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Characterization of new insulators for architectural envelopes with non-traditional materials.

Caracterización de nuevos aislantes para envolventes arquitectónicas con materiales no tradicionales.

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Abstract

This work deepens into the need to study synergies between fundamental criteria for sustainable development in construction: environmental, socio-economic and techno-scientific. According with this, the sustainability of an envelope based on the Sistema Constructivo 3C is characterized, which is self-constructed and uses recycled plastic bottles. This system has a light wooden framework structure that uses a pile of compacted polyethylene terephthalate (PET) bottles inside and two faces, one inside and other outside, with a coating made with traditional cement plaster. In order to consider the social benefit for the development of the Sistema Constructivo 3C, criteria of techno-scientific, environmental and social were used. This system showed high thermal performance in insulation and fire resistance compared to other systems based on traditional materials. A positive synergistic effect was observed between the air and the plastic bottles that allowed increasing thermal performance of the construction system. The air between the bottles decreases the thermal conductivity and the thermal transmittance of the construction system. Besides, the bottles compacted in the core system reduced the flame spread. These beneficial synergies by the use of non-traditional materials could be explored and enhanced according to the thermal properties offered by other non-traditional materials. The implementation of strategies to reuse PET bottles by mechanical means without the use of energy, it exposes the potential of these non-traditional materials for: their use in construction, the development of local resources and capacities, and the promotion of circular economy. The characterization of the construction system presented in this work contributed to generating a manual that, as a work protocol, allowed it to be traced, establishing guidelines for waste management and its subsequent implementation. This manual will allow the training of human resources both for the production of plastic piles and to participate in some process of the construction of the houses.

Resumen

Este trabajo profundiza en la necesidad de estudiar las sinergias entre los criterios fundamentales para el desarrollo sostenible en la construcción: ambientales, socioeconómicos y tecnocientíficos. De acuerdo con esto, se caracteriza la sostenibilidad de un sobre basado en el Sistema Constructivo 3C, que es autoconstruido y utiliza botellas de plástico recicladas. Este sistema tiene una estructura de armazón de madera ligera que utiliza una pila de botellas de tereftalato de polietileno (PET) compactado en el interior y dos caras, una interior y otra exterior, con un revestimiento realizado con yeso de cemento tradicional. Para considerar el beneficio social para el desarrollo del Sistema Constructivo 3C se utilizaron criterios tecnocientíficos, ambientales y sociales. Este sistema mostró un alto rendimiento térmico en aislamiento y resistencia al fuego en comparación con otros sistemas basados en materiales tradicionales. Se observó un efecto sinérgico positivo entre el aire y las botellas de plástico que permitió incrementar el rendimiento térmico del sistema constructivo. El aire entre las botellas disminuye la conductividad térmica y la transmitancia térmica del sistema de construcción. Además, las botellas compactadas en el sistema central redujeron la propagación de la llama. Estas sinergias beneficiosas mediante el uso de materiales no tradicionales podrían explorarse y mejorarse de acuerdo con las propiedades térmicas ofrecidas por otros materiales no tradicionales. La implementación de estrategias para reutilizar botellas de PET por medios mecánicos sin el uso de energía, expone el potencial de estos materiales no tradicionales para: su uso en la construcción, el desarrollo de recursos y capacidades locales, y la promoción de la economía circular. La caracterización del sistema constructivo que se presenta en este trabajo contribuyó a generar un manual que, como protocolo de trabajo, permitió rastrearlo, estableciendo lineamientos para la gestión de residuos y su posterior implementación. Este manual permitirá la formación de recursos humanos tanto para la producción de pilotes plásticos como para participar en algún proceso de la construcción de las viviendas.

1. Introduction

Problems generated by the increase and shortcomings in final disposal of Non-Hazardous Industrial Waste (NHIW) and Urban Solid Waste (USW) produced in the district of General San Martín, Province of Buenos Aires, generated a line of investigation in the Instituto de Arquitectura y Urbanismo (IA) - de la Universidad Nacional de San Martín (UNSAM), for its transformation into new materials or supplies for construction and market creation in the recycling industry. On many occasions, these wastes end up accumulating in landfills for years, decades, or even centuries as they degrade.

The development and technical verification of materials based on NIHW-USW is an important focus of research and development in the world. In the same way, the impulse given to a variety of new materials manufactured from construction and demolition waste and from pruning and crop residues has increased, to try to mitigate the great impact on energy use, CO2 production and environmental pollution associated with the life cycle of buildings.

The International Energy Agency (IEA) estimates that: 60% of the materials that are extracted from the lithosphere are destined for construction, 40% of the primary energy consumed on the planet and 75% of the electricity is destined to buildings, 60% of solid waste is produced in the construction and deconstruction of buildings (1.3 t per person/year) and that approximately 50% of the polluting CO2 emissions are emitted by them. These consumptions and impacts occur during the extraction of raw materials, with their transformation from industrial processes, during the construction of buildings, throughout their useful life, with their use and also at the end of this with deconstruction of the building. The complexity of theses processes makes it difficult to propose strategies that are common in other consumer products. However, these data are already sufficiently illustrative to realize that we cannot continue on this current path and that we must initiate a process of change of great proportions, in our sector, to be able to talk about sustainability. An area where we especially see an intensive use of industrialized materials, which originate from the use of fossil fuels, is the thermal, acoustic and waterproof insulation that we use in the envelopes of our buildings. We understand that there is a great potential for the development of new products or materials, as a result of the reuse or recycling of NIHW-USW, that allow these products to be replaced by solutions with less environmental impact. That is why from the IA UNSAM we have been developing a line of research, accredited in Conicet, an Atlas of Industrial Solid Waste that allows converting this waste into new inputs to incorporate into the world of construction. This repertoire of new materials and techniques of sustainable construction challenge the very heart of technical regulations and propose new logics of analysis to regulatory frameworks; establishing new criteria and weighing new standards, where the requirement and objectives of these protocols are not only established based on strict compliance with their technical dimension but also in light of an environmental cost, which as such, will have a decisive impact when it comes to evaluate their technical performance.

2. State of the question

The performance of envelope in buildings increases as energy consumption decreases to preserve comfort. At the same time, comfort is maintained when: air quality inhibits the development of diseases, the temperature range is comfortable, and noise pollution is low (Sundell 2004, Däumling et al. 2005). Today, indoor air quality has become very important due to forced confinement by the global pandemic. The enclosure must comply with standards that consider: thermal conductivity, acoustic absorption, thermal transmittance (K value), content of harmful substances and fire resistance. K values requirements are defined by IRAM 11.605 standard, for each bioclimatic zone in Argentina. According to IRAM 11603 standard, Metropolitan Area of Buenos Aires (MABA) has a bioclimatic zone III, with temperatures in winter between 8°C and 12°C. Therefore, an enclosure system approved for use in MABA must have a K value less than 1.85 W/m2K. This value ensures that there is no surface condensation inside the home throughout the year, according to the IRAM 11625 standard.

The approval of products for use in construction in Argentina is carried out following the guidelines of the Certificate of Technical Aptitude (CTA), which is governed by the Regulation approved by Resolution SVOA No. 288/90. The CTA requires compliance with a number of essential requirements related to the application of building materials and systems. In general, the homologation of non-traditional materials requires more tests than traditional ones, due to the limited experience in the use of non-traditional materials on site. Non-traditional systems are those that do not have norms, regulations, provisions or resolutions of national organizations that establish the conditions to which the use and manufacture must comply, or that it is not clearly disseminated (Ministerio del Interior Obras Públicas y Vivienda 2019). Among the non-traditional materials are those based on NIHW-USW and reuse sources, such as plastic waste and natural fibers. The certification by CTA focuses only on techno-scientific criteria, so it is unable to weigh the environmental and social impacts that the development of non-traditional materials involve. For example, a product that is easy to manufacture and based on NIHW-USW can bring benefits: environmental (Khatib 2016), reduction of the CO2 load in the environment, soil recovery; social (Kono 2018), job creation in regions with low technological development and improvement of outdoor air quality; and economical.

According to the dictionary of the Real Academia Española (RAE), when we speak of technique we refer literally to the "set of procedures used by a science or art". According to Juan Herreros: “technique appears before us as a powerful instrument of anchoring ideas to their time", so it seems essential that we revise this definition beyond the traditional notion that associates technique only with the positive resources directly involved in the idea of build and extending the limits of this definition so that we allow us to understand our responsibility as actors involved in the construction industry and not only in the endogamous environment of the technical-scientific discourse. The challenge is to identify which are the variables and dimensions that should interest us in this complex and contradictory present, which accounts for a permanent deterioration of our ecosystem and which has led us, contrary to what the Brundtland (Brundtland 1987) report promulgated as a definition of sustainable development, to have today to live with an environmental mortgage.

One strategy to make this possible is to produce transfers from other knowledge that allow us to look at and understand other places, cultural and social contexts, new patterns of consumption, to obtain new references, lexicons and models with which to operate. A comprehensive and holistic look that not only intervenes in the pre-established protocols in the form of rules or norms, but also investigates how to obtain new ideas and instruments with which to negotiate in our imperfect context. In an inequitable world, technology continues to be today an unequally distributed heritage, so we must assume a responsible position to avoid the imposition of the strongest at any scale and promote dialogue, equal and democratic participation with the same resources and possibilities that promote the development of a sustainable conscience that activates a new agenda to reorient our practice.

The development of non-traditional materials plays a fundamental role in the construction of this new agenda and in the fulfillment of at least nine of the 17 Sustainable Development Goals of the 2030 Agenda (Opoku 2019). This agenda was promoted by the United Nations and includes 169 specific goals that must be achieved before 2030. In addition, this year the “New Plastics Economy Global Commitment” was signed, which promotes the reinsertion of plastic waste in the manufacture of new materials. The challenge for construction sector is to ensure that new or renovated building is sustainable throughout the life of the building. This also applies to the materials that make up the building. While many materials are touted as sustainable, they lack beneficial synergy between the three criteria of sustainability (social, economic, and environmental) because they neglect the relevance of synergy. Synergy comes from the Greek word συνεργία, which derives from συνεργός (synergos), which means "to work together". According to the RAE, synergy is the action of two or more causes whose effect is greater than the sum of the individual effects. On the other hand, in one of the first scientific works that mentions the word synergy, the sociologist W. Lester (Lester 1918) defined it as the universal constructive principle of nature. Studying the synergy between criteria is also relevant because it does not always generate benefits. For example, polyurethane is an inexpensive synthetic insulation with high thermal performance, but it contains harmful substances in its chemical composition (techno-scientific criteria) that harm human and environmental health (social and environmental criteria). Therefore, the study of the synergy between the three social, economic and environmental criteria helps to promote sustainable development, but it is usually complex due to the multidisciplinary nature of the subject.

Currently, there are tools that weigh the useful life, recyclability and environmental impacts of materials in construction, but these are still dissociated from techno-scientific evaluations of social and environmental ones. Considering these difficulties, Akadiri (Akadiri2011) and Govindan (Govindan2016) propose indicators for the sustainable selection of construction products. These indicators arise from an extensive review of works and surveys carried out on 490 architects and designers with a long professional career. The indicators are grouped into criteria environmental, techno-scientific, social and economic, which confirms the need for a multidisciplinary and holistic approach for the sustainable selection of materials. The indicators proposed by Akadiri and Govindan are useful to design a methodology for the approval or development of sustainable materials. This methodology can be unified with the one proposed by the CTA, since in this way the essential requirements of the material would be included as indicators of the techno-scientific criteria, together with the social and environmental criteria.

According to works of Akadiri and Govindan, to evaluate sustainability of a material is important to quantify the indicators of each sustainability criterion, then to detect the interconnections that exist between them and finally promote those that generate beneficial synergy. In this way, impacts of criteria social, environmental and economic generated during the manufacture, use and final disposal of the material can be weighed. A quantitative way to compare the environmental performance of products in construction is through their environmental product declarations (EPDs). The EPD is a statement based on a life cycle assessment according to ISO 14025 and EN15804. In Argentina, the development of EPDs is still incipient in the construction industry. However, to get an idea the magnitude of environmental impact of a material, it is useful to compare EPDs developed with the same product category rule in the same geographic region.

The quantification of the techno-scientific criteria in materials is carried out with the characterization process. This process includes micro and macroscopic technical analyzes that report on the mechanical, physical and chemical properties of the material. The characterization of traditional materials in construction is well advanced due to the extensive knowledge of these materials. However, this knowledge is limited in non-traditional materials, so it has to be expanded to facilitate the homologation of these materials. In an interesting work, Asdrubali et al. (Asdrubali 2015) summarize the thermal and acoustic performances of various non-traditional materials based on industrial and agricultural waste. These authors report that in general the thermal performance is characterized, but not the behavior against fire during a fire or the properties related to the degradation of the material. The degradation of a non-traditional material could affect the health of the home and its occupants after a long time (> 1 year). This fact makes the study of degradation less relevant when compared to the thermal study. By improving the thermal performance of the material, the consumption of the electricity bill is reduced and this is perceived easily and quickly. On the other hand, the current regulations in Argentina lack standardized tests that evaluate the degradation performance of non-traditional materials in various environments. This makes both the evaluation of the sustainability of the non-traditional material and the certification difficult. Asdrubali et al. (Asdrubali 2015) also mention that due to the prototypical state of various non-traditional materials, information on their environmental impacts is not yet available. This is due to the fact that most of these material developments are limited only to an experimental and laboratory stage, making their insertion into the construction products market difficult.

3. Objectives

This work arises from the need to draw links between the fundamental criteria for a sustainable approach: environmental, socio-economic and technical. In this line, a non-traditional construction system for self-construction is studied, based on wood and plastic waste. In addition, in order to weigh the social benefit for the development of the construction system, techno-scientific and social criteria will be used.

This social dimension is what can introduce a new factor, which we can call service, which makes the development of a repertoire of new materials timely and necessary (as a result of the reuse or recycling of NIHW-USW waste), in response the deep environmental deterioration and an endless number of new social and cultural phenomena that we can identify.

4. Working hypothesis

Within these processes of invention of new systems, the use of new materials makes special sense, and consequently their techniques jeopardize the traditional logic of certifications and architectural construction regulations. Almost 90% of the material we discard is recoverable.

This creativity of the new resource is based on the possibility of “seeing” the value that each waste has, this value is implicit in the material, in the status that we assign to the materials that come from recycling and the potential possibility that the design has and architecture to transform our perception of waste.

In this context, and with a number of entrenched interests, the application of new inventions in architecture becomes a political issue, where bureaucratic barriers often drive innovation outside of architecture. A well-developed and technically approved transgressive innovation can offer innovative and unexpected solutions.

This repertoire, of new materials and techniques of sustainable construction, challenge the very heart of technical regulations and propose new logics of analysis to regulatory frameworks; establishing new criteria and weighing new standards, where the requirement and objectives of these protocols are not only established based on strict compliance with their technical dimension but also in light of an environmental cost, which as such, will have a decisive impact when it comes to evaluate their technical performance.

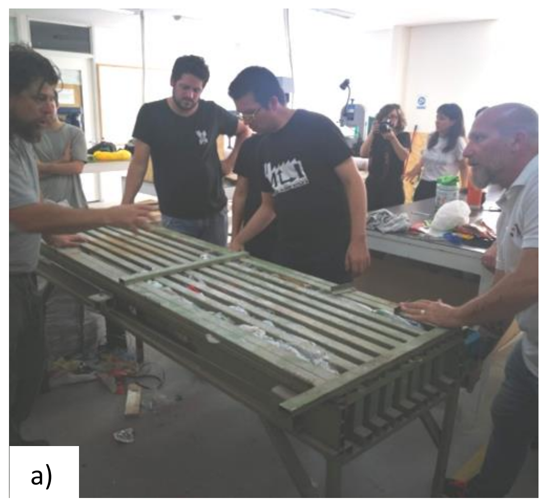
This view allows us to describe this project process and its construction as a research work and include it in a superior network of experiments in which a scientific community participates and is nurtured, which not only appreciates the results but is also interested in reading the initial conditions, the choice of new parameters and the invention of systems that allow the participation of the end user. An ethical dimension of technological development that, on a global scale, allows us to understand and question the logic of the rules by which societies build.

5. Experimental method

5.1 Constructive study system

This work technically characterizes a development that arises from the Sistema Constructivo 3C for insulation of the envelope, based on a wooden framework under the CIRSOC 601 standard. This system was designed using “intermediate” technology (economical and simple implementation, with production capacity industrial with high performance for the pre-manufacturing) and “adapted” (that can use installed knowledge or promote training workshops to transfer this knowledge to the community). The Sistema Constructivo 3C has a structure of three differentiated layers: internal, intermediate and external. The internal face was made up of a 3 cm thick lime-plastered synthetic fiber mesh. The outer face consisted of a synthetic fiber mesh plastered with a water-repellent mortar and lime finish 3 cm thick. However, for the test that measured the thermal transmittance of the material (standard RAM 11564) both on the internal and external faces, they were covered with 12.5 mm thick plasterboard, one vertical and other horizontal. The decision to use these plates on both sides, for the specimen of this test, responds to the fact that the K values of these products are already known, so it is very easy to discount these values to obtain the result corresponding to the compacted PET pile.

The inner layer of the Sistema Constructivo 3C consists of a pile of plastic waste located within the wooden framework and fulfills the role of thermal insulation of the building system. The plastic mound was made up of a compacted bale of recycled polyethylene terephthalate (PET) bottles. In order to promote self-construction of the system, a pulley-activated manual press was manufactured to compact the recycled PET bottles, **(Figure 1a).** The compaction load was adjusted until obtaining molds of dimensions 105 cm x 60 cm, containing 180 compacted bottles, **(Figure 1b).** To build a panel of the construction system, 2880 recycled bottles (16 piles) with a total mass of approximately 96 kg were used. The plastic pile had a mass per area of approximately 18 kg/m2. The wooden frame was made of Ellioti pine slats of 0.18 mx 0.05 m section and variable length. This frame covered a total area of 3 m x 3 m and was built by placing the vertical slats 60 cm apart from each other, **(Figure 1c).** The vertical slats served as a guide to arrange the plastic molds between them.


a)


b)

Figure 1 a) Works with the manual press activated by pulley. **b)** Pile of compacted plastic bottles**. c)** Dimensions and distribution of the wooden slats containing the plastic molds and the application of cementitious plaster. Source: Own elaboration.

5.2 Characterization of the construction system

The thermal and fire performance of the Sistema Constructivo 3C was characterized, using the standards: DIN 4102-1, IRAM 11949, IRAM 11950, IRAM 11912 and IRAM 11564. Depending on the test, samples with different dimensions and typologies were characterized, due to the different objectives and requirements of the above standards. It should be noted that all these tests were carried out in the facilities of the INTI Construcciones laboratories. With these tests it was determined: the behavior against fire of the materials and construction elements (DIN 4102-1), the fire resistance of the construction elements (IRAM 11949 and IRAM 11950), the optical density of the smoke generated by combustion or pyro decomposition of solid materials (IRAM 11912) and the properties of heat transfer in steady state of the building elements (IRAM 11564). Prior to all the tests, the PET bottles were washed to eliminate the remaining residues.

IRAM 11912 standard characterized the optical density of fumes from PET bottles. This test was applied exclusively to PET because the other materials that build up the Sistema Constructivo 3C have extensive experience and knowledge in the literature and on site. **Figure 2** shows the 1 m length of compacted PET bottles and the installation of the oven used in IRAM 11912, which was performed in quadruplicate. The evaluation of the optical density of smoke emitted by PET bottles was carried out without a flame to study their pyrolytic decomposition and with a flame to determine their combustion.

The flammability of PET bottles was characterized with DIN 4102-1 standard. The temperature rise in the furnace hood relative to the initial temperature and the length of the flame spread vertically were measured. This length is evaluated considering the residual length of the specimen that remains unburned after the test. According to DIN 4102-1, the residual length in each specimen must be at least 15 cm and in no case 0 cm, which would indicate that the specimen burned completely. The manufacture of this specimen had to be adapted to a metallic framework that is used to support the specimen according to the regulations **(Figure 2a).** Instead of using the press of compacted PET bottles **(Figure 1b),** a test tube was made consisting of four columns of perforated plastic sheets attached to the metal framework **(Figure 2b).** The bottles had to be cut because the edge of the base of the framework was less than the length of the plastic bottles. The bottle density of the mold had to be extrapolated to PET sheet geometry. These difficulties arose from a limitation of DIN 4102-1 standard, which lacks indications for testing materials with non-traditional geometries such as a bottle. It is relevant to mention that the discrepancy between the test geometries and the original used in the construction system could modify the final technical performance of the system. This modification is relevant when the geometry of the non-traditional material is a variable of the technical performance of the system. For the case of PET bottles, this effect of geometry is being studied by the authors of this work. The above observations suggest that DIN 4102-1 would have to be modified to include the geometrics of non-traditional materials and thereby lessen the difficulties in testing these systems.

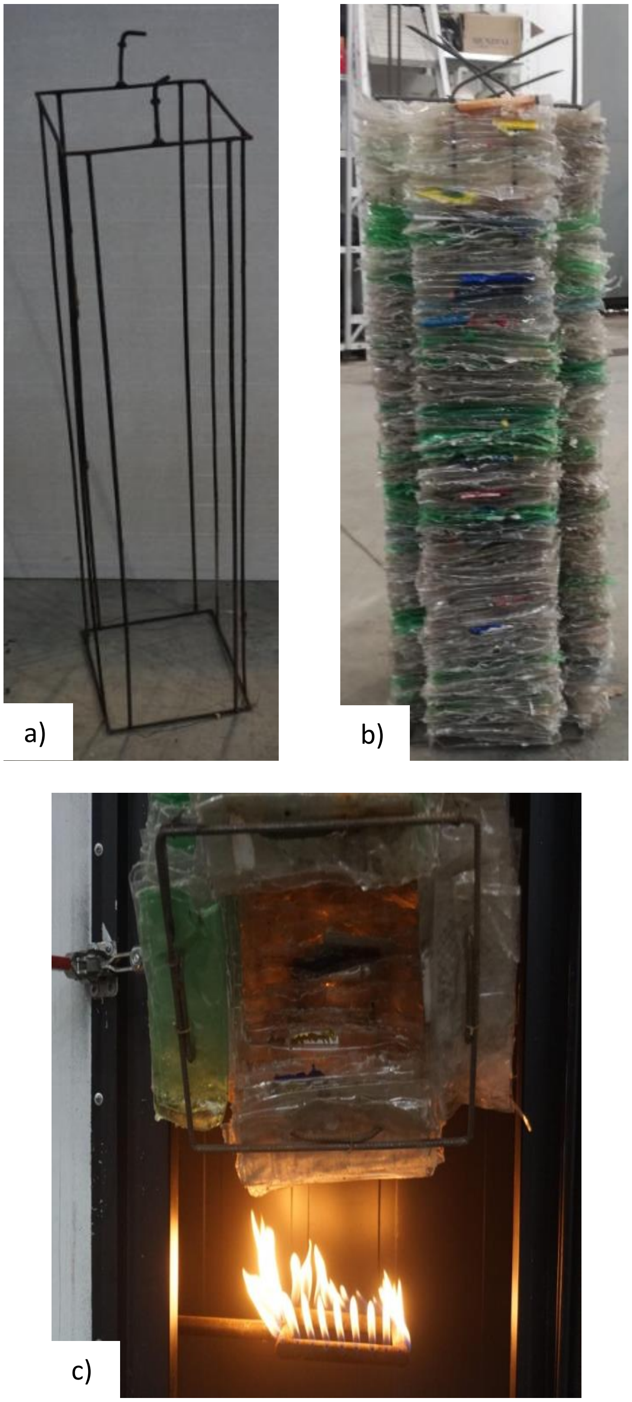


Figure 2 Photographs that show testing of combustibility and optical density of recycled PET bottles. **a)** Lattice of metal rods for the manufacture of the test tube**, b)** arrangement of the PET sheets extracted from the bottles to be able to form the test tube, c) detail of the burners located in the lower part of the test tube. Source: Own elaboration.

The stationary heat transfer properties of the building elements were determined (IRAM 11564). A square specimen with a 2.4 m edge and 0.205 m thickness was tested, using the hot box method with a storage box. This specimen consisted of 16 molds of PET bottles inside a wooden frame covered by gypsum panels on both sides. During the 120 h test, the ambient temperature was 21.9°C. Resistance to fire was characterized with IRAM 11949 and IRAM 11950 standards. A representative sample of a real case of a wall was used, that is, a 3m x 3m surface test piece, **Figure 1b**. This specimen was evaluated as a simple closure without load. To simulate the fire condition, a combustion furnace with eight burners was used on each vertical wall. The temperature measurement on the face of the exposed sample outside the oven was performed with five thermocouples located as shown in **Figure 3**. At the time of starting the test, the ambient temperature was 15°C.

It is important to clarify that the design of the test piece was carried out taking the most unfavorable conditions for this test, since no product was applied to protect the wooden structures or retard their ignition and subsequent fire spread, as well as the choice of termination of their faces with cementitious mortars in contrast to the possibility of having used industrialized plates that have already proven their resistance in this test. This decision was based on replicating the simplest and most economical conditions with which this constructive practice can be transferred to the territory, understanding that this installed knowledge, added to a small-scale economy, would guarantee universal access to this system.

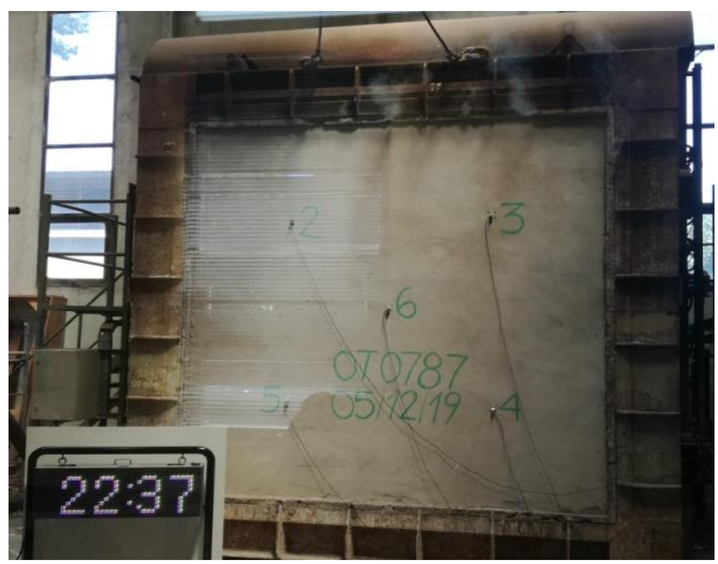


Figure 3 Specimen for fire resistance of 3m x 3m and arrangement of five thermocouples on the face exposed to the exterior, as indicated by the IRAM 11950 standard. This photograph was obtained at 22:37 minutes after the test began. Source: Own elaboration.

6. Results and discussion

6.1 Thermal and fire performance

PET bottles showed a reduced amount of fumes because it was classified as Level 1 according to IRAM 1192. This level corresponds to the best score that can be achieved according to this standard. In addition, PET bottles had low flammability because they were classified as B1 according to DIN 4102-1, **Figure 4.** These results were obtained for the four tested specimens, which confirm similar characteristics between specimens and standardization in the manufacturing process. Although it is true that these PET bottles presented greater compaction than the plastic molds **(Figure 1b)**, these results confirm that PET is a suitable material for use in construction.

Figure 4 Measurement of the burnt and residual lengths, which corresponded to 340 mm and 460 mm, respectively, during the flammability and optical density smoke tests. According to DIN 4102-1, the material exhibits low flammability when the residual length is at least 150 mm for all tests. Source: Own elaboration.

The thermal transmittance of the Sistema Constructivo 3C panel measured experimentally was 1.05 W/m2K, considering apparent convection coefficients of 7.69 W/m2 K for indoors and 25 W/m2K for outdoors. Discounting the thermal effect of the two internal and external plasterboards, the thermal transmittance of the wooden framework with plastic molds was calculated at 1.21 W/m2K. This value is lower than that required by IRAM 11.605 standard for thermal conditioning of buildings. According to this standard, a K value equal to 1.05 W/m2K certifies an interior temperature of 20ºC and the absence of surface condensation for a house built in the MABA region. Category B of the building code of the province of Buenos Aires establishes a value of 0.95, a value that is very close to that obtained with the two plasterboards, taking into account that it is a simple wall and the same plates were used only for the test (since the values K of these products were known and it was very simple to discount them to obtain the tested mole). For its real application, the external face should be replaced by another plate that guarantees resistance to weathering, so that the value required by category B could be achieved using a 6 mm OSB plate added cementitious plate of 10mm thickness on the outside.

Sistema Constructivo 3C demonstrated a fire resistance of FR 60, according to IRAM 11950: 2010. The tested system complied for 60 minutes with the parameters of stability, thermal insulation and tightness to the passage of flames and hot gases measured on the face not exposed to the fire and as such it can be used for two-story homes, according to the IRAM 11949: 2014 standard. According to what was observed at the end of the test, this resistance depends on guaranteeing the integrity of the coating on the interior face of the wall. It should be noted that the FR 60 value was obtained without treating the wood against fire, so the FR value could increase if this treatment is applied. There are various alternatives to protect wooden structures or retard their ignition and subsequent fire spread, also to preserve the integrity of the inner layer of the wall from the use of different types of plates (when we work with dry construction systems) or in the case of cementitious mortars, the need to guarantee a constant thickness of at least 3cm thick, as stated as a recommendation on page 15 of report OT No. 224-0787.

6.2 Standardization in the construction of the construction system

For the Sistema Constructivo 3C to maintain the thermal and fire performance characterized in this work, its manufacture must follow a protocolized standard. The variables of each stage of the process have to be defined simply and clearly, considering that this system is self-constructed. Therefore, the systematic and organized dissemination of this knowledge among the community is a key to ensuring the comfort and safety conditions of their homes.

Many contributions to this protocol were fostered from the performance of the aforementioned trials. Among the relevant variables for the manufacture of the 3C Construction System are the cleanliness and uniformity of the recycled plastic material. The presence of organic residues inside the PET bottles modifies the technical performance of the system and increases the dispersion of the results in the characterization tests. The liquids and organic matter remaining in the bottles have a different physicochemical nature than plastic, which could modify the behavior of the system. For example, during the reaction to fire test (IRAM 11950) that simulates the temperatures of fire, the remaining water inside PET bottles could suddenly evaporate and generate internal pressure in the panel. This pressure could increase to internally break the construction system and then crack it, which reduces its performance against fire. On the other hand, prior to compacting the PET bottles, the labeling tape and its screw cap have to be removed because they are manufactured with other materials. The tape is waterproof varnished paper and the cover corresponds to polypropylene or high-density polyethylene. These materials have a different physical-chemical nature than PET and therefore can modify the thermal and fire performance of the panel.

To ensure the systematization of the Sistema Constructivo 3C manufacturing, the variables of each stage must be kept within specific values. Among these variables are: the compaction load of the bottles, the number of bottles per m2 (which defines the mass per area of the product in 18 kg/m2 and the traceability of the construction system), the method and time of cleaning and drying the bottles, and the thickness of the cementitious plasters on the internal and external faces of the system, in the event that the system chosen to materialize the internal and external layers is with traditional construction systems. The degree of compaction of PET bottles regulates the amount of air present inside the system and, therefore, has an inverse relationship on thermal transmittance and fire resistance. If the amount of air is decreased by severe compaction, the fire resistance increases, but the insulation by the encapsulated air is reduced. The degree of compaction used in this work favored a low thermal transmittance and a high resistance to fire, making it suitable for setting it as a process variable. On the other hand, the homogeneity of the plaster in contact with the fire is relevant to ensure the fire resistance of the system. The plasters encapsulate the plastic molds and the wooden framework, thus protecting them from fire and increasing the resistance of the system.

6.3 Comments on the components of the construction system

Both PET and wood are combustible materials, which burn during a fire and produce gases that are harmful to health, such as carbon monoxide (CO). In a comparative study of the performance of wood briquettes and mixed with plastic, it has been observed that the CO emission is similar between oak wood briquettes and mixtures of recycled PET bottles with sawdust (Zannikos et al. 2012). Oak wood, a hard wood, generates more CO emissions during combustion than soft pine wood, as reported by Kistler et al. 2012. These results suggest that during the fire resistance test (**Figure 3**), the amount of CO emitted per kg of pine wood and bottles could be similar. So adding non-traditional recycled plastic material to the system would not intensify CO emissions during a fire. On the other hand, CO emission from PET could be reduced by using flame retardant additives. These additives reduce the flammability of plastic or delay the spread of flames along its surface. Although this measure is usually applied in industry, these additives tend to have a high environmental impact (Segev et al. 2009), which moves this construction system away from sustainability. In a recent work (Prada Botia et al. 2018), it was shown that recycled PET with flame retardant poorly improves its fire resistance compared to recycled PET. This is because PET, due to its chemical composition, is a thermally stable polymer compared to other waste plastics (Villain 1995). In line with this, PET recycled from bottles also has an oxygen limit index of 21% (Prada Botia et al. 2018), one of the highest values among thermoplastic waste (Omenexus 2020). This index corresponds to the minimum concentration of oxygen that sustains the burning of a material with flames. Therefore, among the existing plastic waste, PET is a viable option as a construction material, because for its combustion it requires a greater amount of oxidizer (oxygen) than other plastics. Finally, recycled PET has a similar limiting oxygen index than pine wood (White 1979), which suggests similar behavior for the start of combustion between both materials.

An additional condition to take into account in the design and use of the 3C Construction System, in relation to precautions against fire, is the need for the layout and execution of the electrical installation to be carried out independently of the plastic molds. Both the laying of pipes and the installation of panels, sockets, centers and actuating keys must be out of contact with the studs, being able to carry out external laying (using applied baseboard or duct systems) or by making canalizations that systematize the passage of these pipes through the use of horizontal or vertical posts specially located next to the wooden crossbars or columns of the structure. This autonomy of the electrical installation will avoid the production of potential sources of fire due to failures in this type of installation.

The construction of the framework using wood is a comparative advantage over other materials such as steel, in terms of environmental performance, mechanical behavior during a fire and thermal insulation performance. A wooden structure is able to retain its mechanical properties at high temperatures for longer than steel, due to the high resistance to creep of wood (Granello et al. 2019). Creep is a phenomenon by which the material permanently deforms under mechanical load at elevated temperatures, depending on the time of application of the load (Ross 2013). This is because the wood burns slowly at approximately 3.05mm / hour, while producing a charred layer on its surface. This surface layer protects and insulates the core of the wood from fire and allows the structure to be maintained

(Lowden 2013), since the layer acts as a thermal insulator. The wood below the charred layer retains a much greater mechanical strength than that of steel at these temperatures. In this way, the timber framing was able to maintain the structural integrity of the panel during the fire resistance test without collapsing, **Figure 3.** Regarding the environmental impact of pine wood, EDPs can be used to get an idea of its performance. environmental compared to other materials that fulfill the same function. The EDPs of pine-based products have global warming potential values, measured in kgCO2/equivalent, much lower than those based on steel. For example, 1 m3 of pine wood board manufactured in Spain (DAP-S-P-01314 2018), generates approximately -685 kgCO2/m3 during its production stage (stages A1, A2 and A3 of the life cycle). In contrast, during the same stages of the life cycle, 1 m3 of structural steel manufactured in the same country generates approximately 6 times more kgCO2/m3 than the previous wooden board (GlobalEPD 001-003.06 rev.3 2013).

7. Conclusions

The study construction system that contains non-traditional materials from plastic bottle waste showed very good performance in thermal insulation and fire resistance compared to other systems based on traditional materials. This system complies with the technical requirements demanded by the Argentine regulations to be used in two-storey homes in the province of Buenos Aires. This regulatory compliance was obtained by following the traceability for the manufacture of the system, which was described in this work. The enhancement of bottle waste exposes the potential of these non-traditional materials for use in construction and to promote a circular economy. This technology, added to an adequate process of "social activation" allows to generate a process of Local development and Circular economy in the communities where it is implemented. At the same time, the fabric of the community is strengthened within and with other communities. These are precisely those where there are great difficulties, or impossibilities, to generate jobs in a formal and sustainable way.

8. References

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