Eco-bricks: a sustainable substitute for construction materials

Eco-ladrillos: un reemplazo sustentable de materiales de construcción

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Abstract

Eco-bricks, polyethylene terephthalate (PET) bottles filled with mixed inorganic waste, have become a low cost construction material and a valid recycling method to reduce waste disposal in regions where industrial recycling is not yet available. Because Eco-bricks are filled with mixed recovered materials, potential recycling of its constituents is difficult at the end of its life. This study proposes considering Eco-bricks filled with a single inorganic waste material to work as a time capsule, with potential for recovering the filling material when other ways of waste valorization are available within those communities that currently have no better recycling options. This paper develops an experimental characterization of density, filler content (by volume), thermal shrinkage, elastic modulus and deformation recovery capacity using four different filler materials: 1) PET; 2) paper & cardboard; 3) tetrapack; and 4) metal. Overall, Eco-brick’s density, thermal shrinkage and elastic modulus are dependent on the filler content. Density and elastic modulus of the proposed Eco-bricks are similar to values of medium-high density expanded polystyrene (EPS) used in nonstructural construction, reason why we suggest that these Eco-bricks might be a sustainable alternative to EPS or other nonstructural construction materials.

Key words: Eco-bricks; inorganic solid waste valorization; physical characterization; elastic modulus; nonstructural materials.

Resumen

Los Eco-ladrillos, botellas de politereftalato de etileno (PET, por sus siglas en inglés) rellenas con residuos inorgánicos, se han convertido en un material de construcción de bajo costo y un método válido de reciclaje para reducir la disposición de basura en regiones donde el reciclaje industrial no está aún disponible. Debido a que los Eco-ladrillos son rellenados con materiales reciclados combinados, se reduce el potencial de reciclaje de sus constituyentes al finalizar su vida útil. Este estudio propone crear Eco-ladrillos rellenados con un solo tipo de deshecho inorgánico para funcionar como cápsulas del tiempo con potencial de recuperar el material de relleno cuando otras formas de valorización de deshechos estén disponibles entre las comunidades que actualmente no tienen mejores opciones de reciclaje. El presente trabajo consiste en una caracterización experimental de densidad, volumen de llenado, contracción térmica, módulo elástico y capacidad de recuperación de su deformación, considerando cuatro materiales de relleno diferentes: a) PET; b) papel & cartón; c) tetrapack; y 4) metal. En general, la densidad, contracción térmica y módulo de elasticidad de los Eco-ladrillos depende del volumen de llenado. La densidad y módulo de elasticidad de los Eco-ladrillos propuestos son similares a los valores de poliestireno expandido (EPS, por sus siglas en inglés) de densidades medias-altas usados en construcción no estructural, razón por lo cual sugerimos que estos Eco-ladrillos pueden ser una alternativa sustentable al EPS u otros materiales de construcción no estructural.

Palabras clave: Eco-ladrillos; valorización de residuos inorgánicos sólidos; caracterización física; módulo elástico; materiales no estructurales.

Introduction

Globally, solid waste generation increases with economic growth, urbanization and development, and will continue at faster rates (Bhada-Tata & Hoornweg, 2012). Approximately 1.3 billion tons of solid waste were generated in 2010 worldwide, and it is expected to increase to approximately 2.2 billion tons per year by 2025 (Bhada-Tata & Hoornweg, 2012). Inorganic waste, which includes paper, plastic, glass, metal and other materials, accounts for 72% of the total solid waste in high income countries, and 36% to 46% of the total solid waste generated in low and middle income countries (Bhada-Tata & Hoornweg, 2012). In particular, around 311 million tons of plastic were produced in 2014 worldwide, where packaging is responsible for 40% of it and PET bottles represent 7% (*Plastics - The facts 2015: An analysis of European plastics production, demand and waste data*, 2015). Between 22% and 43% of wasted plastic worldwide is disposed in landfills (*Plastics - The facts 2015: An analysis of European plastics production, demand and waste data*, 2015; United Nations Environment Programme, 2014) and up to 95% of the litter that accumulates on shorelines, the sea surface and the sea floor, consists on plastic items, including plastic bags, fishing equipment, food and PET beverage containers (Kuhn, 2015). In countries of the Organization for Economic Cooperation and Development (OECD), average recycling rate is 34% (Upton, 2015), but this is not the case for most developing countries. Disposing inorganic waste in landfills, informal dump areas or the sea, means losing its value as potential resources, taking up valuable space, contaminating the environment and deteriorating communities (Bhada-Tata & Hoornweg, 2012; Kuhn, 2015; United Nations Environment Programme, 2014). One alternative to minimize these problems is to recover the plastics, and any inorganic materials, from the waste streams, for recycling or energy generation (United Nations Environment Programme, 2014) or to develop new materials (Gaggino & Arguello, 2010).

Eco-bricks is the name for PET bottles filled with some material (Taaffe, O'Sullivan, Rahman, & Pakrashi, 2014) that could be used as building blocks (Barajas & Vera, 2016). There are experiences of bottles filled with soil, and other filled with compressed inorganic waste materials, particularly plastics, foams, packaging and cellophanes (Kuhn, 2015; Maier & Bakisan, 2014). Communities and non-governmental organizations (NGO's) consider the Eco-brick as a valid recycling way to reduce their plastic waste disposal volumes (Heisse & Arias, 2011; Kuhn, 2015). Moreover, this handmade building block has become an accessible/low cost construction material for social projects in regions where litter and informal dump sites are a common problem and industrial recycling might not be yet available. Examples of regions where there are reported Eco-brick building projects include countries in Latin America, Africa, and South Asia (Heisse & Arias, 2011; Kuhn, 2015; Taaffe et al., 2014). Most of Eco-brick based construction projects are social projects where communities work together for a common goal such as educational centers and recreational spaces(Heisse & Arias, 2011). There exist motivation techniques to get the participants' help with the collection of materials and filling of bottles, such as graded school work (Maier & Bakisan, 2014), or trading complete Eco-bricks per clothing or toys (Kuhn, 2015).

Because of the long time it takes PET bottles and other inorganic materials to degrade, and the idea that in the case of demolition the Eco-bricks could be used again or turned into new building blocks, this device is referred as a sustainable construction material (Heisse & Arias, 2011; Kuhn, 2015). However, both PET bottles used as container of the Eco-bricks as well as the mixed materials used as filler, could be better recycled if more sophisticated separating and valuing process were implemented. Moreover, the Eco-brick performance as construction material depends highly on the materials used to manufacture them and the skills of the workforce involved. There is limited data available on the Eco-bricks physical and mechanical properties from past and current construction projects (Taaffe et al., 2014). To the best of the authors' knowledge, there have been only one study addressing the characterization of Eco-bricks filled with single inorganic materials (Antico, Wiener, Araya-letelier, & Durán, 2017). The latter work provided initial insights mainly on compressive strength of Eco-bricks with single inorganic materials. Consequently, the increasing trend of considering the Eco-bricks the solution for two related problems, recycling inorganic waste materials and low-cost sustainable buildings, makes it important to investigate more about their physical and mechanical properties.

This work proposes a novel recycling and valuing concept for materials used as fillers to build Eco-bricks. Eco-bricks in this work are handmade by unskilled personnel to mimic real actual conditions of manufacturing. Density, filler content, thermal shrinkage, elastic modulus and deformation recovery capacity of Eco-bricks are studied and its performance is compared with similar construction materials used nowadays. The use of cardboard and tetrapack as construction materials is also a novel inclusion of this work that so far has been limited compared to other types of sustainable construction materials (Araya-letelier, Antico, Carrasco, Rojas, & García-herrera, 2017; Araya-Letelier, Antico, Parra, & Carrasco, 2017; Barros & Imhoff, 2010; Cataldo-Born, Araya-Letelier, & Pabón, 2016; Martínez, Etxeberria, Pavón, & Díaz, 2016; Siddique, Khatib, & Kaur, 2008; Soloaga, Oshiro, & Positieri, 2014). Overall, the authors suggest that Eco-bricks filled with a single inorganic waste type could work efficiently as a construction material while preserving in a separate container a single inorganic material that eventually could be recovered when other ways of adding value or recycling would be available.

Sample manufacture

Recycling and valorization

Dry and clean solid urban waste generated from 20 households, distributed around the cities of Santiago and Viña del Mar, Chile, was collected during three weeks for this research work. The four most collected materials were: 1) paper & cardboard; 2) tetrapack; 3) metal; and 4) PET (Table 1). These materials were used as single type fillers to manufacture Eco-bricks. After being collected and sorted, these materials were chopped to allow fitting into beverage bottles of 600 cm^3 used as container of the Eco-brick and the maximum linear size of the chopped materials was 5 cm.

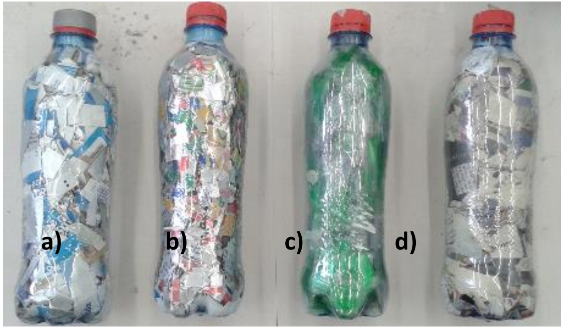
Table 1. Weight distribution of inorganic waste collected to be used as filler of Eco-bricks. Source: self-elaboration.

Sample #	Filler type	% Weight of total collected waste
1	Paper & cardboard	69.6
2	Tetrapack	12.5
3	Metal	11.2
4	PET	4.0
5	Other	2.7

Eco-bricks manufacturing

The filling process was manual, using a ram to compact the filler within the bottle in several layers of recycled material. The manufacturing method was selected to replicate the real manual process that nowadays is followed to elaborate Eco-bricks. Once the bottles were completely filled with a single material, each bottle was closed and sealed with a cap (Figure 1). Samples were preserved at controlled laboratory temperature and humidity (20-25°C temperature and below 50% relative humidity) conditions until testing. Bottles were also saved in a dark space to avoid photo degradation before testing. The amount of collected materials allowed preparing 4 Eco-bricks of each filler (Table 1).

Figure 1. Eco-brick samples with single type fillers: (a) tetrapack; (b) metal; (c) PET; (d) paper & cardboard. Source: self-elaboration.



Sample characterization

Density and filler content

Densities of the Eco-bricks were determined by estimating the ratio between mass and volume of each sample. Eco-bricks mass was determined using a scale. Volume of Eco-brick was estimated following Archimedes principle. Eco-bricks were submerged in water at room temperature (25°C) using a cylindrical container with capacity for 5 liters approximately (150 mm of diameter and 300 mm long). The selected container allowed having good resolution of the water displaced when bottles were submerged. Using a measure tape within the container, the level of water was recorded and the volume of water displaced was estimated. Bottles were dried out after testing and preserved in the same conditions described in the previous section up to the following test.

As volume of filler increases, voids within the Eco-brick are reduced. The amount of filler is expected to affect physical and mechanical properties such as: volume stability, elastic modulus and elastic-plastic recovery behavior of an Eco-brick. Consequently, the weight of each empty bottle and cap were measured. After the filling process, the final weight of the Eco-brick was recorded. The weight of the empty bottle and the cap were subtracted to determine the weight of the filler inside each Eco-brick. Each filler weight was divided by the respective density of the filler material to obtain the filler content (by volume), and the percentage of filler content with respect to the total volume of the empty bottle was estimated.

Thermal shrinkage

Eco-bricks could be used as nonstructural materials in walls and roofs. Therefore, it is important to measure possible volumetric changes of Eco-bricks, due to temperature changes, that may affect the integrity in these structural members. To address these changes, radial thermal shrinkage, $\Delta\varepsilon_r$, is estimated as shown in Equation 1.

$$\Delta\varepsilon_r = \frac{r_{final} - r_{initial}}{r_{initial}} \tag{1}$$

Where $r_{initial}$ and r_{final} are the radius measured at a specific height of the Eco-brick at the beginning and at the end of the thermal shrinkage test, respectively. The thermal shrinkage test procedure and shrinkage estimation of Eco-bricks were adapted from a standardized test to measure longitudinal shrinkage of plastic tubes (INN, 1996).

Three different heights were marked on each sample: 1) near the cap; 2) at middle section; and 3) near the end. Next, the procedure to determine radial changes of Eco-bricks due to temperature variations was carried out in three stages. First, diameters of each sample were measured at room temperature (23.5°C), at the specific heights marked on each sample. Second, samples were submerged in water during 48 hours. Water temperature was adjusted with heaters and controlled automatically using a thermostat. Temperature profile of water was 35°C for the first 24 hours and 65 °C for the remaining 24 hours. Third, samples were cooled down for 24 hours up to room temperature (23.5°C). Then, final diameters were measured at the specific heights marked on each sample.

Elastic modulus

Elastic modulus was included in this research due to its relevance for any structural design. An indentation test was selected for this purpose to extract values of elastic modulus a different locations of the Eco-bricks. As described in previous works, the main assumption of indentation test is that the beginning of deformation during unloading is purely elastic (Horikawa et al., 2009; Norambuena-Contreras, Gonzalez-Torre, Vivanco, & Gacitúa, 2016). Figure 2(a) shows a typical load-displacement curve obtained from an indentation test. During the indentation test, the unloading depth, h_p, the maximum indentation depth, h_{max}, at which the maximum load, F_{max}, occurs and the initial slope at the initial state of the unload, S, where recorded.

The information extracted from the indentation test can be used to determine the effective modulus of elasticity, E^*, using the following semi-empirical relation established by Loubet (Loubet, Georges, Marchesini, & Meille, 1984) as presented in Equation 2.

$$E^* = \frac{1}{2}\sqrt{\frac{\pi}{A_c}}S \tag{2}$$

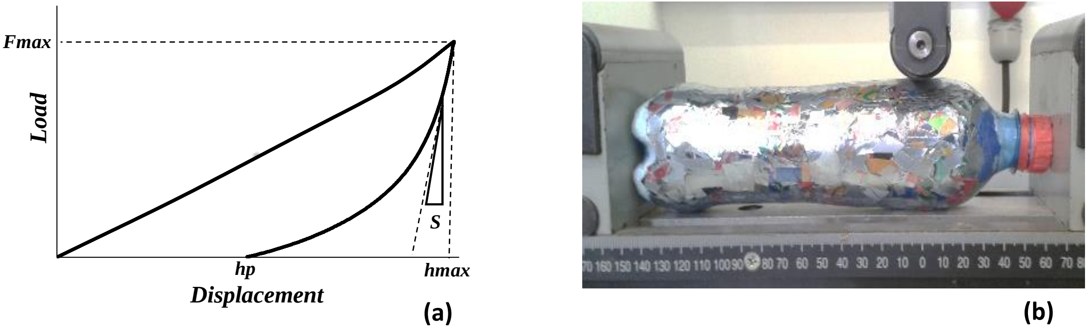
Where, A_c is the contact area between indenter and material at F_{max}. E^* is a function of the elastic properties of the indenter as shown in Equation 3.

$$\frac{1}{E^*} = \frac{1-\upsilon^2}{E} + \frac{1-\upsilon_{ind}^2}{E_{ind}} \tag{3}$$

Where E_{ind} (210 GPa), υ_{ind} (0.3), represent the elastic modulus and Poisson ratio of the indenter and the specimen, respectively.

Indentation was performed at three different heights of the Eco-brick: 1) near the cap; 2) at middle section; and 3) near the end. Figure 2(b) presents the setup of the experiment. h_{max}= 2, 4, 8, 16 mm loading levels were applied monotonically using a cylindrical indenter, and then monotonic unloading was performed in each case until the sample was completely unloaded.

Figure 2. (a) Typical load displacement curve of the indenter. Source: self-elaboration; (b) Indentation test performed near the cap of the Eco-brick. Metal filler sample. Source: self-elaboration.



Recovery capacity of the Eco-bricks

Elastic and plastic deformation of polymers can be studied by indentation testing (Norambuena-Contreras et al., 2016). A recovery ratio (RR) can be estimated, as presented in Equation 4, comparing the values of h_p, and h_{max} (see Figure 2(a)). As RR tends to 1, recovery of Eco-brick is tends to be purely elastic. On the contrary, if RR tends to 0, recovery of Eco-brick tends to be purely plastic.

$$RR = 1 - \frac{hp}{hmax} \tag{4}$$

Results and discussion

Effect of filler content on physical and mechanical properties of Eco-bricks

Table 2 presents the estimated density for each Eco-brick and average filler density used to estimate average Eco-brick filler-volume. Only two samples of metal were elaborated for this work due to the difficulties to reach a significant amount of filler volume using a manual manufacturing process.

Table 2. Measured weight and estimated density of Eco-bricks. Source: self-elaboration.

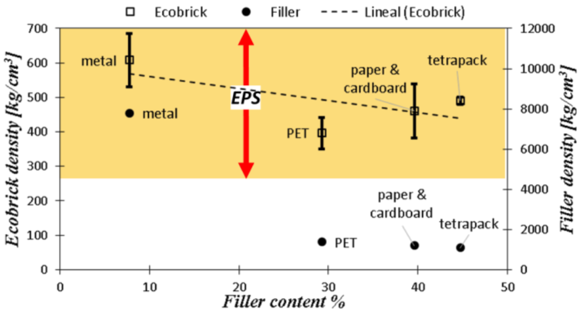
Sample #	Filler type	Eco-brick density (kg/m^3)	Average filler density (kg/m^3)	Average filler volume (cm^3)
1	PET	338.7	1,380	238
2	PET	450.9		
3	PET	398.1		
4	PET	399.1		
5	Paper & cardboard	561.4	1,200	238
6	Paper & cardboard	369.2		
7	Paper & cardboard	455.7		
8	Paper & cardboard	456.3		
9	Tetrapack	506.2	1,100	268
10	Tetrapack	489.4		
11	Tetrapack	480.8		
12	Tetrapack	487.4		
13	Metal	553.9	7,800	46
14	Metal	662.0		

Average value of Eco-brick density was 489.1 kg/m^3. Regardless of the type of filler, the obtained average-density range of Eco-bricks (338.7– 662.2 kg/m^3) is similar to the range of EPS reported previously (280-700 kg/m^3) (Di Landro, Sala, & Olivieri, 2002). This similarity could be attractive to analyze the possible replacement of EPS, used in construction as filler to reduce weight of precast concrete, with Eco-bricks, after further investigation of the materials and its interaction within a structural element. Other potential use of Eco-bricks due to its low density might be as part of nonstructural systems used in construction such as roofing, interior partition walls and ceilings.

Regarding average filler-volume, Eco-bricks filled with metal were in average the samples containing less volume of filler, while tetrapack Eco-bricks were the ones with more volume of filler using a manual filling process (7.7% and 44.7%, respectively with respect to the volume of the container). PET and paper & cardboard samples reached 29.2% and 39.6% of the volume of the container, respectively.

Figure 3 shows the relation between Eco-brick density (square symbols), filler densities (round symbols) vs. the average filler content for each sample. Error bars indicate standard deviation values of the estimated Eco-brick density for each type. The coefficient of variation of Eco-brick density were 17% and 2.2% for paper and tetrapack Eco-bricks, respectively. This dispersion of density could be related to the manual manufacturing process. Possible reasons for this are filler particle-size, and non-uniform manual compaction during the filling process.

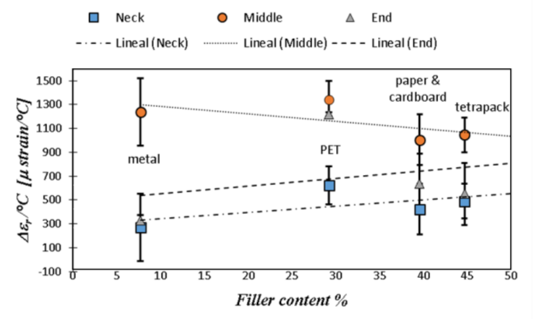
Figure 3. Eco-brick density vs. filler volume estimated from mass measurement and filler density, whose data was obtained from literature. Shaded area represents typical range of EPS density. Source: self-elaboration.



Eco-brick density is inversely proportional to the volume of filler (Figure 3). Observations while manufacturing Eco-bricks of different materials showed that this could be mainly due to difficulties of manual compaction of metal and PET with respect to paper & cardboard and tetrapack. Figure 3 shows how changes of Eco-brick density (53% between metal and tetrapack Eco-bricks) are sensitive to changes in filler content (more than 450% between metal and tetrapack Eco-bricks). Filler content could be considerably different when filler densities are similar. This is the case of PET, paper & cardboard and tetrapack (see Table 2 and Figure 3, round symbols). On the contrary, changes in filler content are significant when comparing PET, paper & cardboard or tetrapack with metal density (more than 600%, as seen in Table 2 and Figure 3, round symbols). This indicates that there is a nonlinear relationship between filler density and filler content.

Figure 4 shows the correlation between $\Delta\varepsilon_r$ per unit temperature ($\Delta\varepsilon_r$/°C) and the estimated average filler content (see Table 2) of the Eco-bricks studied in this work.

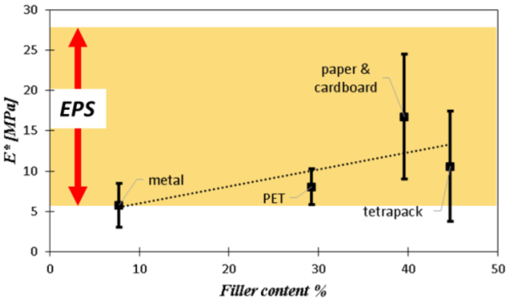
Figure 4. Average values of $\Delta\varepsilon_r$/°C obtained from measures taken at neck, middle and end of each Eco-brick. Error bars indicate maximum and minimum values obtained at the different locations on each Eco-brick (two samples per filler material). Source: self-elaboration.



Square, round and triangular symbols represent estimations of $\Delta\varepsilon_r$/°C near the neck, middle and end sections of Eco-bricks, respectively. Overall, average values of $\Delta\varepsilon_r$/°C at different locations and estimated average filler content converge to a single value within 700-900 μstrain/°C as filler content approaches to the volume of the container.

Figure 5 shows average values of E^* (square symbols) using Equation 2 versus filler content. Error bars represent one standard deviation of E^* obtained for each sample at different locations (neck, middle and end sections). For the set of Eco-bricks in this work, $1/E^*$ was more than five times greater than $(1-\upsilon_{ind}^2)/E_{ind}$. Therefore, it is possible to approximate the real value of modulus of elasticity of Eco-bricks to E^*.

Figure 5. Average and maximum and minimum values of E^* obtained from measures taken at neck, middle and end of each Eco-brick. Shaded area represents typical range of EPS elastic modulus. Source: self-elaboration.

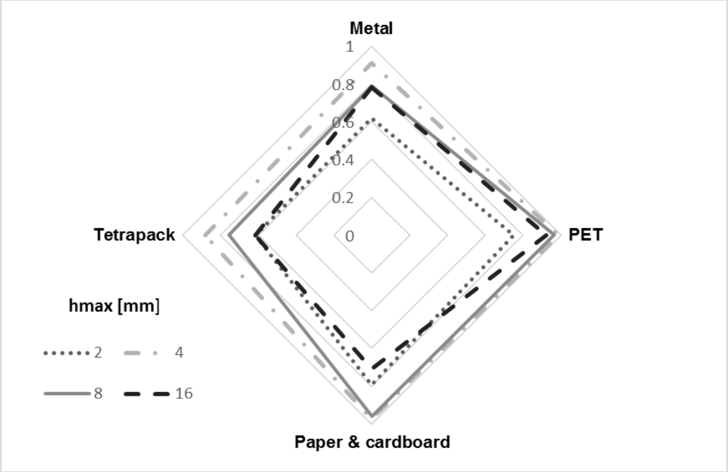


In particular for PET, paper & cardboard and tetrapack fillers, Figure 5 shows an increment of E^* as filler content increases. This indicates that E^*, as Eco-brick shrinkage, is sensitive to Eco-bricks void content rather than density of the filler itself (Table 2). Elastic modulus measured at different positions of the Eco-bricks showed significant dispersion (up to a coefficient of variation of 64% for tetrapack), possibly due to different levels of compaction within each Eco-brick. The range of average E^* in this work is 5.7 MPa (metal) to 16.7 MPa (paper & cardboard). The estimated range of E^*reported in this work, regardless of the type of filler, is similar to EPS. The latter range is similar to the range of elastic modulus of EPS (6-32 MPa).

Deformation recovery capacity of Eco-bricks

The evolution of RR for h_{max}= 2, 4, 8, 16 mm loading levels, for each different Eco-brick, is presented in Figure 6. Overall, when 4 < h_{max}< 8 mm, the RR factor ranges between 0.78 (paper & cardboard and metal) and 0.97 (tetrapack), while for 4 > h_{max} and h_{max} > 8 mm, the RR factor ranges between 0.60 (metal) and 0.92 (PET). For low values of h_{max} (2 mm) it was observed during the test that filler rearranges within the Eco-brick container causing changes in the void structure beneath the indenter. On the contrary, greater values of h_{max} (16 mm) caused crushing of the Eco-brick. For these reasons it is expected a more plastic behavior of the recovery deformation for the extreme values of h_{max} in this work. Specifically for the Eco-bricks in this study, an elastic behavior is expected for loads ranging 4 < h_{max}< 8 mm.

Figure 6. RR values for the different Eco-bricks analyzed under indentation loads of h_{max} = 2, 4, 8, 16 mm. Source: self-elaboration.



Discussion and future work

This research work represents a first step into the characterization of a new type of Eco-brick, containing a single type of material as filler, but still using actual manual practices of manufacturing in order to serve as reference for current Eco-brick construction projects. The valorization or recycling of inorganic waste materials require resources, and become a challenge for most developing countries. Then, the best option sometimes consists on reducing and compacting to minimize waste storage or disposal volumes. Eco-bricks using single type material-filler could work as a temporary time capsule that store clean, dry, separated materials until more efficient processes of valorization or recycling are available in those regions.

Eco-bricks were handmade by unskilled personnel to mimic real actual conditions of manufacturing. As a result, we obtained lightweight Eco-bricks, whose fillers were compacted manually. Results show that Eco-bricks filled with tetrapack present the highest average filler content (268 cm^3) and Eco-bricks filled with metal present the lowest volume (46 cm^3). A direct relation exists between E^* and the filler content for the selected fillers, reaching a highest average value (paper & cardboard Eco-brick) similar to medium density EPS and 30% lower to high density EPS.

Radial deformation due to uniform temperature changes tend to converge to a single value as the filler content increases. Changes of $\Delta\varepsilon_r$ are sensitive to variations of filler content and materials rather than Eco-brick density. Overall, it was found that Eco-brick density, thermal shrinkage and elastic modulus are dependent on the filler content (by volume), rather than the weight of the Eco-brick itself or the material used as filler. The volume of filler is a direct measure of voids content of this composite material. Using results from indentation testing, it was observed that the elastic-plastic behavior of the Eco-bricks is dependent on the magnitude of the load. For the selected levels of load in this work, Eco-bricks show an elastic behavior under a specific range of load (h_{max} varying between 4 mm to 8 mm).

Overall, Eco-brick could be used as a potential sustainable replacement of EPS due to its similar density and elastic modulus. Regarding thermal shrinkage, Eco-bricks can reach high levels of thermal deformation which can be useful to avoid restrained cracking if used to manufacture precast and/or lightweight concrete as a replacement of EPS. The authors acknowledge that the use of Eco-bricks for construction applications is still debatable for different reasons. Some of them are high variability of its physical and mechanical properties. Actual manufacturing practices for Eco-bricks are manual and performed by unskilled personnel. The authors think that variability could be reduced significantly by training personnel, improving quality control during the manufacturing process and using single material as filler. Use of Eco-bricks in housing construction will require other studies such as flammability testing, in order to incorporate these materials to building codes that regulate and promote the correct use of them. Physical and mechanical response of single-filler Eco-bricks, are expected to depend more on the type of filler for higher filler contents not achieved by the use of manual compaction process.

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