Utilizations of recycled glass

Usos del vidrio reciclado

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Abstract

Glass recycling in Mexico accounts for only 12%, making it one of the materials with the lowest percentage in this area. The different applications where recycled glass can be used range from the construction industry, concrete production replacing fine aggregate or cementitious material, ceramic materials, architecture (mortar), glass blocks, road paving and dentistry. Among the sources of discarded glass to be recycled are primarily beverage bottles and window glass; however, there are a wider variety of glass items to be investigated for use as recycled material, as well as their use in these and other applications. From the review carried out in the research work presented here, a different panorama was obtained with respect to other sources of waste glass that can be recycled, without losing sight of the fact that this will contribute to reducing the environmental impact, in a first stage of the area surrounding the Educational Institution in which the work is carried out.

Recycled glass, Concrete, Cement

Resumen

El reciclado de vidrio en México cuenta con solo el 12%, siendo uno de los materiales con menor porcentaje en este rubro. Las diferentes aplicaciones donde el vidrio reciclado puede ser utilizado, van desde la industria de la construcción, elaboración de concretos remplazando al agregado fino o material cementante, en materiales cerámicos, arquitectura (mortero), bloques de vidrio, pavimentación de carreteras y la odontología. Entre las fuentes de vidrio desechado para ser reciclado se encuentran principalmente las botellas de bebida y vidrio de ventanas; sin embargo, existen una variedad más amplia de artículos de vidrio para ser investigados y poder ser utilizados como material reciclado, así como su uso en estas y otras aplicaciones. De la revisión realizada en los trabajos de investigación aquí presentados, se obtuvo un panorama diferente respecto de otras fuentes de vidrio de desecho que pueden ser reciclados, sin perder de vista que con ello se contribuirá a reducir el impacto ambiental, en una primera etapa, de la zona circundante a la Institución Educativa en la que se trabaja.

Vidrio reciclado, Concreto, Cemento

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Introduction

The increase in municipal solid waste (MSW) production is directly related to population growth and current lifestyles, which generally define a higher consumption of goods and services. This trend makes it necessary to put attention to issues related to the collection, management, and final disposal of waste (SEMARNAT, 2016).

In Mexico, 102,895 tons of MSW are generated daily, of which only 83.93% is collected and 78.54% is disposed of in final disposal sites, with only 9.63% of the MSW generated being recycled. According to estimates of the National Association of Plastics Industries (ANIPAC), the national recycling market is worth more than 3 billion dollars; also, in 2019 it is estimated that the production of about 14.9 million tons of solid waste that can be reused, of which 39% corresponds to paper, cardboard and similar products; 30.7% to plastics and 16.6% to glass; and the level of recycling was of the order of 56% of paper and cardboard discarded, 50% in plastics, but only 12% of glass (Sandoval, Ramos & Correa, 2023).

According to the figures mentioned, in Mexico the least recycled solid waste is glass, which makes it a topic of interest to address and propose a possible solution to the problem of confinement in waste landfills of this type of material. This paper presents the generalities of glass, how it is disposed of once the use of this material is fulfilled, where glass waste has been used and a proposal for the recycling of this material.

1. Generalities of Glass

Quartz melts at approximately 1600°C and forms a sticky liquid. If the liquid is cooled rapidly, the silicon-oxygen bonds re-form before the atoms have been able to arrange themselves in a regular fashion. The result is an amorphous solid, known as quartz glass or silica glass (Brown, LeMay, Bursten & Burdge, 2004).

Ordinary glass used in windows and bottles is known as soda-lime glass, and contains CaO and Na_2O, in addition to SiO_2 from sand. CaO and Na_2O are produced by heating two inexpensive chemicals: limestone and sodium carbonate (ídem).

The addition of CoO to soda-lime glass produces the deep blue color of "cobalt glass". The substitution of Na_2O for K_2O results in a harder, higher melting point glass. The use of PbO instead of CaO results in "lead crystal" glass, which is used to make decorative glassware. With the addition of non-metallic oxides, such as B_2O_3, a glass with a higher melting point and greater ability to withstand temperature changes is obtained, which are used where resistance to thermal shock is important, for example, in laboratory glassware or coffee pots (ídem).

A "natural glass" is obsidian, which is a natural combination of oxides melted by intense volcanic heat and vitrified (turned to glass) by rapid cooling in contact with air. Its black and opaque color is due to the relatively high content of iron oxides. Its chemical resistance and hardness compare favorably with those of many commercial glasses (apud Paneque, Díaz & López, 2023).

Today glass is an essential element in key sectors, such as energy, biomedicine, agriculture, electronics, information and communications, optics and optoelectronics or aerospace (Paneque *et al*, 2023).

2. Disposition of glass

Glass is among the most abundant materials on earth, obtained mainly from silicon. With the development of science, technology, and society, it has become one of the most important inorganic materials. Combining transparency, durability, chemical resistance, and compressive strength greater than that of concrete and even steel, it is widely used in house construction and in everyday life (Quirino, Agrawal, Alves, de Figueiredo & Rodrigues, 2023).

Bottles, jars for the pharmaceutical industry, cosmetics, perfumery, household items (Tittarelli, Giosue & Mobili, 2018), in cathode ray tube, containers, light bulbs (Rahim, Che, Mohamad, & Salehuddin, 2015), microwave dishes, television screens, monitors, are some of the shapes and applications of glass that can be seen daily.

After use, the waste glass can be filtered, cleaned, and re-melted for the manufacture of new glass products.

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However, impurities, multiple shapes, color, lack of detection facilities constitute a barrier to the reuse of this material (Hamada, Alattar, Tayeh, Yahaya & Thomas, 2022).

Due to the high cost of cleaning and color sorting, the recycling rate for glass bottles is around 25% and a large amount of waste glass is sent to landfills as waste; since glass is not biodegradable, landfills do not provide an environmentally friendly solution (Tittarelli *et al*, 2018). Waste glass treatment and recycling is a pressing problem that is currently unresolved (Bristogianni & Oikonomopoulou, 2022).

The recycling process is complex, and the cost is relatively high, which leads to a lack of motivation for glass recycling in companies (Quirino *et al*, 2023). Recycling companies realize that they earn little or even have a loss of revenue from processing glass (Rahim *et al*, 2015).

In Mexico, only 12% of the material is recycled and this is mainly due to supply and demand situations (Sandoval *et al*, 2023).

However, in the study by Barfod, Freestone, Jackson, Lichtenberger & Raja (2022), it has been shown that from the first century to the middle of the eighth century A.D. the supply of glass and the recycling of this material played an important role in the economy of ancient cities. his was due to the high demand for glass in urban environments coupled with the higher cost of overland transportation compared to the coastal trade at the time.

This shows the importance of recycling this type of material both in terms of environmental protection and economically, since past times.

3. Use of waste glass

Due to the environmental problems associated with the production of portland cement, some alternatives arise to try to obtain sustainable development, for example, through the development of new, more eco-efficient cementitious materials (Torres, Rodríguez, Alonso & Puertas, 2015).

The construction industry is an attractive option for the utilization of waste glass, as the physical properties and chemical compositions of glass resemble those of concrete raw materials such as cement and river sand (Quirino *et al*, 2023).

On the other hand, the quantities of sand and gravel extracted as aggregates for the preparation of mortar and concrete are 130 million cubic meters each year and represent 59% of the materials excavated in Italy. Therefore, the use of by-products to replace these natural aggregates, as is waste glass, seems an interesting approach to create environmentally friendly composites (Tittarelli *et al*, 2018).

In addition, the process of obtaining aggregates and producing cement has created significant environmental hazards, such as high energy production and excessive CO_2 emission (Hamada et al, 2022). This has motivated the implementation of strategies to reduce environmental pollution, concrete production costs and carbon footprint by partially replacing cement with other low-cost components and more environmentally friendly materials (Redondo, Sánchez, R. Pérez, Gómez & Abellán, 2023).

The waste glass has been used as fine aggregate (partial replacement of sand of 20%, 40% or 60%) (Hamada *et al*, 2022); or as a cementitious material (partial replacement of cement of approximately 50% with silica fume) (Redondo et al, 2023). In the first case a particle size between 2 and 0.15 mm is considered, which is identified as waste glass powder. For the second case the particle size is of the order of microns (2.5, 45, 275 µm). When performing different tests of the concretes made with waste, according to the results obtained for compressive strength at 28 days, Rahim *et al* (2015), identifies as a maximum value 10% to replace the fine aggregate with waste, differing from those presented by Hamada *et al* (2022), from 20% to 30%.

A study was carried out on concrete mixtures (concrete), where sand and cement are replaced by ground glass, in dosages of 25%, 50% and 100% for the former and 10%, 20% and 30% for the latter, maintaining the properties of the mixtures within the parameters of traditional concrete.

The recycled ground glass was obtained from the Empresa de Recuperación de Materias Primas de Villa Clara. The tests were carried out on fresh concrete, slump, in which it was found that the percentage of cement substitution should not exceed 20%. In hardened concrete, compressive strength tests were carried out, where it was determined that up to 25% of the sand can be replaced by ground glass (Columbié, Crespo, Rodríguez & González, 2020).

Frometa, Vidaud, Font & Negret (2020), conducted a study with glass obtained from bottles from the Empresa Provincial de Recuperación de Materias Primas (EPRM), in Santiago de Cuba; however, it mentions that there is no defined producer, and neither are they of national production. The bottles are imported from different countries, which raises several questions regarding their main properties and subsequent performance in concrete. The analysis of properties: chemical composition, granulometry, fineness modulus, absorption, specific weight, among others, determined that the product is suitable to be used as an addition to concrete as a partial replacement of fine aggregate. Based on national and ASTM standards.

Tittarelli *et al* (2018), mentions that the use of waste glass instead of aggregates/natural sand in the composition of mortars is feasible, and the replacement cost represents an advantage. Additional benefits include: (1) less use of natural aggregates, decreasing the cost of exploitation, less invasion of quarry extraction, extension of quarry life, less use of non-renewable natural resources. (2) Recycle that part of glass that would end up in a landfill and thus a greater eco-sustainability in the entire production cycle. (3) Increased architectural value of mortars/concretes, as the visible colored glass particles will produce a pleasing visual effect on the surfaces where the mortar is applied. Since construction requirements such as functional, aesthetic, economic and insulating criteria must be met, the use of different colored glass cullet in cementitious materials is a good alternative. The glass samples used come directly from an as-is hollow waste glass management system to test a mixture of different glass wastes without costly additional treatment. The calcareous sand was replaced by recycled glass in proportions of 0-33-66-100%.

The samples were tested for slump, compressive and flexural strength of mortars, and drying shrinkage, to mention a few. From the results obtained they conclude that it is possible to replace in its totality the calcareous gravel with recycled waste glass of mixed color, to produce architectural mortars without any addition or mixture.

Ultra high performance concrete (UHPC) contains a large amount of cement. This situation places this type of concrete in the "environmentally unfriendly manufacturing product" category. On the other hand, the amount of water in the mix is very low, which leads to early hydration and consequently to a higher shrinkage value compared to conventional concrete (apud Mosaberpanah, Eren & Tarassoly, 2019).

Ultra-high performance vitreous concrete is an environmentally friendly version, which gives technical, economic, and environmental advantages due to the replacement of glass powder by cement. Generally, the particle size of glass powder plays an important role in the effects on the mechanical properties of concrete, especially on the compressive strength (Mosaberpanah *et al*, 2019). In their study models mechanical, rheological and drying shrinkage properties of a UHPC under normal curing conditions, by the addition of nano-silica and replacement of cement with waste glass powder.

The amber glass powder was prepared from glass bottles dumped in the wild, after washing and removing the paper labels, they were crushed and ground to a particle size of 63 µm. The samples were prepared with the following percentages of nano-silica and glass powder, respectively: 0%-0%, 2.5%-10% and 5%-20%.

The addition of nano-silica increased the compressive strength and drying shrinkage at 28 days of age, while it decreased the flowability of fresh UHPC concrete. The addition of glass powder increased the compressive strength, drying shrinkage and flowability of fresh UHPC at 28 days of age.

Glass has favorable properties for construction because it is a material that is tenacious to compression, as well as fan shells, which are made of calcium carbonate shells, becoming materials that are not harmful to concrete and with similar characteristics to conventional aggregate, considering them as alternative components for making concrete (Milla, 2023). He collected glass samples in the city of Huaraz, Peru, and fan shells from the Huarmey dump, Peru. The glass was crushed in a mortar and the fan shells were calcined in a furnace and then ground. Pattern samples and specimens with glass powder and calcined fan shells were made, both materials were added 2% each in the concrete, the design compressive strength was 210 kg/cm2. Simple compression tests were performed at 7, 14 and 28 days.

For both types of specimens, the compressive strength increased as the days of testing increased, being more notable the value at 28 days, because in the pattern samples the compressive strength was 295.4 kg/cm2, while the concrete with the addition of powdered glass and calcined fan shells showed as a result a strength of 306.1 kg/cm2. They conclude that the materials used provide 45.7% to the compressive strength of the concrete.

Arjona, Guzman, Torres, Cedeño & Acosta (2015), perform their work with respect to porcelain stoneware, which is a ceramic product characterized by low water absorption ≤0.5% and mechanical flexural strength >35MPa in accordance with ISO 13006. Porcelain stoneware tile has experienced growth in production and sales, compared to other building ceramics; this is attributed to its high technological properties, especially regarding water absorption, chemical resistance and frost resistance, and mechanical properties such as flexural and abrasion resistance.

It is currently working on the implementation of alternative raw materials to conventional ones, which will reduce production costs and maintain or improve both physical and mechanical properties. The glass used is window glass, as a possibility of using glass powder as a replacement for the traditional flux material used in the production of porcelain stoneware, based on the firing behavior of the green product and the physical-mechanical properties of the sintered material.

The average particle diameters of the ground glass are 35.69 µm. In the fired pieces, the degree of vitrification and flexural strength were evaluated, considering the requirements established in several ASTM standards. From their study they concluded that the incorporation of glass powder as a replacement for feldspar in porcelain stoneware mixtures contributes to a decrease in the maximum densification temperature of samples fired at 150°C, with respect to a standard composition. In addition, although glass powder was shown to be a strong flux, fired specimens with feldspar substitution by glass powder at 25% and 50% by total weight, do not allow to have Bla porcelain stoneware (flexural strength >35MPa and water absorption ≤0.5%).

The raw material normally used for the formulation of porcelain is divided into three main groups of minerals with respect to their function: cay materials improve the plasticity of the body, while non-plastic supplementary materials improve the melting characteristics (flux) and impart structure (filler). Decorative ceramic objects are manufactured using clay, quartz, and feldspar, but nowadays waste materials such as glass powder are being used to make these objects. This waste glass can replace traditional fluxing agents, such as feldspar, without changing the process and quality of the final product.

The influence of waste glass (borosilicate glass and soda-lime) on the physico-mechanical behavior of soft porcelain ceramics was investigated. Technical parameters such as water absorption, porosity, shrinkage, bending stress, wear, bulk density, and microstructural evaluation were determined. The glass was crushed and then ground to a particle size of less than 150 µm for each of the materials used. Samples were prepared for porcelain with soda-lime glass waste and samples with borosilicate glass, in both cases in percentages of 30%, 45% and 55% of the soft porcelain composition.

From the results, it was concluded that porcelain containing soda-lime glass presented better results, indicating that this glass improves mullite growth and increases the formation of the glassy phase, which decreases the presence of pores, resulting in decreased water absorption, increased bulk density and decreased wear (Owoeye, Sayo, Isinkaye & Kingsley, 2019).

There are different methods of glass production, including blowing, drawing, floating, and melting (Quirino *et al*, 2023). In the work, they propose a practical and versatile alternative to the recycling of waste glass to produce hollow blocks, using the furnace melting process. The process includes the design of blocks and characterization tests of the blocks obtained. The material used in this study was sodium calcium silicate glass, post-consumer beverage bottles.

The glass bottles were separated by color, washed, crushed, and sieved on different meshes. The mesh sizes were 4.76, 2.38- and 0.71-mm. Chemical composition, microstructural characterization of the glass and compression tests were obtained. From their results they conclude that higher temperatures and exposure times lead to better adhesion of glass particles and higher crystallinity, leading to an increase in compressive strength.

The study by Perera, Saberian, Zhu, Roychand & Li (2022), concerns the subgrade layer, which often consists of natural/native soil; however, some natural soils, such as expansive or reactive clays, have undesirable attributes, which include high expansion and contraction potential, low bearing capacity, high compressibility, among others.

These characteristics jeopardize the longevity and performance of the entire pavement system. Stabilization of expansive clays could be achieved through two main approaches, i.e., chemical, and mechanical stabilizations. Mechanical stabilization involves the introduction of foreign aggregates, such as glass, rubber, plastic, fibers, to name a few, with desirable physical properties into the reactive clay, thus alleviating its problematic behavior.

Crushed glass has favorable construction properties, such as lower water absorption potential, good mechanical strength, relatively light weight (low specific gravity), durability, workability, etc., making it an ideal material for use in civil engineering applications. Mechanical and microstructural investigations on expansive clay and crushed glass composites for pavement subgrade applications were performed in the research mentioned.

The crushed glass was collected from a 15-location recycling company, where crushed glass is produced by crushing waste glass to a mixture with a particle size no larger than 5 mm. Compaction tests, unlimited compressive strength, repeated triaxial loading, to name a few, were carried out to evaluate the 5%-10%-15%-20% glass content mixes. Among the results are improved flexibility of the clay subgrade, reduction in subgrade thickness and savings in construction cost and time, improved expansion-shrinkage behavior (ibídem, 5).

When building roads, the objective is always to reduce construction costs, and carry dirt are expensive, so when deciding to stabilize the subgrade of a road, a physical-mechanical study must be carried out to make the best decision on whether to treat the subgrade or to improve or replace it. Always avoid additional soil treatment. This is mentioned by Culquichicon & Vasquez (2022), in their thesis work; in which they sought to determine the influence of ground glass for the stabilization of a road.

In their research, they considered the soils of the Simbal-Caserío Simbal Mucha road, Peru, from which they extracted 9 pits, with one kilometer from each other and excavated to a depth of 1.5 meters, according to the country's regulations, from which they obtained the samples to carry out tests with the stabilizing agent, ground glass, in different percentages 6%, 8% and 10%. Ground glass was collected from bottles, broken glass that usually goes to the landfill. It was then washed, crushed, and ground to be sieved in a N°200 mesh (75 microns).

From the evaluation of the results of physical and mechanical properties (humidity, density, CBR index, among others), it was determined that they were improved with the use of ground glass. The amount of glass influenced the compaction properties, the maximum compaction moisture decreased. The CBR index in the standard sample was 7.52%, while for the sample with 8% ground glass it was 38.38%, which when compared with the 100% standard of the MDS has a better value.

The development of glass in medical applications is acceptable worldwide, especially in dentistry and orthopedics. Glass used in biology is known as bio-glass.

Calcium aluminosilicate glass is considered a material slightly like bone and tooth structure and of potential use for dental restorative material. Glass ionomer cement (GIC) is produced from the acid-base reaction between different types of alkali glass powder and polymeric acid. GIC has been used clinically as a restorative material for more than 40 years and researchers have shown increased interest in the development of GIC, such as its physical, structural, and mechanical properties.

In the study of Matori, Ahmad, Mohd, Che, Zainuddin, Wan, Abdul, A. Rahman, Kul, A. Wahab & Effendy (2020), calcium fluoroaluminosilicate glass (CFAS), they generate it from waste materials such as soda-lime-silica glass, raw material to obtain silicon, and clam shell, to obtain calcium oxide. By mixing CFAS powder with polyacrylic acid and water, GIC is formed. The GIC samples are immersed in distilled water for 7, 14, 21 and 28 days of aging; the samples were analyzed to study the structural and mechanical physical properties. As the aging time increases, the density also increases, the compressive strength of 42.23-50.28 MPa, ISO 9917 establishes a minimum value of 50MPa to be used as a material in dental application. From these results, mainly, it is considered that the GIC obtained from CFAS is a material with properties suitable for use in dentistry, especially in luting, base, and liner applications.

From what has been described in this section, it can be observed that the area where most studies have been carried out for the use of recycled glass is in the construction industry, since its properties to react with the elements of gravel, sand and cement are considered. However, there is research that explores different uses for this waste material. It is important to mention that according to bibliographic sources that were taken as reference for this work, they show that there are countless research works focused on physical, chemical, and mechanical properties to improve and increase the amount of waste glass material used in the applications mentioned here.

Results

As part of the review of the articles described in the corresponding section 3, it is worth highlighting the importance that is being given to recycling glass.

To reduce the disposal of this material in landfills that cause damage to the environment, since this is a non-biodegradable material, which generates the permanence of this waste material in a confined area for an indeterminate period. Among the benefits mentioned for recycling glass are (Arjona *et al*, 2015; Hamada *et al*, 2022):

- Economic benefit.
- Reduced impact on the environment.
- Reduction of the cost related to the disposal of glass waste in landfills.
- Reduction of CO_2 emissions and energy consumption.
- Reduction of air pollution because of cement production.
- Public awareness of waste issues and the advantages of reuse.
- Protection of the environment by keeping a large quantity of the main raw materials on earth.

However, it is important to mention that some research considers that there is an additional cost for the preparation and elimination of contaminants in the glass to be recycled; it is also mentioned that glass cannot be recycled continuously, but this depends on the impurities and manufacturing process of the material.

In addition, most of the authors in their research suggest studying other properties different from those presented, varying the percentage of ground glass they use, as well as using different particle sizes, depending on the application in which the incorporation of recycled glass is to be investigated.

They also consider adding other waste materials, mostly organic, to investigate the effect of combining them in the physical and mechanical properties of the "new" material. Under this premise, and due to the low percentage of this recycled material in Mexico, there is a potential field of research to contribute to the reduction of this type of waste, in the first instance, and because the crushed or ground glass is required, is to have equipment that allows carrying out this task and that does not represent a high cost, to obtain the raw material in particle sizes according to those described in the researches presented in this document.

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Conclusions

The recycling of waste glass is an area that is little researched in Mexico, which makes it a potential field for research and proposals for the recycling of this material, in a first stage in the area surrounding the Academic Institution mentioned above, helping to reduce the damage to the environment by reducing the amount of material disposed of in landfills.

It is also concluded that there are other sources of glass that can be recycled that are not usually mentioned, the most common are beverage bottles or window glass, but there are also microwave dishes, evacuated tubes, television and computer monitors, kitchen utensils, among others, so that research in this field can take different aspects and a greater number of applications.

One element that should not be overlooked is that the works described in previous sections were tested based on the regulations of the country where the research was carried out, as well as on international regulations, to validate their results and to ensure that the material they propose can be considered for possible application.

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