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Crushed glass as a substitute for the fine aggregate in mixes of masonry mortars

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— Abstract—

The inappropriate disposal of Construction and Demolition Waste (CDW), particularly glass, leads to many economic and environmental problems. Therefore, the main goal of this research was to evaluate the effects of reusing crushed glass as a partial substitute for natural sand on the compressive strength of masonry mortars. To achieve the above, a conventional mortar mixture (cement, sand, and water) was designed in a 1:4 ratio of cement-sand which works as a control mixture. Based on the design of the base mixture, partial substitutions in dry weight of the natural sand were made for crushed glass in the proportions 10%, 20%, 40%, 60%, 80%, and 100%. Once the mortars were made, they were subjected to a curing process by immersion in water and subsequently tested at curing ages of 7, 14, and 28 days. The experimental results showed that, compared to conventional mortar, replacing sand with crushed glass by 10% increases the compressive strength of mortars, while if the natural aggregate is replaced by 20%, the resistance is like the control mortar. Consequently, reusing crushed glass as a partial substitute for sand is a viable option and contributes to the protection of material banks of natural aggregates and the reduction of excessive accumulation of glass in municipal landfills.

Keywords:

Mortar; sustainability; WCD; crushed glass.

Construction and Demolition Waste (CDW) as the name implies, comes from the activities of building, demolishing, rehabilitating, and restoring structures. Economic development in several countries has generated great momentum in the construction industry, which is reflected in new structures and the remodeling of old ones. However, this progress generates large amounts of CDW. In our country, more than 30,000 tons of CDW are generated per day, of which the recycled percentage is practically zero (Ceñal Ruiz: 2015). Estimates from the Mexican Chamber of Construction Industry reveal that CDWs consist of 39% excavation material, 25% concrete and mortar waste, 24% debris from partitions, masonry, and pavers, and 12% of materials such as metals, glass, and wood (CMIC, 2013). The discharge without separation or treatment of the CDW (often in clandestine sites) generates a relevant environmental impact. As a result of the improper management of CDWs, they get accumulate uncontrollably in clandestine landfills or are used as landfills causing environmental problems, public health, and a bad urban image.

Modern civil engineering has two main objectives: to produce quality materials and to reduce production costs, both aspects taking care of the environment. For this reason, in recent years, several researchers have studied the CDW reuse, specifically crushed concrete and/or mortar debris, as partial substitutes for gravel or sand in the manufacture of new concrete and mortar mixtures (Jiménez, *et al*., 2013; Ledesma, *et al*., 2014; Mora-Ortiz, *et al*., 2020). These new aggregates, which have their origin in the crushing of the CDW, are known as recycled aggregates (RA).

A material that is part of the CDW and has not been as used as the rubble of concrete and mortar is glass. This has favored its excessive accumulation in the landfills of the cities of Mexico and the world. Reusing glass as a partial substitute for sand in the manufacture of mortars would yield economic and environmental benefits, depending on end uses and production scale (Shi and Zheng, 2007). Glass is a material that due to its physical characteristics has not been studied as exhaustively as other elements of the CDW (Marco, *et al*., 2012), which is why research on this material is scarce. Regarding the use of the glass that is part of the CDW, there is a lot of work to be done. However, in the last decade, several researchers have made valuable contributions in the use of this material, for example, Mardani-Aghabaglou, *et al*., (2015) analyzed the performance of crushed glass in the elaboration of concrete concluding that, although the replacement of sand by glass in concrete mixtures decreased the resistance, aspects such as durability increased. Mirzahosseini and Riding (2014) and Nassar and Soroushian (2012a, 2012b) showed that using glass in concrete mixtures to partially replace cement improves the chemical stability of mixtures by reducing the oxidation of reinforcing steel. Kou and Xing (2012) used glass powder in ultralight concrete mixtures concluding that the addition of glass improved the mechanical properties of concrete. Soliman and Tagnit-Hamou (2016), Hendi, *et al*., (2019), and Małek, *et al*., (2021) stated that the use of glass instead of sand reduces the water absorption of concrete mixtures, so most of their mechanical properties improve. Spiesz, *et al*., (2016) concluded that in addition to improving some properties of concrete, crushed glass can be used in the elaboration of translucent and ecologically friendly concrete.

As for the use of glass in masonry mortars, references are scarce. Marco, *et al*., (2012) performed resistance tests on mortar specimens, adding glass powder and other chemical compounds, the results showed that glass powder as a fundamental binder intervenes favorably in the development of compressive strength. In this sense, with such promising results, it is essential to continue in this line of research. The objective of this article is to determine the optimal amount of crushed glass that can be added to mortar mixtures without them seeing their compressive strength significantly reduced. That is, it is intended to know the optimal percentage of substitution of natural sand (AN) by crushed glass that allows obtaining compressive strength like those obtained in a conventional mortar (sand + cement + water).

This research is the first part of a university project that aims to encourage glass recycling through its use in the elaboration of masonry mortar mixtures, with this it would be possible to increase the life cycle of this material, reduce its accumulation in clandestine landfills, reduce pollution, protect natural sandbanks, and produce cheaper masonry mortars.

METHODOLOGY

Material characterization

The first step was to characterize the materials to be used. Figure 1 presents the granulometric distributions of natural sand (AN) and crashed glass used in this research following the procedure of the NMX-C-329-ONNCCE standard (2016). It is observed that the granulometric distributions are within the limits established by the NMX-C-111-ONNCCE (2014) standard for fine aggregates. The natural sand is from the river, taken from the Samaria bank in the municipality of Cunduacán, Tabasco, Mexico. Other laboratory tests carried out on the AN were those indicated in the standards NMX-C-416-ONNCCE (2003) and NMX-C-111-ONNCCE (2014), relative specific weight of solids, volumetric weight, fineness module, and percentage of water absorption. The results are outlined in Table 1.

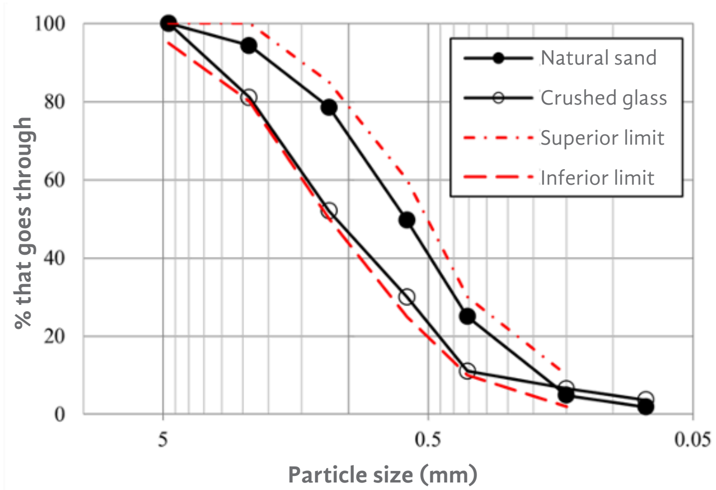

Figure 1. The granulometric curve of sand and crushed glass. Source: Own elaboration

Table 1
Basic characteristics of natural sand

Finesse module	The volumetric weight of loose sand (kg/m³)	The volumetric weight of compacted sand (kg/m³)	Water absorption (%)	The relative specific weight of solids (Ss)
2.97	1512.26	1657.24	1.11	2.60

Source: Own elaboration

The glass that was used in the investigation was recovered from glass containers in a demolition zone in the municipality of Comalcalco, Tabasco, Mexico. The glass was 5 mm thick and was part of gate elements (windows). For this glass to be used as a substitute for natural sand in mortar mixtures, it was necessary to give it the size of a sand particle (figure 2), so it was crushed with the help of a rubber mallet. The glass particles' density was 2.44 g/cm^3, and their water absorption was 0.12%.

Figure 2. Crushed glass used in mortar mixtures. Source: Own elaboration

The cement that was used was Portland Type II Compound brand Cruz Azul, of resistant class 30 R, resistant to sulfates (Cruz Azul Type II CPC 30 R RS), with the volumetric weight of 1510 kg/m3 and relative density of 3.15. This cement complies with NMX-C-414-ONNCCE (2017) and ASTM-C-595/C-595M-19 (2019) standards.

The water used for all mortar mixtures was distilled water. The mixtures used in this research were made in a laboratory with controlled temperature (25° C ±2).

PROCEDURE

To meet the objective of this research it was necessary to elaborate a mixture that would serve as a control parameter, for which, a mixture of conventional mortar (cement + sand + water) was made in a 1:4 ratio (cement-sand). The design of the mixture was made following the method proposed by Saad (1979). This dosage was used in all mixtures following the same procedure and under the same conditions. Table 2 (first line) shows the amounts of cement, sand, and water to make nine buckets of mortar of 5 cm per side.

Table 2
Dosage for the different mortar mixtures used

Mortar	Sand/glass ratio (%)	Cement (kg)	Sand (kg)	Glass (kg)	Water (kg)
Mc	100/0	0.463	2.035	0.000	0.309
Mv^*_{10}	90/10	0.463	1.832	0.204	0.309
Mv^*_{20}	80/20	0.463	1.628	0.407	0.309
Mv^*_{40}	60/40	0.463	1.221	0.814	0.309
Mv^*_{60}	40/60	0.463	0.814	1.221	0.309
Mv^*_{80}	20/80	0.463	0.407	1.628	0.309
Mv^*_{100}	0/100	0.463	0.000	2.035	0.309

Mc = conventional mortar; Mv = mortar with glass

Source: Own elaboration

For the elaboration of the control mixture, the sand was first poured into the container of a standard mortar mixer and mixed at a speed of 140 rpm for 30 seconds, then the cement was added and mixed for 30 more seconds, finally, the water was gradually added and allowed to mix for, approximately one minute (Figure 3).

Figure 3. Mixing of conventional mortar. Source: Own elaboration

Once the mixture was obtained, each of the nine metal molds (previously greased) was filled into three layers, and in each layer 25 blows were applied evenly to remove the greatest amount of trapped air. The molds were left to rest with mortar for 24 hours. Once all the cubes of the control mortar were set, they were dismantled from the molds, and numbering was placed for identification. Next, each mortar was immersed in the curing pile (with clean water) to hydrate the mortar and, subsequently, they were removed from the pile three by three at 7, 14, and 28 days of curing, to be tested at simple compression in a digital electric press brand DAVI.

Starting from the dosage of the control mortar (Table 2), the mortars were manufactured with partial replacement of the AN by the crushed glass. To achieve the above, we gradually substituted the sand's dry weight for crushed glass in the proportions 10%, 20%, 40%, 60%, 80%, and 100%. Table 2 shows the quantities used in all mortar mixtures. The manufacturing and testing process of these mortars was the same as the control mortar. A total of 63 mortar specimens were tested. Figure 4 shows a mortar specimen made with 80% glass and 20% sand, its curing age is 28 days.

Figure 4. Mortar with 80% sand replacement by the crushed glass (Mv*80). Source: Own elaboration

RESULTS

Figure 5 shows the results of the simple compressive strength tests of all the mortars analyzed, as well as their standard deviation. Figure 5a shows the resistances of all mortars at seven days of curing, while Figure 5b and 5c show the resistances at 14 and 28 days of curing, respectively.

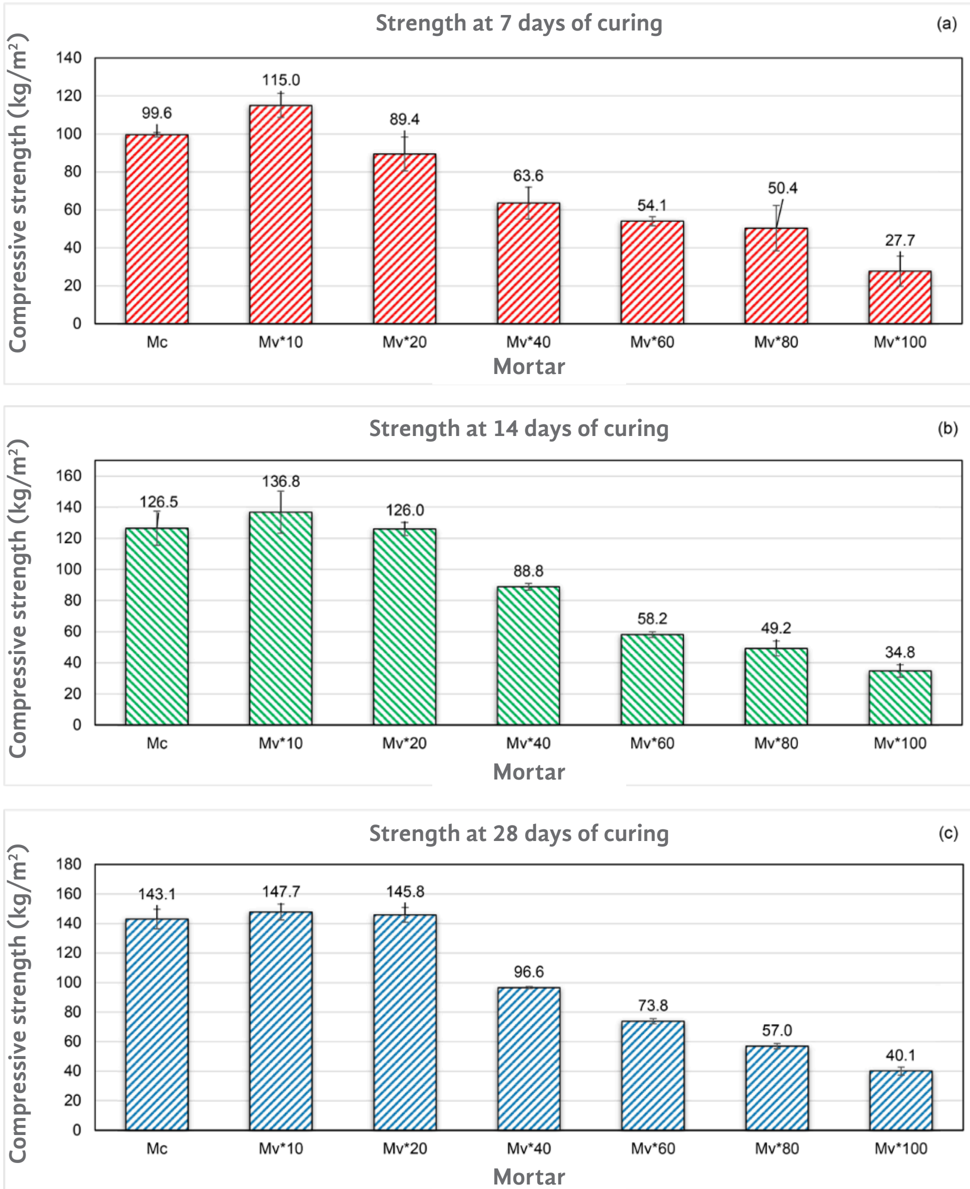

Figure 5. Mortars compressive strength at 7, 14, and 28 days of curing. Source: Own elaboration

It is observed that all mortars increase their resistance as the days of curing increase, so that at 28 days they register their highest resistance, in the case of the conventional mortar (Mc) this was 143.1 kg/cm^2. It is interesting to note that the mortar with 10% replacement of sand by the crushed glass ($Mv*_{10}$) develops a greater resistance than the control mortar at all curing ages, such that, for the 7, 14, and 28 days, increases in resistance of 15.46%, 8.14%, and 3.21%, respectively, were recorded. The reason why $Mv*_{10}$ mortars developed higher final strength (28 days of curing) compared to conventional mortar, lies in the percentage of fines contained in the crushed glass. This fine glass (less than 0.075 mm) filled the small hollows that form between the grains of sand, so by reducing the porosity of the mortars the resistance increased. Researchers such as Vegas, *et al*., (2009) and Jiménez, *et al*., (2013) reached the same conclusions by using finely ground concrete debris as a substitute for sand.

Regarding the mortar with 20% replacement of sand by the crushed glass (Mv^*_{20}), it is observed that at seven days its resistance is 10.24% lower than the Mc mortar, at 14 days its resistance is practically the same and on the 28th day of curing it is 1.89% higher. As in the case of Mv^*_{10} mortars, the reason for the increase in final strength is due to the fine glass content. However, the 28-day resistance of Mv^*_{20} mortars is lower than the resistance achieved at the same age as Mv^*_{10} mortars. This is due to two reasons: 1) glass has a smooth surface that hinders the adhesion of cement paste with this particle, so replacing 20% of natural sand with glass represents a greater number of particles with deficiencies in their adhesion and, 2) the individual density of glass particles (2.44 g/cm^3) is lower concerning those of natural sand (2.60 g/cm^3). Therefore, increasing the amount of glass (after 20%) in mortar mixtures generates lighter and, in the long run, less resistant mortars. Proof of the above is that from 40% of replacement of natural sand by the glass, a gradual and important decrease in compressive strength is observed so that the mortar with the lowest resistance is the one made with 100% replacement of sand by the glass (Mv^*_{100}). That is, for high percentages of substitution, the beneficial effect of the addition of finely crushed glass (seen in Mv^*_{10} mortars) is nullified by the deficiency in adhesion between cement paste and glass.

CONCLUSIONS

In this research, the effect of partially replacing natural sand with crushed glass was analyzed, concerning the compressive strength of masonry mortars. The experimental results showed that, in general, increasing the amount of glass in mortar mixtures harms the strength of mortars. This is essentially due to the low density of the glass particles concerning the density of the sand particles, as well as the lower adhesion of the cement paste with the smooth surface of the glass. However, for the percentages of replacing the sand with a glass of 10% and 20%, the resistance was not affected but slightly improved, the latter concerning the resistance exhibited by the control mortar. This allows us to conclude that reusing glass as a partial substitute for sand in mortar mixtures is a viable option if the percentage of substitution is not greater than 20% by dry weight. With the above, it will be possible to increase the life cycle of this material, contribute to the conservation of the environment by avoiding its excessive accumulation in landfills and protect the natural sandbanks.

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