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Review

Applications of Solar Panel Waste in Pavement Construction—An Overview

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Abstract: Waste from used solar panels will be a worldwide problem in the near future mainly due to the strong uptake in solar energy and the necessity of disposing solar panel systems at the end–of–life stage, as these materials are hazardous. While new techniques and strategies are often investigated to manage the end–of–life of solar panels effectively, there is huge potential in recycling and reusing solar panel waste as components for alternate products. Numerous studies have been conducted on using alternate materials instead of conventional materials in pavement construction. The current study presents a detailed review and a discussion on using solar panel waste materials in pavement construction. The findings present opportunities to use different solar panel waste materials such as glass, aluminium (Al), silicon (Si), and polymer waste as potential replacement materials in various types of pavement construction. The study also presents the current progress and future focus on experimental developments in pavements with solar panel waste to benchmark short–term and long–term characteristics. Finally, the review discusses the impediments that restrict and the drivers that can facilitate the implementation of solar panel waste in pavement construction. The main findings from this review can be used as a quantitative foundation to facilitate decisions on using different solar panel waste materials in pavement construction applications. Furthermore, such findings will also be beneficial for policymakers and industry stakeholders to implement effective supply chain strategies for promoting solar panel waste as a potential pavement construction material.

Keywords: solar panel waste; waste utilization; recycling of materials; pavement construction

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1. Introduction

Rapid population growth and uptake of technologies due to industrialization have intensified energy consumption across the globe. Traditional methods such as coal–based electricity production are the leading form of electricity generation despite being known for the highest carbon emissions per kWh [1]. This is mainly due to the low cost of electricity production, simple conversion processes and easy access to raw materials. Owing to these enormous demands in energy consumption and the perceived environmental impacts, industries, and researchers have experimented with several alternative energy sources that are efficient and environmentally friendly. Solar power is such a form of renewable energy, and it offers several advantages including safety, conversion efficiencies, reliability, and minimised environmental impacts due to cleaner production technologies [2]. Despite the high initial costs, including installation, there is an enormous market potential for solar energy, i.e., using photovoltaic (PV) energy in most developed countries such as the United States, Japan, and Australia [2]. This is mainly due to indirect economic benefits through the observed life–cycle cost savings, government rebates, and increases in asset values. With the commitments to "affordable and clean energy" in the United Nations Sustainability Development Goals (SDGs), it is highly likely that solar power will be the predominant renewable energy type in the near future [3].

One governing concern of solar energy is the end–of–life (EOL) management of solar panels, which are recognised as hazardous waste. Solar panels have a relatively long life cycle of around 30 years and were not a major waste issue during the initial implementation and development phases. However, with the strong uptake and reach of the first EOL cycle since its first implementation, the accumulation of solar panel waste is becoming a serious concern. According to a recent publication, in 2047, Australia will accrue about 1 million tonnes of solar panel waste, which is equivalent to 19 Sydney Harbour Bridges, which further rationalizes the magnitude of the problem [4]. Moreover, due to government incentives for upgrades and replacements, these panels are often completely replaced after about 12–15 years of life cycle even with only minor damage to some panels [2]. This could lead to further acceleration in the waste accumulation of solar panels. The optimum solution would be to facilitate the complete or partial recycling of the panel through the recovery of materials, which can reduce the costs of solar panel production. However, currently, recycling is a small portion of solar panel EOL management and they often end up in huge piles of E–waste as landfill waste. Therefore, every attempt to divert any quantity of solar panel waste from landfills would be considered a benefit and could be used as a promotional response to the upsurge in solar energy use, highlighting the life–cycle benefits.

Construction is one of the leading energy–intensive industries mainly due to the excessive virgin material usage [5,6]. Therefore, both industries and academic researchers are continuously searching for ways to partially or completely replace virgin materials in construction materials [7,8]. Alternative pavement materials replacing virgin materials in both flexible and rigid pavements are widely researched across the world, both as an environmentally friendly and cost–effective practice [9–11]. Using composite waste materials from solar panel waste as a roadway subbase material can be an effective solution to the growing concern regarding solar panel waste. This study aims to provide a contemporary review of the potential applications of solar panels in pavement construction applications. The review also intends to present qualitative and semi–quantitative findings based on previous studies and benchmark future research directions. Furthermore, the findings of the study are also important to policy and industry decision makers in understanding the future opportunities to benchmark the sustainable uses of solar panels over their life cycles.

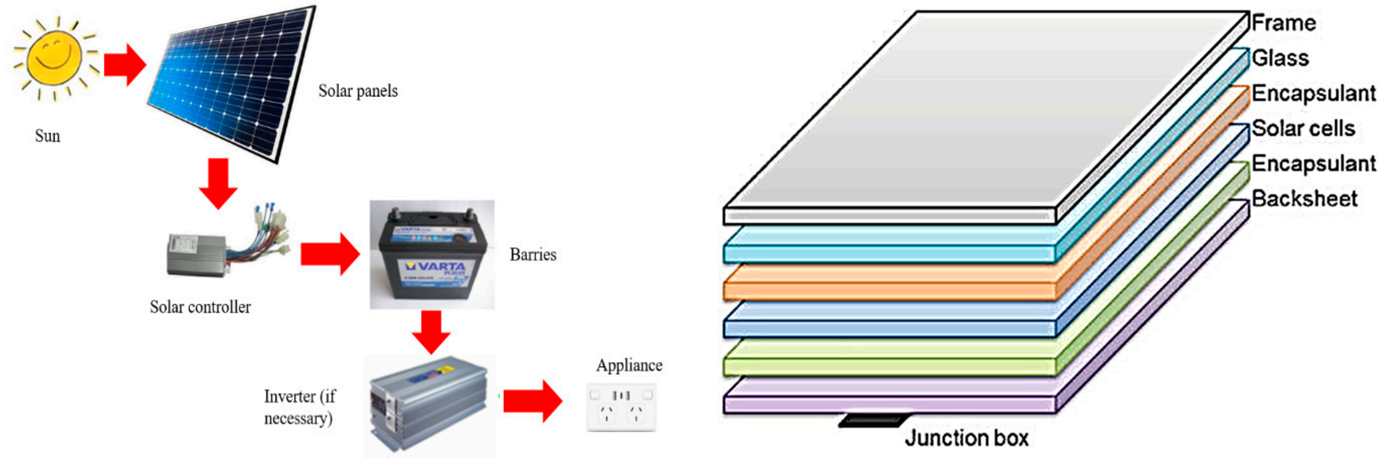
2. Research Methodology

This review study aims to undertake a review investigating the potential of using solar panel waste constituents in pavement construction applications, including concrete and asphalt pavements. A detailed review of the relevant literature precedents is conducted to understand the composition of solar panel systems and identify the potential waste materials that can be effectively used as raw construction materials for pavement. The review study then explores the possibilities of using different material constituents of a waste solar panel as a material replacement in concrete and asphalt pavement construction, focusing on mechanical properties. Subsequently, the review focuses on previous studies that have used various similar waste constituents in different types of pavement construction, with a view to obtaining an understanding of the potential behaviour and future research considerations. Finally, the study discusses barriers and key success factors for using solar panel waste in pavement construction with a focus on future research directions. These findings aim to inform both industry stakeholders and research communities on commercialisation aspects and research directions to improve the sustainability aspect of the product.

3. Composition and Material Properties of a Solar Panel

In this section, the material composition of solar panels is introduced. The environmental hazard of solar panel waste and the end–of–life (EOL) management of solar panel materials is also introduced. The section shows the benefits of recycling wasted solar panels in pavement construction to eliminate these environmental hazards.

A typical solar energy system consists of a solar panel, a solar controller, an inverter, and a group of batteries, with the configuration shown in Figure 1a [2,12]. Effectively, a solar panel (also known as a photovoltaic or a PV module) converts solar radiation into electrical energy. The solar controller regulates the voltage and current to prevent overcharging batteries. The battery group stores the energies, and the inverter converts the direct current into alternate current to use in the household [2]. A solar panel element is the most critical component of the solar energy system, and there are three main types of this component [13]. *Crystalline silicon (c–Si)* is the most common solar panel type used in the commercial market, which can be either monocrystalline or multi–crystalline. The thin–film solar panel consists of amorphous silicon, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS). Concentrator phonotactic solar panels can be dye–sensitized, organic, or hybrid panels. Dye–sensitized panels consist of cells with light–absorbing dye and a metal oxide semiconductor that carries the electric current. C–Si solar panels are extensively used in the market, with a share of over 95% of total solar panel usage. while thin–film and concentrator phonotactics account for around 4% and 0.3%, respectively [2,14]. Due to current excessive usage and the potentially high possibility of waste collection in the future, only the application of waste c–Si panels is considered in this review. It is also essential to understand the composition of c–Si panels to investigate future recycling and reuse options for solar panel waste. Figure 1b illustrates the key components of a c–Si solar panel, which includes aluminium (Al) frames, glasses (tempered glass), polymer (encapsulant and back sheet foil), solar cells, and a junction box [15,16].



(**a**) (**b**)

Figure 1. Solar energy system configuration and composition of a c–Si panel [2,17]. (**a**) Configuration of solar energy system; (**b**) composition of c–Si panel.

Solar cells are the most critical part of the panels; they generate energy and are composed of a silicon (Si) wafer, a silver (Ag) electrode on the front side, and an Al electrode on the rear side. The cells are electrically interconnected (with tabbing) by copper (Cu) wires, creating a string of cells in a series (60 or 72 cells are the standard numbers that are generally used), which assemble into modules [2,17]. The weight percentage of the material in solar panels and their average market values are summarized in Table 1. The results indicate that solar panels are mainly made out of glass (74–76%), polymer (10%), aluminium (8–10%), and silicon (3–5%) [14,16]. These four materials are the dominant material type in solar panels; therefore, potential applications of these waste constituents in pavements would lead to sustainable practices [14].

Table 1. Material composition of c–Si panels.

No	Material	Weight (%)	Price, USD	Reference/s
1	Glass	74–76	0.10/kg	[14,16]
2	Polymer (Encapsulant and back sheet foil)	10	37/m^2 (encapsulant) 20/m^2 (back–sheet foil)	[18,19]
3	Al	8–10	2/kg	
4	Si	3–5	0.95/kg	
5	Cu	0.6–1	5.00/kg	[14,16]
6	Ag	0.06–0.1	574.23/kg	
7	Others (Sn, Pb, etc.)	<0.1	–	

The wider application of solar panels also leads to waste accumulation at the end–of–life (service life 25–30 years) [20,21]. For example, Paiano [21] predicted that the total waste generated by solar panels in 2050 (1,783,268 tons) could be 2125 times the waste generated in 2022 (839 tons) in Italy. Similarly, KEI [22] estimated that the accumulative solar panel waste could be up to 820,000 tons in Korea by 2040. This waste contains environmentally hazardous substances, making its management a challenging task. Specifically, crushed glass powders can cause the lung condition known as silicosis when inhaled [23]. Waste glass also deteriorates in the atmosphere, leading to calcium leaching [24]. Additionally, polymer fractions are a potential pollutant that causes cancer and neurological damage, and it can impair the development of reproductive systems [25]. Aluminium waste can damage the quality of ground and surface waters [26,27]. It can also cause loss of plasma– and hemolymph ions, leading to regulatory failure in gill–breathing animals such as fish and invertebrates [28,29]. Silicon (Si), copper (Cu), silver (Ag), tin (Sn), and lead (Pb) in the waste can also be toxic and harmful to the environment [30]. It is important to recycle these wastes considering their environmental impact and market values [31].

The end–of–life (EOL) management of solar panels is evolving, and it considers the harmful effects and market values of substances in the waste. The EOL management of solar panels is summarized in Figure 2. Solar panels, including their junction boxes and cables, are cleaned as a general step. Visual inspection is then carried out to detect any damage to the panels. Subsequently, three treatments can be carried out: mechanical treatment (also called physical treatment), chemical treatment, and thermal treatment [16]. Mechanical treatment is a physical separation, where crushing and seizing processes are applied to the PV panel modules [13,32]. Prior to this treatment, the frame, electrical cables, and junction box are removed. The remaining parts of the solar panels are crushed and refined to pieces of 4 to 5 mm in size using a hammer mill. During the refinement, glass and polymers are naturally separated from other large pieces due to the size of the mill cutting. The remainder goes through either a thermal treatment or a chemical treatment.

Thermal treatment is the heating and cooling process for separating and recovering valuable materials. The mechanically pre–treated panels are heated to 400–650 °C and cooled down afterwards [33,34]. Polymer components are burned/cracked during the heating process [13]. The treatment can further separate glass from solar cells, recovering glass in the remaining pieces. An overall glass recovery rate of 91% can be achieved by combing mechanical and thermal treatments [33].

Chemical treatment refers to the chemical etching and recovery until the targeted metals are recovered and the remainder from the mechanical and thermal treatments are subjected to chemical treatment. In this treatment, metals are dissolved using various reagents. For example, sodium hydroxide (NaOH) can be used for Si etching, methanesulfonic acid (CH_3SO_3H) and hydrogen peroxide (H_2O_2) can be used for Al etching, and nitric acid (HNO_3) can be used etching of Cu and Ag [16]. After chemical etching, a simple filtration process can be applied to leaching solutions to recover Si. Subsequently, a combination of filtration and heating processes can be applied to recover Al. Copper can then be recovered by adding hydroxy–5–nonyl acetophenone oxime and H_2SO_4 to the leaching solution and using the electro–winning method. Ag can later be recovered by applying hydrochloride acid (HCl), sodium hydroxide (NaOH), and hydrazine hydrate ($N_2H_4 \cdot H_2O$) to the solutions [35].

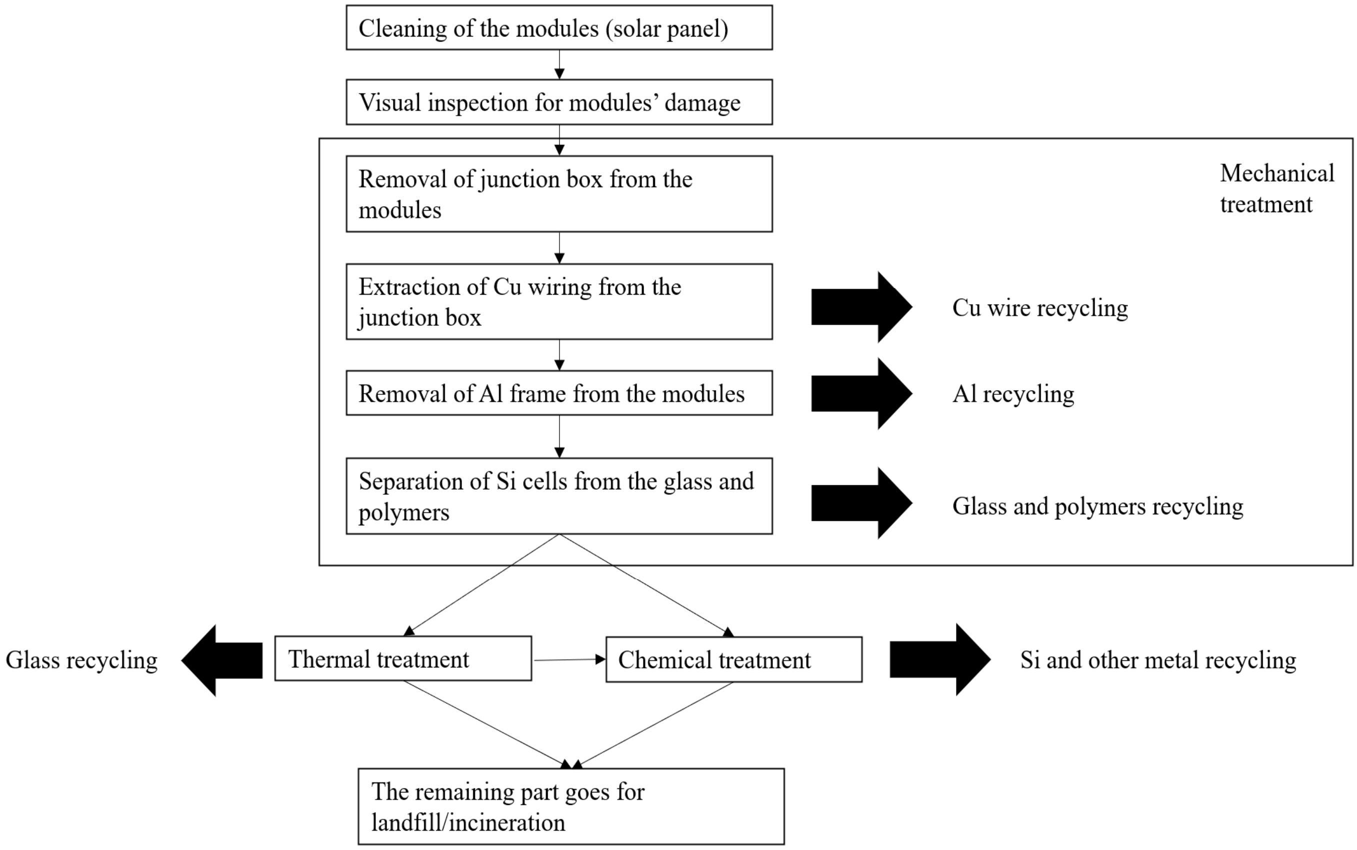


Figure 2. Waste treatment process of a typical solar panel [13].

Although different EOL management methods have been developed for solar panels, they still have negative impacts. Firstly, the uncovered fractions after the mechanical treatment, chemical treatment, and thermal treatment are sent to a landfill and, in some cases, partially incinerated (last step in Figure 3). These fractions still contain Cu, Ag, Sn, and Pb, as none of the current treatments can achieve a 100% recovery rate for these metals [13,35]. Secondly, the treatment procedures, especially the thermal and chemical treatments, are energy–intensive and create harmful impacts on the environment. Weckend et al. [14] mentioned that polymer decomposition in the thermal treatment produces toxic gases and results in high energy consumption. Chowdhury et al. [13] indicated that the silicon etching and rinsing procedure can release toxic gases such as nitrous oxide (NO_2) into the environment. In addition, chemical treatment can be hazardous to human health due to the use of acidic solutions. The remaining acidic solutions after chemical treatment can also be an issue.

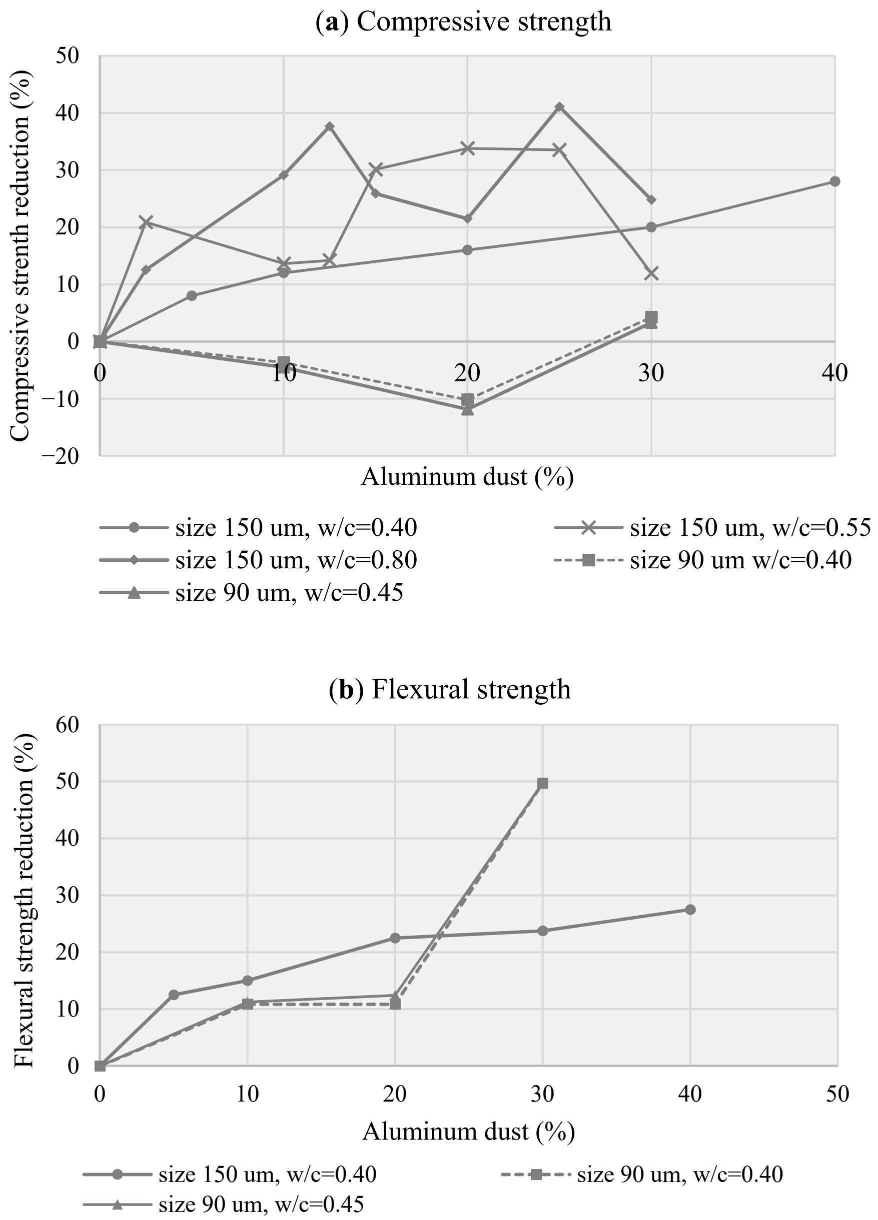


Figure 3. Concrete mechanical properties vs. Al dust levels [36–38]. Al dust content is expressed as the weight percentage of cement replaced by Al dust. (**a**) Compressive strength. (**b**) Flexural strength.

Thirdly, the glass and solar panels can deteriorate under actual working conditions. This can affect the quality of glass and metals recovered from the waste treatment. For example, Ardente et al. [39] raised concerns about low glass quality after recovery. To overcome the limitations cited above (i.e., Chowdhury et al. [13], Weckend et al. [14], and Huang et al. [35]), Imteaz et al. [40], Panditharadhya et al. [41], and Idrees et al. [42] suggested that some components of wasted solar panels (e.g., glass, aluminium, silicon) can be used in pavement construction applications following the mechanical treatment process. The potential feasibility of using c–Si panel waste in the two main types of pavements, i.e., rigid (concrete) and flexible (asphalt) pavements, was investigated in another study [43].

4. Concrete Pavement Applications

Glass, aluminium frames, polymer, and c–Si cells in a c–Si panel are the potential waste materials that can be used for surface, base, and subbase construction in a concrete pavement. Previous studies predominantly focused on investigating the fundamental properties of concrete pavements using glass waste, including compressive, flexure strength, and durability. These studies also considered waste an aggregate replacement, a cement replacement, or a combination of both aggregate and cement replacement material in concrete pavements. In addition, other solar panel waste materials, such as aluminium and silicon, have also been researched as filler materials in concrete pavements.

4.1. Waste Glass as an Aggregate

The use of glass waste in concrete is not a novel research area, as initial studies were reported back in early 1963 by Schmidt and Saia [44]. Some studies attempted to investigate the mechanical properties of using waste glass as a natural aggregate replacement material in concrete. The results highlighted a degradation in compressive and flexure strength with the introduction of waste glass as coarse aggregate replacement material in concrete. This is mainly due to preventions in energy releasement during the hydration reaction, as glass aggregate cannot absorb water. The irregular shape of waste glasses can also affect the bond between aggregates and cement pastes in concrete. It is also worth investigating the angularity number of glass, which can quantify waste glass shape effects on the properties of concrete. However, this quantification has not been carried out so far. Polley et al. [45] and Zheng [46] further indicated that the alkali–silica reaction (ASR) initiated in waste glass particles creates alkali oxides in cement. This reaction can cause pressure accumulation inside the aggregate, leading to concrete expansion and strength degradation.

The shape, size, and type of glass, as well as the mix–design and curing time of concrete, are some of the key factors that affect the mechanical properties of concrete and a summarised representation of previous studies using glass waste in concrete pavements are highlighted in Table 2 [47–50]. As shown in Table 2, Topcu and Canbaz [47] reported a higher level of reduction in compressive strength for concrete containing waste glass compared with other studies, with a loss of 49% in compressive strength when 60% of crushed stone (coarse aggregate) was replaced with glass waste in the concrete. However, according to other studies, the loss in compressive strength is only 23.8% to 27.0%, respectively, when 100% of the crushed stone is replaced with waste glass [48,51]. The resultant comparisons between these two studies are reliable considering the similar type of cement (CEM II) and water–cement ratios in the concrete mix. This could mainly be due to the irregular shape of the waste glass used, which can improve the bond between aggregates and cement pastes [47].

Table 2. A summary of concrete strength changes with different levels of glass used as an aggregate.

Concrete Mix					Concrete Properties		
w/c *	**S/A ***	**Cement Type ***	**Glass Content * (%)**	**Glass Resources**	**Compressive Strength Degradation**	**Flexure Strength Degradation**	**Reference/s**
				Coarse aggregate			
0.48	0.60	CEM I	10–100	Waste bottle	1.3% to 23.8%	–	Terro [48]
0.35	–	CEM I	10–30	–	−7.2% to −34.0%	−10.6% to −15.2%	Turgut and Yahlizade [52]
0.54	0.47	CEM II/B–M 32.5 R	15–60	Waste bottle	8% to 49%	−16% to 33%	Topcu and Canbaz [47]
0.55	0.49	CEM II A–L 42.5 R	5–20	–	0% to 2.5%	–	de Castro and de Brito [53]
0.50	–	CEM I	20–30	Window glass	−5.3% to −28.5%	10.8% to −21.7%	Keryou and Ibrahim [54]
0.55	–	CEM II A–L 42.5	5–20	–	6.5% to 10.5%	7.2% to 19.3%	Serpa et al. [55]
0.52	–	CEM II/A–L 42.5 N	12.5–100	Waste bottle	4.4% to 27.0%	–	Omoding et al. [51]

Table 2. *Cont.*

Concrete Mix					Concrete Properties		Reference/s
w/c *	**S/A ***	**Cement Type ***	**Glass Content * (%)**	**Glass Resources**	**Compressive Strength Degradation**	**Flexure Strength Degradation**	
Fine aggregate							
0.50	0.47	CEM I	30–70	Waste bottle	0.6% to 13.6%	3.2% to 18.1%	Park et al. [56]
0.49	0.75	CEM I	50	–	24.1%	18.1%	Shayan and Xu [57]
0.48	0.60	CEM I	10–100	Waste bottle	1.3% to 41.2%	–	Terro [48]
0.35	–	CEM I	10–30	–	−31.5% to −68.9%	−22.3% to −90.0%	Turgut and Yahlizade [52]
0.53	–	CEM I	10–20	Waste bottle and window	9.1% to −4.3%	−3.6% to 11.2%	Ismail and Al–Hashmi [58]
0.55–0.58	0.49	CEM II A–L 42.5 R	5–20	–	11.0% to 17.0%	–	de Castro and de Brito [53]
0.55–0.58	–	CEM II A–L 42.5	5–20	–	15.3% to 20.5%	20.9 to 28.1%	Serpa et al. [55]
Mix of coarse and fine aggregate							
0.48	0.60	CEM I	10–100	Waste bottle	7.6% to 68.4%	–	Terro [48]
0.47	–	CEM I	15–45	Waste bottle	1.5% to 8.5%	–	Kou and Poon [59]
0.55–0.58	0.49	CEM II A–L 42.5 R	5–20	–	7.0% to 17.0%	–	de Castro and de Brito [53]
0.55–0.57	–	CEM II A–L 42.5	5–20	–	13.7% to 26.7%	17.9 to 34.8%	Serpa et al. [55]

* w/c is the water–cement ratio; * S/A is the sand to aggregate ratio. * CEM I—Portland cement; CEM II/A–L—Portland–limestone cement; CEM II/B–M—Portland–composite cement. * Glass content is expressed as weight percentage of coarse/fine aggregate replaced by glass throughout this paper.

A smaller glass size can reduce the strength degradation level of concrete by causing pozzolanic reactions and filling the pores in concrete mixes. The presence of larger glass particles might further weaken the concrete structure because of their high friability [45]. Ismail and Al–Hashmi [58] suggested that the gradation of waste glass with a size smaller than 0.3 mm can cause significant pozzolanic reactions. Ismail and Al–Hashmi [58], Turgut and Yahlizade [52], and Du and Tan [60] also found an increase in compressive and flexure strength in concrete with increasing fine glass waste contents and improved pozzolanic reactions. However, Terro [48] and de Castro and de Brito [53] showed that the level of reduction in compressive strength is larger when fine aggregates are replaced in concrete compared with coarse aggregate. The conflicting results in these studies show the importance of conducting further studies on optimizing the replaced glass size and content in concrete to obtain sustainable concrete with high strength for pavement material.

The study by Keryou and Ibrahim [54] is the only one of its kind that found strength increments in concrete with larger glass sizes used as coarse aggregate (>4 mm). They claimed that this was because of the interlocking and friction increments among mixed particles in concrete due to the existence of the glass. However, Omoding et al. [51] indicated that ASR over–dominates the interlocking effect and degrades the mechanical properties of concrete accordingly. Therefore, further studies are necessary to investigate the interlocking effects of different glass particles. Moreover, the chemical composition of the glass type (e.g., toughened glass, soda–lime glass, laminated glass, etc.) can also affect the alkali–silica reaction (ASR) and their degradation effect on concrete strength. There are also conflicting findings on concrete strength degradation based on various glass types. Park et al. [56] indicated that green glass showed less ASR expansion than brown glass due to the sizeable Cr_2O_3 component; however, other studies have highlighted contradictory results, such as Dhir et al. [61]. Therefore, future studies are required to establish how the strength of the concrete is affected by the presence of glass waste of varying chemical compositions. The c–Si panel uses tempered glass, and there are limited studies on the effect of using waste tempered glass on concrete strength. Instead, most studies have focused on bottle glass waste in concrete (i.e., soda–lime glass, treated soda–lime glass, or borosilicate glass), as shown in Table 2.

For the concrete mix design, several studies indicated that a lower water–cement ratio can decrease the ASR between glass and cement, leading to smaller strength reductions in the concrete [48,49,52]. Furthermore, Du and Tan [62] showed that concrete containing a large portion of fly ash and slag cement contributes to pozzolanic reactions, potentially increasing strength in concrete containing glass. In addition, the level of strength increase with the extension of the concrete curing time due to the longer pozzolanic reaction time. Besides concrete strength analyses, some recent studies have also estimated the durability of concrete containing different levels of waste glass. The results illustrate an increase in concrete durability due to the addition of waste glass. de Castro and de Brito [53] indicated an enhancement in concrete chloride penetration resistance with the increasing proportion of glass components. The chloride penetration depth reduces by 20% when 10% of the course and fine aggregate is replaced by cement. Du and Tan [62] carried out a rapid chloride penetration test. The results indicate that the total charge passing the concrete was reduced by 66.7% when 30% of fine aggregate was replaced by glass, indicating a significant increase in the chloride penetration resistance.

4.2. Waste Glass as a Cement Replacement Material

Glass is generally converted into powders sized less than 100 µm, and then it is added as a partial cement replacement material in concrete. Some recent studies on using waste glass as a cement replacement in concrete are summarized in Table 3. Similar to the case of aggregate replacement, cement replacement in concrete using glass waste also demonstrates a reduction in the mechanical properties of concrete. Similar to the case of aggregate replacement, the reductions in mechanical properties can be affected by the size, glass and cement type, and mix design of the concrete. The strength reduction is significantly higher as compared with aggregate replacement, mainly due to weaker bonds between cement and aggregates with the introduction of glass particles in the place of cement [63]. The studies further highlighted that if glasses were used with a highly reactive pozzolana in the concrete mix, such as silica fume, the pozzolanic activity of the glass could be promoted. However, silica fume can also contribute to ASR [64]. Therefore, further experimental studies are required to justify improvements in concrete strength due to the addition of silica fume. Pozzolanic activity in glass–cement mixtures can also be promoted by performing heat treatment [65]. However, more experimental investigations are needed to assess the overall impact of heat treatment on the strength of concrete. Moreover, heat treatment can be energy–intensive, which could lead to additional costs, as well as environmental and practical handling implications [66].

Table 3. A summary of concrete strength changes with different levels of glass used as cement.

Concrete Mix				Concrete Properties		Reference/s
w/c	**Cement Type**	**Glass Content (%)**	**Glass Resources**	**Compressive Strength Degradation**	**Flexure Strength Degradation**	
0.75	CEM I	30	Fluorescent lamps	9.1% (38–75 µm glass) * to 31.8% (75–150 µm glass)	–	Shao et al. [63]
0.49	CEM I	20–30	–	21.2% (<10 µm glass)	–	Shayan and Xu [67]
0.49	CEM I	20	Glass beads	12.5% (30–100 µm glass)	–	Shi et al. [68]
0.42	CEM I	10	Window plate glass	6.7% (1–100 µm glass)	–	Schwarz et al. [69]
0.57	CEM I	30	Container (green)	31.9% (<40 µm glass)	–	Khmiri et al. [70]
0.45	CEM I	11–15	Container (green)	4.1% to 21.0% (18–80 µm glass)	5.4% to 47.8%	AL–Zubaid, Shabeeb [71]

Note: * The grain size indicates that over 90% of the glass particles are 35–75 µm, the same for all the grain size indications.

Adding waste glass to concrete can generally reduce its strength. This strength reduction level decreases with the decreasing water–cement ratio of the concrete, owing to the reasons mentioned in case 1 [63,70]. Additionally, Shao et al. [63] compared the strength reduction level for concrete cured after 28 and 90 days. They found that the reduction level lessens with curing time increments since it allows for more time for pozzolanic activity. The curing time increments can also form denser and less permeable concrete microstructures because of the filling effect of glass particles. However, the test results by Schwarz et al. [69] do not support this finding. Therefore, further investigations are required in this area.

4.3. Waste Glass Together as an Aggregate and Cement Replacement Material

Similar to the case of the solo replacement of aggregate or cement with glass, the combined replacement of cement and sand in concrete also results in a reduction in the compressive and flexural strength of the concrete. The reduction mechanism and the parameters that affect the reductions are similar to those given in previous cases. There are only a limited number of studies where the effect of using waste glass as cement and aggregate replacement in concrete is highlighted (see Table 4). However, these studies investigated only a maximum of 20% cement replacement and 50% aggregate replacement in concrete.

Table 4. A summary of concrete strength changes with different levels of glass used as cement and aggregate.

Concrete Mix				Concrete Properties		
w/c	**Cement Type**	**Waste Glass Content (%)**	**Glass Resources**	**Compressive Strength Reduction**	**Flexure Strength Reduction**	**Reference/s**
0.49	CEM I	20% for cement; 50% for coarse and fine aggregate	–	23.9%	–	Shayan and Xu [67]
0.38	CEM I	20% for cement; 50% for fine glass aggregate	–	19.2%	7.8%	Taha and Nounu [72]
0.38	CEM I	20% for cement; 50% for coarse aggregate	–	22.0% (14 days) 2.0% (56 days)	15.8% (14 days) 10.3% (56 days)	Wang and Huang [73]

4.4. Aluminium (Al) Waste in Concrete

In most of the previous studies, aluminium (Al) waste was crushed into a powder (i.e., aluminium dust) and added as a cement replacement material in concrete. These investigations highlight a general reduction in the mechanical properties of the modified materials. Mailar et al. [38] quantified this reduction by testing the compressive and flexure strengths of concrete with different Al dust contents. Concrete samples with two different water–cement ratios (0.40 and 0.45) were tested, with an average Al dust size of 90 µm. Similar tests investigated the mechanical properties of Al–waste–incorporated concrete with an average Al size of 150 µm and water–cement ratios of 0.40, 0.55, and 0.80 (see, for example, Elinwa and Mbadike [36] and Mbadike and Osadere [37]). The resulting compressive and flexural strengths are summarized in Figure 3. The observed test results clearly show that mechanical properties in concrete further reduce with an increase in Al dust content. This can be attributed to the fact that Al dust affects the bonding strength between aggregate and cement paste, thereby reducing the mechanical properties of the concrete [74]. In addition, Al dust can absorb water in the concrete mix, reducing water content and thus affecting the strength of the concrete. Furthermore, Al dust generates hydrogen gas when in contact with water, increasing pressure in the concrete and reducing its strength [36].

Figure 3 highlights a reduction in the compressive and flexural strength of concretes with different Al dust contents. The observed reduction in the mechanical properties of concrete strength is not linear for an increase in Al dust content [36]. Mailar et al. [38] even found an increase in the mechanical properties of concrete with Al dust proportions of 10% and 15% as cement replacement material. This phenomenon is further explained by Hay and Ostertag [75], as Al can be absorbed onto the amorphous silica surface via reactive aggregation in concrete, limiting the ASR expansion and leading to strength increments. Nonetheless, more studies are needed to investigate the effect of Al dust on concrete's mechanical properties comprehensively. Furthermore, Al dust size can affect mechanical properties, but limited studies have made attempts to quantify these changes [37]. In addition, there is a lack of microstructural analysis studies, which could find the mechanism behind the changes in the mechanical properties of Al–incorporated concrete. Despite claims by Mailar et al. [38] that an increase in curing time may improve the mechanical properties of concrete containing Al dust, the test conducted by Elinwa and Mbadike [36] contradict these results.

The durability characteristics of concrete, such as water penetration resistance, acid attack through water absorption, and acid resistance, have been enhanced with the addition of Al dust to the concrete mix [38]. The mass loss after being immersed in sulphuric acid with 5% weight for 30 days was reduced by 57.2% for concrete with a 30% replacement of cement with aluminium dross. This can be attributed to the fact that Al dust can fill the voids in concrete due to its small size, which reduces the pores of the concrete [38]. However, there is a lack of other durability studies on concrete with Al dust, including air permeability, chloride resistance, and sulphate attack resistance tests.

It should be noted here that one study has used Al dust as a partial fine aggregate replacement material in concrete [76]. In this study, 1%, 2%, and 5% of the sand were replaced by aluminium waste in the concrete, and the resulting mechanical strengths indicated a reduction of 3.6%, 18.7%, and 21% in the compressive strength, respectively. In addition, there was an increment in concrete durability based on the water absorption test (66.3% reduction in the water absorption rate at a 5% sand replacement). The decrease in bond strength of the concrete aggregate and the reduction in concrete porosity led to strength reduction and durability increments. Inspired by fibre–reinforced concrete, Muwashee et al. [77] added Al strips to the concrete mix during production, and 22% and 238% increases in compressive and flexural strengths were observed by adding 2.5% Al strips to concrete by volume. This was mainly because Al strips can delay the formation of cracks and make the concrete matrix stronger.

4.5. Polymer Waste in Concrete

Polymer waste in a c–Si panel mainly consists of encapsulant and back–sheet foil. For encapsulant, Dulsang et al. [78] and Khan et al. [79] replaced the cement with different levels of waste encapsulant in concrete manufacturing. They tested the 28–day compressive strength, with the results summarized in Figure 4. The water–cement ratio was 0.40 in both studies. Dulsang et al. [78] found a 68.8% reduction in the compressive strength with waste encapsulant content increasing from 3 to 10%. However, Khan et al. [79] found that compressive strength increases with encapsulant content increments. Waste encapsulant had an average size of 4.5 mm in Dulsang et al. [78] and 0.41 mm in Khan et al. [79]. Large encapsulant size can create internal voids in concretes and affect the bond between the plastic aggregate and the cement paste. This can be avoided with small encapsulant waste sizes [79]. Dulsang et al. [78] also mentioned that encapsulant is a water–reducing polymer. A small encapsulant size may increase its water–reducing effect, enhancing the bond between cement hydrates and the inert aggregates.

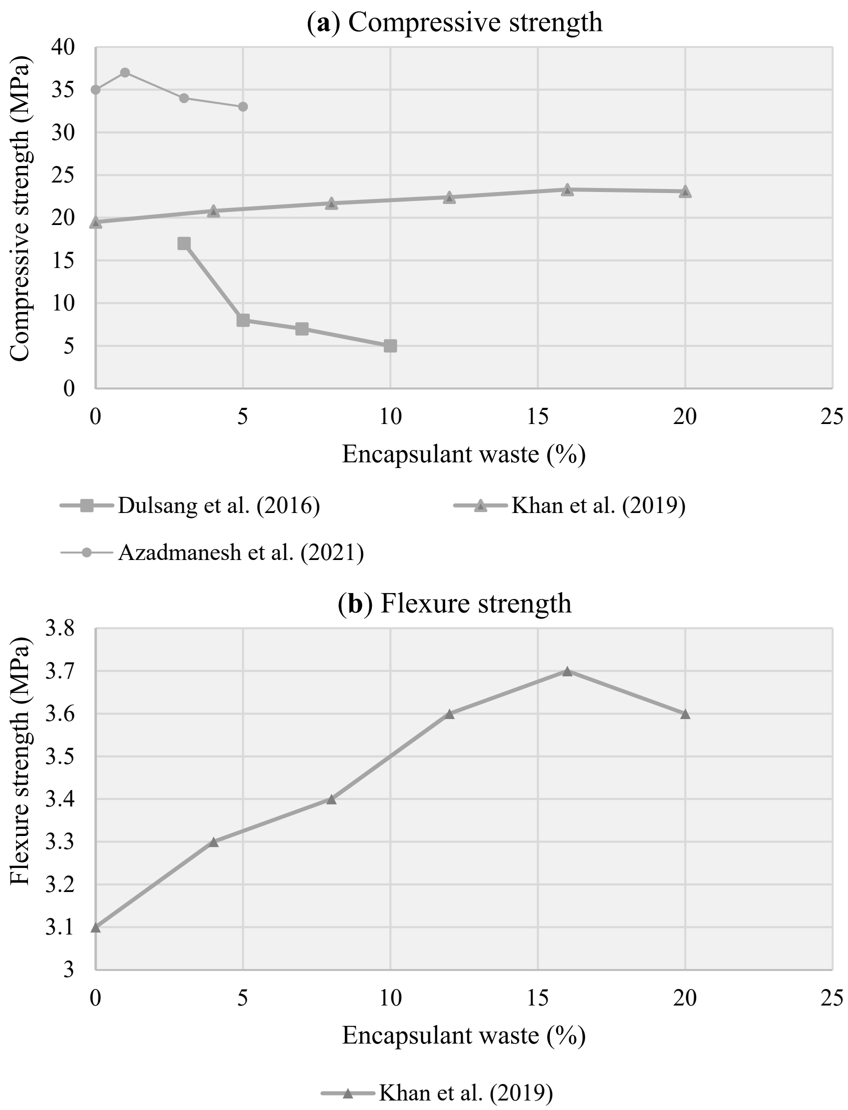


Figure 4. Concrete mechanical properties vs. encapsulant waste levels [78–80]. Encapsulant waste content is expressed as the weight percentage of cement replaced by encapsulant waste. (**a**) Compressive strength. (**b**) Flexure strength.

Apart from studies on regular concrete, Azadmanesh, Hashemi [80] added different levels of encapsulant to Engineered Cementitious Composites (ECC) and tested the 28–day compressive strength afterwards. The encapsulant size ranged from 1 to 7 µm. It could be seen that there was a limited reduction in compressive strength with an encapsulant content of 5%. The study also indicated that a small encapsulant size can prevent strength reduction in concrete. However, it did not show that a small encapsulant size contributes to its water–reducing effect. Otherwise, compressive strength should be increased with encapsulant content increments. Further studies are, therefore, needed.

Only Khan et al. [79] quantified changes in the 28–day flexure strength among these studies. Flexure strength increases by 17% when encapsulant waste reaches 20% due to the water–reducing effect of the encapsulant. More studies are also needed in this field.

For durability, Dulsang et al. [78] showed that concrete's sorptivity coefficient can be reduced by over 92.1% when encapsulant content reaches 10%. They also found that concrete weight loss reduces from 15% to 5% when encapsulant waste increases from 3% to 10%. Increased tortuosity due to encapsulant waste leads to sorptivity reduction and acid–resistance enhancement.

To the best of the authors' knowledge, no studies have been conducted to test the strength and durability of concrete with back–sheet foil (i.e., polyvinyl fluoride (PVF)).

4.6. Silicon Waste in Concrete

There are few studies that have investigated the behaviour of using recycled silicon solar cell waste in concrete. Ren et al. [81] replaced 5% to 20% of cement with silicon carbide (SiC) particles (silicon solar cell contains SiC) in concrete manufacturing. The concrete had a water–to–cement ratio of 0.40. The 28–day compressive strength was tested, and the results are shown in Figure 5. Similar tests have been carried out by Małek et al. [82] and Idrees et al. [42]. Particle sizes of SiC were 50 µm, 5.5 mm, and 27 µm in these three studies. There was an increase in the compressive strength of concrete with an increase in SiC content overall, despite when the SiC content was 5% and 10% in Ren et al. [81].

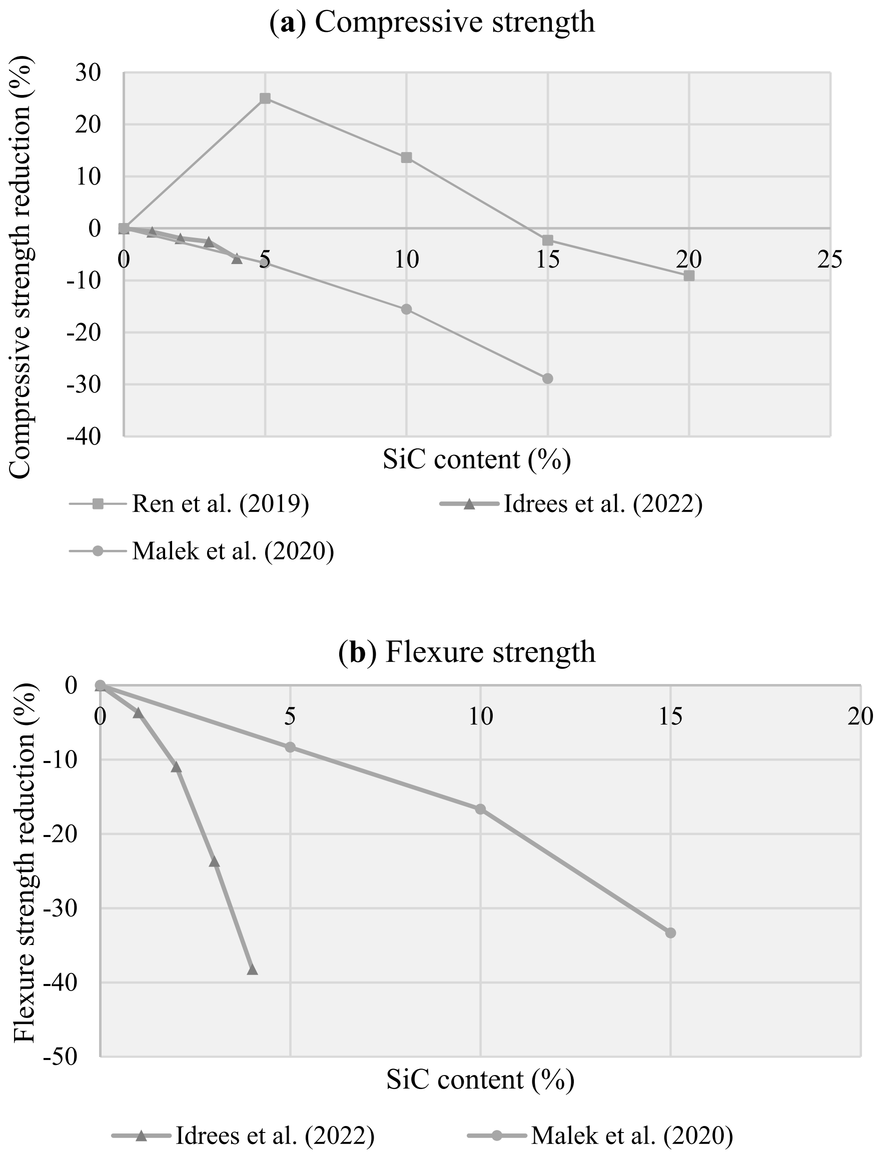


Figure 5. Concrete mechanical properties vs. SiC levels [42,81,82]. SiC content is expressed as the weight percentage of cement replaced by SiC particles. (**a**) Compressive strength. (**b**) Flexure strength.

Based on Ren et al. [81], there is less cement in concrete to produce hydrates when SiC particles partially replace cement. This leads to strength reduction at SiC levels of 5% and 10%. However, SiC is highly abrasive and can act as a reinforcing filter in concrete mixes with significant SiC content. This reinforcing effect dominates the strength reduction effect and eventually leads to an increase in concrete strength. In addition, large SiC particle content can lead to capillary suction, vapour diffusion, and capillary condensation, which can transport water from SiC waste to cement paste, promotes the hydration of the cement in the paste, and increases concrete strength.

Małek et al. [82] and Idrees et al. [42] indicated that the highly abrasive nature of SiC leads to an increase in concrete strength, even with a small amount of SiC content. Małek et al. [82] and Idrees et al. [42] also found an increase in flexure strength due to the highly abrasive nature of SiC in concrete mix and the promotion of hydration in the cement (Figure 5b). More studies are, therefore, needed to clarify the effect of SiC on concrete properties.

Besides concrete, Jiang et al. [83] used SiC particles extracted from silicon solar cell waste in CEM I mortars and observed an increase in compressive and flexural strength. However, Fernández et al. [84] found that an increased proportion of silicon waste can reduce the compressive and tensile strength of concrete with calcium aluminate cement (CAC), as the bond between the cement paste and aggregate can be reduced due to the existence of silicon waste. These contradictory finds indicate that more studies are needed to investigate cement properties containing SiC particles. In addition, based on a study on concrete with waste glass [48,49,52], it is likely that the differences between cement types could also lead to variations in concrete strength, but this needs further studies.

Ren et al. [81] tested chloride resistance with a rapid chloride permeability test for durability. The total charging recorded in 6 h reduced by 85.7% in the rapid chloride permeability test with 20% SiC, indicating a significant increase in chloride resistance. Ren et al. [81] also found water absorption was reduced by 10.7% when SiC content increased to 20%. Adding SiC increases concrete's durability due to the reduction in its porosity. However, Idrees et al. [42] found a reduction in chloride resistance for concrete containing SiC particles. This is because Idrees et al. [42] used SiC particles with s large size (5.5 mm compared with 50 μm in Ren et al. [81]). The large size of SiC particles increased concrete porosity instead. Comparing these two studies indicates that size control over SiC particles is essential before it is added to concrete.

5. Asphalt Pavement Applications

Asphalt is a mix of sand, gravel, broken stones, soft materials, and bituminous binder (asphalt binder) that can be used in the wearing surface and base construction of pavements. Only a handful of studies have been carried out to estimate the properties of asphalt mixtures made with c–Si panel waste components. These studies primarily focused on using different levels of waste glass in asphalt mixtures in pavements and seldom considered other waste constituents in a solar panel [85–90].

It should be noted here that 4.75 mm was the maximum size of the glass aggregates reported in these studies, and 1–2% hydrated lime was added to the asphalt mixtures to improve the cohesion between stone and glass aggregates with bitumen coatings. The observed optimum asphalt content in the glass–asphalt mixtures and the resulting stability (fatigue resistance) in those studies are summarized in Figures 5 and 6. According to the summarised results from the studies in Figure 6, no significant reduction in the optimal binder content of the composite asphalt mixture was observed with an increase in the waste glass percentage of up to 20% as a result of using slaked lime.

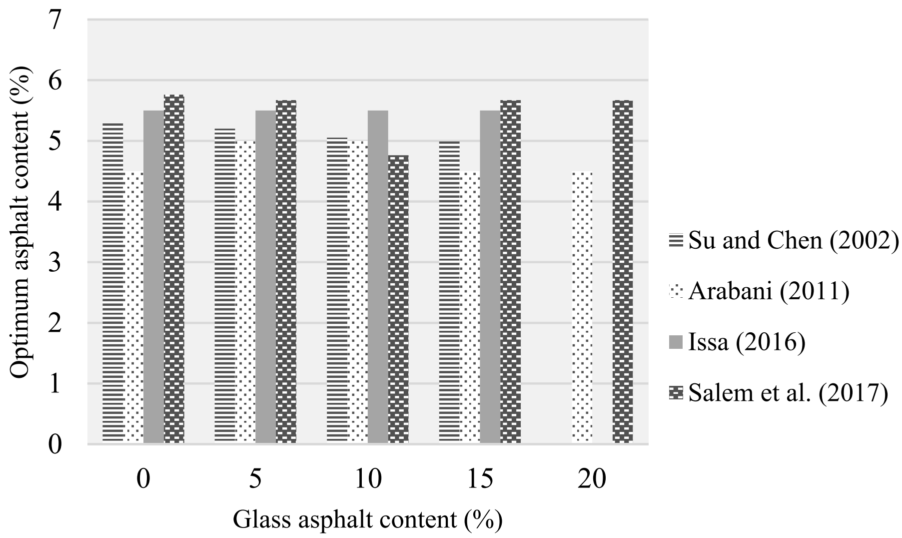


Figure 6. Optimum asphalt content vs. glass asphalt mixtures [86–89].

The results in Figure 6 highlight that stability is slightly reduced with the increase in waste glass in the asphalt mixture. However, until the waste glass content in the asphalt mixture reached 20%, no significant reduction in stability was observed. Adhesion loss between the binder and glass, skid resistance loss, reduced stripping resistance, and increased ravelling potential were identified as the main reasons for this reduction in stability [85]. The presence of broken glass in the mixture has also been reported to contribute to reductions in stability. However, these issues can be corrected by adding lime to the mixture [86]. Marandi and Ghasemi [91] indicated that adding rubber polymers can also eliminate degradation in the stability of an asphalt mixture with a glass content of up to 5%.

Arabani [87], Issa [88], and Salem et al. [89] also summarized the properties of asphalt mixtures with the additions of waste glass based on the Marshall test, as summarized in Table 5. Table 5 shows the changes in flow, voids in the mineral aggregates in asphalt concrete with and without waste glass, the void percentage filled with bitumen in asphalt concrete with and without waste glass, and so on. It can be seen from Table 5 that there was no significant reduction in these properties with the increase in the waste glass percentage in the asphalt–concrete mixture. However, further studies are needed to find a more reliable estimation of these property changes due to conflicts in the current studies. For example, Arabani [87] found an increase in flow with glass content increments. However, Issa [88] found a decrement in the flow instead. In addition, Arabani [87] tested the stiffness modulus of asphalt–concrete mixtures with waste glass content, shown in Figure 7. It can be seen from Figure 7 that adding waste glass to asphalt mixtures increases their stiffness due to the interlocking effect of glass between mixed particles.

Table 5. Properties of asphalt–concrete mixtures with waste glass content.

Glass Content	Bitumen Content (%)	Flow (mm)	Unit Weight g cm^{-3}	Air Void (%)	Voids in Mineral Aggregates (%)	Voids Filled with Asphalt (%)	Reference
0	4.5	2.31	2.337	4.74	13.60	65.13	Arabani [87]
5	4.5	2.26	2.323	5.01	13.95	64.08	
10	4.5	2.42	2.305	5.33	14.45	63.11	
15	4.5	2.63	2.331	5.03	13.31	62.22	
20	4.5	2.63	2.314	5.4	13.78	60.81	

Table 5. *Cont.*

Glass Content	Bitumen Content (%)	Flow (mm)	Unit Weight g cm^{-3}	Air Void (%)	Voids in Mineral Aggregates (%)	Voids Filled with Asphalt (%)	Reference
0	–	2.93	2.40	4.74	–	–	Issa [88]
5	–	2.80	2.25	4.53	–	–	
10	–	2.87	2.13	4.30	–	–	
15	–	2.73	2.10	4.16	–	–	
0		4.32	2.213	4.2	16.5	73.5	Salem et al. [89]
5		4.45	2.248	2.8	15.35	81.0	
10		4.06	2.225	4.4	16.35	72.5	
15		4.57	2.24	3.5	16	77.0	
20		4.11	2.247	2.5	15.2	83.5	

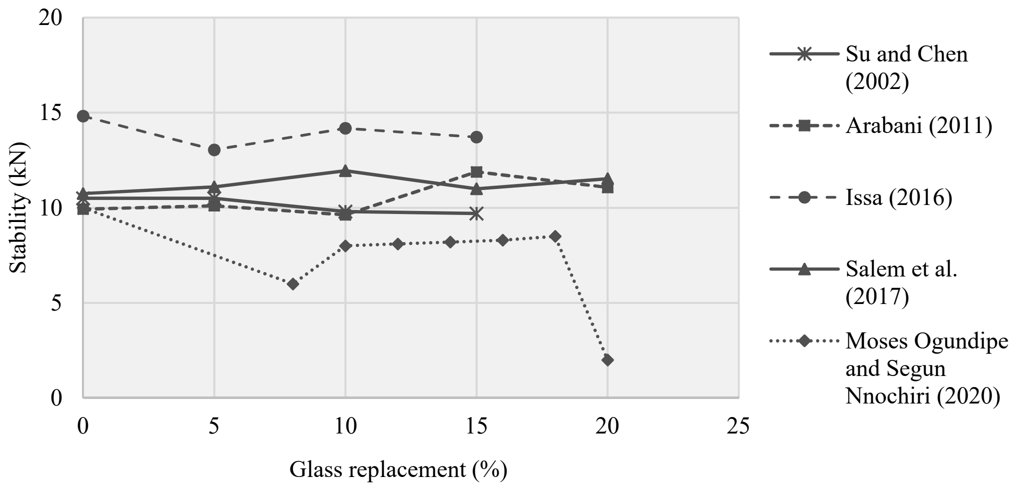


Figure 7. Stability value of glass asphalt mixtures with different levels of glass content [86–90].

In addition to stability, Arabani [87] and Su and Chen [86] found that asphalt mixtures with recycled glass can increase the skid resistance and night visibility of asphalt pavements, eventually leading to improved driving conditions at night. Lachance–Tremblay et al. [92] found no noticeable degradation in compaction ability, rutting resistance, thermal cracking resistance, or asphalt mixture stiffness with 25% waste glass content. Shafabakhsh and Sajed [93] also found that adding waste glass can increase the stiffness modulus, dynamic properties, and resistance of asphalt mixtures against deformation and rutting. Glass can increase the interlocking effect between aggregates, helping asphalt maintain its workability, which includes properties such as stability, skid resistance, night visibility, compaction ability, rutting resistance, thermal cracking resistance, stiffness modulus, dynamic properties, deformation resistance, and rutting resistance. The Federal Highway Administration [94] and Wu et al. [95], through their findings, showed that asphalt mixtures with glass contents of up to 15% and 25% can be used for wearing surfaces and base construction, respectively, in pavement construction. Moses Ogundipe and Segun Nnochiri [90] tested the stability of asphalt with glass sizes of up to 25 mm. They found a significant degradation in mechanical properties, as a large glass size can affect the bond between glass particles and asphalt. The collective interpretation of these studies highlights that larger than 4.75 mm glass pieces can reduce stability in the asphalt mixture. Therefore, it is essential to maintain the crushed glass size at 4.75 mm to avoid the workability degradation of asphalt pavement.

However, asphalt grades and mixing design can also affect workability. The optimum asphalt content and workability in an asphalt–glass mixture can significantly change with different asphalt grades and mixing temperatures [90]. However, there is a severe lack of precedents in the literature relating to this aspect. In addition, most studies have considered incorporating waste glass in hot mix asphalt (HMA) mixtures, while other categories, such as stone mastic asphalt (SMA), have not been considered. Further studies are, therefore, needed to compare properties, such as the workability of SMA asphalt mixtures with different glass percentages [94] (Figure 8).

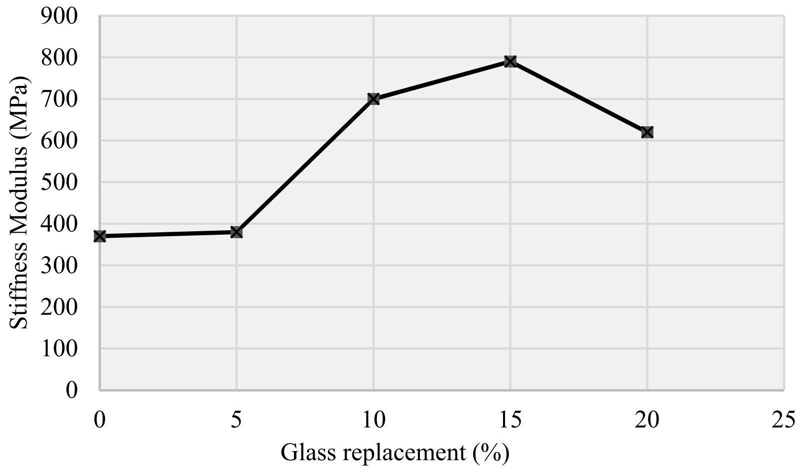


Figure 8. Stiffness modulus of glass–asphalt mixtures with different levels of glass content.

6. Impediments and Drivers of Using Solar Panel Waste as a Pavement Material

Despite numerous research initiatives to promote the use of waste materials in building and construction materials, several limitations hinder the product's translation into a market–ready product. Understanding the problem and parallel research to mitigate or minimize the effects of these barriers is a contemporary requirement to improve the marketability of the product. Despite the satisfactory mechanical properties in using the material either for structural or non–structural applications, the practical implementation of the product is limited due to workability and handling issues. Previous studies highlighted that a reduction in workability as a result of introducing glass powder and other articles is minimized by the introduction of superplasticizer [96]. In addition, the pumpability of concrete can also be affected in circumstances where large concrete pumps are utilised for mass concrete construction activities. This can also result in additional costs and the need for technical skills for either the introduction of supplementary materials or alternative processes. Despite the perceived environmental benefits, contractors and decision–making stakeholders in the construction industry are often hesitant to invest in alternative materials due to low profit margins and a lack of returns. Presently, few to no standards or policies are available that define systematic procedures for using the different waste constituents of a solar panel system in construction materials in order to promote sustainability. A lack of government incentives is another major issue that needs to be addressed to encourage the increased uptake of green materials. Moreover, the majority of countries treat solar panels as general E–waste and lack specific guidelines for safe EOL management and disposal [97]. This is considered a major barrier, and the availability of a guideline would encourage stakeholders to explore and implement innovative methods of using various waste constituents in pavement applications. Supply chain management issues with handling waste materials are a key problem that could demote the potential of using solar panel waste in pavement construction. Often, these solar panel systems are disposed in large quantities, and converting them into useful concrete and asphalt pavement raw materials requires significant supply chain phases that could be energy–intensive and have high costs. Special storage and transportation processes may be required for handling these materials due to the hazardous nature of solar panels [98]. At present, there are no systematic procedures for the systematic handling of solar panel waste. However, if research can be translated into commercial products and applications, there will be increased job opportunities in the supply chain for converting solar panel waste into raw construction material. Due to the potential availabilities of waste across all countries and regions, in the future, local conversion plants can be set up to promote sustainable development.

Potential environmental impacts due to the presence of hazardous and toxic materials, such as lead, lithium, and cadmium, can curtail the use of solar panel waste as a pavement material [97]. Therefore, further research should be focused on investigating leachate impacts due to dumping solar panel waste on pavements, and comprehensive life cycle assessment (LCA) studies should be used to benchmark the environmental benefits [99]. This can also enhance the commercial promotion of the product through environmental and sustainable labelling. At the moment, there is high potential demand for renewable energies across the world, which will lead to an abundance of solar panel waste materials in the future. The availability and abundance of waste materials due to an enhanced degree of end–of–life disposal is a driving factor that can also promote the possibilities of re–engineering them as pavement construction material. In addition to EOL solar panel waste, high amounts of premature solar panel waste, due to poor handling during transportation, installation, and operations, can also magnify the availability of solar panel waste. This can be also considered a driving factor to use it as a pavement material. Moreover, there are multiple potential applications for solar panel waste materials in pavement construction, which can encourage stakeholders to accelerate the market promotion of the product, thus obtaining required certifications and approvals. The circular economy status of a product needs to achieve life–cycle benefits, including material substitution, sustainable design, benchmark environmental impacts through LCA, and end–of–life management [100]. Pertinent policies and regulations should be developed to systematically define the circular–economy–based reverse supply chain processes for both the products (solar panels and pavements) to improve market intake. Similar to government stimulus for solar energy implementations, incentives should be introduced to develop effective EOL management techniques for solar panel waste.

7. Conclusions and Future Research

The heavy uptake of solar panels in many countries is predicted to cause a huge waste problem in the near future as the initial end–of–life periods are approaching since their introduction. Previous studies made significant attempts to improve the production efficiency of solar panels. Some studies also made attempts to recover, recycle, and reuse the waste constituents of solar panels as an end–of–life (EOL) management strategy. Despite many attempts to identify potential EOL solutions, there is still huge potential in reusing solar panel waste due to the predicted massive disposal of solar panels. Construction, on the other hand, is known to be one of the most energy–intensive industries due to excessive virgin material usage. Pavement construction is a similar energy–intensive construction type, and over the past few decades, several studies focused on researching alternate raw materials to replace virgin materials. Therefore, addressing these issues together could pave the way for rapid sustainable development solutions. The current study presented a detailed review of the potential of using different solar panel waste materials as a raw construction materials in both flexible (asphalt) and rigid (concrete) pavement types.

Adding waste constituents from solar panels is likely to affect the mechanical properties of concrete pavement. Most of the studies found that adding the key waste constituents of c–Si panels, such as Al, polymer, and silicon, to concrete can reduce the compressive and flexure strength of concrete. Our review's findings highlight that a reduction in the compressive and flexural strength is not substantial with a glass content of 10% in concrete as a partial replacement material for cement or aggregate. This reduction is often influenced by the glass type, size, and concrete mix design and, therefore, more studies are required to justify the relationship between glass content and the mechanical properties of concrete pavements. Compared with glass, studies have seldom investigated mechanical properties after the addition of Al, polymer, and silicon to concrete pavements. Current findings illustrate conflicting results and, therefore, additional studies are needed to find the optimum particle size and content for these waste elements to maximize their compressive and flexural strengths. Apart from compressive and flexure strengths, abrasion resistance, stiffness, and fatigue cracking resistance are critical properties for pavement construction. To the best of the authors' knowledge, thus far, no studies have been carried out to study the properties of concrete using waste c–Si panels. Additionally, future studies are required to investigate the composite behaviour of the interaction effects between glass, Al, polymer, silicon, and other c–Si panel components on the compressive and flexure strength, abrasion resistance, stiffness, and fatigue cracking resistance of concrete. The durability of concrete pavements is enhanced with the addition of waste materials from solar panels, such as glass, Al, polymer, and silicon. The majority of durability analyses have focused on water absorption and acid resistance tests, while a handful of studies have learned that the chloride penetration resistance of concrete can be improved by adding glass particles. However, limited studies have focused on finding the chloride penetration resistance of concrete composites with Al, polymer, or silicon. Moreover, there are also limited studies on the freezing and thawing durability of concrete filled with waste c–Si panels, which can be a future study focus. Previous studies emphasized that asphalt pavements generally have no noticeable degradation in the workability of asphalt at a glass content level of 25%. However, the effect of adding other c–Si panel components on asphalt workability must be studied. More studies can focus on the durability of asphalt pavement with c–Si panel waste.

The composite behaviour of using multiple solar panel waste materials as pavement material should also be investigated in future studies to upsurge the potential use of waste materials. Future research can also be focused on investigating the use of solar panel waste in low–stress applications, such as walking paths, driveways, and landscape blocks. The commercial implementation of these applications would be relatively simple, as compared with structural applications, due to low structural standard requirements. A c–Si solar panel system includes several material elements that have different residual values. Therefore, it is important to develop a systematic framework that can identify the potential recyclable and recoverable elements of a solar panel and divert the residual waste to investigate the potential applications in pavement construction. Subsequently, based on the supply, research can focus on prioritizing the waste constituents of a solar panel system to replace virgin materials in different pavement types. However, the translation of these research findings to market products is often a daunting task due to practical and legislative implementation requirements. Therefore, further initiatives should be facilitated at the government and organizational levels to strengthen funding support with the intent of driving research commercialization. The results of this review demonstrate the need and potential of using solar panel waste in pavement construction applications. The findings of the study may enable interested stakeholders to understand current trends and future research regarding the use of solar panel waste in pavement construction.

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