Recycling of End-of-Life Photovoltaic Panels Glass into Concrete

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Abstract: Australian installation of photovoltaic (PV) solar panels has grown considerably in the past decades. Adopting these solar panel systems enables us to transition to clean energy and reduce carbon footprint. However, the enormous quantity of installed PV panels has led to an issue concerning the disposal of end-of-life (EoL) PV panels. This paper thus explores the viability of mortar containing PV glass as fine aggregate by investigating its compressive strength and the potential to alkali silica reaction (ASR). The replacement ratios were 20%, 50% and 80% of natural sands. The results indicate that, up to 80% natural sands can be replaced by PV glass without significantly detrimental impact on the mechanical performance. Regarding ASR, the results show that it is safe to replace up to 50% natural sands with PV glass.

Keywords: recycled PV glass; sand replacement; compressive strength; workability; alkali silica reaction.

Introduction

The Clean Energy Regulator in Australia has reported that Australian households possess one of the highest numbers of rooftop PV installations in the world. According to data as of 31 July 2021, the total number of small-scale PV installations has surpassed 2.8 million across the nation, with over 90% of these installations completed after 2010. While the quality and durability of PV panel technology continues to improve, the average lifespan of existing systems is estimated to be between 20-25 years [1]. PV panels consist of multiple layers of material contained within a metal frame (as depicted in Figure 1), with the PV cell layer located beneath a protective glass layer consisting of various silicone polymers [2].

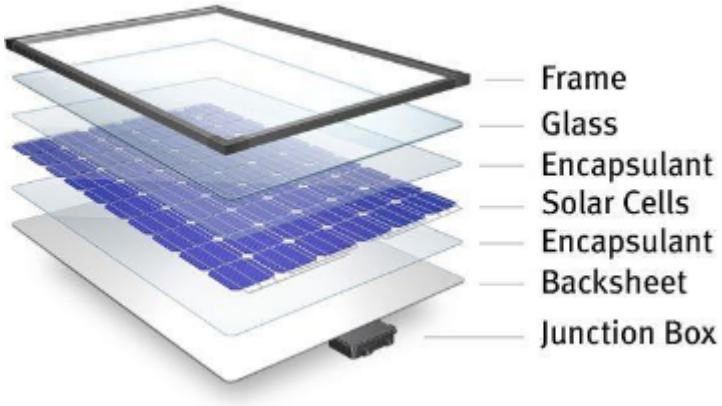

Figure 1: Main components of a PV Panel [3]

It has been predicted that the amount of PV waste generated globally will reach 78 million tonnes per year by 2050 [4]. Although the production cost of PV panels is currently low, recycling materials for use in new panels is not economically viable [5]. This means that a significant amount of PV panels will end up in landfills in the coming decades. While in use, PV panels are subject to various environmental stressors such as dust and hailstorms, which can cause physical damage and lead to glass breakage and loosened frames. Other factors that contribute to the deterioration of PV panels include UV radiation, corrosion, non-

functional modules, moisture build-up between layers caused by humidity and local pollutants, encapsulant discoloration and delamination, ultimately leading to reduced stability [6, 7].

PV panels can also become defective during the manufacturing process, damaged during shipping and installation. These factors, in addition to the natural wear and tear of components over time, ultimately lead to PV panels reaching their "end-of-life" (EoL) [6]. However, managing the disposal of EoL PV panels is complicated by the absence of a consistent recycling framework nationwide, as waste collection services rely on regional agreements with industry partners. This results in higher costs associated with disassembling, sorting, and recycling complex materials relative to the low volume of EoL PV panels available for recycling at any given time [8].

The Waste Electrical and Electronic Equipment (WEEE) directive governs the collection and recycling of EoL PV panels in the European Union (EU). EoL PV panels are sorted into the "discarded electronic device" category and at least 80% of the panel is recycled [9, 10]. In Europe, the cost of recycling PV panels is factored into the manufacturing fee, placing responsibility on manufacturers to ensure that units do not end up in landfills [9]. Conversely, in the United States (US), recycling programs are market-driven and managed by private companies and local councils, incurring additional costs [11].

The adoption of solar panels in Australia through the Renewable Energy Target (RET) program has been primarily concentrated on small-scale residential installations. This is evident from the substantial number of PV systems installed on rooftops, with Queensland alone having 40.4% of homes equipped with PV systems [12]. Moreover, the growing body of research, such as that conducted by Mahmoudi et al. [13], highlights the urgency of developing a local solution for managing the increasing volume of solar panel waste in Australia.

Due to the absence of a national framework, the management and disposal of solar waste in Australia vary across states and territories. Presently, private companies are responsible for dismantling and reclaiming the aluminium frame and junction box of the solar panels, while inverters can be recycled via an e-waste collection agency [14]. However, to address the issue of solar waste in Australia, industry-led and co-regulatory stewardship has been advocated. Elecsome has worked on the establishment of a PV panel upcycling plant, led by Ojas Group [15].

To address the issue of end-of-life PV panels and sand shortages for concrete, incorporating solar PV glass into concrete could be a potential solution. In separate studies conducted by Sadati and Khayat [17] and Du and Tan [18] , the impact of PV glass on concrete was investigated. The research revealed that when more than 30% of cement was replaced with PV glass, there was a reduction in early-age strength, with reductions exceeding 35%. The effect on later compressive strength when using PV glass in concrete was inconclusive in both studies, with some showing a small increase and others showing a small decrease. However, these results only apply to cement replacement. Another study by Tamanna et al. [19] explored replacing sand with PV glass at intervals of 20%. When a 20% replacement of sand with PV glass was used, it resulted in a 7% increase in 28-day strength. However, when the replacements were increased to 40% and 60%, the strength of the concrete decreased by 8% and 11%, respectively.

In a study by Stehlík et al. [10], the feasibility of using recycled PV panel glass as a partial or complete substitute for aggregate in concrete masonry was investigated. The researchers found that a concrete mix with glass aggregate of 1-2mm and 4-8mm, along with coarse aggregate, showed better performance in compressive strength, reaching 21.8MPa. Meanwhile, the counterpart with an equal amount of cement/water but a varying proportion of PV glass ranging from 1-2mm and 4-8mm and without the coarse aggregate reached a maximum of 11.7MPa. Although it had a lower density, this mix showed a potential solution for lightweight aerated concrete blocks suitable for load-bearing walls.

In a study conducted by Cheng [20], the impact of PV panel waste on the durability and mechanical properties of cement-based materials were investigated. The research involved exploring various mix ratios, which involved replacing fine aggregate with PV panel waste products and adjusting the cement content. The results showed that incorporating small amounts of PV panel waste as a replacement for fine aggregate (10-20%) and cement (5-10%) improved the compressive strength during the curing process. However, higher proportions of both materials only showed an increased compressive strength in samples aged longer periods [20]. Furthermore, the study observed that the addition of PV glass enhanced the workability of the mixture [20].

Mariaková and colleagues [21] conducted a recent study on the use of waste glass, including PV panel waste, as a replacement for fine aggregates in high-performance concrete (HPC). They compared the flowability, tensile bending strength, and compressive strength of a consistent mix ratio for HPC while using different types of glass (grinded glass, milled glass, PV glass) in each mix. However, cracks in the sample prevented further testing of the PV panel mixture, which was then optimized for further analysis. The results indicated that the workability was highest for the mix with PV panel waste, but its tensile and flexural strength was the lowest among the reference design. The addition of waste glass increased the visible pores in the samples, and the compressive strength reached only 42.2MPa, compared to the reference strength of 124.3MPa. The study concluded that this may have been due to the chemical composition of the PV panels used.

Following on from the research, it is illustrated that there has been limited investigation into the use of PV panel waste in concrete production, which highlights the necessity for further exploration. The present study aims to address that gap by preparing different mixes of cement mortar with varying percentages of PV glass, assessing their workability using the slump test and evaluating their compressive strength after a specific curing period. Additionally, the study will investigate the alkali silica reaction (ASR) of the cement mortar to ensure that the inclusion of PV glass does not have a detrimental impact on the material's durability. The findings of this study have the potential to contribute to the development of more sustainable and energy-efficient building materials.

Materials and Methods

The study used General Portland Cement, conforming to AS 3972 (2010), and Class-F fly ash classified according to ASTM C618, 2014, for mixes containing fly ash. PV glass was obtained using a patented process that crushes glass by enforcing collisions through high-speed vortex. The particle size distribution (PSD) of fine aggregates and glass fines was determined using Mastersizer 3000 equipment, and the PSD curves for glasses are shown in Figure 2.

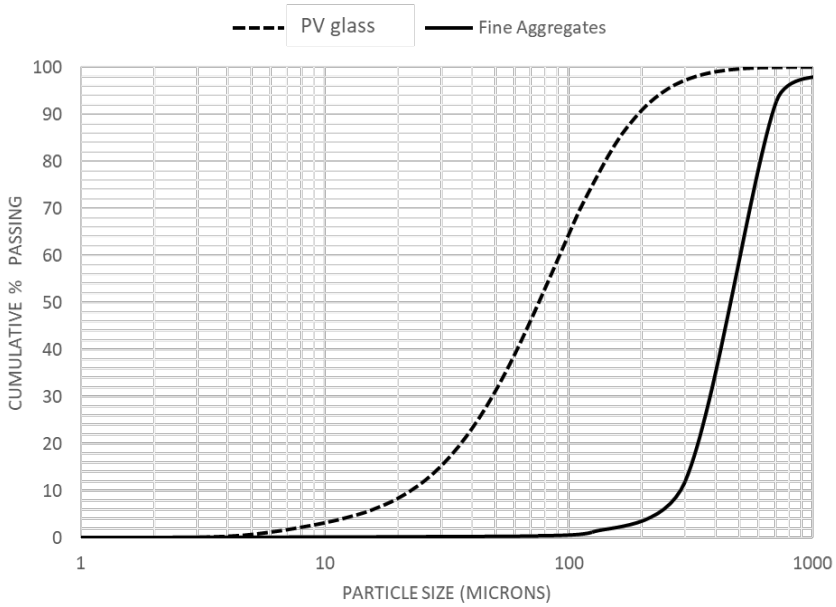

Figure 2: Particle Size distributions of fine aggregates and glass fines

Mortar cube specimens were prepared for compression testing as per AS 1012.9:2014. The specimens cast were of 50 mm × 50 mm × 50 mm size. The samples were de-moulded after 1 day and were cured in saturated lime water until the test day was reached. Compressive strength was measured using a Technotest machine. Three samples each were tested at 3 days, 7 days and 28 days, and average values are reported. Mortar bar specimens were cast for ASR test in accordance with AS 1141.60.1. The dimension of bars is 285 mm × 25 mm × 25 mm, excluding the stainless-steel studs at both ends. The bars were de-moulded 1 day after casting, following by 1 day in saturated lime water at room temperature and a further day in lime water at 80°C. Zero reading of the length was taken after this and then the bars were submersed into 1M NaOH solution for the accelerating process. Further readings were taken at 1, 3, 7, 14, 21 days to show the expansion of the bars.

The mix design of the mortar used in the study is shown in Table 2.

Table 1 Mix design of the mortar containing PV glass.

Sample ID	Cement (g)	Fly ash (g)	Sands (g)	Glass (g)	Water (g)	Superplasticizer (g)
Reference	420	180	1652	0	330	4.2
PVG20	420	180	1321	331	330	7
PVG50	420	180	826	826	330	6
PVG80	420	180	331	1321	330	8

Results and Analysis

Workability

Figure 3 and **Table 2** show the results of the slump test among the four mixes. All the fresh paste exhibited desirable workability with 30-40 mm slump values out of the total height of 76 mm. Also, there was no obvious bleeding or segregation found in the paste.

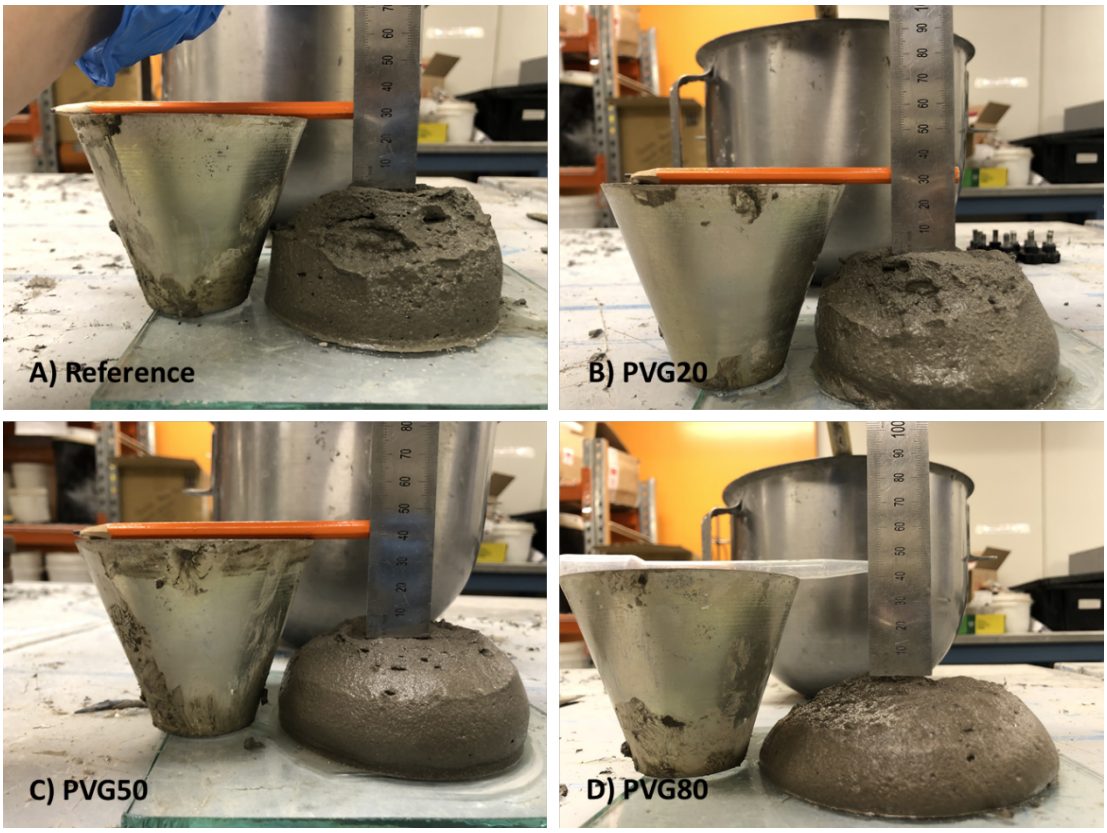

Figure 3 Slump tests of different mixes: A) reference, B) PVG20, C) PVG50, and D) PVG80.

Different dosages of superplasticizer were used in each mix to achieve a similar slump value. The results in **Table 2** indicate that the addition of PV glass fines in mortar mixes required more superplasticizer compared with the reference mix without glass fines. This finding was consistent with the literature [22]. However, as for the trend amongst the changing content of glass fines, the results differ from the finding from literature that the workability of mortar/concrete weakens as the ratio of glass fines increases [23]. As shown in **Table 3**, the PVG20 mixture consumed 7 g superplasticizer to reach the slump of 30 mm, while the PVG50 with the slump of 40 mm only used 6 g. When the replacement ratio increased to 80%, 8 g superplasticizer was required to achieve the slump of 40 mm, higher than the PVG50 mixture. This interesting observation can be attributed to the impurity within the PV glass fines. Further microstructural research needs to be conducted to find out the reason.

Table 2 Slump values of all four mixes.

Samples	Superplasticizer (g)	Slump (mm)
Reference	4.2	30
PVG20	7	30
PVG50	6	40
PVG80	8	40

Compressive strength

Figure 4 shows the result of compressive strength of all the four groups of samples. Surprisingly, the PVG20 samples exhibited higher compressive strength than the reference mortar at both 3, 7 and 28 days. It is possible that the addition of PV glass fines in the PVG20 mixture provided a denser packing of particles, resulting in improved interparticle contact and higher strength. It could also be due to the chemical composition of the PV glass fines, which may have had a positive effect on the hydration process of the

cement. Further research would be needed to fully understand the mechanisms behind this observation. Although the strength of PVG50 and PVG80 were found to be lower than the reference, the values are still comparable. This finding demonstrates the feasibility of incorporating PV glass fines into mortar and concrete.

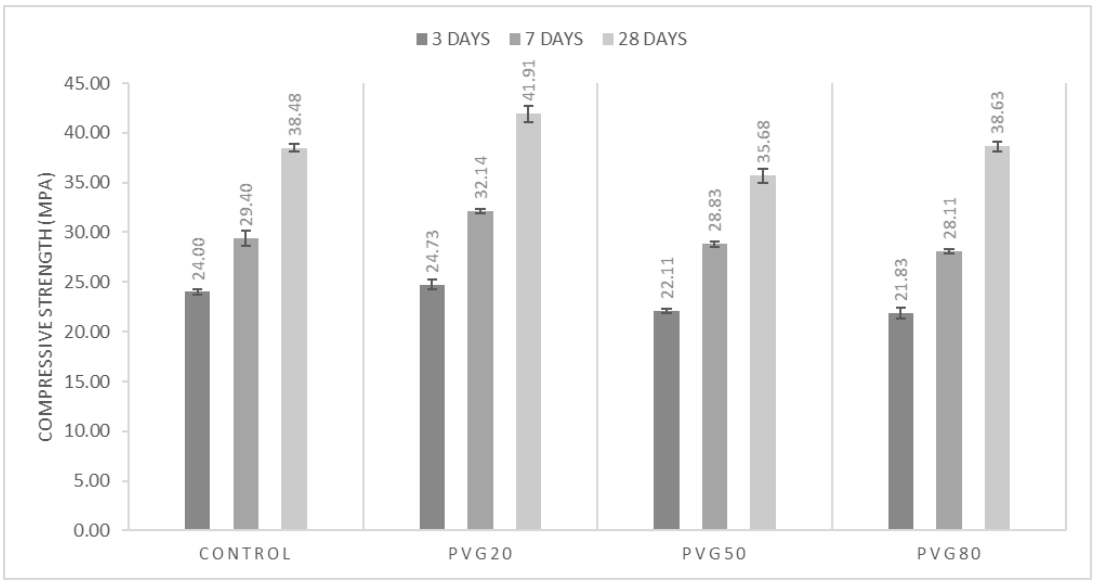

Figure 4 Compressive strength of mortar samples at the age of 3, 7 and 28 days.

Potential alkali-silica reaction

According to ASTM C1260, the expansion less than 0.1% after 14-day heated-submersion are indicative of innocuous behaviour regarding ASR. When the expansion is beyond 0.2%, the aggregate is deemed as alkali-silica reactive aggregate. For the expansion between 0.1% and 0.2%, particular attention shall be exercised to monitor and suppress the potential ASR of the aggregate.

The ASR testing results are shown in **Figure 5**. It is clear that all the samples containing PV glass show innocuous behaviour, possessing the expansion rates less than 0.1% after 14-day submersion. This finding can be attributed to the addition of fly ash, which suppresses the potential alkali-silica reaction by its pozzolanic property. Nonetheless, the data also show that the expansion of samples increases as the PV glass replacement ratio rises. The samples with 50% glass replacement doubles relative to the control, and the expansion of the samples containing 80% glass is close to the innocuous limit of ASR. These results suggest that it can be considered safe to replace up to 50% sands with PV glass fines. The ratio of 80% may also be acceptable but the mix should be improved to mitigate the ASR of the PV glass.

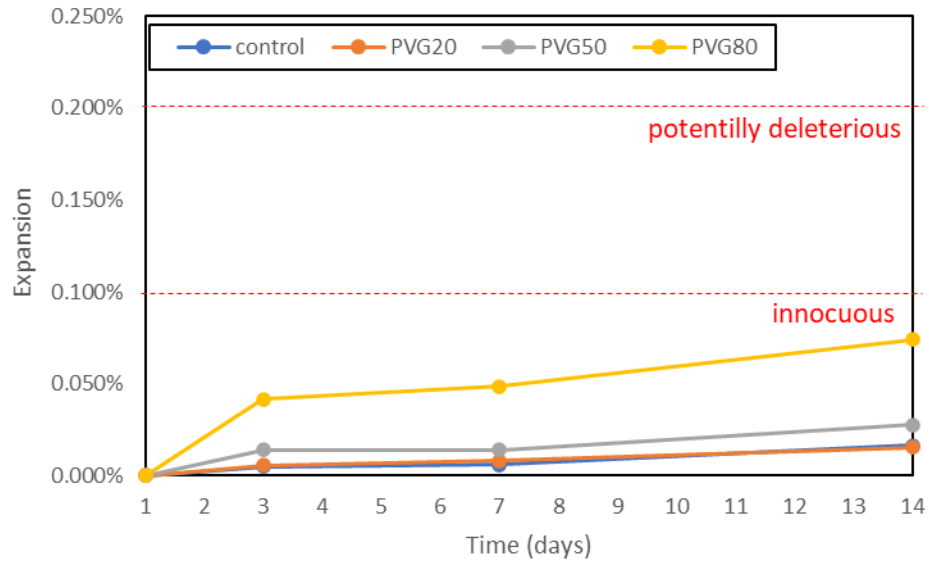

Figure 5 Expansion of control and PV glass samples after ASR testing.

Conclusions

In conclusion, the study demonstrated the feasibility of incorporating PV glass fines in mortar mixes. All the fresh paste exhibited desirable workability with 30-40 mm slump values, and there was no obvious bleeding or segregation found in the paste. The addition of PV glass fines in the mixes required more superplasticizer compared to the reference mix without glass fines. The PVG20 mixture exhibited higher compressive strength than the reference mortar at both 3, 7, and 28 days, which could be due to the denser packing of particles and/or the positive effect of the chemical composition of the PV glass fines on the hydration process of the cement. The strength of PVG50 and PVG80 were found to be lower than the reference, but still comparable. All the samples containing PV glass showed innocuous behavior regarding ASR, with expansion rates less than 0.1% after 14-day submersion, which can be attributed to the addition of fly ash. However, the expansion of samples increases as the PV glass replacement ratio rises, with the expansion of the samples containing 80% glass close to the innocuous limit of ASR. The study suggests that replacing up to 50% sands with PV glass fines can be considered safe, but the mix should be improved to mitigate the ASR of the PV glass if the replacement ratio is 80%. Further research is needed to fully understand the mechanisms behind the observed results.

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