# Applications of Recycled and Crushed Glass

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Glass is a substance that is present in most houses since glass-based items are made and consumed in relatively high quantities. This has led to the buildup of glass in concerning quantities all over the world, which is a problem for the environment. It is well known that glass has several advantageous physiochemical features that qualify it as an appropriate material for use in the construction industry as an aggregate. The features include being non-biodegradable, resistant to chemical assault, having low water absorption, having high hydraulic conductivity, having temperature-dependent ductility, having alterable particle gradation, and having a wide availability in a variety of forms and chemical compositions.

Keywords: glass ; recycled glass ; crushed glass ; sand

## 1. Short History

The earliest glass ever discovered in its natural condition is what's known as volcanic glass. This kind of glass was formed when lava was rapidly cooled. People fashioned spearheads and jewelry out of it and subsequently utilized the spearheads in hunting. Despite this, it is believed that the production of glass began in Egypt around 1400 BC. This exhibit details the whole process of creating and processing glass, down to the equipment and machines available. After the Egyptians taught the Phoenicians how to make glass, the Phoenicians continued the trade by sending decorations, vases, and flasks made of glass all across the globe. Perhaps it was also for this reason that people at first believed that they were the ones who found glass—another pivotal period in the development of glass occurred around the turn of the 20th century. A Roman artisan came up with the idea for a long, thin iron pipe with a tiny bulge at one end and a wooden extension at the other, and they used it to blow air through. Because of this, a technique known as blowing glass came into being and remained used for a significant time [1][2].

It is stated that Venice was once a significant center for the production of glass. The glass experts recruited to work here were sequestered on the island of Murano so they would not expose the process used to produce glass. Murano glassmakers were also responsible for the creation of the very first glass mirrors in the 12th century. Giorgio Agricola, a well-known artisan from Venice, is regarded as the "father" of the technical aspects of glassmaking. He detailed the procedure for producing glass in the year 1500. The procedure of burning came into usage in the 16th century, after the technique of blowing, primarily throughout the 17th and 18th centuries, particularly for the production of glass, tiles, and pipes. The technique involves simply pushing the glass into the shape of a strip using a set of rollers, which pull the strip at a high speed while simultaneously cooling it gently for stress relief.

Even though lead crystal was an English innovation, the first plant in France to create lead crystal was the St. Louis factory in 1784. Later, in 1823, the famed Baccarat crystal factory came into being. Both factories are located in France. Sir Alastair Pilkington created float glass in the United Kingdom between 1952 and 1957. The production of float glass begins with the glass being heated to a temperature of around 1000 degrees Celsius, at which point it is molten and is poured continuously from the furnace into a shallow bath of molten tin. It disperses evenly throughout the can's surface as it floats on top of it. Following the annealing process, the glass takes on the appearance of a polished product, with surfaces that are almost perfectly parallel. Shortly later, the same Sir Alastair Pilkington was a pioneer in the technique of pyrolytic deposition. This approach is used in production and involves spraying metal compounds onto glass while heated to a high temperature. This approach is perfect for insulating against the heat.

The aim to increase the quality of glass and its physical attributes led to the invention of tempered glass in the middle of the 20th century. This is accomplished by heating the material in a toughening furnace to around 700 degrees Celsius and then rapidly cooling it. This process brings the tensions inside the glass to a state of equilibrium, which endows the glass with unique properties such as very high resistance to intense mechanical impact and stability when subjected to changes in temperature. If it breaks, the object disintegrates into relatively few fragments, which significantly lowers the probability of suffering an injury. When it comes to interior doors, partitions, glass furniture, glass shower cubicles, elevators, stairs, store windows, and commercial premises, fully toughened glass is the material of choice [1][2].

## 2. Use of RCG in Geotechnical Applications

The use of waste glass in traditional geotechnical applications is often under-researched and limited to a few applications; this may be because of a lack of knowledge of its geotechnical and environmental properties. That's because it's impossible to reuse broken glass [3]. Numerous studies have shown RCG's potential for use as a geomaterial since it has many of the same qualities as a natural aggregate [4]. Thoroughly cleaned glass can fully replace the role of natural granular components [5]. According to the American Society for Testing and Materials (ASTM), most cullet might be on par with clean sand.

Both structural and nonstructural fill applications benefit from the use of fine RCG. While RCG has several potential geotechnical applications, the most typical ones are drainage blankets, filter media, soil stabilizers, and backfill material for road pavements and embankments. In addition to its usage as a soil stabilizer, drainage blanket, and filtering medium are further geotechnical uses of RCG. Only a few studies have looked at RCG's potential in geotechnical settings.

There have been many studies on the effects of fine RCG on various soils in recent years. Olufowobi et al. [6] conducted tests on clayey soil, varying the amounts of powdered RCG while keeping the cement content at 15%. They measured the effects on shear strength, CBR, and compaction. After being exposed to 5% RCG, it was found that the MDD of modified clay increased somewhat, from 25.37 to 25.90 kN/m$^3$. At a concentration of 10% RCG, however, the shear strength metrics of modified clay improved most noticeably, with the friction angle also increasing from 15 to 17 degrees. Based on their results, the researchers concluded that the sweet spot for RCG is anywhere between five and ten percent, depending on the nature of the improvement to be made. Amiri et al. [7] investigated the influence of RCG on the geotechnical characteristics of kaolinite at doses ranging from 10% to 50% and particle sizes from 2.36 mm to 1.18 mm. The study's results showed that up to a percentage of 50% replacement, RCG improved the friction angle, compressive strength, and MDD of kaolinite. When compared to other possible materials, RCG is a viable option for enhancing the geotechnical properties of cohesive soils. This alternative would be cheap, easy to get, and environmentally sound. The behavior of compaction and strength was investigated by Arabani et al. [8] using poorly graded sand stabilized with cement at 5% and 7% concentrations and RCG at 20%, 40%, and 60% concentrations. The RCG utilized had a particle size less than 12.7 mm in diameter. The research found that the CBR, compaction, and shear strength characteristics of modified sand significantly improved with the addition of 60% and 7% of RCG and cement, respectively. This was especially noticeable after the introduction of these two additives. In particular, the mixture of 60% RCG and 7% cement had a UCS that was 3.5 times higher than before. Canakci et al. [9] investigated the effects of RCG fine enough to pass through a sieve with a 75-m aperture on the clay's density, toughness, and uniformity. There were 3%, 6%, 9%, and 12% RCG additions to the formula. Incorporating RCG into clay led to a sustained improvement in the material's compressive strength. The pozzolanic activity of RCG at finer grain sizes may account for the observed increase in CBR. In addition, this tested the effects of 3, 7, and 28 days of curing on the unconfined compressive strength (UCS) of RCG-clay samples. Results showed a significant correlation between the UCS of samples and curing time; however, the addition of 6% RCG yielded the greatest results in increasing the clay's UCS.

Difani et al. [3] performed a study on the effect of RCG on the geotechnical behavior of biosolids and found the following: (Bio). The tests made use of both the pure and mixed versions of the ingredients. The preparation of the biosolids resulted in mixtures because of the varying RCG applications at various concentrations. The study found that mixes of RCG 40/Bio60, RCG 50/Bio50, and RCG 60/Bio40 improved geotechnical performance, particularly in terms of shear strength. Overall, the study's findings suggested that mixtures of RCG and biosolids might effectively substitute natural aggregates in many geotechnical contexts, including as a material for filling embankments. The researchers arrived at this conclusion after discovering that mixtures of RCG and biosolids showed great promise for replacing natural aggregates in several geotechnical applications. Attom [10] investigated the potential of RCG to mitigate the swelling pressure from clayey soils.

Makowski and Rusenko [11] investigated the viability of using RCG (mean particle size 0.40 mm) as an alternative beach infill material. The study aimed to find viable alternatives to sand for use in reinforcing erodible coastlines. It was necessary to conduct chemical and biological tests on RCG to assess its viability as a replacement for sand in beach filling. The study suggests that RCG may be utilized instead of sand to both forestall the emergence of erosional hotspots and mitigate their effects [12].

To determine the effect of varying percentages of crushed glass on the geotechnical properties of soil mixtures, researchers have studied the physical properties of crushed glass for soil enhancement purposes, as in [13][14][15]. The glass was combined with processed dirt, often sand 25.4 mm or smaller. The results indicated that crushed glass had an average specific gravity of 2.5, a peak density of 16.2 $kN/m^3$ with normal Proctor compaction, a maximum density of 18.1 $kN/m^3$ with modified Proctor compaction, and an inner resistance of around 51 degrees. According to [13][14][15], who summarized the research of Dames and Moore, using crushed glass as a substitute for natural aggregates in construction is helpful.

## 3. The Use of RCG in the Manufacture of Tiles and Bricks

According to the published research, RCG has been employed in producing tiles and bricks in several experiments. RCG has been extensively examined as a fluxing material, notably as a substitute for feldspar, in the context of the tile industry. In porcelain stoneware tiles, Luz and Ribeiro [16] investigated the behavior of RCG as a potential replacement for traditional fluxing chemicals. The process of densification of the samples was sped up by RCG, which also resulted in an improvement in the samples' decreased open porosity and absorption. However, certain unfavorable effects, such as greater shrinkage and higher closed porosity, were also seen at higher proportions of RCG. These effects were observed. According to the findings of the research as a whole, the dependability of stoneware tiles may be improved by adding a very tiny amount of fine RCG in addition to feldspar. According to the results published by other researchers who came to the same conclusions, RCG might be used as a partial alternative for feldspar in manufacturing porcelain sanitary ware.

Aneke Frank Ikechukwu [17] reported the results of research on masonry bricks made from mixtures of Ordinary Portland Cement (OPC), recycled concrete (RCG), and fly ash (FA) in varying percentages. The masonry bricks were manufactured with 5%, 10%, and 15% additions of OPC to the raw materials, respectively, the total weight of FA and RCG combined. Compared to burnt clay bricks, which have an average compression strength of 3.8% greater, the manufactured bricks had a considerable resistance to compression. The compressive strength of all the bricks created for the research met the standards set by the South African National Standard Code SANS 227 (i.e., 7 MPa) for each load-bearing masonry brick. The scanning electron microscopy (SEM) study showed that the voids found in the microstructure of the 5% OPC bricks had low strength, the consequence of an incomplete pozzolanic reaction. This was determined by identifying the void spaces as the primary reason for the low strength. Additionally, the impacts of sulfate salt were considerably resisted on the surface of all the examined bricks, including FA and RCG. This was because the bricks included aluminosilicate compounds, which generated pozzolanic processes inside the matrix of the brick. Because of the increased strength formed in the bricks after they were produced, the tested bricks displayed brittle features in their stiffness. As a result of the percentages of RCG particles, this demonstrated the presence of a significant proportionality between the dynamic modulus and the ultrasonic pulse velocity (UPV). The coefficient of determination (R2) for this relationship was comparable to 90%.

The characteristics of RCG and white clay (thin film transistor-liquid crystal display) were investigated by Lin [18] as potential raw materials for the production of ceramic tiles Tile samples were made by incorporating 0–50% RCG into the ceramic mixture. Several tests, including bulk density, water absorption, fire shrinkage, and hardness, were administered to tile samples that had been changed. In general, the findings showed that using certain RCG as a raw material to manufacture ceramic tiles with adequate strength and microstructure qualities is feasible. This was proved by the findings. In a study that was quite similar, Kim et al. [19] (2016) looked into the possibility of using RCG, which stands for liquid crystal display, in ceramic tiles instead of feldspar. During the preparation of the samples, 40% of the feldspar in the ceramic mixture was substituted with RCG. In general, the findings of the experiments demonstrated that the tile samples that included RCG had a dense microscopic structure and better properties, such as a higher coefficient of thermal expansion and a lower water absorption rate. As a result, using RCG as a partial replacement for more traditional raw materials and fluxes in stoneware tile products is technically viable.

Several studies have evaluated the possibility of using RCG as an additive in the production of bricks. In research carried out by Loryuenyong et al. [20], the impacts of RCG on the mechanical and physical properties of clay bricks were investigated. The qualities of the clay bricks that resulted from the experiment were analyzed, and various percentages of RCG were included in the mixture. These percentages included 5%, 15%, 30%, and 45%. According to the conclusions, if clay is mixed with anywhere from 15 to 30 percent RCG, it is possible to produce versatile bricks that are versatile enough to be used in various environments. However, the use of RCG at levels greater than 30% has the potential to negatively affect the performance of bricks in several ways. These methods include a drop in compressive strength and a modulus of rupture lower than expected. The findings of the research indicated that RCG concentrations of up to 30% may be applied to clayey bricks without risk.

Lin [21] made an effort to investigate the viability of ecobricks by substituting RCG for clay in their production (optical). The samples were prepared by firing them at temperatures ranging from 800 to 1000 degrees Celsius using varying percentages of RCG as a replacement: 0%, 10%, 20%, 30%, and 40%. This showed that adding RCG to clay bricks may improve their characteristics, such as their specific gravity, water adsorption rate, and compressive strength. The same research, however, found that the presence of RCG proportionally increased the shrinkage in the bricks, especially at replacement proportions greater than 30%. This was particularly true when the replacement percentage was greater than 30%. It was determined that the best amount of RCG substituted for clay in bricks is around 30%.

Federico [22] conducted research to investigate how RCG affects the characteristics of burnt clay bricks. Eleven sets were constructed with A containing no glass, B containing 5% glass, C containing 5% glass, D containing 10% glass, E containing 10% glass, F containing 15% glass, G containing 15% glass, L containing no glass, X containing no glass, FL containing no glass, and FX containing no glass. Every set had a total of 30 different samples. Set A was designated as the test group, while the other groups were considered the control groups. A variable proportion of RCG was present in B, D, and F, but all of them had the same size of glass mesh. Each sample of C, E, and G had a unique proportion of RCG content while having the same glass mesh size. As a result, research was done to determine how the qualities of the bricks were affected by factors like the amount of RCG present and the size of the particles. In addition, samples L, X, FL, and FX were made to evaluate how the bricks were affected by the technique and the temperatures at which they were fired. To make the clay more malleable, lignosulfonate, in the amount of 20 milliliters, was mixed in with the water before the mixing process began. The results of the tests revealed that the percentage of RCG had a meaningful impact on the compressive strength of the material. It was determined that G (15.1%) had a compressive strength of 133.4 MPa, which was the highest value

When Dondi et al. [23] added 15% RCG to burned clay bricks, the bulk density rose by 1.1%. Another study came to a similar conclusion, reporting an increase of 2% when 25% RCG was added. Phonphuak et al. [24]. also showed that the brick specimens' density rose by 3.5% when the bricks included 10% RCG. Additionally, research indicated that when less than 10% RCG (soda lime glass) was added to the bricks, the bulk density of the samples was minimally impacted by the quantity of waste glass in the mixture or the specified firing temperature [25]. This was the case even though the amount of RCG supplied to the bricks was less than 10%.

Additionally, it was noted that the bulk density increased dramatically with a rise in firing temperature when there was an addition of RCG content that was greater than 20%. The proportion can improve the quality of the bricks produced while allowing for acceptable shrinkage. Additionally, additional studies have demonstrated that RCG might produce bricks with the same or improved quality while reducing the required energy.

## 4. The Use of RCG in Water Filtration

To make polluted water suitable for consumption or use in some other capacity, it must first go through a process known as water filtration, which consists of removing particulates and other contaminants from the water using a filter medium. The selection of RCG as a filter medium is contingent on various criteria, such as the specific gravity of the particles as well as their form, size, and porosity [26].

In the treatment of septic tank effluent in intermittent recirculating biofilters, Hu and Gagnon [27] and in polishing filters for household wastewater Gill et al. [28]; Healy et al. 2010; Horan and Lowe [29], RCG has been evaluated as a wastewater filter medium. It has been claimed that RCG may retain 79% to 98% of total suspended particles in recirculating biofilters while also removing approximately 94% and 96% of BOD and ammonium nitrogen, respectively Elliott. The removal of 73% of the chemical oxygen requirement and 28% of the total nitrogen was reported for RCG by Gill et al. [30] when it was used as a tertiary filter medium. Researchers Salzmann and colleagues investigated using RCG as a tertiary filter medium for water treatment in municipal lagoons. They found that RCG had the same capacity for removing suspended particles as sand did and identical performance for ammonia and chemical oxygen demand parameters.

The outcomes of the study indicated that the use of RCG as a filter medium led to a decrease of 10% in the number of media required for the filtration process. The findings of the research indicated that RCG provided performance that was comparable to that of sand and, in some instances, even better. Similarly, the performance of RCG was evaluated alongside conventional sand media for high-rate filtration by the Clean Washington Center [31]. The usage of RCG was shown to enhance water clarity when compared to typical sand, as indicated by a 25% drop in the National Turbidity Unit (NTU) in conjunction with a 23% improvement in backwash efficiency. These results were seen in the research. The outcomes indicate that the amount of RCG needed for filtering is 20% smaller than that of natural sand. This provides a greater economic benefit throughout the processing, shipping, and disposal operations since RCG requires less material overall. The effectiveness of RCG as a filter medium in treating municipal drinkable water was investigated by Evans et al. [32]. The quality of the water obtained from RCG was discovered to be equivalent to that of sand in terms of the number of particles, the turbidity, and the quantity of metals present. Therefore, RCG presents an opportunity to replace sand in water filtering applications while simultaneously improving the quality of the effluent produced.

Omer et al. [33] experimented with the replacement of coal with RCG. The use of broken recycled glass as a potential alternative to silica sand in dual-media filters has been researched to discover a suitable substitute. Experiments with inline filtration were carried out on a pilot scale using raw water obtained from three different water sources. The turbidity of the raw waters used in the experiments ranged from 6.0 to 14.0 NTU in each case. During the studies, two filter columns that were physically similar were run in parallel. The first filter was made up of 62.5 cm of silica sand and 41.5 cm of anthracite coal, while the second filter was made up of 62.5 cm of crushed recycled glass and 41.5 cm of anthracite coal. The combined bed depth of the two filters was 104 cm. The following is a list of the characteristics of the medium: The effective dimension of the glass is 0.77 mm, and its homogeneity coefficient is 1.41. The effective size of the sand is 0.79 mm, and the uniformity coefficient is 1.33. The effective size of coal is 1.45 mm, and the uniformity coefficient is 1.39.

When no coagulant was used; when 5 and 10 mg/L of alum were used; when 5 and 10 mg/L of ferric chloride were used; and when no coagulant was used. These are the five different times that the tests were carried out. The amount of filtering performed was at a rate of 11.5 m per hour. Researchers examined the turbidity, particle counts, and head losses as functions of time and then compared the findings. It was discovered that the following things are correct: Since the effluent turbidities and particle counts of the two filters were relatively comparable to one another, this indicates that the effluent quality was essentially the same when broken glass was used instead of silica sand as the media in the filter. In most of the tests, the filter constructed with broken glass performed superiorly to the filter that contained sand regarding the clean-bed head loss and overall head loss. Additionally, the filter created with broken glass had fewer severe head losses owing to clogging than the filter that included sand. It has been established that shattered glass may be an efficient alternative for silica sand in the process of dual-media filtration, which uses two different types of media [33].

Selda Yiğit Hunce et al. [34] conducted tests with three different media, namely silica sand, crushed recycled glass, and re-crushed recycled glass. The same sieved fractions, i.e., 0.85–0.71 mm, 1.00–0.85 mm, and 1.18–1.00 mm, were used for all materials. Performing tests with the same sizes of different materials allowed investigation of the effect of particle shape on filterability. The sphericity of the glass fractions was significantly lower than that of the sand medium, while lower differences in sphericity were observed between the crushed and RCG fractions. The tests showed that the glass fractions produced better filter performance than sand and silica.

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