Evaluation of household waste materials for façade components in primary educational workshops. Mechanical and fire properties

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Abstract

An important amount of human household waste can be reused, as it is presently done all over the world in numerous social initiatives such as "Do It Yourself" proposals. Some waste containers have sufficiently good mechanical properties that make these containers promising candidates as some architectural elements. For example, this waste can become non-load bearing façade components, which have to withstand much smaller stresses than structural elements such as columns and beams. This article is part of a broader research project that is developing low-cost new solar control devices for school façades reusing household waste. These façade components will be assembled during workshops by elementary school communities. This present research paper studies this cladding use of the household waste and analyzes these waste-based components mechanical and fire properties by carrying out laboratory tests. These test results will be the base of future simulations and friendly-use tables for children during the aforementioned workshops. Conclusions for this research article are: a) that plastic waste materials have similar properties to new plastic materials for construction although they have been built for packaging purposes and their implementation in façades requires further studies and caution; b) tetra pack has particularly interesting properties which had been largely unexplored.

Keywords: Household waste, Tetra Pak™, mechanical properties, school buildings, façades, solar control, educational workshops.

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1. Introduction

At a global level humans dump high amounts of waste to the environment, 242 million tons of plastic waste in 2016, from which only a low percentage around 19% is recycled (Hoornweg & Bhada, 2012). This dumped waste brings serious impacts on our planet such as the plastic marine litter to which governments are responding with new directives, such as the latest

European Communion (Of, European, & Council, 2018). This directive asks their member countries to collect separately at least 90% of single-use plastic bottles by 2025 among others. This is a crucial challenge for our society because it will be difficult to change from dumping to recycle, which are the worst and better waste hierarchy alternatives, respectively. Even more challenging and better alternatives to diminish waste generation and its environmental negative effects would be prevention and reuse (Gharfalkar, Court, Campbell, Ali, & Hillier, 2015). Preventing waste generation requires teaching and promoting waste knowledge and awareness among population from its childhood (Ward, Wells, & Diyamandoglu, 2014). Reusing waste saves materials from the waste cycle and takes it back to the use cycle (CTUP, MATTONI, & IIM, 2015; Mansour & Ali, 2015). From all waste the part generated from everyday houses activity, called household waste (Andreasi Bassi, Christensen, & Damgaard, 2017), could have a crucial role in prevention and reuse waste management alternatives because it involves people of all ages from its generation to management.

Household waste has been reused as building components numerous times until present. Most of these experiences have been applied to façades, for example: the 19 century Antoni Gaudí's broken ceramics for cladding (Faulí, 2014); the 20 century North America gold rush houses with glass bottle façades (Thomsen, 2012) and following similar examples (Ludacer, 2009) and 21 century schools constructed using plastic bottles (Mansour & Ali, 2015). There are a few of these examples that could have been built to bring solar protection to some exterior spaces and façades, such as several proposals from the Do-it-Yourself (DIY) social movement (Nováková & Achten, 2014; Watson, 2012).

These solar control devices are crucial in order to provide edifice users lighting and thermal comfort. In educational centers, proper lighting (Michael & Heracleous, 2017) and thermal comfort (Zomorodian, Tahsildoost, & Hafezi, 2016) have a positive influence on the learning process of pupils. In Spain, public schools discomfort from a lack of solar control is a well-known problem that has become unbearable in the last years. In this sense, numerous educational centers do not satisfy current indoor environmental requirements for educational premises because they are former buildings that were constructed following obsolete regulations. Moreover, they are non-educational edifices that became school centers (Martinez-Molina, Boarin, Tort-Ausina, & Vivancos, 2017) and numerous recent premises were built following strict time and cost limitations during a recent urgent need of school edifices (Pons & Aguado, 2012).

Tensed solar control devices for these school façades can be built using lightweight materials in a tensed or curtain format as some previous patents have proved (Ehrsam, 2012; Hesse, 2004; MERMET, 2016; Pereira, 2010). At present there are numerous lightweight materials used in various façades (Marzo & Quintans, 2005). These materials are commercially available as semi-finished parts in the form of fabrics, cushions, sheets or panels with small thicknesses. Some commercially available lightweight materials are presented in Table 1 with the focus on their mechanical and fire properties.

There is also ongoing research on lightweight waste-based materials for structures and façades. These materials have different origins, some come from a second processing cycle (Hanif, Diao, Lu, Fan, & Li, 2016; Hanif, Lu, & Li, 2017; Pinto et al., 2012) while others are directly reused from the after-market step, like reused plastic bottles for exhibition pavilions (Kovacs et al., 2017; Nováková, Šeps, & Achten, 2017). These lightweight components have different connections and fastenings, most of them with self-drilling screws connected to a non-load bearing façade substructures (Schittich, 2006). The screws have different pullover tensions, for example 0.47 to 3 kN for steel sheets with thicknesses from 0.8 to 2 mm (Hilti, 2015).

Table 1. *Selected physical properties of commercial lightweight materials and components for façades.*

Material	Tensile modulus E (GPa)	Tensile strength σ_M (MPa)	Failure strain ε_B (%)	Density ρ (kg/m^3)	Format	Thickness (mm)	Surface weight (kg/m^2)	Specific strength (kN m/kg)	Tensile strength per surface weight (10^3 kN /kg)	Fire classification	Reference
PTFE	0.4	7-30	200-400	2150-2200	Fabric	0.1-0.3	0.2-0.6	3-14	13-174	B, s1 d0	(Mark, 2007; TEMME OBERMEIER, 2018)
ETFE	1.5	46	230	1700	Cushion	0.1-0.3	0.1-0.5	27	90-338	B-s1, d0	(Ebnesajjad, 2002; ETFE-MFM, 2017; IBU, 2019)
PMMA	2.5-3.3	55-75	3-5	1170-1200	Sheet	2-45	2.3-54	46-64	1-32	E	(BARLO XT, 2005; Mark, 2007)
Aluminum	69	230-520	3-32	2700	Sheet	1.0	2.6	85	90	A1	(Götz & Nevén, 2017; Luxalon, 2005)
Steel	200	673	586	7850	Sheet	0.4	3.1	86	214	A1	(CSTB, 2015; GMBH, 2015)
Steel	200	673	586	7850	Fabric	2	15.7	86	43	A1	(GKD, 2019)
PC	2.1-2.4	70-90	100-120	1200	Panel	0.8-40	0.9-4.0	58-75	18-100	B-s1, d0	(Mark, 2007; SABIC, 2008)
Timber	7.4-21.6	5.5		771	Panel	6.4	4.9	7	1	D-s2, d2	(Östman, BL. & Mikkola, 2006; UNIBOARD, 2019)
PVC	1-3.5	40-75	30-80	1320-1580	Panel	6	7.9-9.5	30	4-10	B-s2, d0	(DUMAPLAST, 2019; Mark, 2007)
(Al/PE composite				1967	Panel	3-4	5.9-7.6			A2-s1, d0	(ALUCOBOND, 2019; Alucoil, 2018)
Timber & bakelite				1350	Panel	6	8.1			B-s2, d0	(PRODEMA, 2018)
HPLP				1350	Panel	6	8.1-8.4			D-s2, d0 a B-s2, d0	(BBA, 2015)
OPC & fibers	17			1762	Panel	8	14.1			A2-s1-d0	(EUROPANELS, 2014)

PTFE: polytetrafluoroethylene (Appendix A presents a complete list of abbreviations); ETFE: ethylene tetrafluoroethylene; PMMA: polymethyl methacrylate; PC: polycarbonate; PVC: polyvinyl chloride; Al: aluminum; PE: polyethylene; HPLP: high pressure laminated panels, for example made of of cellulose fibres and synthetic resin; OPC: Ordinary Portland cement; specific strength equals tensile strength divided by material density (kN m/kg); tensile strength per surface weight equals tensile strength divided by surface weight (kN/kg); fire classification according to EN 13501-1.

Although many different materials are available for solar control devices applicable to school façades, there is a lack in developing innovative low-cost solar control devices reusing household waste. This lack is the aim of a funded research project (Pons, Peña, & Habibi, 2018), which researches on new waste-based light façade components that will be assembled during workshops by elementary school communities. These workshops were designed by a group of multidisciplinary experts in order to include crucial architecture, pedagogic, primary teaching and waste issues (Pons, Habibi, & Peña, 2018b). During these experiences, primary students design and construct these façade elements, incorporating waste directly reused from the after-market. In the numerous workshops carried out until now, among other learning activities, students collect, classify and prepare the required household waste following this workshop guideline. This sorting out is very important so that the resulting façade elements are built with the appropriate material and format because, although most containers of the same material have similar composition and width due to package optimization, there are differences of size and shape due to commercial purposes (Grumezescu & Butu, 2019). Until now this waste has come from students' families and the containers readily available from the European Union program "EU School Milk Program" in which these schools participate (EU, 2020). These sources have been more than sufficient until now, although the researchers have backup sources in case of need such as sustainability centers (AB, 2020).

The present article is the part of this broader project that aims to determine the main physical properties of household waste for building solar control devices during elementary school workshops. These properties will be used to: a) characterize these waste materials and compare them to other façade materials, b) to simulate solar control devices based on these materials using finite elements methods so to finally c) define prototypes to be used in the previously mentioned workshops. In this case, non-toxicity and low allergic requirements have been considered compulsory for these workshops. Therefore, toxic, allergic and unsafe materials and components are beyond the project boundaries (Pons, Habibi, & Peña, 2018a). To achieve this goal, this research paper will define the required properties to be studied, carry out tests to determine the corresponding values in order to do future simulations and prepare tables of values so children can use them during workshops. The household waste materials studied in this work were found to be the best alternatives for this specific study case, which was found in a previous research step (Pons, Habibi, et al., 2018a).

In a first step the main properties to analyze in detail in this project were defined taking into account these new solar control devices requirements and main components. These requirements were the mechanical needs from a school façade element of the sample: compact up to 8-storey buildings in urban areas, following European Eurocode 1 (Gulvanessian, Formichi, & Calgaro, 2009) and local standards (Ministerio de la Vivienda, 2009). As a result, these devices had to withstand maximum wind loads less than 1 kN/m^2. The main components were waste-based joints, bars and foldable surfaces that shape the aforementioned best alternatives of louvres and curtains according to the previous research step. The utility model ES 1224335 U (Patent No. ES 1224335 U, 2019) explains these design components in detail. The best alternatives satisfied the requirements of solar control devices in building façades and openings (Kuhn, 2017) which are thermal and visual comfort, daylighting and passive solar gain control among others. Therefore, the studied main properties were those needed for carrying out structural simulations of these utility model components using finite elements software tools (Chen & Liu, 2014). These properties were: tensile, flexural, shear, density, Poisson's ratio and fire properties.

In a second step the existing literature was searched for the reused waste reported properties, unstudied properties were identified and the tests and specimens necessary to determine them were defined. Then these tests were carried out and the unreported properties were determined. The reused household waste materials of interest for this work were high density polyethylene (HPDE - Appendix A presents a complete list of abbreviations), polyethylene terephthalate (PET), polystyrene (PS), polyamide (PA) and carton packages, so-called “tetra briks” (brand name, Tetra Pak, Switzerland, referred to as “Tb”). Tb can be considered as a wood/polymer composite made from a total of six layers of paper (≈75%), low density polyethylene (≈20%) and aluminum (≈5%) (Yilgor et al., 2014). These materials are anisotropic due to the rolling or extrusion process used in their production.

The tensile properties, densities and fire behaviors of HDPE, PET, PS, and PA have been widely studied (see for instance (Mark, 2007), (McKeen, 2009), (Shen et al., 2017), (Yang et al., 2018), (Lu & Wilkie, 2011)). Nevertheless, few reports on the material properties of Tb are available and most of them study the use of Tb as a component or filler for composite materials such as Tetra Pak/sawdust composite boards (Sun & Zhang, 2013), agglomerate laminates with HPDE (Carrillo, Ventura, Gamboa, & Cruz-Estrada, 2014) or Tetra-Pak/polyethylene composite panels (Bekhta, Lyutyy, Hiziroglu, & Ortynska, 2016; Ebadi, Farsi, & Narchin, 2017). However, the properties of Tb alone have not been reported to the best of our knowledge.

The aim of this work is to analyze the mechanical and fire properties of household waste containers as part of a broader research project that is developing new low-cost solar control devices for school façades reusing household waste. Finally, conclusions are drawn as well as recommendations and future work is proposed.

2. Materials and methods

2.1. Materials

The household waste elements used in this study were: 1) plastic bottles made of high density polyethylene (HPDE) with a thickness of 0.6 mm; 2) plastic bottles of polyethylene terephthalate (PET) with a thickness of 0.2 mm; 3) polystyrene (PS) yogurt cups with a thickness of 0.2 mm and 4) Tb with a thickness of 0.4 mm were used. The main products used for the joints were: 5) a commercially available polyamide threat (referred to as “Tp”) with a diameter of 2.3 mm and a breaking strength of 144 kg according to the supplier was employed for joining the different materials, 6) brass steel eyelets 4 mm internal hole diameter, 7) copper wire staples sized 22/6 (DIN, 1963), 8) white wood glue water-based polyvinyl acetate adhesive and 9) universal transparent glue polyurethane based and solvent free.

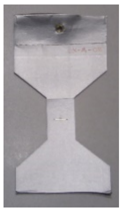
These waste elements and products define the project façade solutions, which are described in the previously mentioned utility model ES 1224335 U. This model has nine crucial joints that were studied in this article test campaign and can be classified as primary and secondary. First the primary basic joints used alone and as part of most joints, referred to as J1p, are knots between Tp. Second, the primary main joint between the solar control device and the window (J2p) is composed of two bottle caps having small holes and joined with Tp and the previous knotted J1p. This J2p works inserted in an aluminum guide. Third, the secondary joint between PS yogurt cup and Tp (J3s), which includes Tp, J1p and a bottle cap. The next 5 joints (J4s-J8s) are composed of a waste material, joint products, a eyelet and Tp with J1p. The samples of these joints were prepared as follows: rectangular strips with dimensions of 60x20 mm^2 were cut from the HDPE (J4s) and PET bottles (J5s) and fitted with two eyelets. Likewise, strips with dimensions of 120x14 mm^2 were cut from Tp. Five of these Tp strips were stacked together and joined either with staples (J6s), glued with white wood glue (J7s) or with transparent universal glue (J8s) and also fitted with two eyelets. These samples had two pieces of Tp threaded through the eyelets. Finally, the secondary joint with a single staple connecting two overlapping Tb sheets (J9s), which was tested in three directions as shown in Figure 1.

Table 2 presents these nine joints with a description of their household waste components, products and tested samples and the different joints are depicted in Table 3. As previously said, this article presents the test campaign based study of these joints and the unreported properties of the household waste elements in order to build the new solar control devices. These device components and joints followed the non-toxicity requirements cited in the previous section that had been defined in previous research steps.

***Table 2**. This research project new joints and samples description.*

Joints			Samples
code	**Type**	**Components**	**Set**
J1p	Primary	Knots, 2 Tp	
J2p		2 drilled bottle caps, Tp, aluminum guide	J2p with Tp at 0° & 90°
J3s	Secondary	PS yogurt cup, Tp, J1p, bottle cap	J3s
J4s		HPDE sheet, 1 eyelet, Tp, J1p	2 units of J4s together
J5s		PET sheet, 1 eyelet, Tp, J1p	2 units of J5s together
J6s		5 Tb sheets, staples, 1 eyelet, Tp, J1p	2 units of J6s together
J7s		5 Tb sheets, wood glue, 1 eyelet, Tp, J1p	2 units of J7s together
J8s		5 Tb sheets, universal glue, 1 eyelet, Tp, J1p	2 units of J8s together
J9s		2 Tb sheets, 1 staple	J9s in 3 directions (Figure 1)

***Table 3.** The specimens built to study the nine joints described in Table 2.*

Codes								
J1p	J2p	J3s	J4s	J5s	J6s	J7s	J8s	J9s
								

2.2 Methods

Table B.1 in the Appendix B shows pictures of the tested specimens and Table 4 summarizes the studied properties, tests and followed standards. The density of Tb was determined according to ISO 1183-1 (ISO, 2004) and was found to be 0.78 ± 0.01 g/cm^3. The determination of the maximum tensile load, tensile properties following ISO 527-1 (ISO, 2012) and flexural properties in accordance with ISO 178 (ISO, 2010) was performed at room temperature using a universal testing equipment (Sun 2500, Galdabini, Cardano al Campo, Italy) equipped with a 1 kN load cell and a video extensometer (Mintron OS-65D, Mintron, Taipei, Taiwan) to measure the strain. All tests started with a preload of 1N. The maximum tensile loads were determined at a test speed of 50 mm/min (tests M01-M10 and M15-M18, see Table 4). The tensile properties of PET and Tb were determined on die cut type 1BA specimens at a test speed of 10 mm/min while HDPE was tested using the same specimen type at 100 mm/min test speed. The Poisson's ratio of Tb was also determined in tensile tests on die cut type 1BA specimens at a test speed of 1 mm/min and at an axial strain of around 0.3 following the recommendations in ISO 527-1. Both axial and transversal strains were measured using a video extensometer. The flexural properties of Tb followed a 2 mm/min test speed according to ISO 178.

Three types of shear tests were performed on two overlapping Tb sheets joined with a single staple. In one case the staple was placed parallel to the tensile load (referred to as X direction) and in the other two cases the staple was oriented normal to the tensile load (referred to as Y and Z directions). Details of the three specific test set-ups can be seen in Figure 1.

The fire tests were carried out using a cone calorimeter (Ineltec, Barcelona, Spain). Tb samples were placed horizontally in a retaining metal frame and a constant heat flux of 35 kW/m^2 was applied from a 25 mm distance. Each test defined Heat Release Rate (HRR) curves and the following parameters: time to ignition (TTI), peak heat release rate (PHRR), PHRR time, fire growth rate (FIGRA), total heat emitted (THE) and ash content. In one test series the outer surface (i.e. paper/HDPE surface) of the Tb samples was exposed to the heat source and in the other series the inner surface (i.e. HDPE/aluminum surface) of the Tb samples was exposed to the heat source. A total of three samples was analyzed in each test series.

Table 4. *Properties, tests and standards followed or used as guide and specimens studied.*

Property	Standard	Specimens			Test code
		Units	Components	Size (mm)	
Tensile	None	10	J2p	Ø31.5x12	M01
		4	J2p 90°	Ø31.5x12	M02
		10	J5s	60x20x0.02	M03
		10	J3s	73x73x53	M04
		10	J6s	120x14x2	M05
		10	J7s	120x14x2	M06
		10	J8s	120x14x2	M07
		10	J4s	60x20x0.02	M08
		10	Tp	Ø2.3x203	M09
		10	J1p	Ø2.3x300	M10
	ISO 527-1	10	HPDE	Sample type 1BA, ISO 527	M11
		10	PET		M12
		10	Tb		M13
		10	Tb 90º		M14
Flexural	ISO 178	10	Tb+J6s	80 x 10 x 4	M15
Shear	None	10	Tb+J6s-X	180 x 90 x 1	M16
		10	Tb+J6s-Y	180 x 90 x 1	M17
		10	Tb+J6s-Z	263x32x0.8	M18
Density	ISO 1183	5	Tb	40x40x0.4	M19
Poisson's ratio	ISO 527-1	3	Tb	Sample type 1BA, ISO 527	M20
		3	Tb 90º		M21
Fire properties	ISO 5660-1	3	Tb+J6s	100x100x4	F01
		3	Tb+J6s	100x100x4	F02

X: direction X; Y: direction Y; Z: direction Z; see Figure 1.

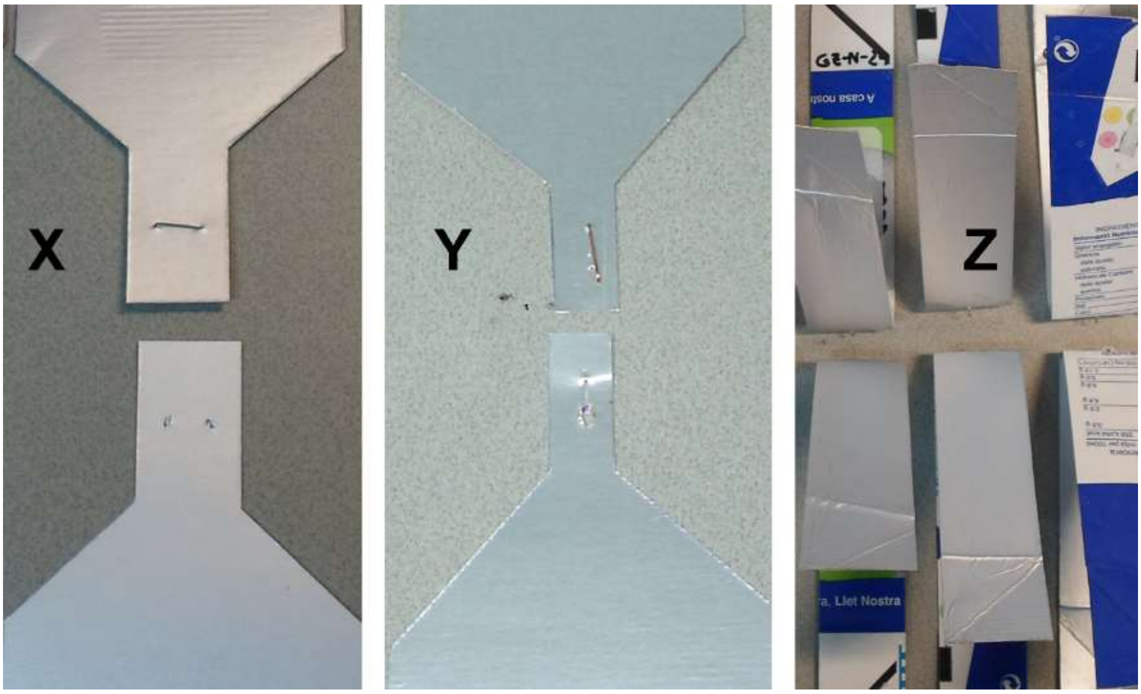


Figure 1. Test set- ups of tests M16, M17 and M18

3. Results and discussion

This section presents the results of the tests shown in Table 4 of the specimens presented in Table 2 and 3. Then it analyses the resulting mechanical and fire properties taking into account each element requirements depending on its expected role in the primary students' solar control devices, which the aforementioned utility model ES 1224335 U describes. For example, it validates if the primary joints will fulfill the required mechanical properties. After this analysis, the validated elements and their properties will be the base of future steps such as the workshop guidelines. This section also analyzes the waste elements general mechanical and fire behavior. It also compares these article experimental results to other waste and lightweight materials properties from other sources, in order to have a general magnitude of these waste materials behavior.

3.1. Maximum tensile loads

The maximum tensile loads of the mechanical tests M01-M10 and M16-M18 are compiled in Table 5. Representative force-displacement curves from M01-M10 tests are shown in Figure 2-3.

Considering the average load, it can be seen that the polyamide threat Tp (test M09) was the strongest of all tested samples with a maximum load of 858 N. As expected, join J1p consisting of two pieces of Tp knotted together (test M10) exhibited a comparably lower value of 753 N since knots are considered as weak points in threads where stress concentration occurs.

Similarly, the main joint J2p which consisted of Tp knotted to two bottle caps which were inserted in an aluminum profile (test M01) exhibited a comparably lower strength of 629 N. This strength decreased even further to 359 N when the aluminum profile was turned about 90º. Joint J3s could withstand a load of 141 N and consisted of a yogurt cup with a small hole in the bottom and Tp knotted to a bottle cap which was inserted in the yogurt cup.

The other joints consisted of rectangular HDPE (J4s), PET (J5s) and Tb strips fitted with brass steel eyelets. Recall that five of the Tp strips were stacked together and joined either with staples (J6s), glued with wood glue (J7s) or with universal glue (J8s) and brass steel eyelets. Although PET exhibits a much higher tensile strength as compared to HDPE and Tb as will be shown in the next section, PET is also known to be notch sensitive. This explains why the eyelets were easily torn off at a relatively low force of 67 N. In contrast, HDPE has a much lower notch sensitivity due to its outstanding toughness. Consequently, the eyelets were torn off at a relatively higher force of 123 N. Nevertheless, the strongest joints were the Tb samples and high tensile forces of 352 N, 389 N and 362 N were found for J6s, J7s and J8s, respectively.

Regarding the shear tests, the joint between two overlapping Tb sheets joined with a single staple exhibited maximum shear forces of 32 N, 25 N and 17 N for the X, Y and Z direction, respectively.

These tensile and shear test results show that the tested joints can be divided into three groups taking into account the average loads. The first group includes joints with high load bearing capacities such as Tp, nodded Tp (J1p) and the main joint (J2s), being crucial components of waste-based façade designs. The second group is the medium-strength secondary joints such as J6s, J7s and J8s. Finally, there are the weak components such as J3s-J5s and J9s. However, using multiple of these weak components increases the strength and thus gives a resistant and reliable secondary joint.

Generally, the load bearing capacities of these joints is much lower as compared to present façade connections with up to 3 kN, as mentioned in the introduction. The main joint of this work has a load bearing capacity similar to the less resistant commercial connectors for façades that support 0.47 kN, also referred in section 1. However, the strength of these waste-based connections can be sufficient if the number of connectors is defined accordingly to the façade loads. The maximum tensile loads and deformations will be used for future computer simulations of the façade. Since the maximum load on a complete façade of a given size is known, the necessary number of façade elements can be determined with the knowledge of the maximum tensile loads and deformations of the façade elements.

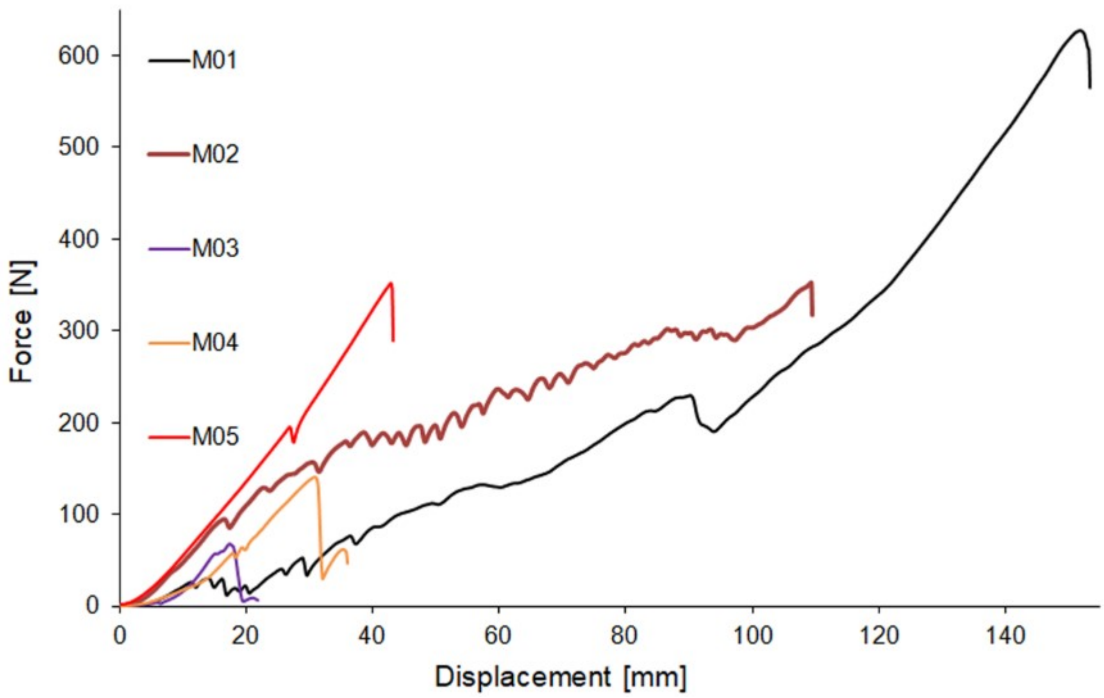


Figure 2. Force-displacement curves from M01-M06 tests.

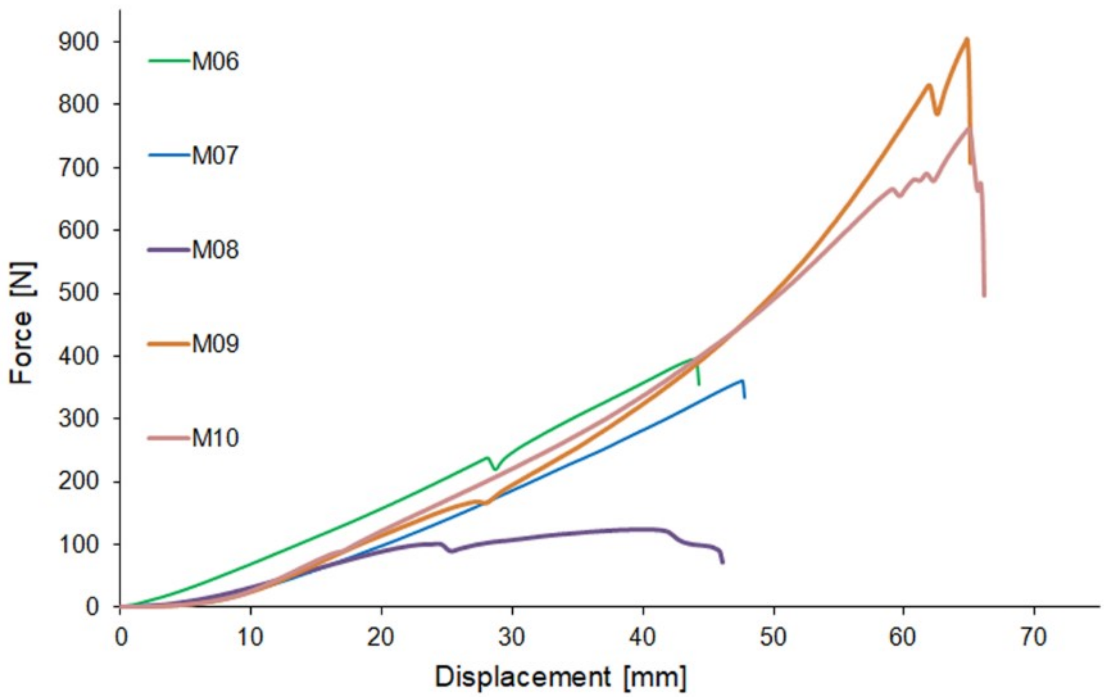


Figure 3. Force-displacement curves from M06-M10 tests.

Table 5. Main results of the mechanical tests M01-M10 and M16-M18.

Test code	Components	Maximum (N)	Minimum (N)	Average load (N)	Standard deviation
M01	J2s	674.1	582.1	628.6	31.9
M02	J2s 90°	407.8	335.3	359.4	33.1

M03	J5s	107.3	41.1	66.9	19.3
M04	J3s	155.7	130.2	140.7	10.0
M05	J6s	398.3	295.1	352.4	32.2
M06	J7s	450.1	369.8	389.0	41.5
M07	J8s	409.8	320.4	361.5	25.7
M08	J4s	153.0	106.0	123.0	14.0
M09	Tp	932.0	784.0	858.0	49.0
M10	J1p	838.0	650.5	753.3	64.0
M16	Tb+J6s-X	35.6	30.9	32.4	1.7
M17	Tb+J6s-Y	26.8	24.0	25.3	0.9
M18	Tb+J6s-Z	19.5	12.8	17.2	2.1

3.2. Mechanical properties

The tensile properties of HDPE, PET and Tb both in the main direction and transversal direction are compiled in Table 6. Representative tensile stress-strain curves are depicted in Figure 4. Among the tested materials, PET exhibited by far the highest tensile strength of 148 MPa together with a high yield point around 110 MPa. Nevertheless, it showed a relatively low modulus of 1.6 GPa and a failure strain around 28%. According to the literature (Awaja & Pavel, 2005; Mark, 2007), the tensile strength of unoriented bulk PET is 50 MPa. However, in the current work the tested PET samples were extracted from PET bottles. Note that during bottle production an injection molded PET preform is heated and then stretch blow molded into the final bottle form. Stretch blow molding transforms the bulk material into a highly bi-axially oriented PET with an increased, orientation-induced crystallinity which results in a much higher tensile strength as compared to the bulk PET (Awaja & Pavel, 2005).

As expected, Tb exhibited different mechanical properties in the main and transversal direction. The tensile strength was 57 MPa in the transversal direction (i.e. Tb 90°) and 32 MPa in the main direction. Similarly, a high stiffness of 5.3 GPa was found for Tb 90º which decreased to 2.1 GPa for Tb. A higher stiffness and strength typically leads to a lower failure strain. This was also the case here; the failure strain was 4% and 2% in the main and transversal direction, respectively. Additionally, the Poisson's ratios μ of Tb and Tb 90° were also determined during tensile tests performed at 1mm/mm. μ of Tb was found to be 0.43 ± 0.03 whereas a μ of 0.36 ± 0.01 was measured for Tb 90°.

The tensile properties of HDPE were typical for a semi-rigid and tough polymer and matched well with the ones reported in literature (Mark, 2007). Comparing the four studied materials, the modulus of HDPE was only 0.9 GPa and therefore comparably lower. Nevertheless, its tensile strength was even higher than the one of Tb. HDPE exhibited a failure strain of >800% which reflects its outstanding toughness in contrast to the (semi-)brittle behavior of bi-axially oriented PET or Tb.

***Table 6**. Tensile properties of HDPE, PET, Tb and Tb90°.*

Test code	Components	Tensile modulus E (MPa)	Tensile strength σ_M (MPa)	Failure strain ε_B (%)
M11	HPDE	949 ± 260	36.1 ± 3.9	816 ± 99
M12	PET	1625 ± 599	147.8 ± 9.9	28 ± 3
M13	Tb	2135 ± 293	32.4 ± 1.6	4.3 ± 0.4
M14	Tb 90º	5346 ± 749	56.8 ± 3.1	1.9 ± 0.2

Additionally, in order to study more about Tb layers connected with staples already used in tests M06 and M16-M18, the test M15 tested the flexural properties of ten Tb layers joined with staples. The results were: a Flexural modulus of 414 ± 60 MPa, a Flexural strength of 10 ± 1 MPa and the samples did not show a yield point and did not break. These results will be useful to simulate the new waste-based solar control devices.

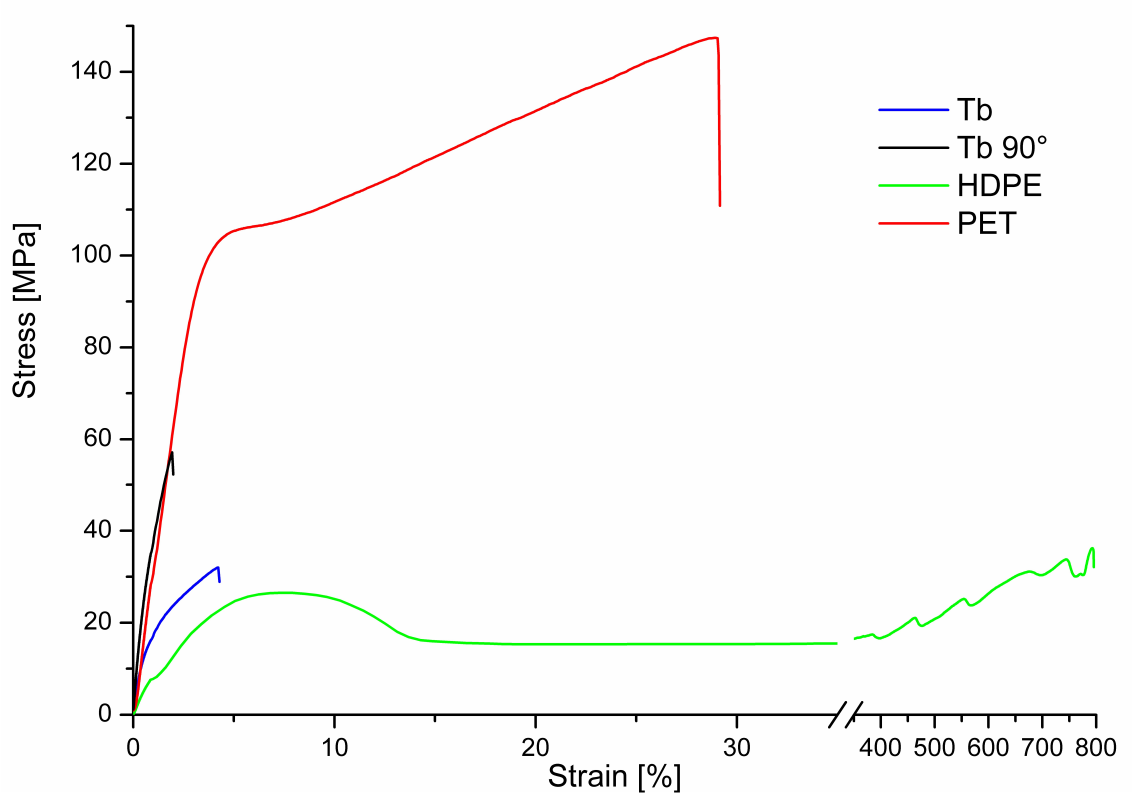


Figure 4. Representative Tb, Tb 90°, HPDE and PET stress-strain curves from tensile tests.

As compared to other lightweight materials for building claddings, the waste-based materials presented here exhibit promising properties. For example, Tb used as a sole sheet exhibits a surface weight of 0.312 kg/m^2 considering a thickness of 0.04 cm, a specific strength of 42 kN m/kg and a tensile strength per surface weight of 101 x 10^3 kN/kg. On the other hand, these household waste elements have similar tensile properties as plastic lightweight components which are used as façade materials at present. As expected, they have lower mechanical properties than metals. However, as light material, Tb has a high specific strength greater than the reference plastics in Table 1 and a tensile strength per surface weight similar to the compared steel and aluminum panels. In consequence, these household waste materials could be used in façades similarly to plastic materials but with caution because they were not designed for this purpose. The results presented in the previous sections will be useful in order to model and simulate these project solar control devices in finite elements and prepare a design guide for the construction of these devices during participatory workshops.

3.3. Fire properties

A comparison of the measured fire properties of Tb and other materials from the literature is shown in Table 7. These tests were carried out on Tb exposing both sides. According to the aforementioned tests for Tb and references for HPDE, PET and PS (Lu & Wilkie, 2011; Shen et al., 2017; Yang et al., 2018) all these household waste containers have a poor behavior exposed to fire. Considering their TTI, Tb has the lowest followed by PS, PET and HPDE, having PS and PET a similar TTI to Tetra Pak-based boards and lower than plywood and solid wood boards (Yilgor et al., 2014). Taking into account their PHRR, PS has the greatest followed by HPDE, PET and Tp, the latter having a slightly worse fire behavior than solid wood. This is explained by the composition of Tb which is made of 63 wt.% cardboard, 30 wt.% HDPE and 7 wt.% aluminum (Korkmaz, Yanik, Brebu, & Vasile, 2009).

Table 7. Comparison of fire properties of different materials as determined by cone calorimetry.

Sample	TTI (s)	PHRR (kW/m^2)	PHRR time (s)	FIGRA (kW/m^2s)	THE (MJ/m^2)	Char (%)	Reference
Tb cardboard*	25 ± 2	280 ± 6	31 ± 2	9.0 ± 0.3	44.9 ± 16.5	10.9 ± 5.9	this work
Tb aluminium**	31 ± 7	266 ± 59	533 ± 155	0.5 ± 0.3	52.2 ± 10.2	19.1 ± 0.2	this work
PS	36 – 53	656 – 1238	127 ± 13	10	110 ± 1	n/a	(Lu & Wilkie, 2011)
HPDE	79 ± 1	465	184	2.52	95	8.1	(Shen et al., 2017)
PET	40	560	119	14.1	78	n/a	(Yang et al., 2018)
Tetra Pak-based boards	47 – 54	108 – 121	n/a	n/a	n/a	27 – 37	(Yilgor et al., 2014)
Plywood boards	78	139	n/a	n/a	n/a	22	
Solid wood boards	66	227	n/a	n/a	n/a	34	

Legend: Heat Release Rate (HRR) curves and the following parameters: time to ignition (TTI), peak heat release rate (PHRR), PHRR time, fire growth rate (FIGRA), total heat emitted (THE), not available (n/a).

* The outer cardboard/HDPE surface of the Tb samples was exposed to the heat source.

** The inner HDPE/aluminum surface of the Tb samples was exposed to the heat source.

To sum up, regarding the fire properties in general, the waste containers studied have a similar behavior to synthetic polymers (Chow, Leung, Zou, Dong, & Gao, 2006, 2008) like PMMA in Table 1 which has an Euroclass E. In consequence, the following advices are given for these waste-based devices: a) do not put close to flame and b) Tb elements should be built in such a way that the polyethylene/aluminum layer is on the outside (i.e. external) surface.

4. Conclusions

The main novelty of this project is the contribution to the knowledge of these waste materials as construction materials. To sum up, the studied materials are good façade components and joints according to the presented mechanical and fire studies. Their properties are different from more conventional facade materials such as metals or cementitious materials but are more similar to contemporarily used materials such as plastics. Waste connections and joints have low load bearing capacities compared to present connections for façades but by using numerous elements they are expected to be able to withstand façades loads. Their poor fire behavior is an important weakness which should also be taken into account. Nevertheless, waste materials from domestic containers were not designed for façade purposes so they should be introduced cautiously in the construction sector.

The main findings of this work are the studied physical properties of “tetra brik” which were not yet reported to the best of our knowledge. This research has pointed out its anisotropic mechanical behavior. Tb exhibits two main directions due to its production process; parallel to the short edges of the Tb package it is stiffer and stronger but also more brittle as compared to the other direction of the Tb package.

5. Future works

These findings will be considered in future works such as a computer modeling and simulation of the solar control devices in order to improve them. These devices alternatives were defined in a previous research step (Pons, Habibi, et al., 2018a). The best alternative types are exterior louvres and curtains because of their light and thermal comfort, low cost, high workability and safety for elementary children among others. In this regard, Figure 5 presents a first design and prototype of this alternative, which will be improved in the next research steps.

Figure 5. First design and prototype to develop in future works.

After optimizing these alternatives, guidelines about these improved devices for the workshop will be prepared. These guidelines will consist in easy-to-use tables for children and teachers. They will follow the three properties studied in this project: mechanical properties, fire behavior and durability. Further steps will include studying the weathering and aging of these materials. From applying these workshops extensively, further conclusions will be drawn about the direct reuse of after-market waste materials for workshops. The performance of these waste containers and the resulting solar control devices can then be compared to the performance of recycled materials obtained from a second processing cycle of these same waste containers and their resulting devices.

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Appendix A

Table A.1 with the abbreviations used in the text

ABBREVIATIONS	Relevant values
PTFE	Polytetrafluoroethylene
ETFE	Ethylene tetrafluoroethylene
PMMA	Polymethyl methacrylate
PC	Polycarbonate
PVC	Polyvinyl chloride
Al	Aluminum
PE	Polyethylene
HPLP	High pressure laminated panels
OPC	Ordinary Portland cement
HPDE	High-density polyethylene
PET	Polyethylene terephthalate
PS	Polystyrene
PA	Polyamide
Tb	Tetra brik sheet
Tp	Polyamide threat
BST	Black Standard Temperature
CHT	Cylinder Head Temperature
HRR	Heat Release Rate
TTI	Time to ignition
PHRR	Peak heat release rate
FIGRA	Fire growth rate
THE	Total heat emitted

Appendix B

Table B.2. Specimens after testing

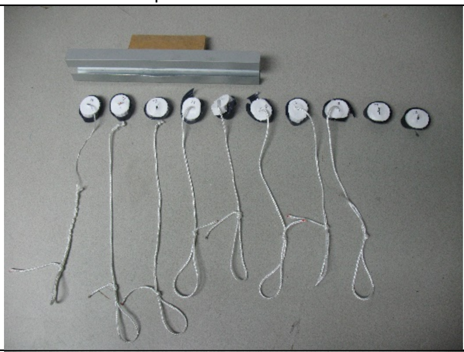
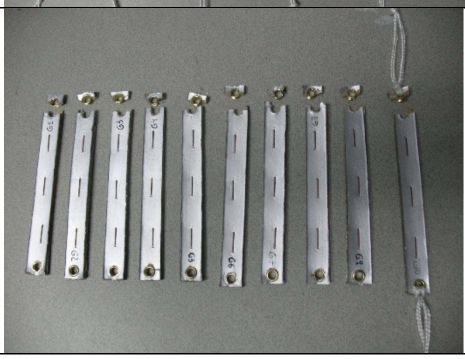
Test code	Specimens after test
Figure A1. M01 & M02	
Figure A2. M03	
Figure A3. M04	
Figure A4. M05	

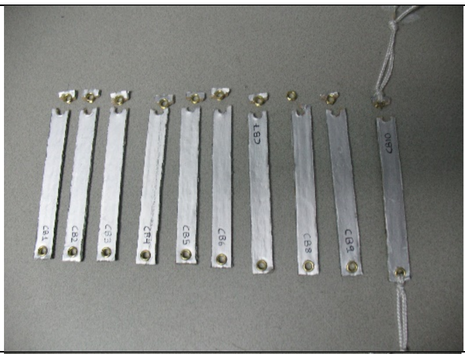
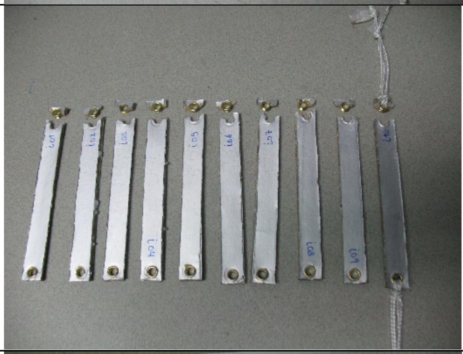
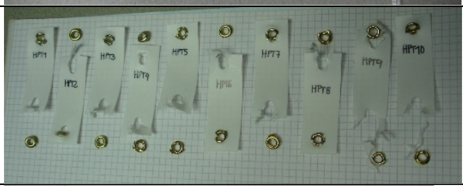
Figure A5. M06	
Figure A6. M07	
Figure A7. M08	
Figure A8. M09	
Figure A9. M10	
Figure A10. M11	

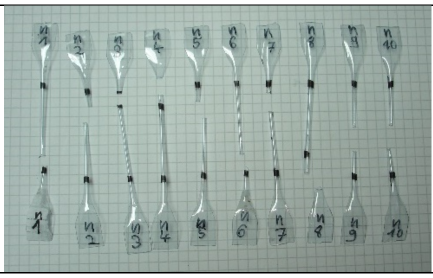
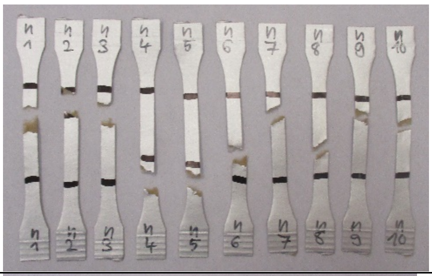
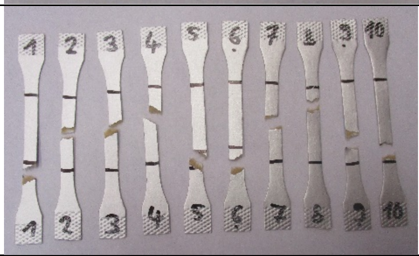
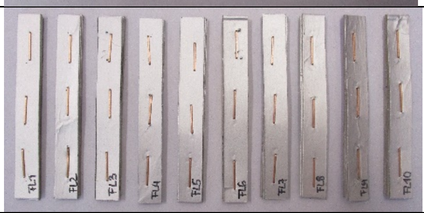
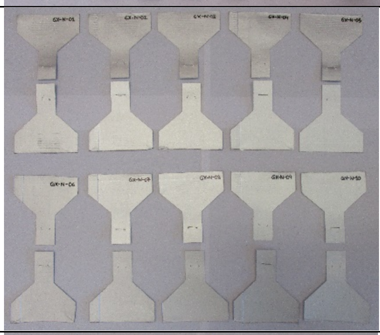
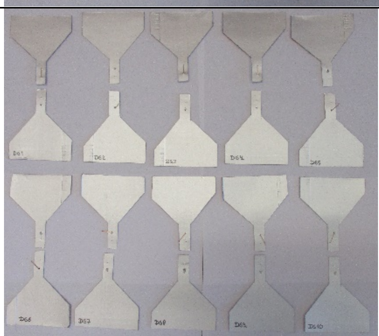
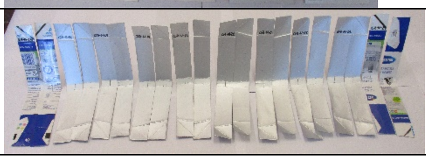
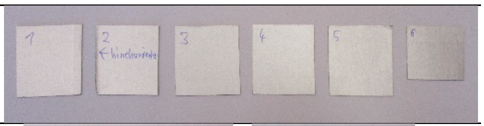
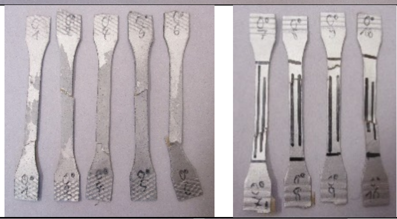
Figure A11. M12	
Figure A12. M13	
Figure A13. M14	
Figure A14. M15	
Figure A15. M16	
Figure A16. M17	
Figure A17. M18	

Figure M19	A18.	
Figure M20	A19.	
Figure M21	A20.	
Figure F01	A21.	
Figure F02	A22.