig. 9. The relation between Flexural istrength and Compressive istrength compared to the volume of WGA.

that isplitting tensile istrength decreased due to increasing the proportions of crushed WG in the concrete mixtures. Wang [84] stated that concrete WG containing 20% and 40% has a compressive istrength of 35 and 21 MPa, respectively and isplitting tensile istrengths were more than those of the reference concrete sample.

The test of 28 day-splitting tensile istrengths of GA mortars was conducted by Tan and Du [54] as shown in Fig. 12. The GA mortars showed isplitting tensile istrengths changing from 2.85 to 3.95 MPa. By 25% of clear, brown, green, and mixed GA, the tensile strength of mortar presented a small increase. Nevertheless, the high replacement level of fine aggregate by GA decreased tensile strength regardless of the GA' colour. In the same concrete mix, the colour of GA has a significant effect on the splitting tensile strength [54,96, 118], as ↱shown in Fig. 13.↱ On the other hand, the increase in the splitting tensile strength may be attributed to the increase in the pozzolanic reaction, which results in the production of denser CSH [119–121].

Fig. 13 demonstrations the relationship between isplitting tensile istrength and Compressive istrength compared to the volume of WGA. The relationship equation is shown in the figure.

Afshinnia and Rangaraju [89] revealed that in concrete samples comprising GA, the use of GP as an aggregate replacement could improve the splitting itensile strength at 28 curing days, whereas the use of GP as cement replacement exhibited no positive effect on the isplitting tensile strength compared to the reference concrete sample. Fig. 14 illustrates the isplitting tensile istrength values of concrete comprising WG conducted by previous studies. Overall, the use of GP as concrete materials could improve the overall concrete performance due to the activation and curing conditions [115].

4.2.4. *Modulus of elasticity*

The modulus of elasticity (MOE) of concrete is a function of the normal-density and cementitious matrix, lightweight aggregates,

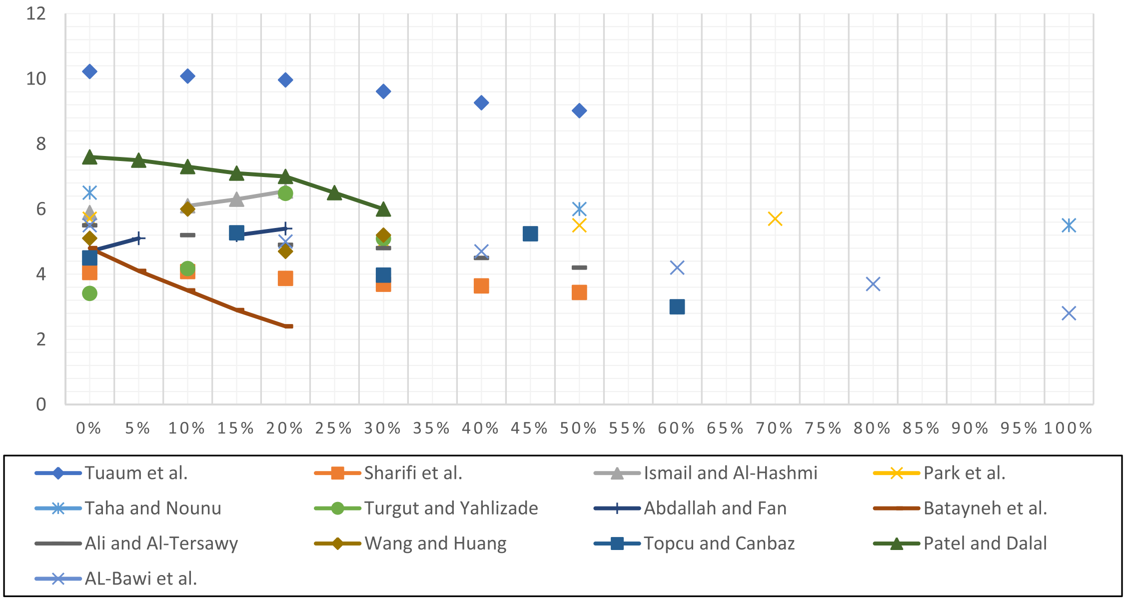


Fig. 10. Flexural strength values of concrete comprising WGA by the previous studies.

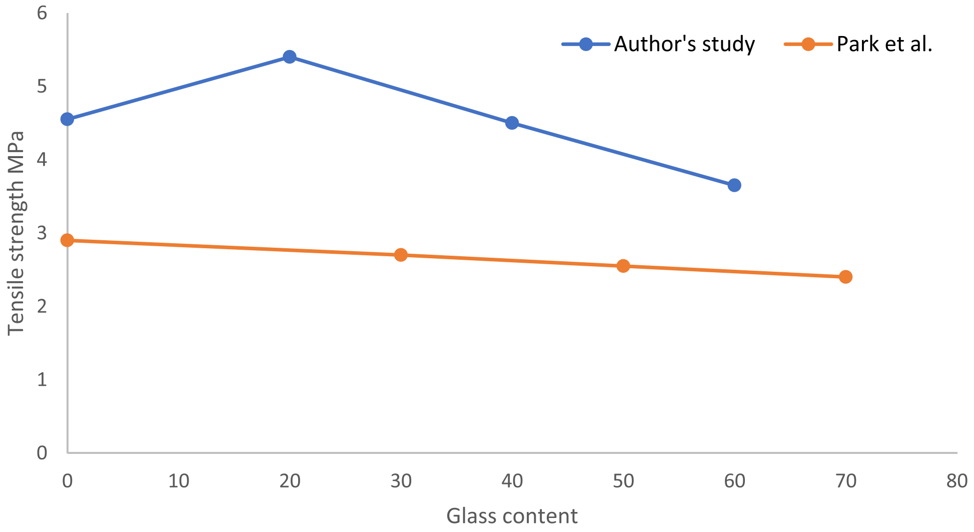


Fig. 11. Effect of Waste glass content on the tensile strength of concrete [87].

and their relative proportions in the concrete mixtures [122]. The incorporation of fine WGA in concrete led to an increase in the value of the modulus of elasticity [84,86]. Nevertheless, Ali and Al-Tersawy [47]stated that the use of crushed WG as a fine aggregate replacement resulted in decreasing the modulus of elasticity. Moreover, for the concrete containing crushed WG as fine aggregates, increasing the crushed WG replacement levels led to reducing the modulus of elasticity [47,84]. However, Abdallah and Fan [86] reported that the MOE recorded the highest value at 14 curing days for concrete comprising 5% crushed WG followed by concrete comprising 15% and 20% crushed WG, whereas the concrete comprising 20% crushed WG achieved the highest MOE at 28 days, followed by concrete comprising 15% and 5% crushed WG. Table 6 illustrates the effect of WG as an aggregate on some concrete properties. The effect of WG on the modulus of elasticity is inconclusive as the experience of various researchers have a lot of dissimilarities.

4.3. *Durability properties*

4.3.1. *Water absorption and sorptivity*

The incorporation of coarse and fine GA achieved better performance of concrete in terms of water absorption by capillarity for

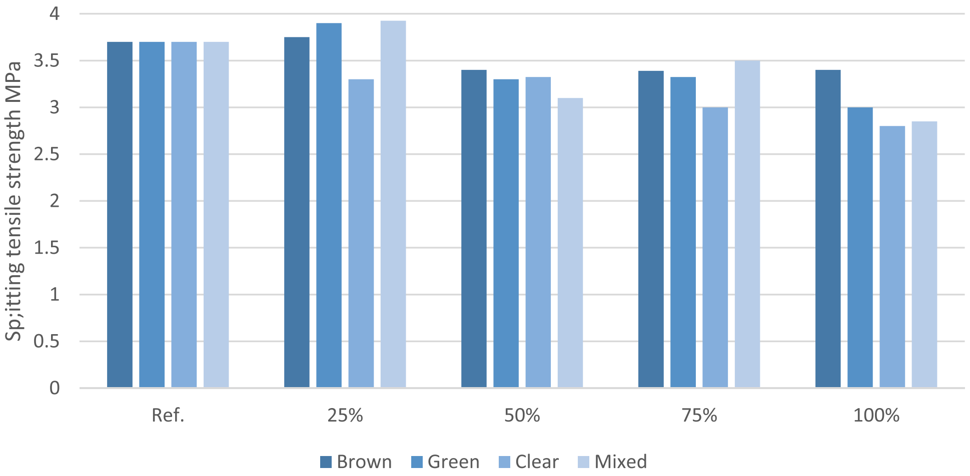


Fig. 12. Split tensile strength of mortar and GA [54].

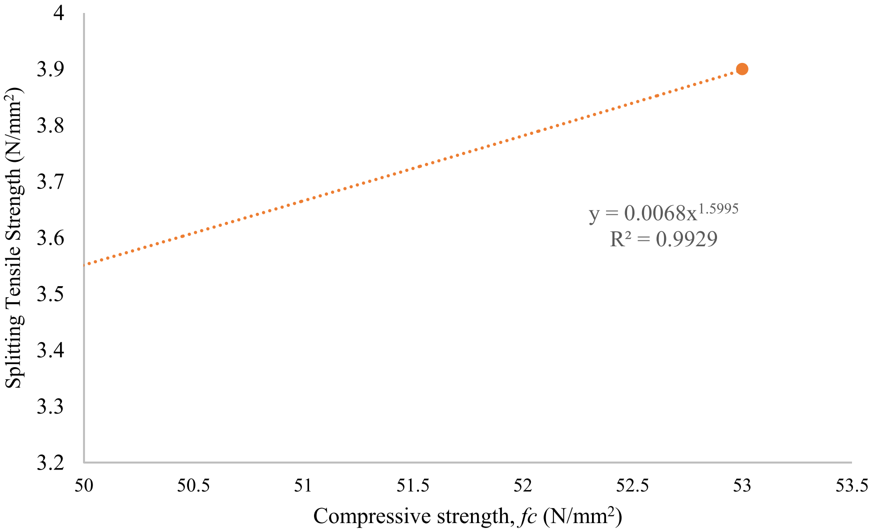


Fig. 13. The relationship between compressive strength and splitting tensile strength relative to the volume of WGA.

every replacement level and, therefore, the mixes with either coarse or fine GA were used for replacement quantities up to 10% [52]. Many researchers [52,88,104] observed a substantial decrease in sorptivity and water absorption that corresponded with an increase in the recycle glass aggregates (RGA) content and observed that incorporating WG improved the concrete durability. Tuaum et al. [85] conducted experimental tests on the RGA in concrete to examine water absorption by immersing the concrete samples in water for all the concrete mixtures as shown in Fig. 15.

It was found that the incorporation of RGA led to a slight decrease in the water absorption rate. This decrease was attributed to GA, which does not absorb water. A similar result was obtained by other researchers [52,102,127]. The use of waste glass aggregates (WGA) as fine aggregate at 50% replacement level was 7.11% that was a maximum water absorption after 72-hour immersion for the reference concrete while the lowest absorption was 6.29%. It is normally supposed that when the water absorption rate is less than 10%, it can be considered as good quality concrete [50]. Malik et al. [93] proved that increasing the WG content in the concrete mix resulted to a decrease in the water absorption rate and average weight reduced by 5% for the concrete mix with 40% WG content, producing WG lightweight concrete. The water absorption of the glass particles is very less when compared with the natural aggregates, leading to a reduced water absorption of the WG concrete.

4.3.2. Drying shrinkage

Choi et al. [128] emphasised that the heavyweight WG could be used as a concrete material by evaluating the expansion by alkali-silica reaction (ASR), drying shrinkage, and heavy metal leaching of mortar.

Fig. 16 shows the test results, which revealed that, at early ages, the drying shrinkage strain was not important, but at later ages, the

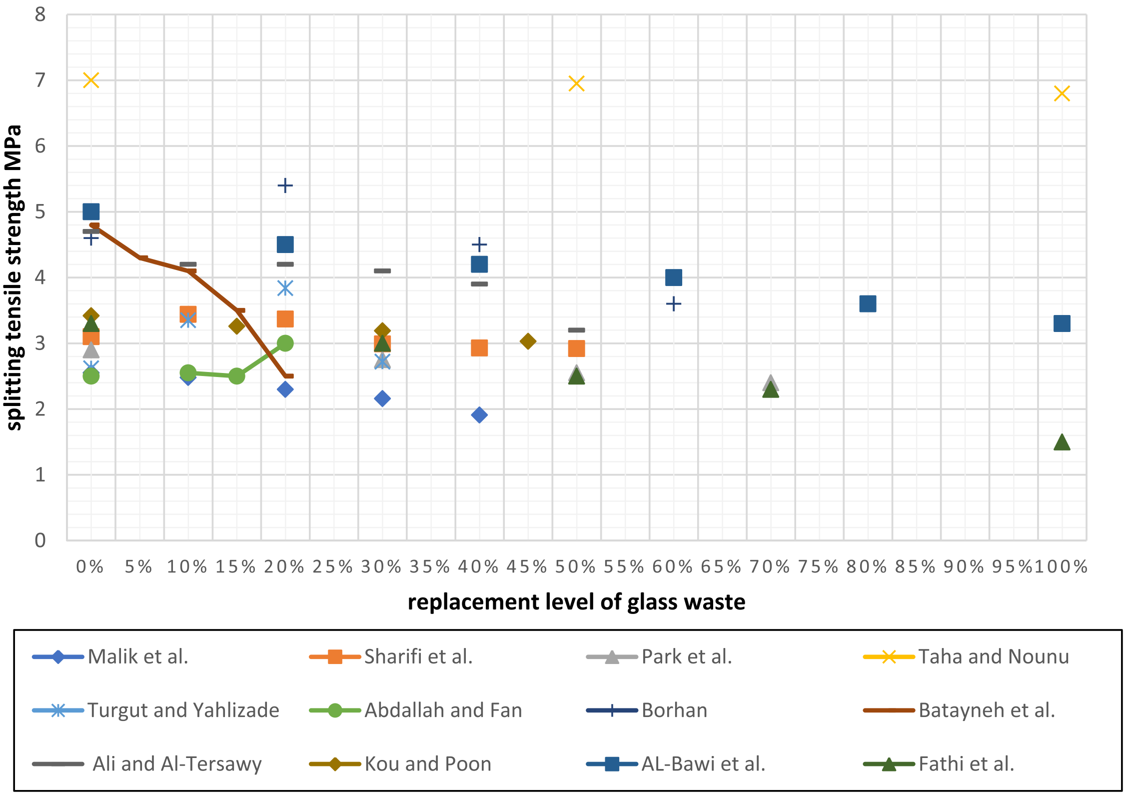


Fig. 14. Splitting tensile strengths of concrete comprising GW as aggregates.

Table 6
Effect of WG as an aggregate on the concrete properties.

Ref.	Glass aggregate%	Slump or flow	Density	Compressive strength	Flexural strength	Tensile strength
[85]	0, 10, 20, 30, 40, 50%	250 ± 10	2347–2385	48.33–55.62	9.02–10.22	–
[98]	0, 30, 50, 70%	–	–	46.5–68	–	–
[123]	0, 10, 20%	100	2191–2484	27.4 – 33.1	–	–
[124]	0, 18, 19, 20, 21, 24%	–	2350–2480	35 – 46.5	5 – 6.18	–
[99]	0, 20, 45%	–	–	42–68	4.5	2.5–3
[125]	25, 50, 75, 100%	–	1700–2000	21–45	–	–
[93]	0, 10, 20, 30, 40%	25–50	2356–2483	25.69–35.11	–	1.91–2.55
[126]	0, 10, 20, 30, 40, 50%	–	–	24.33–31.3	–	–
[94]	0, 10, 20, 30, 40, 50%	655–735	2300.8–2414	44.52–48.51	3.44–4.08	2.92–3.44
[55]	0, 10, 15, 20%	5–7.5	2382.9–2400	40.3–45.9	5.89–6.55	–
[59]	0, 10, 20, 30, 50, 100%	7.5–13	–	27 – 44	4.5 – 6.7	2.4– 2.9
[96]	0, 50, 100%	50–140	2370 – 2440	64–69	5.1–7.6	6.2–9.5
[95]	0, 10, 20, 30%	–	–	23.5–39.7	3.41–6.48	2.33–3.84

large difference started between different mixtures at the same test periods. The decrease in the drying shrinkage values of the cement mortar samples with heavyweight WG as a fine aggregate replacement was qualified to the lower water absorption value of the GA [106,129]. The influence of decreasing the drying shrinkage was more noticeable with an increase of the replacement level of heavy weight WG [54,130]. The outcomes of these investigations demonstrated a reduction in the drying shrinkage with the increase in the replacement levels of the heavyweight WG.

4.3.3. Chloride ion penetration and sulphate attack

Liu et al. [131] conducted an experimental study for testing the durability of concrete using WG as a fine aggregate replacement of 8% sodium chloride solution, 5% sodium sulphate solution, and 10% sodium sulphate solution as shown in Fig. 17. Four replacement levels by volume (the replacement of fine aggregate by crushed RG), as 0%, 30%, 60%, and 100%, were measured. The chloride ion penetration with the concrete depth direction, icompressive istrength, and MOE of concrete were determined along with attack time. The outcomes showed that even though compressive istrength and MOE were reduced, an improved resistance to chloride ion

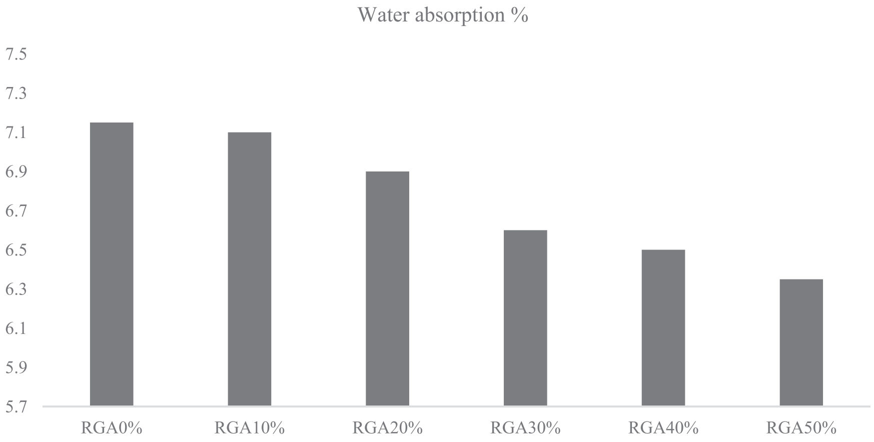


Fig. 15. Water absorption of concrete mixtures containing RGA [85].

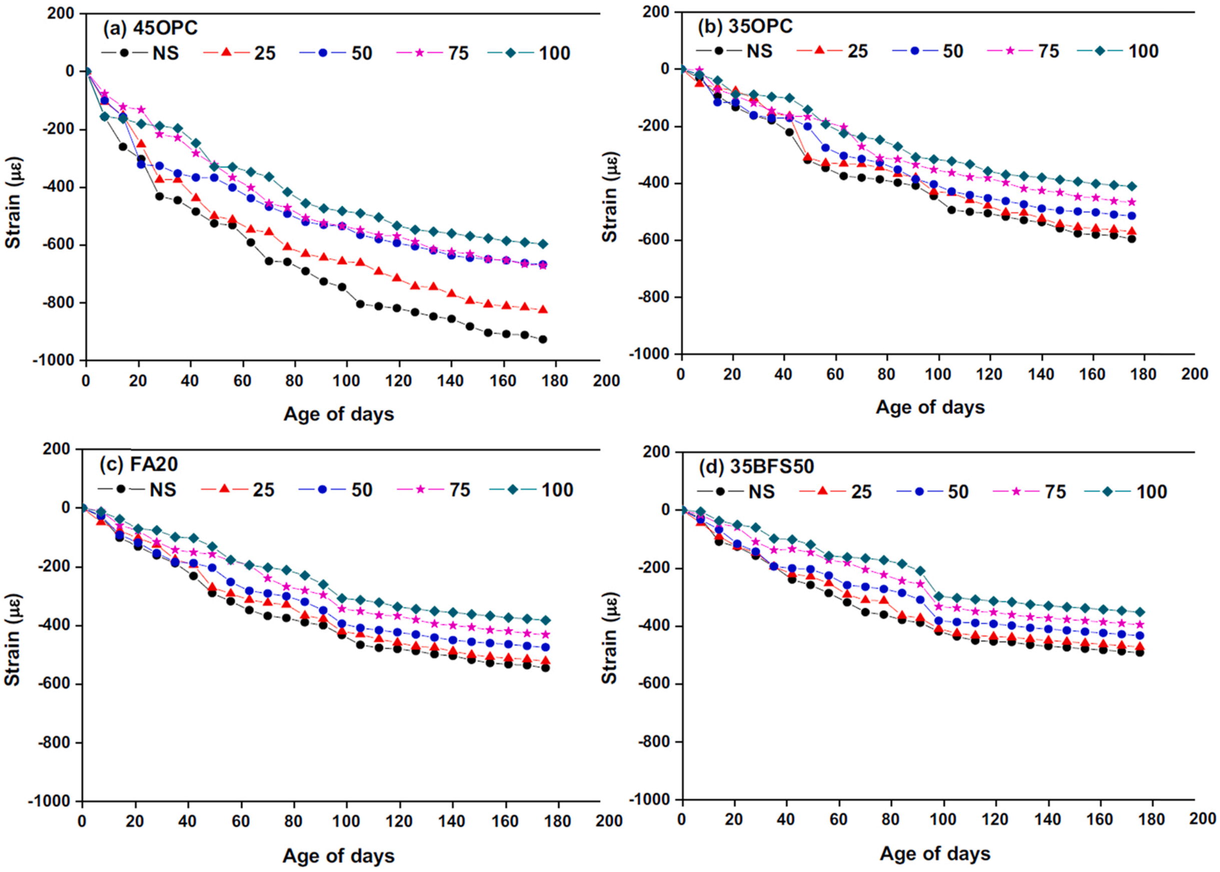
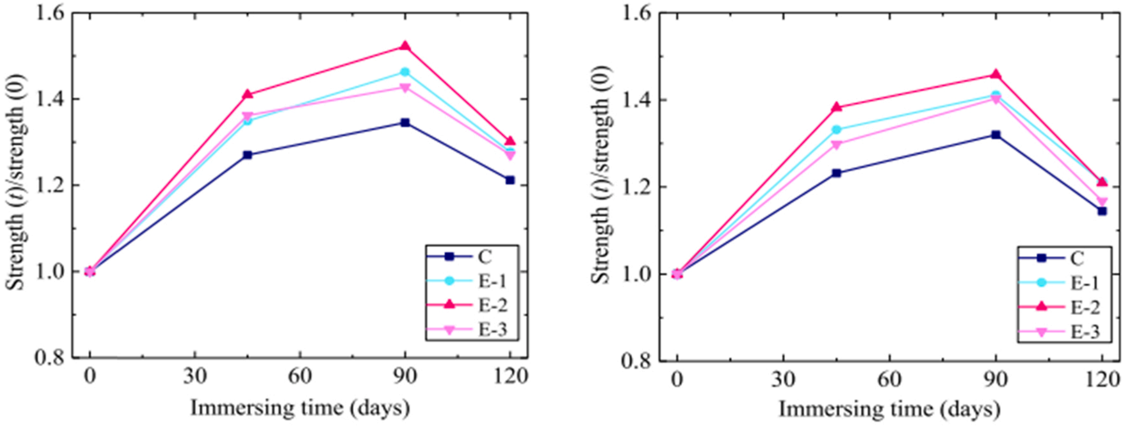


Fig. 16. Test results of drying shrinkage [128].

penetration has been noted while using crushed RG instead of fine aggregate at different replacement levels. Additionally, the compressive strength, rather than MOE of concrete containing crushed RG, is more sensitive to sulphate attacks. By comparison, the increase in the strength of crushed RG was obviously greater than that of the reference iconcrete under sulphate attacks. The utilisation of crushed glass as a partial substitute for natural aggregates has led to an improved resistance to sulphate attack and chloride ion penetration, even though there was a reduction in the mechanical properties.



a) 5% Na_2SO_4 solution b) 10% Na_2SO_4 solution

Fig. 17. Standardisation of compressive strength versus immersion time [131].

5. Summary and conclusion

The steady increase of waste glass in the latest years made it dumped into open areas and ↱landfills. Because of this, waste is not biodegradable materials, making it harmful and non-desirable ↱materials and less eco-friendly. Therefore, many studies used these wastes as construction materials ↱to achieve eco-friendly and economic materials. In addition to that, the use of waste glass powder (WGP) in ↱cement can decrease the final cost of concrete produced to be a more economical material because ↱the WGP is much cheaper than cement.↱

In this paper, the sustainability, mechanical property, behaviour at fresh stage, durability and the engineering applicability of a new category construction material, i.e., recycled glass concrete was reviewed and examined. The following conclusions may be drawn:

1) The utilisation of WGA in concrete production as a concrete material is a promising method of benefitting from voluminous quantities of WG disposed of in open areas and landfills worldwide, thereby reducing the carbon footprint, decreasing the consumption of natural resources, and advancing the construction industry.
2) The best results are noted when crushed waste glass (CWG) are used as an appropriate replacement of fine aggregate in concrete manufacturing. The best replacement level of fine aggregate depends on many factors and, thus, varied in different studies. Generally, the optimum replacement levels for better results varies from 20% to 30% for fine aggregates and 10–20% for coarse aggregates.
3) The slump values of the self-compacting mortar decreased due to the increase in the WG content. The mechanical properties are governed by the size and quantity of the glass particles and the curing conditions of the concrete/mortar. The early curing age demonstrated lower strength, while the late curing age exhibited higher strength. The concrete containing powdered glass exhibited better mechanical and durability properties on account of the refined pore structure and densified microstructure.
4) Furthermore, the bulk density, sorptivity, and water absorption of self-compacting mortar mixes decreased due to the increase in the WG content. The unit weight of the concrete comprising GA is lower than that of the concrete mix comprising a natural aggregate.
5) Previous studies generally concentrated on investigating the concrete comprising soda-lime glass. Very few studies have been conducted to address the effect of other types of WG as cement or aggregate replacement in concrete production. Despite the inconclusive nature of the results, incorporating WG in concrete and cement paste has a great potential for structural and non-structural applications.

6. Recommendations for future works

The existing literature has established the prospect of using recycled waste glass in concrete. Thus, recommendations and directions for future research are provided as follows:

1. The effects of WG on high-strength concrete mixtures should be intensively studied. The environmental impacts and economic aspects of using WG should be investigated.
2. The potential of waste glass powder as a precursor or activator in geopolymer/alkali activated mortar should be further investigated with self-healing and self-sensing properties.

3. The mechanical properties like abrasion resistance, and the durability properties including the behaviour at high temperature, acidic and sulphate environments should be investigated. Additionally, the resistance to freezing-thawing, water permeability and porosity of cement and geopolymer concrete need to be examined.
4. Micro-structural studies such as thermo gravimetric analysis (TGA), scanning electron microscopy (SEM), mercury intrusion porosimetry (MIP) essentials to be confirmed with the durability and mechanical properties of GW concrete.

Author Contributions

All authors contributed to this research. The structure of the paper and data collection were prepared by Hussein Hamada. Alyaa Al-attar conducted some discussions on the results obtained.↱ Analysis and discussion were conducted by Bassam Tayeh. Blessen Thomas conducted a proofreading for the paper.

Declaration of Competing Interest

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