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A comprehensive review on mechanical and durability properties of cement-based materials containing waste recycled glass

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Abstract

Disposal of consumer waste is a major challenge in urban areas around the world. In the field of building materials, it has long been recognized that many types of wastes can be used instead of raw materials. In addition, production of binders such as Portland cement is a CO_2 intensive process. However, for widespread use of wastes in construction, it is important that the properties of resulting building materials are satisfactory. For concrete, the most important are the fresh, hardened and durability properties. A promising waste material that can be utilized to create sustainable concrete composites is waste recycled glass. In this paper, literature dealing with use of waste recycled glass as partial replacement of either cement or aggregate in concrete is systematically reviewed. The focus of this review is the influence of recycled waste glass on the engineering properties of concrete. Main advantages and drawbacks of using recycled waste glass are discussed. The aim of this review is to identify major research needs in the field that will help bring this class of materials closer to worldwide practical use. Given that concrete is the most used man-made material in the world, such development would significantly reduce the need for landfilling of waste recycled glass that is unsuitable for reuse in glass production.

Key words: Waste glass powder, glass powder sand, supplementary cementitious materials, mechanical properties, durability.

1. Introduction

Portland cement is the main binder in concrete. However, production of cement is not environment friendly: a ton cement produces almost 0.7 ton of CO_2. This CO_2 is a major contributor to the greenhouse gases which cause global warming (Huntzinger and Eatmon, 2009; Pade and Guimaraes, 2007). Therefore, there is a need for alternative binder materials such as fly ash (Wang et al., 2004), silica fume (Chaipanich and Nochaiya, 2009), slag (Pan et al., 2017), etc. that can partially or completely replace Portland cement in concrete. In the past 30 years, the focus has been mostly on supplementary cementitious materials (SCMs). SCMs are materials which react in the pore solution of hydrating cement either hydraulically or pozzolanically (Federico, 2013). These include clays, zeolites, fly ash, ground granular blast furnace slag, silica fume, etc. (Juenger and Siddique, 2015; Lothenbach et al., 2011; Snellings et al., 2012). By replacing (a part) of cement in concrete with SCMs, three types of benefits can be achieved: engineering, economic, and ecological. Engineering benefits include the possibility of modification of the fresh or hardened properties of concrete by adequate use of SCMs; for example, compressive strength of concrete can be increased by using silica fume (Poon et al., 2006). Economical benefits can be achieved by (partially) replacing cement with cheaper alternatives such as fly ash (Domínguez et al., 2016; Siddique, 2004). Ecological benefits include a lower environmental impact of concrete SCMs that is achieved by a reduction in CO_2 emissions and raw materials consumed as a result of less cement manufactured. Furthermore, the use of waste materials otherwise bound for landfill is an additional ecological benefit (Malhotra and Mehta, 2014). However, one of the limiting factors for the use of alternative materials as pozzolans in concrete is the lower reactivity of the materials when compared to cement (Snellings, 2016). Overcoming this requires increasing the reactivity of SCMs. Several methods such as chemical activators (calcination), acidic, mechanical (prolong grinding) and thermal (elevated temperature) treatments can be effectively used to increase the reactivity of natural pozzolans (Shi, 2001). The particle size of SCMs can be reduced by prolonged grinding to increase dissolution rate and solubility (Mirzahosseini and Riding, 2015). Chemical solutions can change the properties of the surface of SCMs which can accelerate the pozzolanic reaction (Day and Shi, 1994).

An abundant waste material that can potentially be utilized in concrete is recycled waste glass. Already in 1994, it was estimated that 9.2 million tons of consumer glass was disposed of in the United States alone (Shi and Zheng, 2007). In Hong Kong, 300 tons of waste glass are disposed of daily (Ling et al., 2013). While a part of this glass is readily recycled in the glass manufacture industry, not all used glass can be recycled into new glass because of impurities, cost or mixed colors. Therefore, already several decades ago, research has started on the possibility of using waste glass in concrete production.

Chemically, crushed waste glass contains large quantities of silicon and calcium with an amorphous structure; therefore, it has a possibility to act as a pozzolanic or even a cementitious material (see

Table 1) (Jani and Hogland, 2014). Therefore, waste glass in concrete has been used either as an aggregate or as a partial cement replacement.

Table 1. Comparison of the chemical composition of cement, sand, and different colored glass (Jani and Hogland, 2014; Nassar and Soroushian, 2012; Taha and Nounu, 2008)

	Cement (%)	Clear glass (%)	Brown glass (%)	Green glass (%)	Crushed glass (%)	Glass powder (%)	Sand (%)
SiO_2	20.2	72.42	72.21	72.38	72.61	72.20	78.6
Al_2O_3	4.7	1.44	1.37	1.49	1.38	1.54	2.55
CaO	61.9	11.5	11.57	11.26	11.70	11.42	7.11
Fe_2O_3	3.0	0.07	0.26	0.29	0.48	0.48	2.47
MgO	2.6	0.32	0.46	0.54	0.56	0.79	0.46
Na_2O	0.19	13.64	13.75	13.52	13.12	12.85	0.42
K_2O	0.82	0.35	0.20	0.27	0.38	0.43	0.64
SO_3	3.9	0.21	0.10	0.07	0.09	0.09	-
TiO_2	-	0.035	0.041	0.04	-	0.09	-
Loss on ignition	1.9	-	-	-	0.22	0.36	7.6

Utilization of waste glass in concrete, either as a pozzolan or aggregate material, has an effect on its behavior (

Table 2). In order to use such concrete in large quantities (i.e. in structural applications), it is important to know its engineering properties. Therefore, this review aims to summarize the existing research with a focus on fresh, mechanical and durability properties of cementitious materials where recycling glass powder is used as both binder (i.e. partial cement replacement) and fine aggregate. A thorough search of published articles from different peer reviewed sources was undertaken where glass powder has been used for the production of cement-based materials such as mortar and concrete. After collecting the relevant articles, they were then categorized into those dealing with mechanical and durability properties of mortar and concrete. The various properties authors have researched and discussed under these two headings (mortar and concrete), were carefully extracted. Thereafter, each property was reviewed from the different submission of authors and a position statement arrived at from these authors. Where differences or similarities exist, these were discussed extensively. Therefore, this paper can be used as a valuable source of data for the researchers for their future studies since it is summarized most recent outcomes on the use of recycle glass in cement-based materials.

Table 2. Effect of waste glass (WG) content on cement-based materials

Authors	Type of WG	WG (%)	Type of test	Main finding
(Bostanci et al., 2016)	Fine aggregate	15	Mechanical & durability	No significant difference
(Gautam et al., 2012)	Fine aggregate	10 to 50	Mechanical	Up to 20% WG was acceptable
(Lu and Poon, 2018)	Fine aggregate	25 to 100	Fresh, Mechanical & durability	Workability & fire resistance improved but strength reduced
(Bisht and Ramana, 2018)	Fine aggregate	18 to 24	Fresh, Mechanical & durability	Up to 21% WG was acceptable
(Wang and Wang, 2017)	Fine aggregate	10 to 30	Mechanical & ultrasonic pulse velocity	Equal or slightly higher strength
(Yu et al., 2016)	Fine aggregate	65 to 85	Mechanical	Strength increased
(Atoyebi and Sadiq, 2018)	Fine aggregate	10 to 30	Mechanical	Up to 20% no change is strength
(Hooi and Min, 2017)	Binder	10 to 30	Mechanical	Up to 10% WG was acceptable
(Hajimohammadi et al., 2018)	Fine aggregate	30	Mechanical & Thermogravimetric analysis	No change is strength but weight loss is higher
(Khan and Khan, 2017)	Binder	10 to 30	Mechanical	Up to 30% WG was acceptable

2. Fresh properties of cementitious materials using glass powder

The fresh properties of cementitious materials are essential for the material to be transported, placed, and cured properly (Neville, 1995). This section reviews the literature on the fresh properties of concrete containing waste recycled glass.

2.1. Workability of cementitious materials

Workability of concrete is defined as the ease of handling and determines how easily concrete can be moulded on site. When cement is replaced by waste recycled glass powder in mortar mixes, e.g. as shown in Figure 1a, no significant difference in slump is observed (Islam et al., 2017; Parghi and Alam, 2016). In some studies, an increase in slump has been reported, attributed to the low water absorption of glass (Nassar and Soroushian, 2012). However, (Kamali and Ghahremaninezhad, 2016) found that the influence of waste glass as cement replacement on the slump depends on the glass powder type. In their study, they tested two glass powders coming from different recycling processes: while one resulted in increased slump, the other showed an opposite trend. The cause of this behavior is unclear. However, with a partial substitution of cement and sand by waste glass powder, acting as a binder and fine aggregate, respectively, the slump value of the concrete reduced significantly (Adaway and Wang, 2015; Park et al., 2004; Shayan and Xu, 2006) (Figure 1b).

When waste glass powder is used as aggregate replacement, it may produce different workability compared to natural sand concrete. Several studies reported a decrease in workability (slump) proportional to the percentage of waste glass used in concrete (Chen et al., 2006; Limbachiya, 2009; Topcu and Canbaz, 2004). This is attributed to the geometry of waste glass: sharper edges, more angular shape and higher aspect ratio of glass particles reduce the flowability of mortar by hindering the movement of cement paste and the particles (Tan and Du, 2013). Therefore, workability is expected to decrease, as shown in Figure 1b However, some studies reported that waste glass has no clear influence on the slump (Du and Tan, 2014a). (de Castro and de Brito, 2013) suggested that the relationship between the slump and waste glass addition is complex, and that the behavior is highly dependent on the size of the aggregates replaced. While for coarse aggregates there is a slight increase in slump as replacement ratio increases for a constant w/c ratio, the opposite happens for fine aggregates. As the fines replacement ratio increases, the loss of workability means that the w/c ratio has to increase to achieve required slump. On the contrary, slump flow of self-compacting concrete (SCC) increased when sand was replaced by glass aggregates (see Figure 1c) (Ali and Al-Tersawy, 2012). This is attributed to the weaker cohesion between the glass aggregates and the cement paste due to their smooth and impermeable surfaces (Kou and Poon, 2009). The higher slump flow at higher glass replacement ratios was a result of the higher compactness of concrete granular skeleton. Since glass powder is finer than sand, it can improve packing of the coarse aggregates, thereby reducing porosity. Glass powders also have low water absorption and smooth surface which may contribute to higher slump, as shown in Figure 1c.

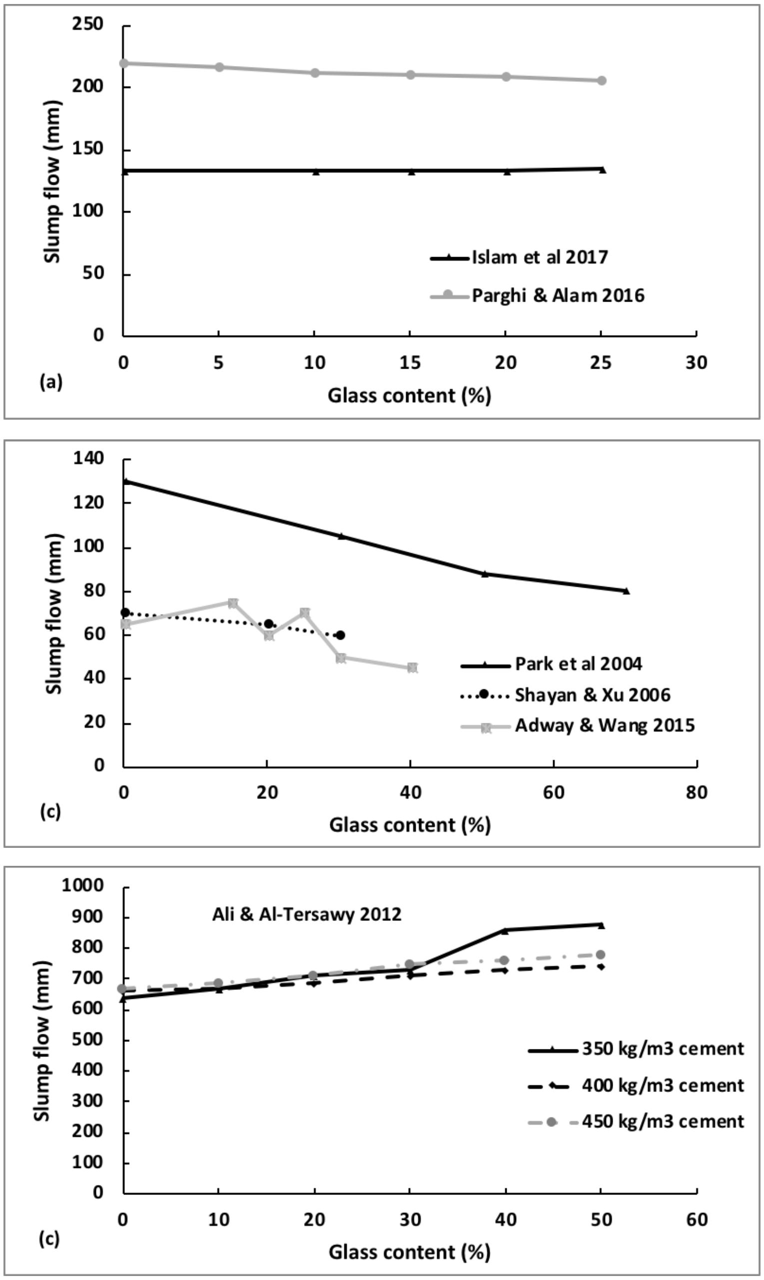


Figure 1. Influence of waste recycled glass on slump behaviour of (a) mortar, (b) concrete and (c) SCC using glass powder (Adaway and Wang, 2015; Ali and Al-Tersawy, 2012; Islam et al., 2017; Parghi and Alam, 2016; Park et al., 2004; Shayan and Xu, 2006).

For low slump concrete, workability cannot be measured using a slump test. An alternative is the compaction factor, which is defined as the ratio between the weight of partially compacted concrete and weight of fully compacted concrete. Figure 2b shows the compacting factor of concrete with different glass aggregates. Clearly, the compacting factor reduces as the glass aggregate increases. This reduction can be attributed to higher flow at higher glass content ratios, lower absorption capacity and granular geometry (typically smooth surface) of glass particles, which improved the porosity of concrete (Park et al., 2004; Piasta and Sikora, 2015).

2.2 Air content and compaction factor

The incorporation of fine glass aggregates may allow a considerable amount of air into fresh mortar as shown in Figure 2a. This may be due to the shape of glass particles, which are predominantly lamellar and may facilitate air entrapment (Oliveira et al., 2013). (Park et al., 2004) found that air content steadily increased from 12.2 to 41.4% for concrete containing glass sand content of 30%, 50% and 70%. (Tan and Du, 2013) reported no significant change in the air content when different types of fine glass aggregates were used in concrete up to 75%. However, for concrete with 100% brown and clear glass sand, air content increased by 30% to 100%. This was attributed to the sharper edges and higher aspect ratio of glass sand, which causes more air to be retained at the surface of glass particles. When waste glass is used to replace fine aggregates, (Du and Tan, 2014a) observed a reduction in air void content for low replacement ratios (25%), but an increase for high replacement ratios (100%). This was attributed to two opposing effects: on the one hand, the glass particles (used in their study) have smoother surface compared to natural sand, resulting in better packing and less retention of air voids; however, glass particles also have a more irregular shape compared to natural sand, resulting in large surface areas that retain more air voids. With low replacement ratios the former effect is more dominant, while for high replacement ratios the latter effect becomes dominant.

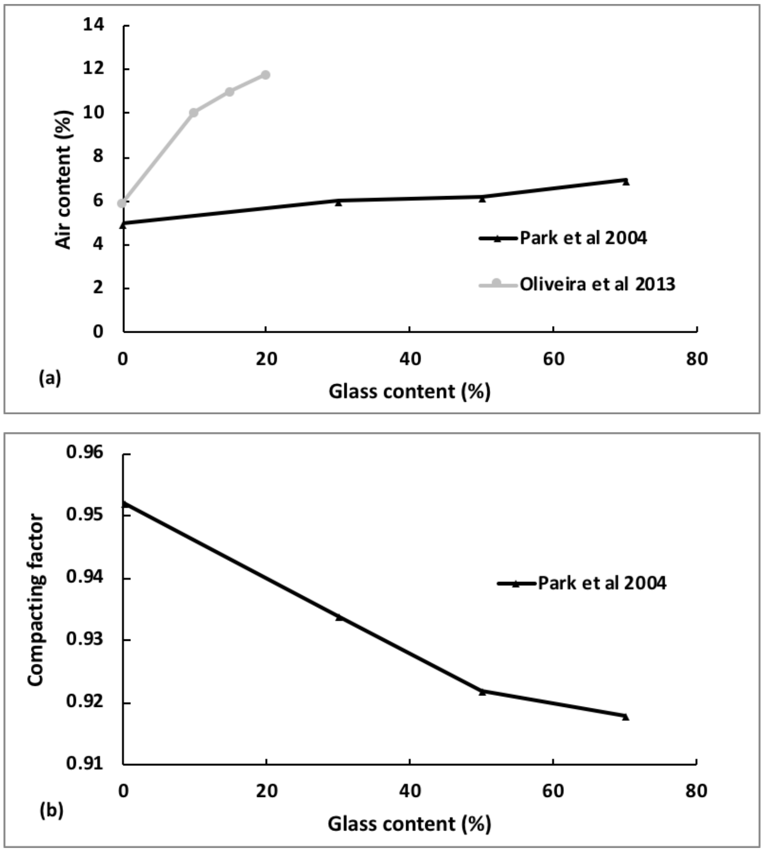


Figure 2. Influence of waste recycled glass on (a) Air content (%) and (b) compacting factor of cementitious composite using glass powder (Oliveira et al., 2013; Park et al., 2004)

2.3. Bleeding and Segregation

The effect of recycled fine glass aggregates on bleeding and segregation was studied by (Ling and Poon, 2011). The flat shape and smooth surface of glass aggregates contributed to the slightly higher bleeding and segregations of mortar mixes. Bleeding and segregation of mortar became pronounced when more glass aggregates were used. Similarly, (Taha and Nounu, 2008) observed severe segregation and bleeding in when up to 50% and 100% of natural sand was replaced by coloured waste glass. (Shayan and Xu, 2006) observed bleeding only when a high amount (30%) of cement was replaced by waste recycled glass. When self-compacting concrete is concerned, (Kou and Poon, 2009) found that the segregation increased in proportion to waste recycled glass percentage. In general, it can be stated that bleeding and segregation increase with increasing waste glass sand content.

2.4. Setting time and hydration of concrete

From a practical point of view, setting time is important as it determines the timeframe available for construction workers to place the fresh concrete. Figure 3 shows the influence of incorporating different percentages of waste glass powder on the setting time of concrete. It can be seen that both initial and final setting times of concrete increase as the glass content increases. However, other studies have reported that the glass powder facilitates the hydration of cement paste (Kamali and Ghahremaninezhad, 2016; Schwarz et al., 2007; Schwarz and Neithalath, 2008). (Kamali and Ghahremaninezhad, 2016) stated that up to 20% addition of glass powder in concrete does not lead to significant changes in the setting time of cement paste.

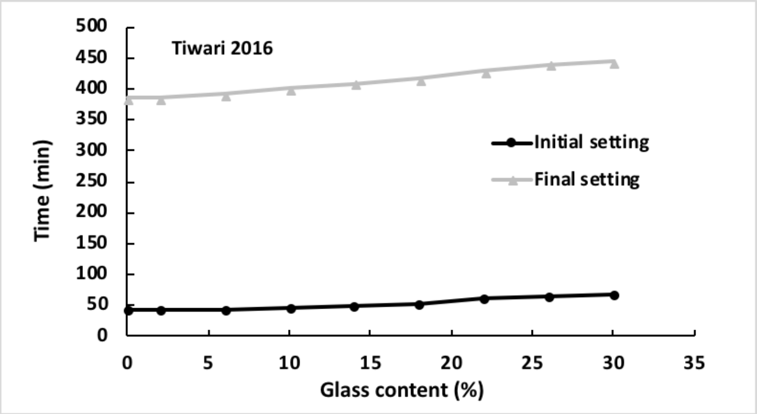


Figure 3. Influence of incorporating recycled waste glass on the setting time of concrete (Tiwari et al., 2016)

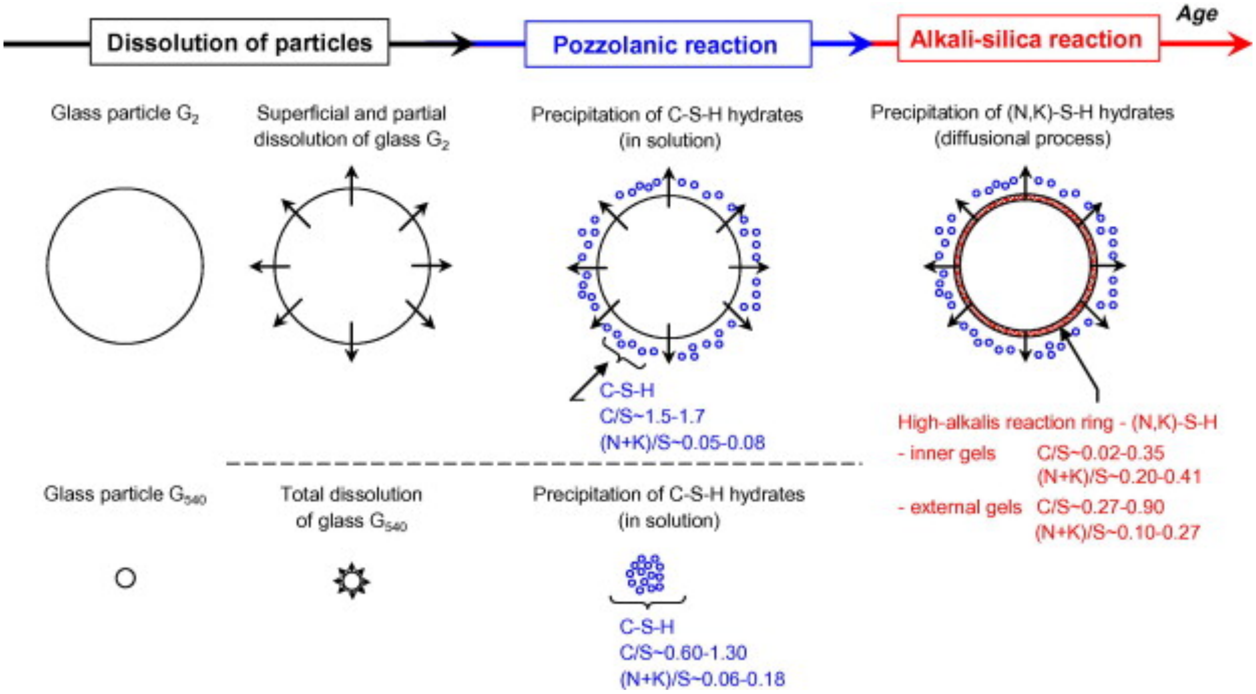
The hydration reaction is affected by a partial substitution of Portland cement with recycled waste glass. First, the maximum heat evolution rate and the total heat generated reduce continuously with higher OPC replacement percentage due to the dilution of cement and the slower pozzolanic reaction of waste glass (Du and Tan, 2014b; Kamali and Ghahremaninezhad, 2016; Shao et al., 2000). This is similar to the effect of other (inert) additions such as e.g. limestone filler (Bentz, 2006), diatomite (Ergün, 2011), or functional microcapsules (Šavija and Schlangen, 2016). Lower hydration heat is beneficial for preventing early-age temperature related cracking that is common in thick structural members and massive concrete structures. On the other hand, small recycled glass particles may act as nucleation sites for hydration product (mainly C-S-H) formation, thereby increasing the rate of the hydration reaction (Du and Tan, 2014b). At the same time, the high alkali content in waste glass may act as a catalyst in the formation of C-S-H at an early age (Du and Tan, 2014b). Therefore, it seems that the presence of waste glass reduces the time needed to reach peak temperature in semi-adiabatic conditions (Du and Tan, 2014b). A balance between these two opposing effects will, in the end, determine the temperature development in the concrete. Although in most references a reduction of hydration heat was reported, (Poutos et al., 2008) found that the inclusion of glass sand in the matrix increased temperature during hydration. Significantly higher temperatures are generated during hydration of concrete made with glass aggregates than with natural aggregates. This trend was more marked with green glass than concrete made with amber or clear glass.

At later stages of the hydration process, calcium hydroxide (CH) is consumed in the pozzolanic reaction of the waste glass. With higher substitution levels, the CH content drops (Du and Tan, 2017), especially at later ages (Du and Tan, 2014b). In the beginning, this is caused by the previously described dilution effect. At later stages, the CH is consumed by the pozzolanic reaction of the waste glass (Chen et al., 2006; Idir et al., 2011). Calcium hydroxide from cement hydration slowly reacted with glass powder to form C-S-H (Du and Tan, 2017). With higher glass powder replacement, calcium hydroxide consistently decreases in the hydrated paste, particularly when more than 30% cement was substituted by glass powder. Therefore, there is a maximum amount of waste glass that may be used as cement replacement. (Du and Tan, 2014b) first suggested that this maximum is around 60%. Later, however, they observed (based on the CH content) that the complete pozzolanic reaction can occur only if the waste glass powder content is under 30-45% (Du and Tan, 2017). Therefore, fine waste glass is a promising pozzolanic material: in fact, (Schwarz and Neithalath, 2008) suggested that it exhibits pozzolanicity levels equal to or greater than that of fly ash.

3. Alkali-silica reaction (ASR)

It is well-known that inclusion of glass aggregates in concrete may trigger the ASR (Dyer and Dhir, 2001; Jin et al., 2000). Typically, the silica-rich nature and amorphous structure of the glass powder react with calcium hydroxide of Portland cement and forms a siliceous gel. This gel within the cement paste absorbs water and swells. Sufficient swelling pressure can cause microcracking, expansion and ultimately deterioration of the surrounding concrete. It is intuitively expected that concrete incorporating recycled waste glass would be susceptible to alkali-silica reaction due high silica content of the waste glass (

Table 1). However, unlike siliceous aggregate particles, recycled waste glass particles are not inert in the cementitious matrix: as already described, recycled waste glass may act as a pozzolanic material. Therefore, the alkali-silica reactivity of concrete containing waste aggregate glass is complex. Chemical reactions of coarse and fine particles and the order of their occurrence is shown in Figure 4. It can be seen that the particle size of waste recycled glass has a marked impact on the occurrence of ASR: while coarse particles will be only partially dissolved in the hydration process, fine particles may be completely consumed by the pozzolanic reaction even before ASR is triggered. (Idir et al., 2011) suggested that particles with low surface area (less than 4.5 m^2/kg) may be susceptible to ASR. On the other hand, several studies have reported that partial replacement of cement by fine recycled waste glass can, in fact, reduce the ASR related expansion (Lee et al., 2011; Matos and Sousa-Coutinho, 2012; Serpa et al., 2013). This is attributed to its pozzolanic reactivity, which consumes calcium hydroxide and reduces the amount of free alkalis in the pore solution. For example, (Kamali and Ghahremaninezhad, 2015) found that modified mortars with glass powders and fly ash all showed a reduction in ASR expansion with mortars modified at 20% replacement being most effective in reducing ASR reaction. Similar findings were reported by (Serpa et al., 2013). (Ismail and Al-Hashmi, 2009) measured the expansion of mortar specimens made of 0%, 10%, 15%, and 20% waste glass as fine aggregate. They found that with the increase in waste glass content, the expansion of the specimens was reduced when compared to the control specimens. In all specimens, the total expansions were less than 0.1% according to ASTM C1260. They stated that the decrease in the expansion of the specimens is due to the reduction of available alkali due to the consumption of lime (liberated by the cement hydration process) by its reaction with fine waste glass and the expected reduction of the system alkalinity. Similarly, (Chen et al., 2006) found lower expansion in mortar bars with various E-glass contents (5%, 10%, 15% and 20%). The expansion decreased as E-glass content increased and expansions of all specimens were lower than 0.10%, which denote no potentially deleterious expansion with E-glass in concrete. Lower alkali content (Na_2O and K_2O) of E-glass may have contributed to the lower expansion. Furthermore, (Metwally, 2007) observed lower expansion with a higher percentage of glass powder in concrete when cement was partially (5%, 10%, 15% and 20%) replaced by glass powder. They also concluded that the available alkali, $Ca(OH)_2$ (liberated lime from cement hydration process) had been consumed by reacting with waste glass powder, thereby decreasing the alkalinity of the system.



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286 **Figure 4.** Schematic representation showing successive reactions of coarse and fine glass particles in the
287 cementitious matrix (Idir et al., 2011)

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In Figure 5, it is shown that inclusion of waste glass (WG) sand in concrete contributes to the expansion due to ASR (note that WG% is waste glass weight percentage with respect to total sand including waste glass). Expansion increases with increasing glass powder sand percentage in the concrete mix. However, for the same amount of glass powder, the rate of expansion depends on the type of glass. A comparison of Figure 5a and b shows that the use of brown glass results in a higher expansion compared to green glass. Expansion measurements up to 14 days when sand is replaced with brown glass powder sand at 10%, 50% and 100%, revealed the increase in expansion of 140%, 540% and 807%, respectively. For the same green glass powder content in concrete, the expansion rates were increased by 40%, 159% and 217%, respectively. The difference may be attributed to chromium (III) oxide (Cr_2O_3), which is added to the glass to create a greenish hue and is considered to repress the expansion (Park and Lee, 2004). Nevertheless, the expansion rates noticeably increased with an increase in waste glass content, regardless of the type of waste glass used. When coarse recycled waste glass particles are used, it may be suggested to use preventive measures to suppress ASR, such as SCMs (Du and Tan, 2013) or lithium admixtures (Topçu et al., 2008).

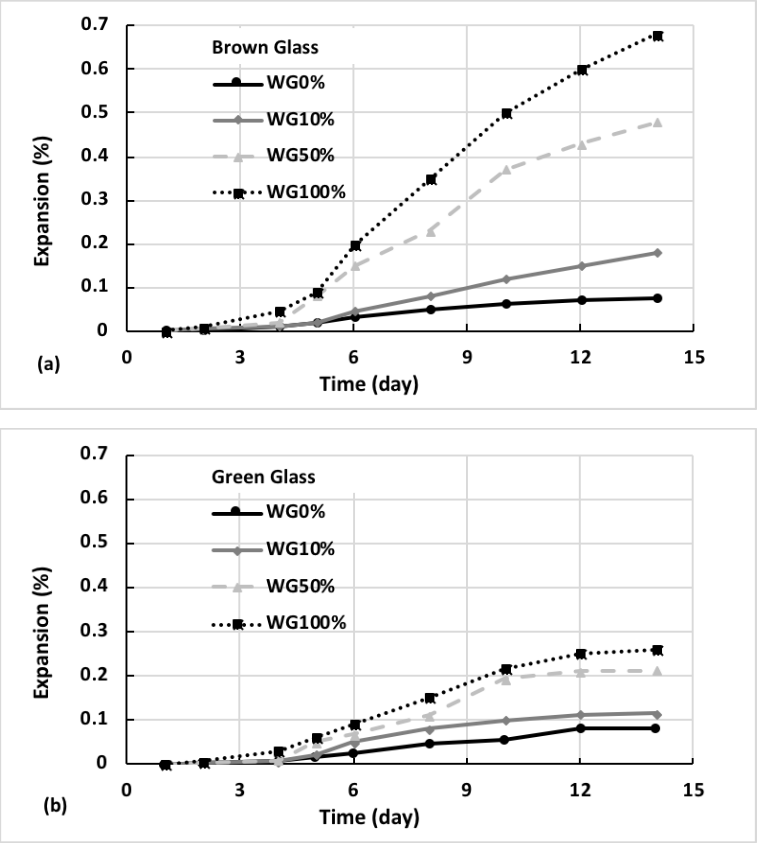


Figure 5. Influence of waste glass powder as fine sand on expansion of mortar bars (Park and Lee, 2004).

However, the relationship between the use of waste aggregate glass and alkali silica reaction in concrete may be even more complex. (Saccani and Bignozzi, 2010) reported that there is a relationship between the chemical composition of waste glass and expansion. They suggest that, in view of glass recycle broadening, expansive compositions should be determined and selective procedures introduced for treatment of post-consumer glass. On the other hand, (Maraghechi et al., 2012) found that the alkali-silica reactivity of waste aggregate glass is caused by residual cracks in the interior of glass particles. The reactivity of residual microcracks depends on their size. Cracks width thinner than of approximately 2.5 μm was found to remain intact after 14 days of ASTM C1260 test. Further, image analysis of SEM micrographs that larger glass particles include a significantly higher percentage of reactive microcracks (>2.5 μm) which could explain why larger particles are reactive while smaller glass particles are innocuous. Similar findings were reported by (Du and Tan, 2013). This is an alternative to the mechanism described in Figure 4.

4. Mechanical properties of blended glass powder cementitious composite

For practical application of concrete, the most important mechanical properties are compressive and tensile (mostly measured indirectly in the form of flexural or splitting) strength, and Young's (elastic) modulus. This section summarises the literature on the influence of recycled waste glass powder on mechanical properties of concrete when used as both binder and aggregate.

4.1. Compressive strength

The influence of recycled waste glass addition on the compressive strength of concrete is complex (Alomayri, 2017). The reason is that, as shown in Figure 4, recycled waste glass has a two-fold influence on the concrete microstructure. On the one hand, it is an aggregate material, and its strength and bond with the cement matrix will affect the strength; on the other hand, it is pozzolanic, and its addition will result in an increased amount of strength contributing solids (such as C-S-H) in the matrix. The interplay between these two (opposing) influences will determine the resulting effect on the compressive strength.

Several researchers have examined the influence of incorporating glass powder in concrete on its compressive strength (Al-Zubaid et al., 2017; Ling and Poon, 2013; Wang, 2009). For example, (de Castro and de Brito, 2013) and (Afshinnia and Rangaraju, 2016) reported a decrease in compressive strength as a result of recycled waste glass used as aggregate. This was attributed to the fact that the aggregate paste bond (Diamond and Huang, 2001; Scrivener et al., 2004) is weaker when recycled waste glass is used compared to quartz aggregate. The same trend was observed in self-compacting concrete (Ali and Al-Tersawy, 2012; Kou and Poon, 2009). On the other hand, several studies have reported that, although early age strength is lower compared to the reference when recycled waste glass is used, later age strength is increased (Du and Tan, 2017; Ismail and Al-Hashmi, 2009; Kamali and Ghahremaninezhad, 2015). (Nassar and Soroushian, 2012) stated that a significant increase in the later age strength is achieved through formation of a denser and less permeable microstructure which is a result of the filling effect of sub-micron sized glass particles. As shown in Figure 6, up to 90 days, the compressive strength of the concrete decreases with increasing amounts of glass sand. However, in the same mixes, the slight increment in the strength was noticed for glass sand replacement up to 20%. No significant changes in the strength were noticed for mixes with more than 20% glass sand. This may be due to the fact that up to 20% replacement of cement or sand by waste glass powder may raise the pozzolanic reaction and also act as a filler material, thereby filling most of the voids between the large aggregates in concrete.

The compressive strength of concrete is influenced by the type of glass powder, as shown in Figure 6. Significantly lower strength was found when recycled green glass powder in concrete was used as a partial replacement of cement (up to 15%). However, except for 15% replacement, the differences in strength between brown and neon glass powder were insignificant. The high compressive strength observed at 13% of neon glass may be attributed to the high amount of calcium carbonate ($CaCO_3$), which has a major effect on the compressive strength.

(Park and Lee, 2004) reported that compressive strength gradually decreased by 2-49% when fine glass powder replaced 10%-100% fine sand. It is clear that there is no consensus in the literature on the influence of recycled waste glass on compressive strength of concrete. However, some studies have concluded that a maximum of 20-30% glass powder could be used in concrete, either as fine aggregates or binder, without any detrimental effect on the compressive strength (Khan and Khan, 2017). From Figure 6 and Figure 7, it can be seen that the strength development of glass powder concrete is higher at later ages. It has been suggested that, at early ages, recycled glass powder prepared at microlevel acts more as a catalyst than pozzolanic materials (based on Na_2O and alkali contents) (Vaitkevičius et al., 2014). Therefore, it can be expected to have a slower strength development at early age.

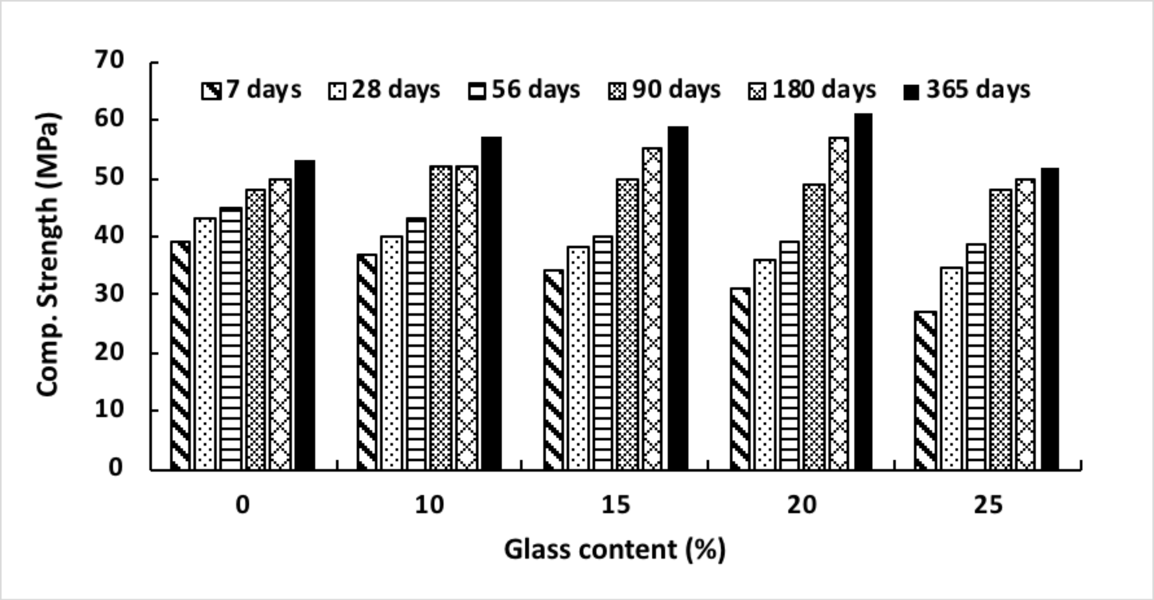
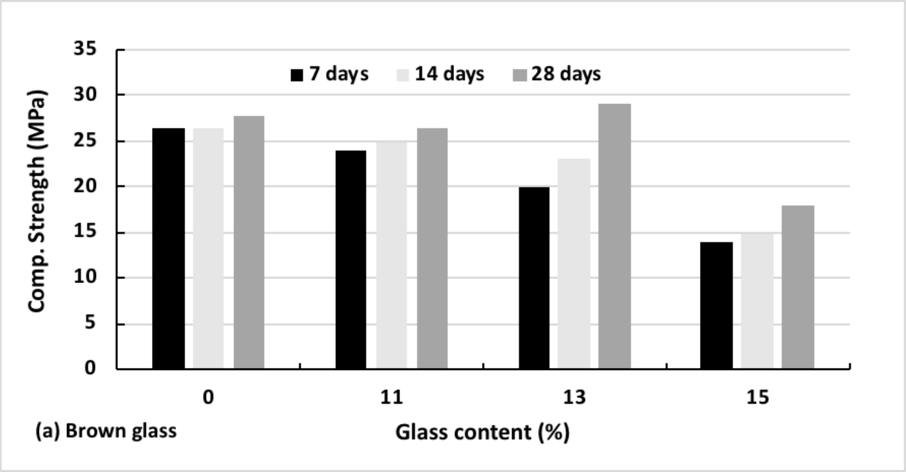
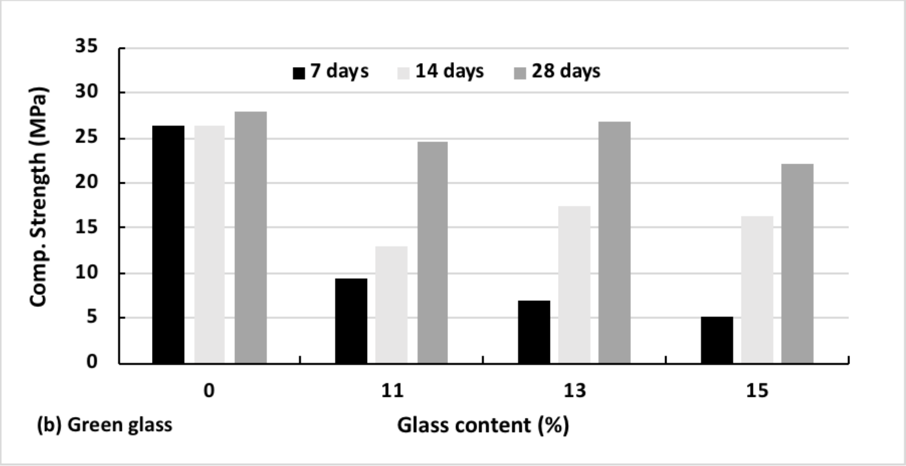


Figure 6. Compressive strength development in concrete with different glass powder content (Islam et al., 2017)





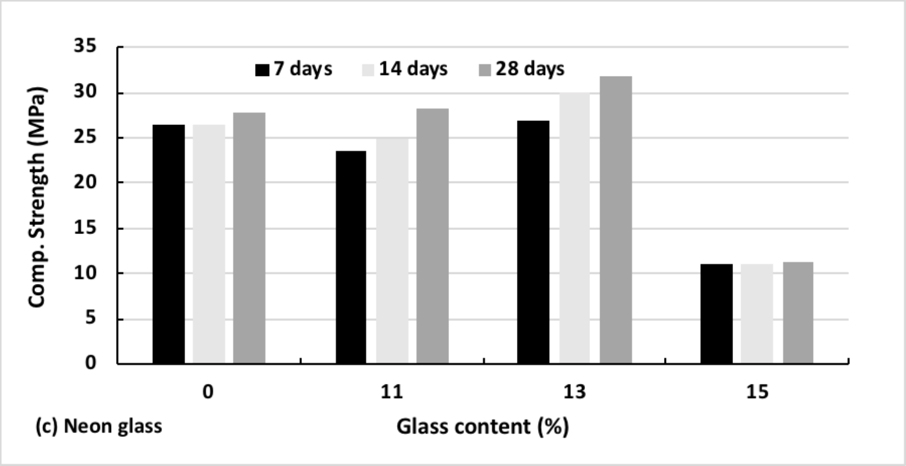


Figure 7. Effect of glass type on the compressive strength development of concrete with different glass powder content (Al-Zubaid et al., 2017)

4.2. Flexural strength

Flexural strength of recycled aggregate concrete shows similar trends to its compressive strength. Flexural strength increases when glass powder is used in concrete, both as a binder and as fine aggregate (Ali and Al-Tersawy, 2012; Ismail and Al-Hashmi, 2009; Parghi and Alam, 2016). As shown in Figure 8a, with time, the flexural strength of mortar gradually increased by 21% to 49% when glass powder replaced cement by 5% to 25%.

(Ismail and Al-Hashmi, 2009) used waste glass sourced from an industrial workshop in concrete as an alternative to fine aggregates. The maximum size of glass aggregates was 2.36 mm, and about 54% of the total particles were retained on the sieve size 0.60 mm. Test results revealed that with 10% to 20% replacement of sand with fine glass powder, about 3.6% to 11% higher flexural strength was achieved compared to the control. (Siad et al., 2018) reported about 7% to 12% enhancement in flexural strength in high volume fly ash based engineered cementitious composite (ECC) where fly ash was replaced in the mix with 15% and 30% recycled glass powder. The discharge of the high amount of alkalis and aluminate from glass powder and fly ash formed a new form of C-S-H. The new C-S-H formed is close to C-(N, A)-S-H with a low Ca/Si ratio thereby forming a dense microstructure, which enhanced strength compared to the corresponding C-S-H formation in the reference mix without glass powder (Jawed and Skalny, 1978; Puertas et al., 2011).

On the contrary, (Ali and Al-Tersawy, 2012) observed that the flexural strength of self-compacting concrete (SCC) gradually decreased with increasing fine glass sand, as shown in Figure 8b. In the study, recycled glass was collected from the glass industry, and 99% glass particles were passed through a 2.36 mm sieve size, while about 65% of total particles were restrained on a 0.60 mm sieve. It could be inferred that the differences between studies may be attributed to the source, grain size and type of waste glass used in the mixes. The mineral compositions of different glass types vary, which may have different reaction mechanisms with binders in concrete. Also, the processing of glass powder can significantly influence the properties of concrete. The finer and angular surface area of particles means higher demand for water for better lubrication, as well as lower workability of the mix.

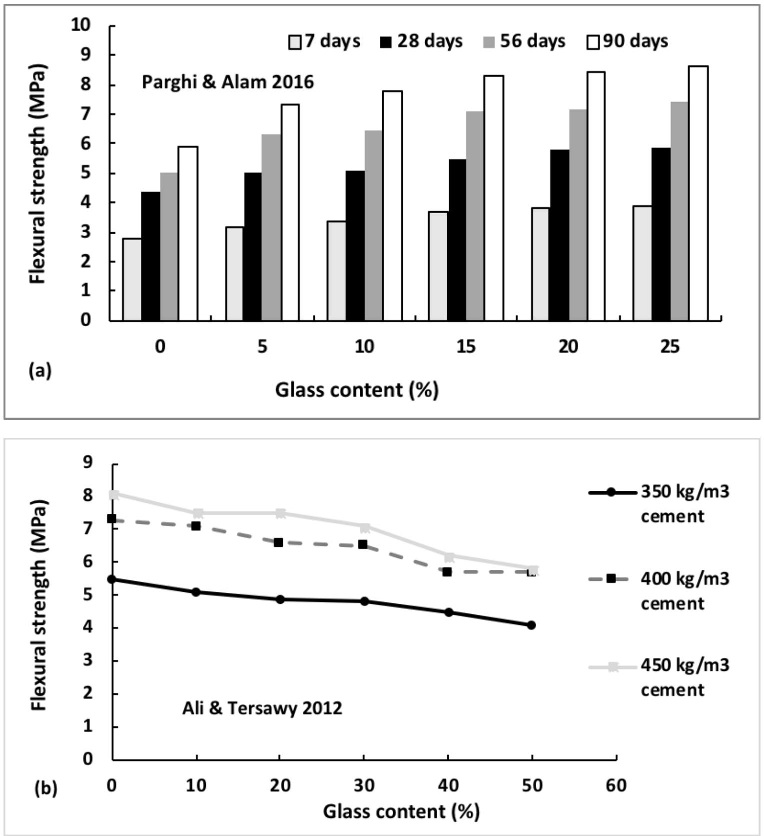


Figure 8. Effect of glass powder content on flexural strength (a) cement replaced by glass powder in mortar and (b) sand replaced by fine glass aggregates in SCC (Ali and Al-Tersawy, 2012; Parghi and Alam, 2016)

4.3. Splitting tensile strength

The aggregate size and binder material significantly influence the concrete properties (Fu et al., 2014). The effect of partially replacing sand with displaced liquid-crystal display (LCD) glass powder on the splitting tensile strength of concrete is shown in Figure 9. No significant difference in splitting strength is found up to 40% replacement of sand with LCD glass powder (Wang, 2009). (Metwally, 2007) reported a slight increment (4% to 12%) in splitting strength of concrete with blended finely milled waste glass up to 20%.

(Tan and Du, 2013) studied the influence of distinct types of glass (brown, green, clear and mixed) as fine aggregates on the properties of mortar. The study showed that with 25% of brown, green, clear and mixed glass powders, the splitting tensile strength of mortar increases. However, the splitting tensile strength reduces with higher percentages of glass sand, regardless of the glass colour. For the clear glass sand mortar, the splitting tensile strength decreased consistently with increasing glass content (Tan and Du, 2013).

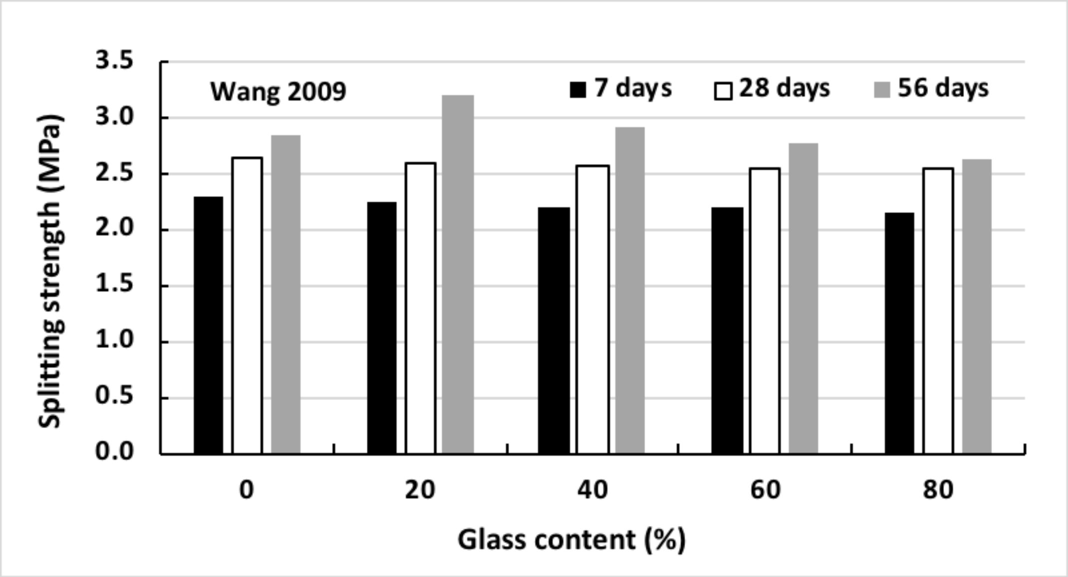


Figure 9. Splitting tensile strength of concrete containing different percentages of LCD glass powder as sand replacement (%) (Wang, 2009).

4.4. Young's modulus

Tests show that the elastic modulus decreases as the fine aggregate content of glass powder increases, see Figure 10a. The 28 days compressive strengths of concrete with 0% glass powder of Figure 10a were 46 MPa (Series 1), 62 MPa (Series 2) and 68 MPa (Series 3) (Ali and Al-Tersawy, 2012). Conversely, the elastic modulus shows lower values for each of the series. Several factors have been put forward to explain the decrease of elastic modulus with increasing waste glass content. These are the inherent physical characteristics of the glass, a weak aggregate-matrix interfacial bond and cracks in glass particles. In contrast to the higher strength concrete, for the low to medium strength concrete (20 MPa, 30 MPa and 40 MPa, Series 1 to 3, respectively, in Figure 10b), the results show a negligible difference in elastic modulus compared to the control mix without glass powder (Limbachiya, 2009).

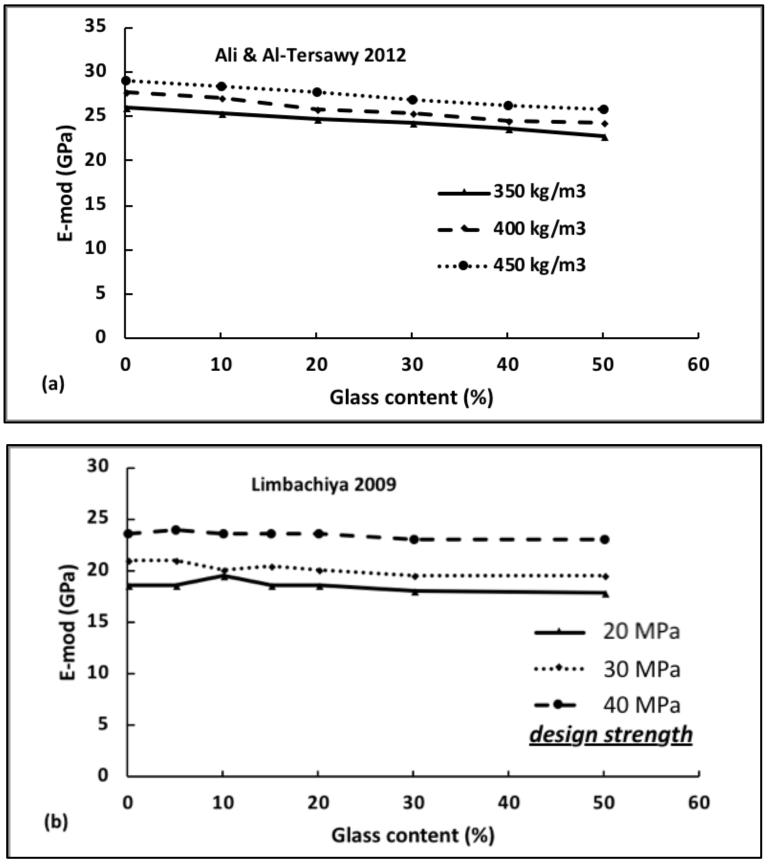


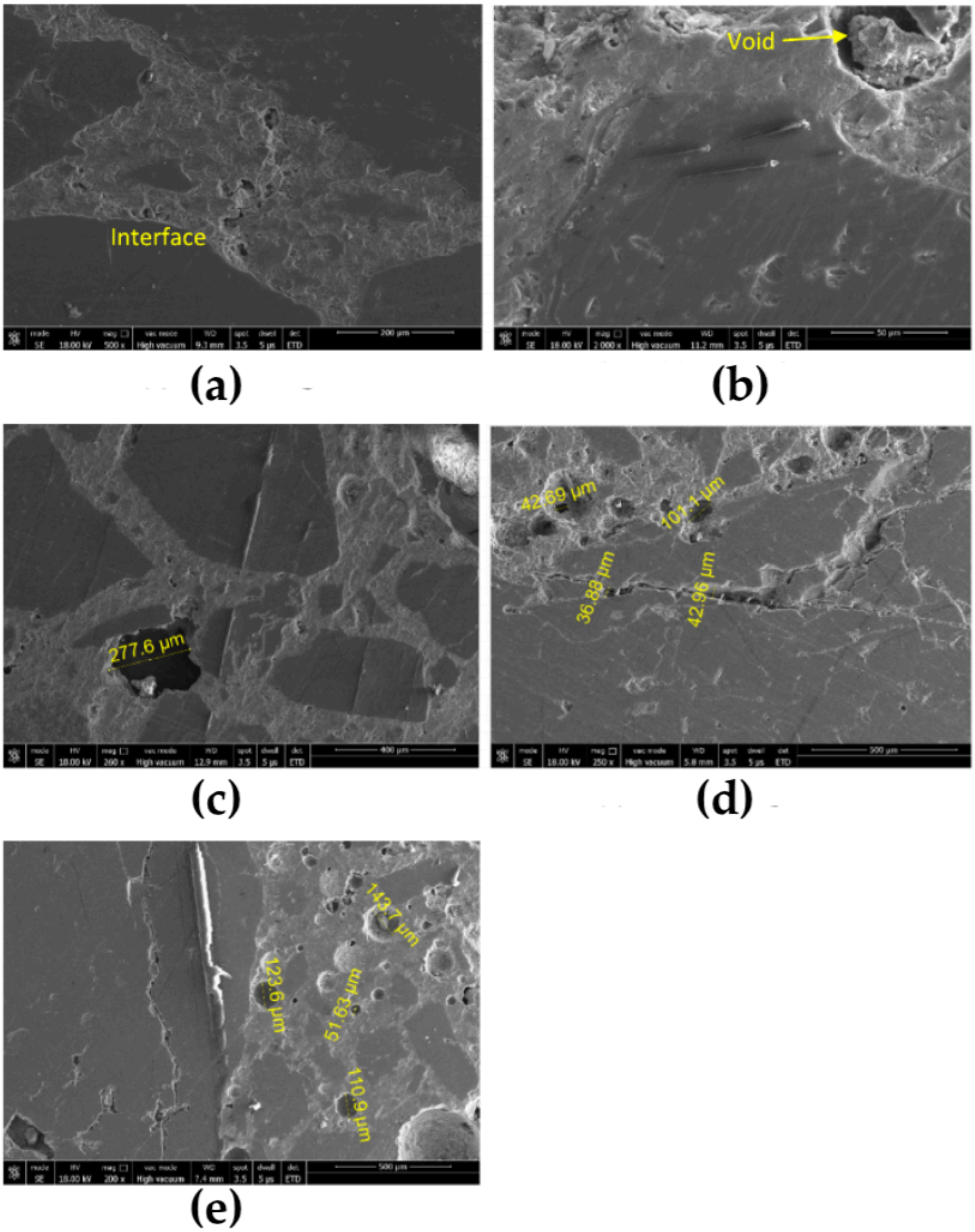
Figure 10. Effect of recycled glass powder aggregates on Young's modulus of concrete (Ali and Al-Tersawy, 2012; Limbachiya, 2009).

Clearly, glass powder used as a binder influences the mechanical properties of concrete more positively compared to glass powder sand. The observed difference in the performances of glass powder is due to the different pozzolanic reaction mechanism of its fine and coarse particles in cementitious materials (see Figure 4). Finer particles contribute more to the reaction mechanism than coarse particles. It is also observed that between 20-30% glass powder content in concrete (both as a binder and sand), a slightly higher strength can be expected at later test ages. Beyond 20-30% glass powder contents, a negative influence on the strength of cementitious materials can be expected. The adverse effect is attributed to accelerated C-S-H or C-A-S-H formation of the high alkali content of glass, the CH available for pozzolanic reaction and further hydration of binder continuously declining with recycled glass content (Juenger and Jennings, 2001; Shao et al., 2000; Zhang et al., 2000). At a high alkali content, the microstructure of C-S-H becomes heterogeneous and may negatively affect the rate of strength development in cementitious materials with high levels of glass powder content.

5. Microstructural analysis of recycled glass powder concrete

Addition of waste recycled glass has an effect on the concrete microstructure, especially the aggregate/paste interface (ITZ). SEM micrographs depicting this are shown in Figure 11. Here, hairline cracks and voids can be seen passing through these interfaces. When waste glass is used as (partial) replacement of fine aggregate, a denser matrix forms (Ali and Al-Tersawy, 2012; Bisht and Ramana, 2018). On the other hand, the addition of waste glass causes occurrence of air voids at the interface (as shown in Figure 11b). At higher percentages of waste glass addition, these negative effects become more dominant (Figure 11c-e). This is one of the causes of lower strength at higher WG percentages.

The mechanism of recycled glass powder as binder in concrete is completely different than aggregates. A study by (Du and Tan, 2017) showed that the ITZ of concrete improves when cement was partially replaced by the glass powder. A denser micro structure such as less porosity and unidentified ITZ thus strong bond between the paste and aggregates in the matrix was found in glass powder mixed concrete than reference concrete without any glass powder. The higher pozzolanic reaction of glass powder led to form more C-S-H gel and improved both mechanical and durability performance of glass powder concrete.



(a) (b) (c) (d) (e)

Figure 11. SEM micrographs of concretes containing different percentages of discarded beverage glass as fine aggregate (Bisht and Ramana, 2018): (a) 0%; (b) 18%; (c) 20%; (d) 22%; (e) 24% (measurements show dimensions of air voids formed at the interface)

6. Long term properties

Apart from fresh and hardened properties, long term behavior of concrete containing waste recycled glass is crucial for its practical application. In practice, two parameters are important: volumetric stability and long-term durability. These two are coupled, as cracking caused by e.g. restrained shrinkage may have detrimental effects on concrete durability. Long term properties of recycled glass aggregate concrete are reviewed in this section.

6.1. Drying shrinkage

The effect of glass powder content on the drying shrinkage of concrete has been extensively studied (Guo et al., 2015; Limbachiya, 2009; Shayan and Xu, 2006). In one study, different percentages of natural sand by mass were replaced by the waste glass powder in two design concrete strengths (Series 1, 30 MPa; Series 2, 40 MPa) and drying shrinkage was measured at 90 days, as shown in Figure 12a (Limbachiya, 2009). No significant difference in drying shrinkage was found for addition of glass sand powder up to 50%. (Shayan and Xu, 2006) also found that up to 20% of binder replacement by glass powder in concrete has no influence on the drying shrinkage, as shown in Figure 12b. However, more than 20% replacement of binder by glass powder causes increased shrinkage.

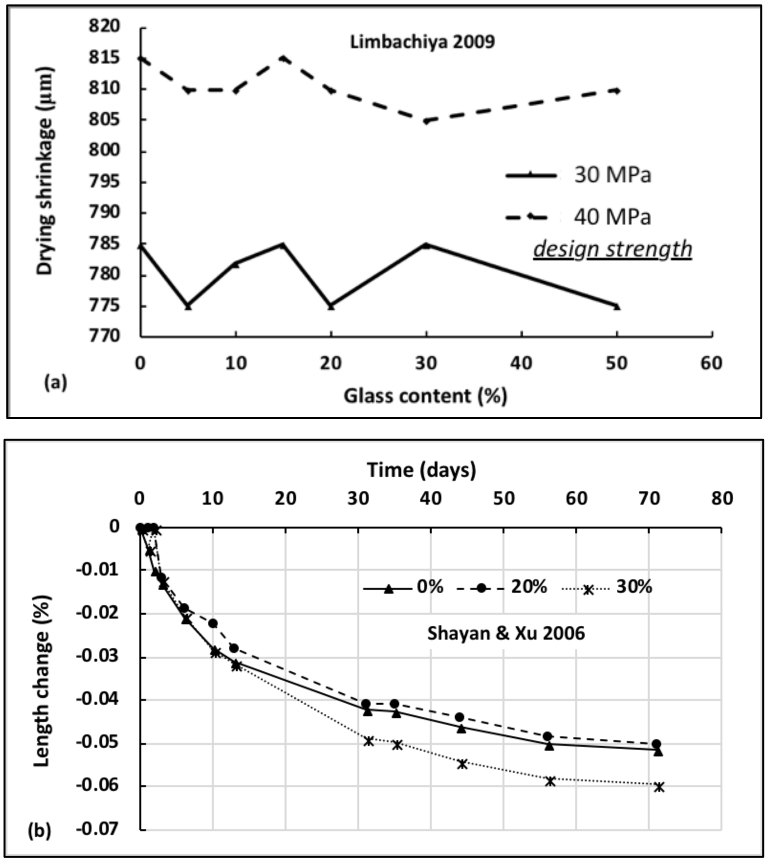


Figure 12. (a) Total drying shrinkage of concrete with different glass powder aggregate content at 90 days and (b) drying shrinkage of concrete prisms containing different waste glass content as cement replacement (Limbachiya, 2009; Shayan and Xu, 2006)

6.2 Water absorption

Use of recycled waste glass may have an effect on water absorption of concrete. As shown in Figure 13a, (Du and Tan, 2017) measured the water penetration depth in concrete where cement was partially replaced by waste glass. Lower water penetration was observed in concrete with up to 60% glass powder than the control mix. Similar findings were reported by (Parghi and Alam, 2016) with cement replacement in concrete up to 30% by glass powder as seen in Figure 13b. Pozzolanic activity of recycled waste glass plays an important role in water absorption of concrete. (Schwarz et al., 2008) reported that, at early ages (14 days), concrete with 10% waste glass had higher water absorption compared to the reference concrete. At 90 days, however, the trend was reversed, demonstrating the influence of the waste recycled glass replacement in pore structure refinement. Similar results were reported by (Nassar and Soroushian, 2012).

(Guo et al., 2015) collected post-consumer beverage glass bottles and crushed them up to a maximum size of 2 mm. The recycled waste glass sand was then used to partially replace natural sand up to 100% in steps of 25%. It was found that at the early test stage of samples (4 hrs), water sorptivity decreased significantly with increasing recycled glass content. It was concluded that the specimens with less glass content had more pores and cracks that remained unfilled, allowing faster uptake of water at the early stage (Guo et al., 2015). Overall, lower water absorption was observed with higher glass powder content, when all specimens were tested for 24 hrs.

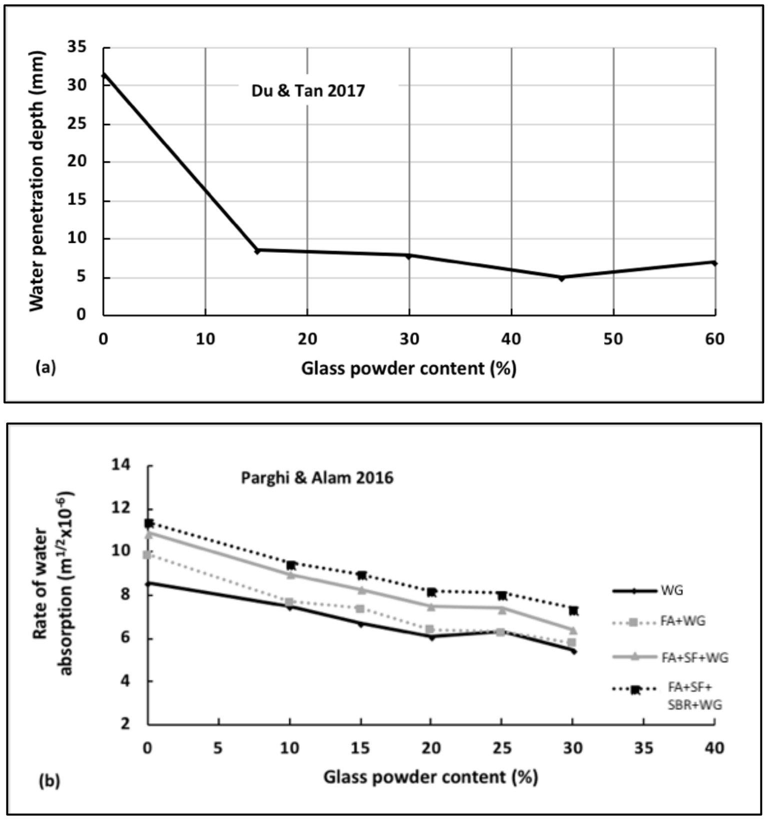


Figure 13. Influence of waste recycled glass on water absorption in concrete. (a) water penetration depth of concrete with varying amounts of glass powder; (b) rate of water absorption of recycled glass concrete after 28 days curing (note: mixtures containing WG- waste glass; FA- fly ash; SF- silica fume; SBR- styrene butadiene rubber) (Du and Tan, 2017; Parghi and Alam, 2016).

6.3. Chloride ingress

Pore structure, aggregate permeability, and the aggregate-cementitious matrix interface in recycled waste glass concrete may influence the chloride diffusivity of the composite. (Shayan and Xu, 2006) replaced 20% and 30% cement with recycled glass powder and tested cored samples collected from submersed marine exposure condition at 220 days and 380 days using a rapid chloride permeability test (RCPT). Lower charge (signifying better chloride resistance) was measured passing through the specimens with increasing glass powder content. The authors attributed the improvement in the resistivity of concrete with waste glass powder exposed to a marine environment to the concrete composition and pore solution chemistry. (Tan and Du, 2013) studied the influence of varying percentages of sand replacement with different types of glass powders on mortar mix tested using the RCPT method. Their findings are presented in Figure 14. Lower permeability of glass powder specimens contributed to the higher resistance to chloride transport, resulting in lower total charge passing. Another reason may be due to the better packing efficiency of glass powder of mortar and pozzolanic reaction which consumed more CH and improved permeability (Kou and Poon, 2009). The improvement in resistance to chloride ion penetration was also observed in self-compacting mortar with up to 100% sand replaced with glass powder after exposing to different temperatures (Guo et al., 2015). (Lee et al., 2018) also found lower chloride penetration depth and lower total charge passing capacity in concrete at 56 days of testing, when 20% of cement was replaced by glass powder. They concluded that the pozzolanic reaction and pore filler capacity of glass powder improved the resistance of concrete to chloride penetration. Improvement in chloride ion penetration and total charge passing in glass concrete was also noticed in other studies (Wang et al., 2009; Zidol et al., 2017).

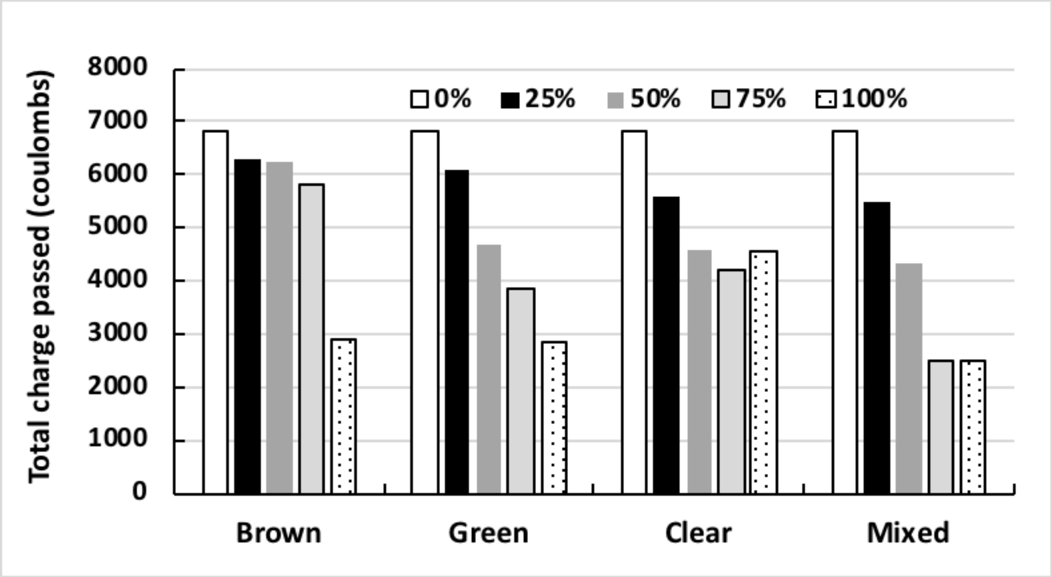


Figure 14. RCPT results of different fine glass aggregates with different percentages in mortar (Tan and Du, 2013).

6.4. Freeze-thaw attack

In cold climates, it is important that concrete is resistant to cycles of freezing and thawing. Figure 15 shows the scaling mass loss of concrete up to 50 freeze/thaw cycles where 20% of cement was replaced by waste glass powder and compared with the control mix. About 30% lower mass loss was recorded with glass powder concrete than with the control mix. Better filling effects and greater pozzolanic action of waste glass in concrete improved the performance against freeze-thaw attack. Lower mass loss was also reported by (Abendeh et al., 2015) where concrete prism specimens with different glass (as binder) content (0%, 5%, 10% and 15%) were exposed to 100, 200 and 300 freeze-thaw cycles. It was concluded that the inclusion of glass powder as binder makes concrete less thermally conductive, increased the production of C-S-H gel due to greater pozzolanic reaction leading to reduced risk of expansion due to ASR reaction and thus improved the permeability of concrete. (Al-Akhras, 2012) concluded that the resistance of glass powder (as binder) concrete to freeze-thaw damage increased with increase in the glass powder replacement level from 6% to 18%.

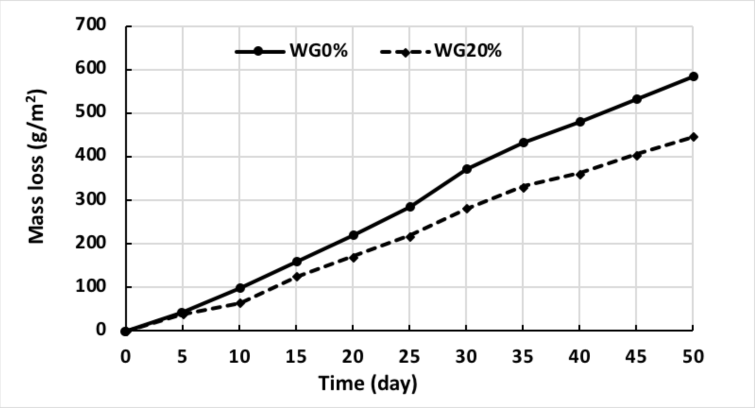


Figure 15. Mass loss of concrete without (WG0%) and with 20% (WG20%) waste glass powder subjected to freezing and thawing (Lee et al., 2018)

6.5. Carbonation and oxygen permeability

Initiation and propagation of reinforcement corrosion are associated with the presence of CO_2 and oxygen (Ho and Lewis, 1987). Therefore, resistance of concrete to carbonation and ingress of oxygen is an important durability parameter. (Sales et al., 2017) studied the influence of various types of glass powder as binder on concrete carbonation and oxygen permeability, as shown in Figure 16. For the carbonation test, after 28 days of water curing, specimens were kept in carbonation chamber for 60 days at an atmosphere of 5% CO_2, 48% relative humidity and a temperature of $27.5 \pm 2°C$. Carbonation depth increased with increasing glass powder content regardless of the glass type (see Fig 17a). Higher carbonation depth was related to lower relative humidity (48%), where it is assumed that low humidity condition could impede the diffusion of CO_2 in the pores. It is reported that carbonation accelerates when relative humidity is between 50% and 75% (De Ceukelaire and Van Nieuwenburg, 1993). Almost double carbonation depth in self-compacting concrete specimens with 10% glass powder was also observed by (Matos et al., 2016). Since recycled waste glass powder acts as a pozzolanic material in the cement matrix, it consumes calcium hydroxide (CH) in the reaction. Since CH content is lower, the CO_2 will primarily react with the C-S-H, thereby increasing the porosity of the matrix even further and speeding up the carbonation process. This is similar to the process of carbonation of blended cements, which are known to be more susceptible than ordinary Portland cements (Ngala and Page, 1997; Šavija and Luković, 2016).

Oxygen permeability found to be decreased with the increase of different glass powder content in concrete as shown in Figure 16b. This is due to the chemical compositions and the structure of silica, which favors for greater pozzolanic reaction. This reaction reduced the porosity of concrete and its permeability. Note that the specimens in Figure 16b were cured in water for 60 days, which may provide sufficient moisture for hydration of binders and improved permeability of concrete. Also, particle size was found to be a significant factor for oxygen permeability. Self-compacting concrete with 10 μm glass powder showed the best performance in oxygen permeability compared with coarser powder of 20 μm and 40 μm. This effect became more dominant with the curing time (Tariq et al., 2016).

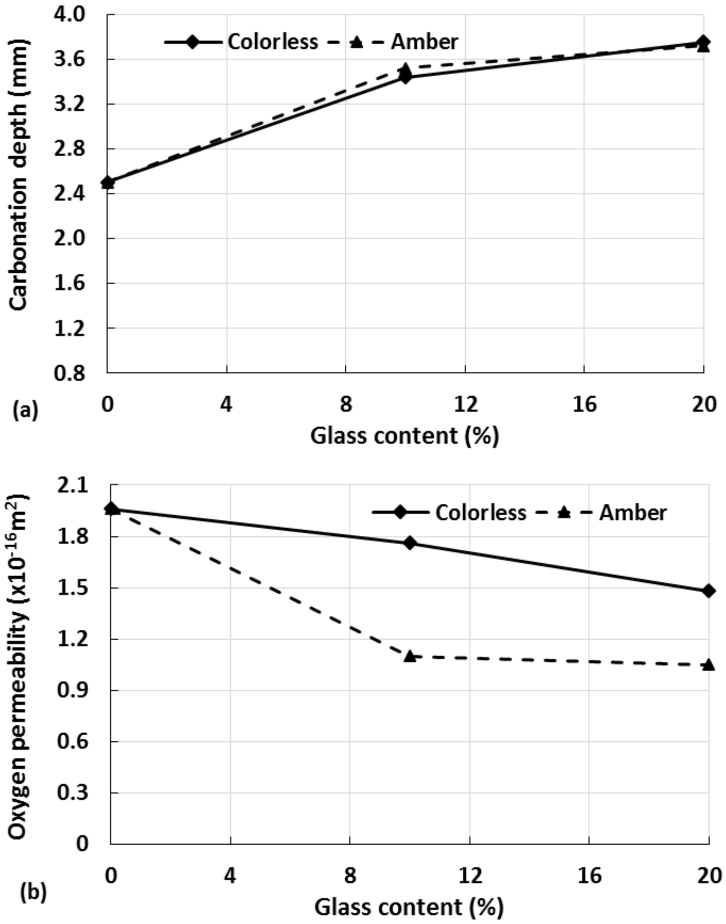


Figure 16. (a) Carbonation depth and (b) oxygen permeability of concrete with different percentages of glass powder used as binder (Sales et al., 2017).

6.6. Other durability properties

Apart from durability properties of concrete discussed above, recycled glass powder has an effect on other durability indicators as well. For example, it affects partially concrete resistivity (Matos et al., 2016), sulfate resistance (Wang, 2009), lead leaching (Romero et al., 2013), etc. (Matos et al., 2016) reported about 160% higher resistivity (unit kΩ.cm) when fine sand was replaced with 50% glass powder at 86 days. Similar behaviour was also noticed when cement was replaced by 10-20% with glass powder in concrete (Sales et al., 2017). Sulfate resistance of concrete also improved when LCD glass sand was used in concrete and it was improved with the extension of the curing age. For the inclusion of 20%-80% glass sand, about 27% to 61% less weight loss was found in waste glass concrete than reference concrete specimens (Wang, 2009). Other durability properties are scarcely studied and more research is needed to draw sound conclusions.

7. Concluding remarks

Numerous research studies have been performed in the past two decades on concrete utilizing waste recycled glass as partial replacement of aggregate or binder material. The literature clearly shows that, from a technical and engineering point of view, recycled waste glass can be utilized in concrete production. Such use has potential to: (1) find suitable use for huge quantities of waste glass that is not suitable for reuse in the glass industry and is therefore bound to be landfilled; and (2) find a more sustainable alternative to natural raw materials used in concrete, namely Portland cement and river or crushed aggregate. Nevertheless, from the presented literature study it is clear that utilization of waste recycled glass in concrete production is far from straightforward and that more research is needed before it can be applied in large quantities in practice. Based on the presented analysis, the authors were able to identify four areas where major research efforts are needed in order to achieve this:

1. *Addressing the variability of waste recycled glass and its effect on concrete properties.* It was observed that variability in terms of chemical composition (i.e. colour) and particle shape has a significant influence on concrete properties. If the influence is fundamentally understood, it would be possible to create optimal concrete mixtures (in terms of fresh,

hardened, and long-term properties) for different classes of recycled waste glass. This would, of course, need to be coupled with waste separation technologies and dependent on different steps taken in the process. For this goal to be addressed, a close cooperation between the waste recycling industry and researchers in concrete technology is needed.

2. *Optimization of mixture properties.* Research studies have shown that there seems to be a maximum amount of waste recycled glass that has no or little detrimental effect on the engineering properties (most studies put it at 20% per volume). However, engineering demands are always dependent on the application. In some cases, for example, lower strength is sufficient, and more recycled waste glass can be used in order to reduce the environmental impact of the concrete. Fundamental insights in the behaviour would enable optimizing mixture designs for each application.
3. *Combined use of waste recycled glass as cement and aggregate replacement.* It may be possible to use higher amounts of waste recycled glass if a part of both aggregate and cement could be replaced. More research is needed to test and quantify these effects.
4. *Life cycle analysis and lifecycle costing.* It is important to quantify the impact of use of waste recycled glass in concrete. From literature studies it seems that, most of the time, it is better to use recycled waste glass as partial replacement of cement than as partial replacement of fine aggregate. Furthermore, this seems more environmentally friendly, as less cement is used. However, in order to obtain a very fine particle distribution, more energy needs to be spent in milling and grinding of waste glass. In order to properly compare these effects, they need to be quantified. More research needs to be performed in this area.

The vast body of literature has showed, beyond any doubt, that concrete with recycled waste glass is a promising building material. It is already proved in some studies that finer glass particles (in micro scale) have capability to improve the hydration process (C-S-H gel) of different binders. Although glass particles have gained attention, much research is required to set a guideline for using them in cement-based materials in proper manner. Different glass types have different chemical compositions, hence different chemical reactions with binders may occur. Therefore, based on types of glass and binder, it is necessary to define the applications of their uses. Optimum content of glass particles for different applications is also necessary since random uses may not satisfy or optimize their uses in the cementitious materials. New studies are also required to gain confidence using such materials in a conservative sector like the construction industry. Additionally, introduction of waste materials into the public domain needs an evaluation and understanding of the impact they may have on the environment and human health. Finally, the cost and sustainability of waste glass in cement-based materials have not been considered here which should be the new scope of future research. Finally, it is expected that waste glass as supplementary binder or aggregates in cement-based materials can already be used in small scale pilot projects. Such pilot projects should be continuously monitored in order to, together with described research activities, increase the confidence of the construction sector in this material.

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