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Smart and Multifunctional Materials and their Possible Application in Façade Systems

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Abstract

Today's society needs to face challenging targets relating to environment and energy efficiency, and therefore the development of efficient façade systems is essential. Innovative concepts such as Adaptive Building Façades might play a role in the near future, as their dynamic behaviour could optimise the performance of a building. For their successful development, a balance between sophistication and benefit is necessary and the implementation of Smart and Multifunctional Materials in building envelopes could be the key, as they have the ability to repeatedly and reversibly change some of their functions, features, or behaviours over time in response to environmental conditions. However, these materials were predominantly developed for use in other fields, and there is a lack of specific technical information to evaluate their usefulness in façade engineering. The aim of this paper is to collect the critical information about promising responsive materials for use in the design of Adaptive Façades, in order to help designers and technicians in decision-making processes and to scope possible future applications in façades. Investigated materials were analysed from the Building Science standpoint; their weaknesses and threats in the built environment were highlighted, and their technical feasibility was examined through the study of their availability in the current market.

Keywords

responsive, autoreactive, intelligent, adaptive, design, innovation

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1 INTRODUCTION

Architecture and façade engineering are usually considered to be “conservative” fields in relation to the application of innovative materials. The complexity of requirements that they have to meet, as well as their interdisciplinary nature, make it difficult to achieve paradigm changes. However, new challenges, such as NZEB targets and low-carbon-based economies, put pressure on the development of new design approaches and strategies. Thus, the implementation of Smart and Multifunctional Materials might be more achievable than it may have seemed some years ago. These materials can respond reversibly and intelligently to changes in the surrounding environment without any external actuators, and this could be useful when designing adaptive, responsive, or intelligent façades, as the robustness of complex mechanisms is a critical issue (Loonen, Trčka, Cóstola, & Hensen, 2013).

Broadly speaking, the best known responsive materials are Smart Materials, highly engineered materials that can modify their function or behaviour (Addington & Schodek, 2005). Addington and Schodek (2005) distinguish two types of materials according to the way they react. Type 1 materials change in one or more properties in direct response to a variation in the surrounding environment. Some of these materials are already being applied in building technology, such as electrochromic windows (Addington & Schodek, 2005; Gavrilyuk, Tritthart, & Gey, 2007; Granqvist, 2014), which change their surface emissivity when there is a change in the voltage field (see Section 3). On the other hand, Type 2 materials react by transforming one energy form to an output energy in another form. For instance, electroactive materials transform electrical energy into mechanical energy and vice versa (Madden, 2008).

Additionally, some new composite materials also present multifunctional properties, as they were designed to have a desired multiple response, and are referred to as Multifunctional Materials (MM) in this paper. At this point, it is important to note that multi-ability, or multi-function, has a different denotation than the concept of adaptability, as different objectives can be fulfilled consecutively and not only concurrently (Loonen et al., 2013). Thus, MMs are non-homogenous materials in shape and/or composition, and if their anisotropy is properly controlled, they behave differently according to the external conditions (Reichert, Menges, & Correa, 2015). For example, thermobimetals comprise two sheets of differing metals alloys which, as they are laminated together, expand at different rates causing the bending of the component as a response to a temperature gradient (Adriaenssens et al., 2014; López, Rubio, Martín, Croxford, & Jackson, 2015). This bending could create various desired but not concurrent façade morphologies, and the different geometries might enhance the performance of a façade component. For instance, the cladding of a ventilated façade could be as closed as possible in the insulation mode (function 1) or have an open-joint configuration in the heating-dissipation mode (function 2) (Juaristi, Monge-Barrio, Sánchez-Ostiz, & Gómez-Acebo, 2018). Furthermore, in recent years, the development of complex software and innovative manufacturing processes allow for greater control of the structural composition of the materials, which make possible the design of multi-functional and multi-property elements. These materials, designed by computational techniques, are also known as Information Materials (Kretzer, 2017) but their possible application in façade technologies is still unclear and they were not addressed in this paper.

The general consensus about multi-functional or adaptive materials is that they are often too sophisticated and therefore expensive (Kretzer & Hovestadt, 2014), and that even so, their service life is too short. However, there is a lack of technical information to establish this assumption as true for each SM or MM. This paper studies not only the common characteristics of a material family, but goes further in the analysis of specific materials. It enables the detection of potential materials for the building industry and the determination of whether they would perform properly in façade applications. To foresee this possibility, first the possible roles of a material in a dynamic façade element were proposed and their design potential and limitation analysed (Section 3). Secondly, different properties predetermining the dynamic performance of the material were explained (Section 4) and, to conclude, the importance of knowing specific physical properties of these materials was highlighted and further areas of research were suggested (Section 5).

2 METHODOLOGY

This paper collected technical information about Smart and Multifunctional Materials applied not only in the façade industry but in any field, as long as their operational scenarios and scales of adaptability matched with façade requirements. The criterion for the inclusion of adaptive materials in this review was the operational scenario, the fatigue life, and their scale of adaptability (defined in Section 4), according to their possible roles (Section 3). For instance, thermochromic materials with potential uses in external claddings were only included when they perform at ambient temperature and when their fatigue life is longer than the service life of the façade element. When considering materials with kinetic responses to be applied in movable double skins, only materials with reactions of a magnitude of centimetres were considered.

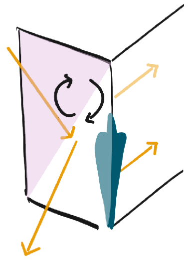
The results shown in this paper were obtained from scientific papers, Open Access Material Databases (materia,n.d.-a; Materiability, n.d.-a) and from market products information (Dynalloy, Inc., n.d.; Fraunhofer Institute for Applied Polymer Research IAP, n.d.; Kanthal, n.d.; LCRHallcrest, n.d.; QCR Solutions Corp, n.d.; Smart Films International, n.d.). Scientific papers were particularly interesting for identifying different adaptive materials and understanding their dynamic operation. However, when scoping possible innovative roles, online multidisciplinary databases and market available products were especially valuable as their information helped to analyse design potential and limitations.

3 POSSIBLE APPLICATION OF SM/MM IN ADAPTIVE FAÇADE ELEMENTS

3.1 SMART WINDOWS

The application of SM/MM in smart windows provide two types of dynamic performance: shading and climate control (Fig. 1). Those Smart Materials used for a shading reaction are the most developed and are mainly available in the market as part of window components (Addington & Schodek, 2005; Granqvist, 2014; Lampert, 2003; Mlyuka, Niklasson, & Granqvist, 2009). At the present time, these materials can be implemented as thin films (Gavrilyuk et al., 2007; Granqvist, 2014; Mlyuka et al., 2009; Seeboth, Ruhmann, & Mühling, 2010; Smart Films International, n.d.), directly in the glass using nanotechnology in the chemical composition (Granqvist, 2014; materia, n.d.-b; Seeboth et al., 2010) or as inks, pigments or dyes (QCR Solutions Corp, n.d.; Seeboth et al., 2010).

The main families of technologies that provide a shifting surface colour are electrochromics, thermochromics, and photochromics, and their differentiation factor is the input by which their response is activated. Electrochromics react to a change in the voltage field (Gavrilyuk et al., 2007; Granqvist, 2014); thermochromics change their colour at a set temperature (Kretzer, 2017; Ma & Zhu, 2009); and photochromics change when they are exposed to UV radiation (Zhang, Lee, Mascarenhas, & Deb, 2008). Similarly, in thermotropics, the change of the light scattering properties at certain operational temperatures is caused by a phase separation process at molecular level (Seeboth et al., 2010).

Possible Component	**Role**	**Material Family**	**Autorreactive facade element**	**Color**
 Smart Window	Self Shading	Electrochromics	A. film B. special chemical composition/ nanotechnology	BL / transparent W GR GR / transparent
		Thermochromic	A. film B. ink/pigments C. Dyes	BL BL GN BR GR PU / transparent R O PI GN B / transparent OC / transparent
		Photochromic	A. film	BL BL Y R GN GN O BR PU PI PI / transparent
		Thermotropic	A. film B. special chemical composition/ nanotechnology	GR BR BL Y GR BR GN BL B / transparent
	Heating effect	Thermoelectrical	A. film	transparent

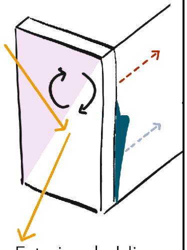
Legend

W	White	BL BL	Blue	BR BR	Brown	O	Orange	GN GN GN	Green	PU	Purple
B	Black	GR GR	Grey	OC	Ochre	Y	Yellow	PI PI	Pink	R	Red

FIG. 1 Responsive materials that could be used in smart window components and meaningful design features.

3.2 OPAQUE ADAPTIVE FAÇADE COMPONENTS

Even if the application of responsive materials in opaque façade components is less developed than in transparent façade components, there is a wide range of possible roles for which they could be used. Firstly, they could be used in exterior claddings to modify the surface temperature to optimally control the thermal performance of the outer skin (Ma & Zhu, 2009). Experimental assessments were made for materials that change their colour at a specific temperature (thermochromics), but as electrochromics or photochromics modify their solar heat radiation factor, this effect might also modify the surface temperature of façades, and therefore, their thermal performance. All of these materials are Smart Materials, which means that the available colour range depends on their chemical composition, and as there are, as yet, few chemical structures providing this responsive performance, there are few colour options for each material family (Fig. 2). Besides, most of the time these colours are vivid, which could be a challenge when applying them in some urban contexts. Anyway, to really evaluate the application of these materials in responsive façade elements, the holistic behaviour of the system needs to be considered, as it is illogical to try to collect solar thermal energy throughout the cladding if the envelope completely blocks thermal flux.

Possible Component	Role	Material Family	Autorreactive facade element	Color
 Exterior cladding	Temperature change (color switch)	Thermochromic	A. film B. ink/pigments C. Powder D. Plastic pellets E. Dyes	BL BL GN BR GR PU / transparent R O PI GN B / transparent OC / transparent
	Solar reflectance change (opacity switch)	Electrochromic	A. film	BL / transparent
		Photochromic	A. film	BL BL Y R GN GN O BR PU PI PI / transparent

Legend

W White	BL BL Blue	BR BR Brown	O Orange	GN GN GN Green	PU Purple
B Black	GR GR Grey	OC Ochre	Y Yellow	PI PI Pink	R Red

FIG. 2 Responsive materials that could be used in opaque exterior claddings and meaningful design features.

To tackle this problem, components made by SM or MM could be applied in the intermediate façade layer as embedded devices that control heat flow (Fig. 3). Phase change materials are good examples of responsive thermal control materials and, while they are no longer widely used in the building environment, the current scientific research is quite advanced and shows that they have high potential for reducing heating and cooling energy demand (Cabeza, Castell, Barreneche, De Gracia, & Fernández, 2011).

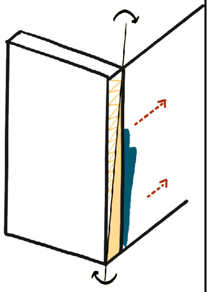
Possible Component	Role	Material Family	Autorreactive facade element	Color
 Intermediate Layer	Integrated thermal control	Thermoelectrical	A. device	irrelevant
		Phase Change Materials	A. intermediate layer B. device	W / transparent

FIG. 3 Responsive materials that could be used in intermediate layers and meaningful design features.

Lastly, interior cladding could also have an adaptive reaction that would be useful in controlling the hygrothermal conditions of the interior environment (Fig. 4). Materials that have high humidity absorption, such as natural porous materials or hydrogels, could be used not only to achieve a suitable level of humidity in the air, but also to cause an evaporative cooling effect (Markopoulou, 2015). This behaviour could be integrated directly in the material used in the interior surface (Maeda & Ishida, 2009; Watanabe, Fukumizu, & Ishida, 2008) or as devices (Raviv et al., 2014).

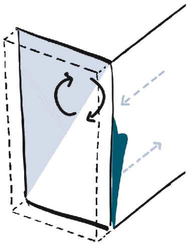
Possible Component	**Role**	**Material Family**	**Autorreactive facade element**	**Color**
 Interior cladding	Integrated hygrothermal control	Hydrothermally solidified soil bodies	A. Interior surface	BR GR W / customized
		Natural porous materials		They can be coated / painted
		Hydrogels	A. device B. surface	W / transparent

FIG. 4 Responsive materials that could be used in opaque interior claddings and meaningful design features.

3.3 MOVABLE OR KINETIC SKINS

Reactive materials with a kinetic or shape-changing ability might also have a broad field of application in movable skin façades (Fig. 5). The most developed role is shading, as these materials modify their dimension when an external stimulus exists, such as temperature rise or solar radiation incidence. They could trigger the motion of the outer skin when they are incorporated in the external surface (Adriaenssens et al., 2014; Fiorito et al., 2016), when they are placed at joints, or as external actuators in flexible components. There are already some built examples (Laughlin & Howes, 2012), however, mechanical actuators are more widely used than those that are embedded in materials (Loonen et al., 2013).

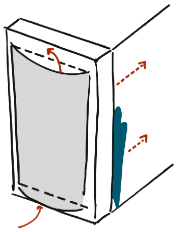
Possible Component	**Role**	**Material Family**	**Autorreactive facade element**	**Material´s finish**
 Movable double skin	(1) Enhance / block thermal dissipation (2) Auto-reactive air dampers (3) Automatic shading devices	Electroactive polymers	A. surface B. actuator	transparent
		Thermobimetals	A. surface B. actuator C. joint	metal
		Shape Memory Alloy		
		Heat sensitive plastics		miscellaneous
		Light responsive polymer		
		Shape Memory Polymers		
		Shape memory Hybrids		
	(1) Enhance / block thermal dissipation (2) Auto-reactive air dampers	Natural Hygromorphs	A. surface B. actuator C. joint	wooden
		Hygromorph bi-layer composites		
		Hygromorph Bio-composites		-
		Synthetic Composites	A. actuator B. joint	-
		Hydrogels		white/ transparent gel
	Auto-reactive air dampers	CO2 Responsive Polymers	A. actuator B. joint	-

FIG. 5 Responsive materials that could be used in movable double skins and meaningful design features.

Furthermore, materials that modify their dimensions in reaction to different inputs could be used to provide automatic ventilation, as was demonstrated in a functional prototype which responded to humidity (Reichert et al., 2015). Although several materials with a kinetic response were found in the literature review, such as CO2 responsive polymers (Lin & Theato, 2013), hydrogel actuators (Markopoulou, 2015), or materials responding to temperature changes (Adriaenssens et al., 2014; Fiorito et al., 2016; López et al., 2015), their possible façade performance was not explored. Even so, their potential to provide automatic ventilation according to these environmental inputs looks promising. The main drawback of these possible new roles is that if responses were self-induced, it would make it impossible to override adaptation in contrast with the electrical input. For that reason, climate and use conditions should be considered with an overall perspective to determine if the construction of auto-reactive air dampers would be suitable for energy and comfort requirements.

Lastly, these kinds of materials could also enhance the thermal behaviour of ventilated opaque façades (Juaristi et al., 2018). They could open or close the air cavity between the outer and inner skin depending on the exterior temperatures and wind conditions. The convective movements occurring in the cavity could be enhanced or blocked to control thermal dissipation.

3.4 DESIGN POTENTIAL AND LIMITATIONS

One of the most challenging tasks when trying to face the dissemination gap between different scientific fields and façade engineering was to learn *how* these materials look. Each sector has its application scale, roles, and restrictions, and usually, SMs and MMs are manufactured in such a way that they are not adequate for the built environment, making it even harder to envision their potential new uses. In order to boost the implementation of innovative materials in façades, technology applicators need to understand the determining factors of each material and the detection of the following design parameters is essential:

- Available colours (Fig. 1 - Fig. 5)
- Possible geometries due to material family and type of façade elements (Fig. 1 - Fig. 5)
- Thickness
- Width
- Length
- Assembly method
- Manufacture process

Such information was found for electrochromics (Granqvist, 2014; Smart Films International, n.d.), thermochromics (materia, n.d.-b; Materiability,n.d.-b; Mlyuka et al., 2009; QCR Solutions Corp, n.d.; Smart Films International, n.d.), photochromics (LCRHallcrest, n.d.; Reichert et al., 2015), thermotropics (Seeboth et al., 2010), shape memory alloys (Dynalloy, Inc.; Fiorito et al., 2016; Madden, 2008), electroactive polymers (Fiorito et al., 2016; Jiang, Kelch, & Lendlein, 2006; Madden, 2008; Markopoulou, 2015; Samatham, Kim, & Dogruer, 2007) and hydrogels (Materiability, n.d.-c), as they are currently commercialised products and manufacturers provide useful information for design considerations. Besides, materials belonging to the same product family usually have some similar characteristics, especially regarding the possible geometries. For instance, thermochromics and electrochromics come mainly as rectangular rolls and sheets (materia, n.d.-b; Smart Films International, n.d.), whereas self-shaping materials are most often manufactured as strips (Dynalloy, Inc., n.d.; Kanthal, n.d.; Materiability, n.d.-d; Fiorito et al., 2016; Jiang et al., 2006), wires (Dynalloy, Inc., n.d.; Fiorito et al., 2016), beams (Adriaenssens et al., 2014) and sheets (Fiorito et al., 2016; Samatham et al., 2007).

Little information was found in relation to assembly methods and manufacture process, and more research should be undertaken to get this information, which would be necessary in order to foresee more design options beyond those commercially available.

4 DYNAMIC OPERATION AND ADAPTIVE MATERIALS

When classifying Smart and Multifunctional Materials in families, the common feature is the dynamic operation that they are able to provide (Addington & Schodek, 2005). Accordingly, in this section, we detected and grouped specific materials and studied the relevant properties that enable an understanding of their adaptive performance. Based on the parameters that Loonen et al. established as key factors for climate responsive façade elements, it is essential to find accurate information about the mechanism of actuation of each material, the range and velocity of adaptation, the type of control, the operational scenario and their fatigue life (Loonen et al., 2013).

4.1 CONTROL OF VISIBLE LIGHT AND SOLAR TRANSMITTANCE. REVERSIBLE COLOUR CHANGE

Responsive materials can enhance thermal performance and/or daylight by switching visible transmittance and/or solar heat gain coefficient. Nowadays, there are several electrochromic, thermochromic, photochromic, and thermotropic products available on the market, mainly for smart windows. Fig. 6 shows visible transmittance and solar transmittance range for some of these products. Colour is of great importance, as the lighter it is, the more daylight is provided and the less solar transmittance is blocked. If the purpose of the material is to boost indoor natural light, the use of some of these electrochromic products is questionable, as their highest value doesn't reach 40% visible light transmission. Indeed, if the aim is to control thermal performance, then solar transmittance is the key parameter to look at in this graph.

Furthermore, when applying electrochromic materials, a balance should exist between the required electrical current and the obtained energy saving; oxide films look like a promising solution to meet this purpose (Fig. 7). Finally, some commercialised thermochromics (QCR Solutions Corp, n.d.; Smart Films International, n.d.) and photochromics (LCRHallcrest, n.d.) that are available on the market don't have a suitable life-span for façade engineering, as UV degrades them quickly. The reason why this does not happen in switchable windows may be due to the fact that the glass blocks the majority of UV radiation, which could extend the service life of the component.

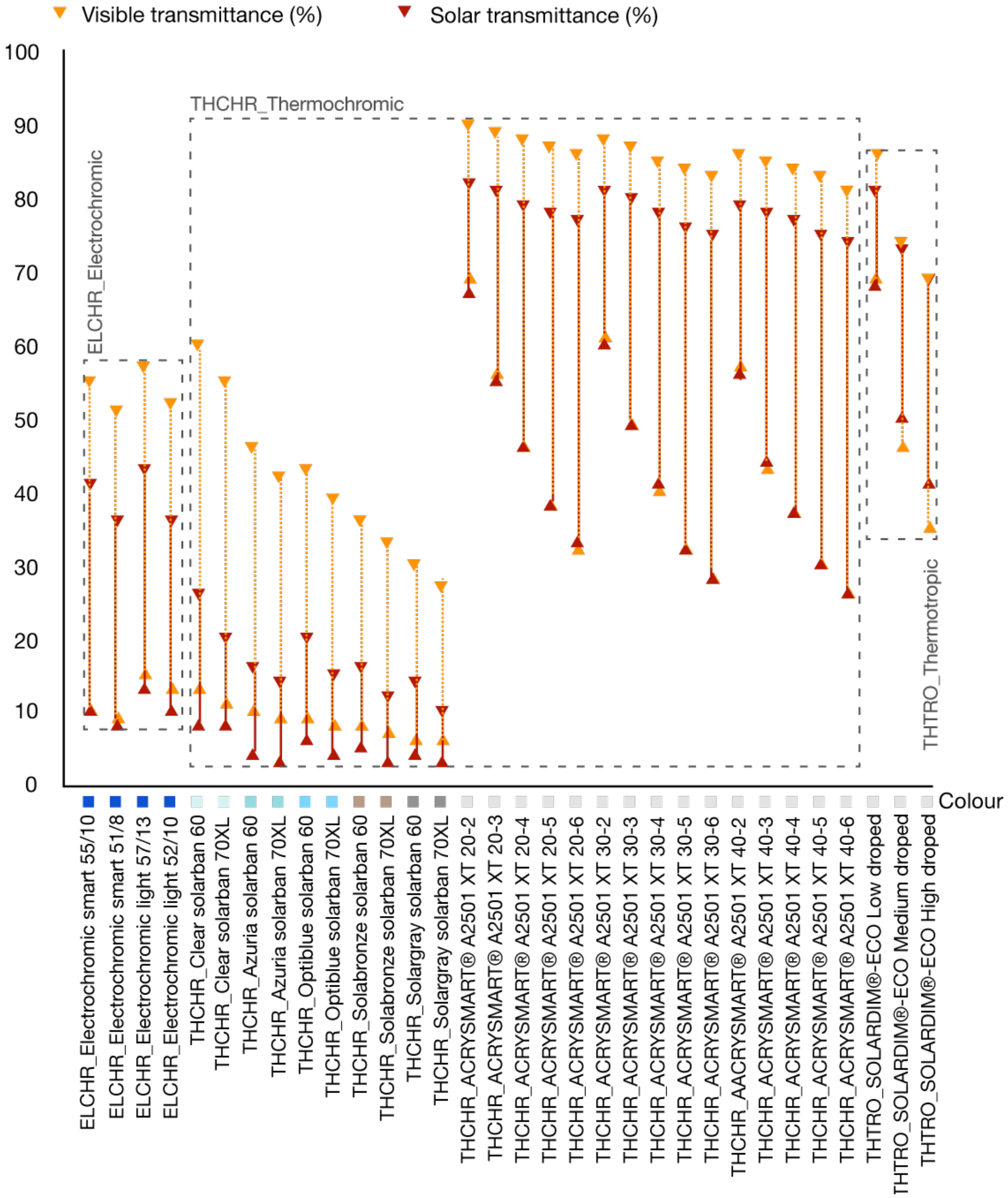


FIG. 6 Visible transmittance and solar transmittance of some electrochromic, thermochromic, and thermotropic products available on the market

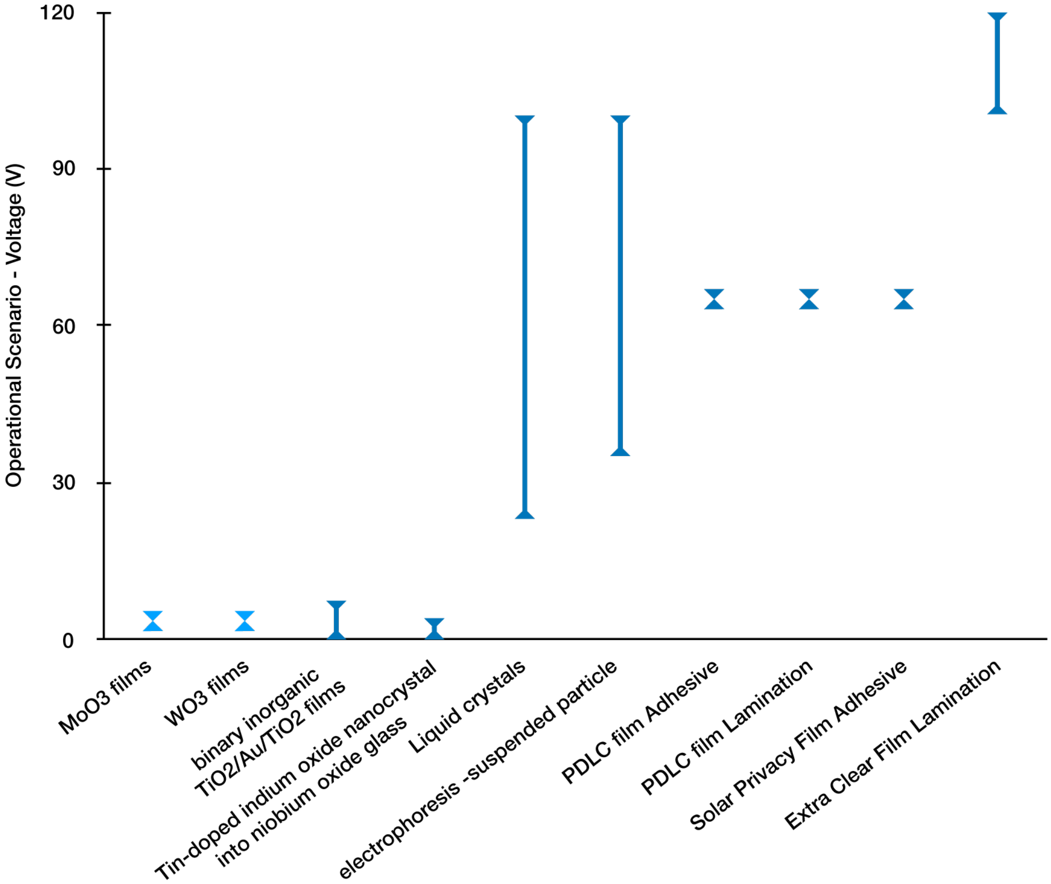


FIG. 7 Required voltage to activate some meaningful electrochromic materials

4.2 REVERSIBLE HEAT FLOW DIRECTION

Thermoelectrical materials, such as Bi2Te3 based compositions, create a hot and cold junction when an electrical input is applied and a temperature difference occurs between the two faces of the material as a result. If these materials were applied in façades, the direction of thermal flux could be controlled to obtain the desired effect (the enhancement of energy exchange or the insulation) (Addington & Schodek, 2005; Ibañez-Puy, Bermejo-Busto, Martín-Gómez, Vidaurre-Arbizu, & Sacristán-Fernández, 2017).

4.3 ELECTRICALLY ACTIVATED MECHANICAL DISPLACEMENT (AND THE CONVERSE)

Electroactive materials, also known as piezoelectric materials, can produce a mechanical displacement when an electrical current is applied and conversely, the material can produce an electrical signal when a mechanical displacement occurs, as molecular structures are electrically polarised when a stress force is applied to the material (Kornbluh, 2008; Madden, 2008; Samatham et al., 2007). This could be applied in kinetic façade components, and there are already some built examples, such as the ShapeShift project, which employed a silicone- and acrylic-based dielectric elastomer to trigger the motion of the skin (Rossi, Augustynowicz, Georgakopoulou, & Sixt, n.d.).

The determinant property when analysing the suitability of these materials for innovative adaptive façade system application was the required electrical current (control) to achieve a reversible deformation (quantitative value of the response). From Fig. 8, it can be seen that a large amount of energy is necessary to produce a meaningful shrinkage deformation, which makes questionable the use of piezoelectric and electroactive polymers if the aim is to reduce the energy demand of the building.

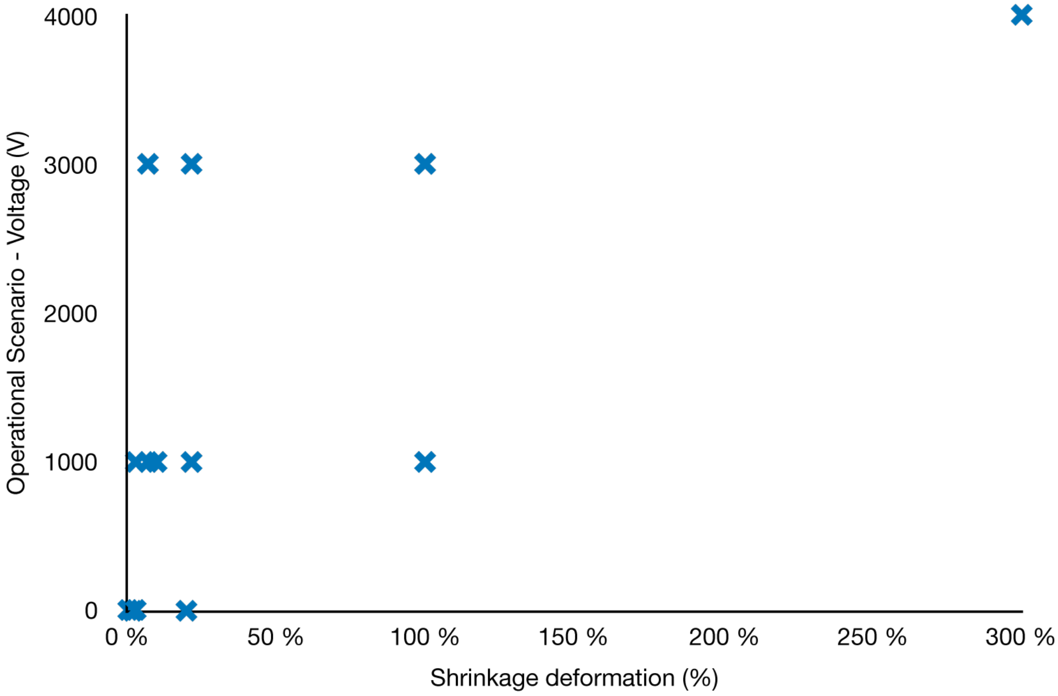


FIG. 8 Required electrical current to achieve certain level of shrinkage deformation for some electroactive materials

4.4 REVERSIBLE EXPANSION AND POSSIBLE BENDING

Electroactive polymers can also reversibly bend due to the electrical charges. The current generates the attraction of the opposing charges and the repelling forces between equal charges, and as a result, the thickness of the polymer contracts while it expands in length. Moreover, there are several materials that could provide this bending reaction, for instance, shape memory polymers and shape memory alloys reversibly change their shape (in one or more directions) when they reach an operational temperature; this is due to thermal-elastic transformations at molecular levels.

Apart from the aforementioned Smart Materials, there are some Multifunctional Materials that were designed to achieve the desired bending under specific environmental conditions (Table 1). Thermobimetals, for example, are composed of two metal sheets that have different coefficients of thermal linear expansion, which makes the composite material bend when it is exposed to a temperature gradient (Adriaenssens et al., 2014). Bi-layer hygromorph composites are also based on the same principle, but their differences in the coefficient of linear expansion are based on their capacity to absorb ambient humidity (Reichert et al., 2015).

SMART MATERIAL FAMILY	SPECIFIC MATERIAL	MULTIFUNCTIONAL MATERIAL FAMILY	SPECIFIC MATERIAL
Electroactive Polymers	Silicone and acrylic based dielectric elastomer(Rossi et al., n.d.), Polyvinylidene fluoride (PVDF) (Madden, 2008)	Thermobimetal	ASTM TM2 bimetal, Ni-Fe alloy (Adriaenssens et al., 2014) (containing 41%, 37% and 36% Nickel) (Kanthal, n.d.)
Shape Memory Polymers	Polymer Resin Systems, Polystyrene (Markopoulou, 2015; materia, n.d.-b; MatWeb Material Property Data, n.d.), Composite from multiple photocurable Methacrylate based copolymer network (Ge et al., 2016)	Hygromorphs	Bi-layer composites Ex. Composite mixture of glass fibre, epoxy bonding and Maple wood (Reichert et al., 2015)
Shape Memory Alloy	Ni-Ti alloy (55%-56% Nickel and 44%-45% Titanium) (Dynalloy, Inc., n.d.; Madden, 2008)		

TABLE 1 Autoreactive materials which have the ability to reversibly expand and bend

For the consideration of their possible application in façade engineering, the main restriction was their adaptability range. In the reviewed literature, we found several materials in other fields that change their shape by bending, but as we already explained in Section 2, we only compiled those that deformed by at least at a centimetre.

4.5 MOISTURE ABSORPTION

Hydrogels (Table 2) are well-known hygro-expansive materials, as they have the ability to dramatically increase their volume when they absorb moisture (Raviv et al., 2014). They could constitute actuator devices for kinetic façades that aim to respond to humidity variations, which might have some benefits in the hygrothermal performance (Markopoulou, 2015).

SMART MATERIAL FAMILY	SPECIFIC SMART MATERIAL	MULTIFUNCTIONAL MATERIAL FAMILY	SPECIFIC MULTIFUNCTIONAL MATERIAL
Hydrogel	Hydrophilic UV curable polymer(Raviv et al., 2014), Polymers of hydroxyethyl, Insoluble polymers of acrylate, Insoluble polymers of acrylamide, Insoluble polymers of polyethylene oxide(Markopoulou, 2015)	Hydrothermally solidified soil bodies	Sepiolite clay, Allophane (Emile, 2002; Watanabe et al., 2008), Earth ceramics
		Natural Porous materials	Cedar (Emile, 2002), Silica gel, Mixture of gibbsite and clay material(Watanabe et al., 2008), Mesoporous material derived from kaolinite, Mesoporous material derived from metakaolinite(Maeda & Ishida, 2009)

TABLE 2 Autoreactive materials triggered by ambient humidity

In addition, the academic literature on moisture absorption and passive cooling has revealed the emergence of new multifunctional materials that could control the hygrothermal conditions of the indoor environment (Maeda & Ishida, 2009; Watanabe et al., 2008). Inspired by the suitable performance of natural porous materials in humid and hot climate conditions, hydrothermally solidified soil bodies were developed in such a way that the porosity of their micro-structure could enable the self-regulation of the water content in the surrounding air through capillary condensation. However, as far as the authors know, there are no experimental validations that prove this assessment and they should be instigated in order to discover the potential of these promising multifunctional materials for their application on interior claddings.

5 DISCUSSION AND CONCLUSION

5.1 MEANINGFUL PHYSICAL PROPERTIES

Adequate performance of the façade must be ensured by each element of the system. SMs and MMs need to provide a suitable adaptive reaction while accomplishing traditional façade requirements regarding safety, economy, and comfort. Furthermore, materials need to behave optimally during their whole service-life. The physical properties of such materials determine whether they can perform properly in the proposed role. For instance, some of these materials might be required to fulfil structural performances, so their structural properties, such as compressive strength, bending strength, or elastic modulus need to be appropriate. If they were to perform kinetic work, then performed work, elastic modulus, and fatigue life would be fundamental. Finally, depending on their position in the façade system and the relationships with the other building materials, fire resistance and fire containment, rain and water-vapour resistance, thermal properties, and fenestration properties would be required.

Nevertheless, as we are not expecting the same behaviour for a coating and for a metal sheet, firstly, the material family needs to be detected, so that we can determine what kind of performance can be demanded from a particular type of material. After that, according to their performance in the whole façade system, specific properties are sought. In general, commercially available adaptive façade materials provided the meaningful physical properties in their data-sheets, but when analysing materials used in other fields, it was not possible to find out this technical information.

5.2 TOWARDS PROMISING NEW ROLES

Most of the Smart and Multifunctional Materials shown in this paper were sophisticated raw materials, highly engineered or designed. However, they could be used to develop simple façade products as, by applying them, it wouldn't be necessary to make intricate details including complex electronics or mechanical actuators. Still, there are few examples in architecture that include Smart or Multifunctional Materials, and even fewer built façades. Thus, it was difficult to get accurate, essential technical information regarding specific façade requirements and meaningful dynamic operation parameters. Nowadays, smart glazing is technologically the most advanced and new roles beyond are yet to be explored. Moreover, a wide variety of Multifunctional Materials could be created, inspired by promising reactions of Smart Materials. As their complexity comes mainly from the design process instead of their raw material availability or engineering process, overcoming this intellectual challenge could inspire a great opportunity to achieve new functionalities in architecture.

5.3 FURTHER RESEARCH

Overall, more experimental assessments are needed in order to get indispensable information regarding design characteristics, dynamic operation, and physical properties, as, so far, only a few responsive materials available in the building industry make their technical information available. Furthermore, assessments should be done at building scale, as these materials might behave unexpectedly and the value of their reaction might be non-linear at different scales (Kolarevic, 2014). Last but not least, more information on suitable operational scenarios and optimal scales of adaptability would help us to establish a greater degree of accuracy on this matter.

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