Waste Glass in Cement and Concretes: A Review on Characteristics and Challenges

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Abstract. Every year, the world is producing around 100 million tons of waste glass (WG), the majority of them are going to landfills that create massive environmental problems. One approach to solve this problem is to transform waste glass into construction materials. Glass is recyclable; however, the melting temperature of the glass is highly dependent on its color that requires sorting before recycling. To overcome this challenge, many researchers and end-users are using broken glass in concrete either as a binder or aggregates. While significant investigations have done in this area, however, the outcomes of these studies are scattered, and difficult to reach a firm conclusion about the effectiveness of WG in concrete. In this study, the roles of WG and its impact on microstructural and durability properties for both cement and concrete are critically reviewed. This review reveals that the amorphous silica in WG effectively participate to the hydration and geopolymerization process and improve concrete microstructural properties. This behavior of WG help to produce durable concrete against shrinkage, chemical attack, freeze-thaw action. The optimum replacement volume of binders or natural aggregates and particle size of WG need to be selected carefully to minimize the possible alkali-silica reaction. This review discusses a wide range of parameters for durability properties and challenges associated with WG concrete, which provides necessary guidelines for best practice with future research directions.

Keywords: waste glass, ASR, aggregate, durability, waste materials, glass powder, concrete, admixtures, cement replacement, partial replacement.

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INTRODUCTION

The production of concrete requires a significant volume of natural aggregates and non-eco-friendly cement. The extraction of natural river sand and stone chips for concrete construction is increasing day by day, paving us to a shortage of natural resources. The extraction of river sand causes a change in river bed level and hydrological strata, affecting the regular stream directions [1,2,3]. Furthermore, cement production requires substantial energy and emits a large amount of carbon dioxide [4,5]. It was reported that one ton of ordinary Portland cement (OPC) production can release around 0.85 ton of carbon dioxide, which ultimately causes around 5–8% of total emissions in the world [6,7,8]. Thus, dependency upon cement binders and natural aggregates hinders the development of an eco-friendly and sustainable construction sector [9]. Therefore, researchers are always welcomed in finding alternatives to these conventional ingredients.

Globally, around 130 million tons of glass are being produced each year among which approximately 100 million tons are being discarded as waste [10]. Among the WG, only 21% are being recycled [11], and the rest are going to landfill because of the variations in colour and compositions, and being broken and complex. In Australia, according to the statistics of 2019, the WG recycling rate is around 57%, and the rest of them is dumped as waste [12]. Moreover, exporting the WG from Australia is also being banned [12]. Besides, in other countries like UK, USA, Hong Kong, Singapore, the WG recycling rate is less than 50% [13,14,15]. The highest recycling rate is reported in EU (73%) [15]. Thus, a considerable amount of WG is being landfilled each year, which needs to be properly managed.

As the glass powder containing amorphous silica, thus it can be a perfect substitute for natural sand. Moreover, the high toughness and abrasion resistance nature of glass particles are helpful when used as an effective substitution of natural aggregate in cement and geopolymer concrete. Additionally, the fine glass powder is highly pozzolanic and amorphous, thus can be perfectly introduced into concrete as a partial substitution of binders [13,15]. Most of the previous researches concluded that the fine WG powder helps to increase the pozzolanic reactions in cement-based concrete and contributes to making a densely packed concrete matrix, thus provides high mechanical performances [16,17,18,19]. Additionally, the filler effects and hydraulic characteristics of WG powder also affect the strength development in WG concrete [13,20]. Moreover, glass powder can be effectively utilized as a source of silica, as a precursor or activator solution for geopolymer production. Besides, WG powder can be used as precursors, aggregates, or for developing activator solutions for geopolymer concrete. The WG powder effectively accelerates the geopolymerization process and results in better strength in the final geopolymer concrete [21].

The most common concerning factors are the high alkalinity of WG powder solution and the negative effect of expansion due to the alkali-silica reaction (ASR) gels, which is negatively affecting the strength and durability properties of concretes [22,23]. Although the risk of ASR expansion in geopolymer concretes is less than the cement concrete [24], still it is a concerning point for all researchers.

The durability of concrete is an important parameter that needs to be analyzed before applying it to any environmental exposures. The required durability properties for a typical concrete structure are resistance against shrinkage, chemical penetration/attack, high-temperature variation, freeze-thawing cycle. The dense and compact microstructure is noticed in cement and geopolymer concrete with WG powder [25,26,27]. Thus, the concretes with WG are reasonably durable against any exposure conditions. However, in-depth review in this regard is mandatory to come to any conclusions.

There are some review studies on WG incorporated concrete [28,29,30], but most of those are focused on the mechanical properties of cement-based concrete. In those published review papers, the effect of particle size and amount of glass on the physical and mechanical properties of WG concrete are described. However, the correlation between the role and reactivity of WG within the concrete and the process parameters are not analyzed in those review papers [13,31,32,33].

2. Characteristics of WG in Concrete

Waste glass can be used in concrete as a replacement for binder or substitution of inert materials. However, depending upon the role of WG in concrete and expected outcomes, the typical size of WG particles can be selected. As reported in the literature, the particle size and chemical compositions of WG are the main points that need to be carefully selected during mix design. A typical flow diagram, as shown in Figure 1, explains the size selection and activity of WG in cement concrete.

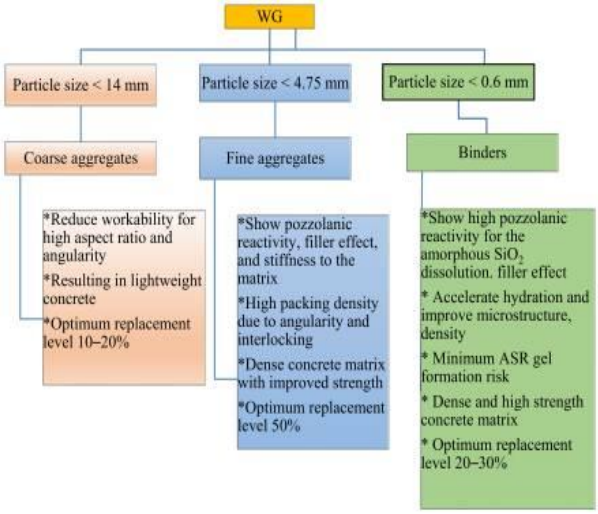

Figure 1. Roles of WG in cement concrete

The main chemical constituents of waste glass are SiO2 (71–75%), CaO (8–11%), Al2O3 (0.95–2.5%), Na2O (0–14.5%), MgO (1.6–3.6%), Fe2O3 (0.3–1%) [20,33]. Given the high SiO2 and mostly amorphous nature, WG plays a vital role in concrete, starting from the hydration of binders and up to the final state of strength development. A short induction period is observed for hydration of WG-bases binder, and consequently, the peak heat flows shortly [34,35]. This is an indication of the accelerated production of hydration products (C–S, C–S–H) and a sign of more strength development. According to ASTM C618 [36], materials with 75% pozzolanic index are relatively sufficient to include as supplementary cementitious material, where typical WG powder shows more than 80% pozzolanic index in 28 days age [37]. Observing the amount of reacted Ca(OH)2, heat flow during hydration, and final products of hydration, it can be ensured that the WG powder can undoubtedly improve the structure and strength of the concrete matrix [38].

However, to ensure high pozzolanicity, the particle size of WG powder should well below the optimum limit around 38–75 µm [39,40]. Beyond the optimum level of cement replacement, the pozzolanicity and reactivity could be decreased abruptly, as the deficiency of CaO may be started with higher-level replacement, thus resulting in a low amount of CH products [41,42]. Therefore, the inclusion of WG powder should within between 10–30% of the binder, as recommended in previous literature [41,42]. Contrary, it was reported that the early strength development of WG concrete is low.

In general, the reactivity and role of WG in cement concrete are primarily dependents on its particle size, chemical composition, and replacement level. To achieve the best performance, the threshold particle size and optimum replacement level to be designed following the pozzolanic reactivity and ASR guidelines[43-45].

Environmental Benefit of WG Concrete.

Recycling of WG as a construction material simultaneously reduces solid waste management problems, demand for landfills, and carbon footprints and problems on resource preservation [14]. The environmental impacts of PC and WG concrete were investigated by Hilton et al. [25], and they revealed 13.2% reduced environmental impacts for WG concrete compared with PC. In addition, a 20% reduced global warming potential in WG concrete is a good contribution to environmental sustainability compared to PC.

Glass-based cement produces approximately 0.17–0.42 gCO2/gWG powder, resulting in up to an 83% reduction in CO2 production compared with OPC [46]. Similar results were obtained from the study of Patel et al. [47], who reported that eutrophication, ozone depletion, the energy embodied, acidification rate, photochemical instability, and WGP reduce with the increasing content of WG in a cementitious mixture; a significantly high environmental benefit is ensured in comparison with control groups. These studies represented the environmental benefit of WG concrete. The recycling of WG could be a major source of raw materials and can facilitate saving natural resources and nature. The total solid waste management system will be benefitted, and a healthier environment can be expected in the future. However, the long-term serviceability, carbon footprints, environmental impact assessment is needed to be done on WG base cement and geopolymer concrete to rate this composite as a sustainable material.

Challenges in WG Concrete and Remedies

ASR Expansion in WG-Based Concrete

One of the major challenges of WG concrete is the presence of high silica, and alkali content in glass and cement causes the ASR, which could cause expansive gel formation [22,23,48]. The ASR expansion is accelerated with the presence of Na and K ions [48]. The ASR gel produces expansive stresses along the reaction zone, which may cross the limit of the tensile strength of concrete; thus, cracks can be developed. Thus, an additional pre is created for penetration and absorption of the external solution and consequently deteriorates the durability.

However, the risk associated with ASR gel formation can be minimized using finer WG powder instead of coarse glass aggregates. The critical particle size of WG powder is margined by researchers as 1–1.18 mm [39,49]. However, some of the literature marked 0.6 mm particle size as a safe limit [50]. For example, the replacement of 70% fine aggregates with 36–50 µm particles of WG powder in concrete did not exhibit any harmful ASR expansion in previous research [51]. Moreover, researchers concluded that the glass sand particle size below 4.5 mm without any surface cracks does not show any expansive ASR gel formation for up to 40% sand replacement level [52]. Micro-cracks in the WG particle are not desirable, as they create pores and store solutions for future reaction, and consequently, ASR reactivity increases. This ensures that only particle size is not solely affecting the ASR risk; some other factors like the content of WG, nature of cement and aggregates, mix ratio, the water-cement ratio of the concrete mix also influencing ASR gel formation. Therefore, depending upon the chemical properties of WG and maintaining an optimum level of replacement and particle size, ASR risk can be minimized. However, properly graded WG powders can enhance the density and reduces the ASR expansion. Besides, the presence of lithium ions suppresses the expansion by changing the ASR gel composition [53,54].

Low Adhesion between WG and Cement-Paste

Low adhesion between cement paste and WG is another major issue, which is a reason for strength reduction in concrete [55]. Porous and weak ITZ can develop from the weak adhesion of WG powder and binder paste [56]. The main causes of low adhesion are the smooth surface of WG and micro-crack within particles [57]. A rough surface of WG can provide interlocking with cement paste, but excessive roughness could generate a porous structure. Well-graded glass particles are suitable for high packing density. The pretreatment of WG using heat or polymer resin can increase bond strength with bonder paste, which needs further investigation to be established. The mechanical properties and durability of WG concrete can degrade if micro-cracks are present in WG. The preparation of WG powder and aggregate should be under supervision.

CONCLUSIONS

This review includes a critical discussion on the current research progress of cement containing waste glass. WG addition significantly altering the microstructure and product characteristics of concrete; thus its durability needs to be investigated broadly. Current research progress is not sufficient to address significant guidelines and examples of durable WG-based concrete. The following conclusions are drawn from the state-of-the-art review:

- The waste glass acts as a rich source of silica in concrete. Thus the pozzolanic activity increases, hydration product formation increases, and microstructures get improved after the addition of fine WG in concrete. To optimize the silica dissolution and pozzolanicity, the optimum particle size of WG must be maintained as recommended around 38–75 µm.
- Very limited research has been conducted on the durability of WG-based concrete; thus the recommendation for optimum level of WG inclusion replacing binders or aggregates in concrete remains an open research question. However, based on current knowledge, it is estimated that the optimum level of binder replacement could be around 20–30%, and this range is approximately 30–50% for fine aggregate. Beyond the optimum level of replacement, a porous concrete matrix will result in lower durability.

- The most critical issue of glass incorporation is the ASR and expansive gel formation within concrete. This issue is less critical for geopolymers compared with cement concrete. The ASR expansion can be minimized by using fine WG powder (<75 µm), replacing cement instead of aggregates, and adding recommended by-products, such as silica fume, fly ash, and slag optimum level of around 10–30%.

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Відходи скла в цементі та бетонах: огляд характеристик та проблематик

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Анотація. Щорічно у світі виробляється приблизно 100 мільйонів тонн відходів скла (ВС), більшість з яких відправляється на сміттєзвалище, що створює масштабні проблеми для навколишнього середовища. Одним із підходів до вирішення цієї проблеми є використання відходів скла ну виробництві будівельних матеріалів. Скло піддається переробці, однак температура плавлення скла значно залежить від його кольору, що вимагає сортування перед переробкою. Для подолання цієї проблеми багато дослідників та кінцеві користувачі використовують подрібнене скло в бетоні як в'яжучий матеріал чи заповнювач. Хоча багато досліджень було проведено в цій області, результати цих дослідів різняться і складно дати чіткий висновок щодо ефективності використання ВС у бетоні. У цьому огляді розглядаються ролі ВС та їх вплив на мікроструктурні властивості як цементів так і бетонів. Огляд показує, що аморфний діоксид кремнію у ВС ефективно бере участь у процесах гідратації та поліпшує мікроструктурні властивості бетону. Ця властивість ВС сприяє виробництву довговічного бетону стійкого до усадки, хімічного впливу, морозостійкого. Оптимальний об'єм заміщення в'яжучих матеріалів або природних заповнювачів та розмір часток ВС потрібно обирати обережно для мінімізації можливої лужно-кремнеземистої реакції. У цьому огляді обговорюються різноманітні параметри та виклики, пов'язані з ВС у бетоні, що надає необхідні рекомендації для найкращої практики та напрямки майбутніх досліджень.

Ключові слова: відходи скла, лужно-кремнезомиста реакція (ASR), заповнювач, довговічність, відходи матеріалів, скляний порошок, бетон, добавки, заміна цементу, часткова заміна.