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POSSIBLE RECYCLING OF WASTE GLASS IN SUSTAINABLE FIRED CLAY BRICKS: A REVIEW

*Yuecheng Xin, Abbas Mohajerani, Halenur Kurmus and John V. Smith

School of Engineering, RMIT University, Melbourne, Australia

*Corresponding Author, Received: 24 Nov. 2020, Revised: 22 Dec. 2020, Accepted: 05 Jan. 2021

ABSTRACT: The total production of waste glass (WG) in Australia during the period 2016 to 2017 was about 1.1 million tonnes, and approximately 467 kilotonnes were deposited in landfills, while 612 kilotonnes were recycled. The current recycling techniques practiced for crushed waste glass (CWG) are limited, resulting in a growing environmental challenge. Therefore, there is an interest in the development of novel technologies to recycle WG. Previous laboratory testing suggests that incorporating recycled CWG in the production of bricks may allow a reduction in firing temperature while maintaining brick strength. Furthermore, increasing the glass content and reducing the particle size of the glass significantly improved the physical/mechanical properties of the fired clay bricks, especially compressive strength. Besides, a dense and uniform structure was observed in the microscopic images after adding WG in fired clay bricks. A linear relationship was found between thermal conductivity and WG content. Therefore, incorporating CWG in fired clay bricks is a practical and feasible way to develop an environmentally friendly construction material and solve a growing waste issue.

Keywords: Waste glass, Recycling, Fired clay bricks, Physical and mechanical properties, Sustainability, Geomaterials.

1. INTRODUCTION

Bricks are a common construction material used widely around the world [1]. The production of fired clay bricks relies on extensive mining of natural resources and the use of non-renewable raw materials. Therefore, the development of environmentally friendly and energy-efficient building materials by the addition of waste has become crucial. Several studies have been conducted on recycling various wastes in fired clay bricks. Such wastes include cigarette butts [2], biosolids [1], microplastics [3], olive mill wastewater (OMW) [4], rice husk [5], foundry by-products [6], and marble powder [7]. Figure 1 illustrates the overall trend of documents published by year on recycling wastes and waste glass (WG) in fired clay bricks. An upward trend in the number of papers published on recycling WG in fired clay bricks can be seen to increase dramatically following the year 2015.

WG is a readily available domestic material, and around 11 million tonnes of glass containers are manufactured each year. Typically, WG is deposited in landfills, and therefore landfills are facing a growing issue with the space available for WG [8]. For instance, the amount of waste generated per capita in Australia has gradually increased to an unprecedented level in the recent period [9]. According to the Australia National Waste Report [10], a total of 1.1 million tonnes of WG was generated in the 2016 to 2017 period alone. Six hundred and twelve (612) kilotonnes of WG was recycled, and landfills received the remaining four hundred and sixty-seven (467) kilotonnes. Besides, the disposal of solid waste has an immense impact on the environment, economy, and health, which is a significant management issue that many countries are facing. Based on the statements from the World Wildlife Fund (WWF), recycling WG is a feasible method to reduce the space consumed in landfills [11]. Likewise, using recycled glass to produce glass products decreases the use of energy and raw materials, and as a result, the related air pollution and water pollution can be reduced by 20% and 50%, respectively [11]. However, the methods used to quantify the environmental impacts were not provided. Evidently, using CWG as an additive in the making of fired clay bricks is becoming popular.

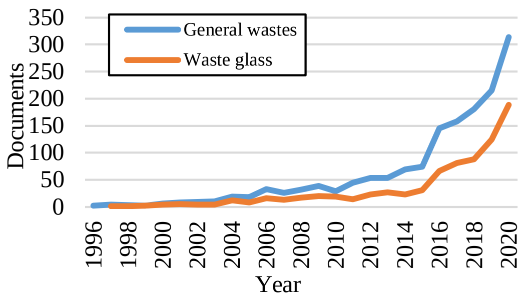

Fig. 1 The number of documents published between 1996 to 2020 on recycling wastes and WG in fired clay bricks. (Database source: Scopus)

In Victoria, according to the fact sheet from NetBalance [12], each year, around 257,000 tonnes of glass waste is produced. The majority is from glass packings such as beverage bottles, jars, beads, and bowls. The remaining glass waste is from post-consumer glasses, flat glass (windows), and other sources. While 195,000 tonnes are recovered, only 124,000 tonnes are crushed into glass cullet for glass manufacturing. Victoria's recycled glass inventory was estimated to exceed 300,000 tonnes in 2014, mainly contaminated by ceramics, stoneware, Pyrex glass, and plastic. Besides, in 2014, the fact sheet from NetBalance estimated that up to 62,000 tonnes of glass would be sent to landfills [12].

Most glass packaging is collected from households or commercial sites (such as bars, clubs, sports venues, hotels, and restaurants) in mechanised, bin-based, fully commingled systems. On-site glass crushers are often used to reduce volume. The mixed materials are sorted from paper grades, plastics, and metals by using the recycling facilities in the capital and regional centers. The glass is then sent to one of the beneficiation plants, including Visy, SKM, and Polytrade [13].

In addition to reusing glass waste for packaging production, many other options can be considered. The glass can be used for water quality projects as a filter medium. Similarly, large quantities of CWG can potentially be accommodated in various road base and sub-base applications [13]. Currently, there is a great interest in recycling CWG in construction materials. As a result, CWG is found being incorporated in the production of concrete, asphalt concrete, and ultra-lightweight fiber reinforced concrete [8].

The objective of this paper is to collect and review major research studies on the recycling of CWG in fired clay bricks. Six CWG recycling proposals and practices are studied, including; mix 30% back dust and 70% superfine WG by weight, recycled personal computer and television WG, soda-lime glass powder WG, shop glazing window WG, thin-film transition liquid crystal display (TFT-LCD) WG powder, and the combination of sludge and WG.

2. TYPES OF GLASS

According to chemical composition, almost all commercial glass belongs to one of six basic categories or types. They are soda-lime glass, lead (crystal) glass, borosilicate glass (Pyrex), aluminosilicate glass, ninety-six silica glass, and fused silica glass. Table 1 lists the applications of six different types of glass.

Table 1 Type of glass and applications.

Glass	Applications
Soda-lime glass	Windows
	Bottles
	Light bulbs
	Jars
Lead (Crystal) glass	Electrical applications
	Thermometer tubing
	Art glass
	Lead Crystal Tableware
Boro-Silicate glass (Pyrex)	Chemical production applications
	Lamp covers
	Baking and soufflé dishes
	Heatproof kitchenware
Aluminosilicate glass	Combustion tubes
	Gauge glass for high-pressure steam boilers
	Halogen-tungsten lamps
Ninety-six percent silica glass	Fiber optics
	UV-transmissive lamp tubes
	Precision optics
	Refractory tubes
Fused silica glass	Aerospace applications

3. RESEARCH ON RECYCLING WASTE GLASS

3.1 Mix 30% Back Dust and 70% Superfine WG by Weight (Mix WG Powder)

Federico [14] studied the effects of CWG on the properties of fired clay bricks. Eleven sets were prepared with A (0% glass), B (5% glass), C (5% glass), D (10% glass), E (10% glass), F (15% glass), G (15% glass), L (0% glass), X (0% glass), FL (0% glass), and FX (0% glass). Each set contained 30 samples. Set A was categorised as the control group, and the remaining were test groups. B, D, and F contained different percentages of WG with the same glass mesh size. C, E, and G contained different percentages of WG with the same glass mesh size. Accordingly, the influence of WG content and particle size on the properties and durability of the bricks were investigated. In addition, samples L, X, FL, and FX were prepared to investigate the influence of the methodology used and the firing temperatures on the bricks. Lignosulfonate (20 ml) was added to the water during the mixing process to increase the plasticity of the clay. The test results showed that the proportion of WG had a significant effect on compressive strength. The maximum compressive strength was found to be 133.4 MPa for G (15% glass).

3.2 Recycled Personal Computer and Television WG (Lead Glass)

According to a study of European countries, the disposal of personal computer monitors, and television sets is becoming a growing issue. Approximately 25,000 m^3 of personal computer monitors and television sets are being produced per year [15]. Moreover, a high concentration of lead, barium, and strontium exists in the funnel and panel of the cathode ray tube display, which results in the technical problem of re-using personal computer monitors, and television glass to manufacture new glass. Therefore, personal computer monitors and television glass were added into fired clay bricks. Three different mixture ratios of clay and glass were prepared: control sample without waste (C0), 2% and 5% funnel glass (CT2 and CT5) by weight (wt.), and 2% and 5% panel glass (CS2 and CS5) by wt. Besides, the samples were fired at three different temperatures 900°C, 950°C, and 1000°C. The firing shrinkage, bending strength, water absorption, open porosity, and bulk density were investigated. The results revealed the bricks incorporating CWG resulted in higher bulk density, bending strength, and firing shrinkage, and lower water absorption. The maximum bending strength (22.8 MPa) was found for bricks incorporating 5% screen glass, with a firing temperature of 950 °C.

3.3 Soda-lime Glass Powder WG

Demir [16] investigated the effect of milled WG on the properties of fired clay bricks. The waste was added at a ratio of 0%, 2.5%, 5%, and 10% by wt. The samples were fired at four different set temperatures of 850°C, 950°C, 1000°C, and 1050°C. The results revealed a linear relationship between shrinkage and the firing temperature. Shrinkage increased with an increase in temperature, while the increase in firing temperature resulted in a decrease in porosity and water absorption. As shown in Table 2, the results revealed that an increase in firing temperature improved the compressive strength of the bricks modified with WG.

Table 2 Compressive strength test results [16].

Waste glass content	Compressive strength MPa		
	850 °C	950 °C	1050 °C
0%	16.45	19.50	20.37
2.5%	18.75	22.65	24.50
5%	20.15	25.13	27.15
10%	20.62	27.56	29.35

Another paper was published by a group of researchers led by Phonphuak, which investigated incorporating WG (soda-lime glass) in fired clay bricks to reduce the furnace temperature during the firing process to save energy [17]. The study was performed by utilising various percentages of glass (0%, 5%, and 10% by wt.) at firing temperatures from 900°C to 1000°C. The results revealed an increase in bulk density with a decrease in water absorption and drying shrinkage. This phenomenon can be explained by the addition of glass, which contains sodium oxide (Na_2O), and a non-crystalline structure, which assists during the firing process of bricks by increasing the glassy phase. In addition, the Na_2O assisted in the vitrification of the bricks resulting in higher density, lower water absorption, and drying shrinkage.

In 2017, a group of researchers led by Sarmeen completed a study confirming the firing temperature can potentially be decreased from 1050°C to 650°C during the firing of bricks with the addition of WG powder (borosilicate glass, coloured glass, and soda-lime glass) [18]. The ratio of glass content used in the study included 0%, 20%, 35%, and 50% by wt. and the specimens were fired at 650°C, 850°C, and 1050°C. Moreover, as shown in Table 3, the results indicated that bricks modified with 35% soda-lime glass (SLG) had greater compressive strength compared to borosilicate glass (BSG) and coloured glass (CG).

Table 3 Compressive strength test results [18].

WG content	Compressive strength MPa		
	650 °C	850 °C	1050 °C
0%	21.88	22.22	25.62
35% SLG	28.88	31.79	35.14
35% BSG	24.18	27.44	31.78
35% CG	26.84	27.04	30.08

Furthermore, a study was completed by Ponce's team regarding the addition of various sizes of glass cullet in red clay bricks with a focus on the subsequent physical and mechanical properties [19]. All specimens were air-dried at room temperature for 72 hr and later fired at 1000°C for 12 hr. The bricks modified with glass cullet demonstrated lower water absorption compared to the controlled bricks. The compressive strength of bricks increased with the decrease in the particle size of the glass cullet. The results showed that increasing the glass content and reducing the particle size of the glass significantly improved the properties of the fired clay bricks for water absorption and compressive strength.

3.4 Shop Glazing Window WG (Soda-lime Glass)

Abdeen [20] studied the performance of fired clay bricks containing waste glazing window glass. The selected contents of waste glazing window glass included 0%, 10%, 20%, 30%, and 40% by wt. The firing temperatures for the fired clay bricks incorporated with glazing window glass were 900°C, 1000°C, and 1100°C. The result revealed that the compressive strength of the fired clay bricks increased with the increase in glazing window glass content and firing temperature, as shown in Table 4.

Table 4 Compressive strength test results [20]

WG Content	Compressive strength MPa		
	900°C	1000 °C	1100 °C
0%	18.61	21.33	28.82
10%	22.91	30.67	47.45
20%	20.41	32.34	77.75
30%	21.91	42.75	96.37
40%	17.88	43.17	55.98

3.5 Thin-film Transition Liquid Crystal Display WG Powder (Lead Glass)

In 2018, Chao-Wei [21] investigated the addition of TFT-LCD WG in fired clay bricks. The ratio of TFT-LCD glass content used in this study were 0%, 10%, 20%, and 30% by wt. The specimens were fired at 900°C, 950°C, 1000°C, and 1050°C. Several tests were conducted to evaluate the effects of adding TFT-LCD WG powder in fired clay bricks. The results displayed a decrease in water absorption and an increase in compressive strength with the increase in TFT-LCD WG content in the fired clay brick samples. The maximum compressive strength (48.2 MPa) was reached by adding 20% glass cullet into bricks and firing at 1050°C.

3.6 The Combination of Sludge and WG (Soda-lime Glass)

Rahman et al. investigated the effects of adding WG in textile sludge-based bricks [22]. The bricks containing textile sludge demonstrated a decrease in mechanical properties with an increase in porosity. However, based on previous studies, it was clear the addition of WG in fired clay bricks increased compressive strength and water absorption. Therefore, textile sludge and WG additions were combined and incorporated in fired clay bricks for the purpose of this investigation. 0%-40% sludge by wt. and 5%-10% WG by wt. were added into the production of bricks. All specimens were fired at 1150°C. The results confirmed that the addition of WG to the textile sludge-based bricks improved the compressive strength, shrinkage, and water absorption properties. In addition, the bricks incorporating sludge and WG were tested for heavy metal leaching. The results revealed that the leachate concentrations for heavy metals for bricks incorporating WG and sludge were below the standard regulatory limits. Therefore, recycling fabric sludge and WG in the production of fired clay bricks may be an environmentally friendly solution to a growing pollution issue.

A group of researchers investigated the use of WG in addition to galvanised sludge in brick production to boost the immobilisation of heavy metals [23]. Galvanized sludge is a by-product from galvanization and surface treatment plants, which is a typical solid waste. Various contents of WG were studied, including 0%, 10%, 15%, 20%, 25%, and 30% by wt., while the galvanised sludge content studied was 10%. The firing temperatures tested were at 850°C, 950°C, and 1050°C, respectively. The experimental results revealed a WG content greater than 15% in conjunction with the addition of 10% galvanised sludge in fired clay bricks, resulted in leachate concentrations below the regulatory limits. Therefore, WG can be used as an enhancer in conjunction with hazardous wastes (galvanised sludge) in the production of fired clay bricks for the stabilisation and solidification of heavy metals.

4. RESEARCH FINDINGS ON RECYCLING OF WASTE GLASS

4.1 Bulk Density

Dondi et al. observed bulk density increased by 1.1% with the addition of 15% CWG in fired clay bricks [15]. Similarly, a study found a 2% increase with the addition of 25% CWG [24].

Phonphuak et al. also proved that the density of the brick specimens increased by 3.5% for bricks incorporating 10% CWG [17]. Besides, a study found that when less than 10% WG (soda-lime glass) was added to the bricks, the bulk density of the samples was slightly affected by the amount of waste glass in the mixture or the selected firing temperature [18]. Moreover, with the addition of WG content greater than 20%, the bulk density was observed to increase significantly with the increase in firing temperature.

4.2 Apparent Porosity

Apparent porosity is the percentage ratio of the void space in the specimen to the total bulk volume of the specimen, without considering the volume of the sealed pores. Due to the high decarbonisation reactions, the apparent porosity decreased with the increasing firing temperature and WG content. The apparent porosity for a controlled brick specimen was found to be 43.27%; however, with the addition of 15% WG, the apparent porosity decreased to 39.02% [24]. It was found the porosity reduced with the increase in WG content. When the glass melts at a temperature of about 500 °C, the voids in the bricks are filled [19].

4.3 Microstructure And Colour

Less densification and binding were displayed in the microscopic images of control bricks. In the control brick samples, irregular interconnected shaped openings were noticed, however, after incorporating 25% by wt. WG in the brick samples, a dense and uniform structure was observed. Moreover, after adding WG to the brick samples, lighter-coloured bricks were observed due to the lower Fe_2O_3 content found in clay compared to WG [24]. In 2009, a study stated that the firing temperature and the amount of WG applied to the mixture determined the amount of glassy phase produced. At a temperature above 850°C, increasing the WG content increased the fluxing action [16].

4.4 Water Absorption

The addition of WG in fired clay bricks resulted in a decrease in water absorption. The results from Kazmi et al. revealed a reduction in water absorption from 20.34% for controlled bricks to 19.07% and 17.17% with the addition of 15% and 25% WG in fired clay bricks. A linear relationship between porosity and water absorption was found for bricks incorporating WG [24]. Additionally, the particle size of the WG had a great effect on water absorption properties [14]. Besides, a group researcher led by Dondi found water absorption to decrease regardless of the type of glass, including PC glass and TV glass [15]. With the increase in firing temperature, water absorption decreased. The samples fired at 850°C displayed a marginally greater absorption of water than the samples fired at 950 °C and 1050 °C. This is due to the fact that any temperature above 850°C results in an increase in the glassy phase, increasing density, and therefore reducing water absorption [16].

4.5 Thermal Conductivity

Density, porosity, WG content, and the firing temperature are the main factors that affect thermal performance [24]. The thermal conductivity of bricks recycled with WG was found to act linearly to the WG content. For instance, thermal conductivity increased from 0.53 to 0.59 W/mK with the addition of 25% WG in fired clay bricks compared to control bricks. Furthermore, a linear relationship was found between bulk density and thermal conductivity, whereby the increase in bulk density resulted in an increase in thermal conductivity (within the reasonable range of traditional burnt clay bricks for masonry construction. i.e., 0.4-0.7W/mK [24]) with the increase in WG percentage in fired clay bricks [24].

5. CONCLUSION

In conclusion, this study provides a review of the research conducted in utilising various WG types in the production of fired clay bricks. The six CWG recycling proposals and practices studied are 30% black dust and 70% superfine WG, recycled personal computer and television WG, soda-lime glass powder WG, shop glazing window WG, thin-film transition liquid crystal display (TFT-LCD), WG powder, and the combination of sludge and WG. The effects of the WG particle size, WG content, firing temperature, and brick preparation process on the physical and mechanical properties of fired clay bricks are analysed. The distinct procedures and sample types followed in recycling WG into fired clay bricks are summarised in Table 5.

Furthermore, whether WG is added exclusively or with the addition of another waste, the addition of WG in fired clay bricks demonstrates encouraging physical and mechanical properties, particularly with the improvement in compressive strength. Moreover, the addition of WG assists in reducing the maximum desired firing temperature and, consequently, the firing time contributes to mini-

Table 5 Summary of some of the research conducted in recycling various WG types in fired clay bricks

Glass sample type	Particle size	Waste glass by wt.	Drying process	Firing process	Ref.
Back dust and superfine	150 -300 µm 75-150 µm 45-75 µm	0%, 5%, 10% and 15%	Air dry for 24 hr Oven dry for 12 hr at 110 °C	Fired between 999.6°C and 1106 °C	[14]
Recycled PC and TV waste glass	Passing 0.25 mm sieve	2% and 5%	Air dry for 48 hr Oven dry at 100°C overnight	Fired at 900°C, 950°C and 1000°C with 4 hr soak time	[15]
Crushed waste glass powder (bottle)	21 µm	0%, 2%, 2.5%, 5% and 10%	Air dry for 24 hr Oven dry at 110 °C	Fired at 850°C, 950°C, and 1050°C with a heating rate of 3°C/min and held for 2 hr	[16]
Soda-lime glass	Ball mill crushed (1 hr)	0%, 5% and 10%	Air dry for 24 hr Oven dry for 24 hr at 110 °C ± 5°C	Fired at 900°C, 950°C and 1000°C and held for 1 hr	[17]
Soda-lime glass, coloured glass, and borosilicate glass	0.85 mm	0%, 20%, 35%, and 50%	Air-dry overnight Oven dry at 110°C for 24 hr	Fired at 650°C, 850°C and 1050°C for 3 hr with a heating rate of 5°C /min and soaking period of 15 min	[18]
Crushed Glass Cullet	<500, <300, and <212 μm	0%, 20%, 25%, and 30%	Air dry for 72hr	Fired at 1000 °C for 12h	[19]
Shop Glazing windows	150 μm and <600 μm	0%, 10%, 20%, 30% and 40%	Air dry for 24 hr Oven dry at 45°C for 6 hr and then at 110°C for 24 h	Fired at 900°C, 1000°C and 1100°C with a heating rate of 2.5°C/min until 600°C reached, and then 5°C/min until 900°C reached, 1000°C and 1100°C	[20]
Thin-film transition liquid crystal display waste glass powder	Ball mill crushed	0%, 10%, 20%, and 30%	Set one: air dry for two days Set two: air dry one day Set three: Oven dry at 100°C for one day Set four: oven dry at 50°C for one day	Fired at 900°C, 950°C, 1000°C, and 1050 °C	[21]
Combination of sludge and waste glass (bottle)	<250μm	5% and 10%	Air dry for one day and oven-dry overnight	Fired at 1150°C	[22]
	<74µm	0%, 5%, 10%, 15%, 20%, 25% and 30%.	Oven dry for 24 hr at 110°C.	Fired at 850°C, 950°C, and 1050°C with a heating rate of 300°C/h for 3 hr until target temperature reached	[23]

mising the world's carbon footprint. Besides, the reviewed research studies reveal and confirm the addition of WG in fired clay bricks is a feasible and effective approach to reduce the growing amount of WG (with certain content and firing temperature) in landfills worldwide. Furthermore, the partial replacement of clay with WG in brick production will assist in decreasing the consumption of natural materials.

6. RECOMMENDATIONS

Based on the review, the following research and developments are recommended for widespread industry adoption:

- Further study is recommended to determine the optimal ratio of WG content in fired clay bricks, in addition to the optimal firing temperature.
- A comprehensive study on the combination of WG with other waste additives is recommended with an emphasis on environmental implications.
- A life cycle assessment is recommended to evaluate the negative and positive environmental impacts of incorporating WG in fired clay bricks.

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