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Permanent Materials in the framework of the *Circular Economy* concept: review of existing literature and definitions, and classification of glass as a Permanent Material

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1. Introduction

In recent years the policy makers are increasingly involved in defining strategies, political and legal actions to implement and enforce the concepts of *Sustainable Development* and *Circular Economy*, in order to ensure a future where the challenges of resource scarcity, environment pollution, climate change, etc can be kept under control, or even overcome.

In the framework of such legislations, a "responsible" management of resources must be promoted by minimizing the waste streams sent to landfill disposal and incineration, and by preferential usage of resources that are effectively *renewable* or indefinitely *recyclable* over time.

Renewable resources already have a well established definition, and have been extensively covered by scientific literature, international standards and national and worldwide legislation. On the contrary, for materials infinitely recyclable in a closed loop, without loss of quality or appreciable need of integration of new resources in the recycling process, an equally well established definition does not exist, even though in recent years the name "permanent materials" is starting to emerge and to be used in official documents, marketing campaigns, international standards, etc.

The aim of this study is to collect information from the most relevant and recent documents concerning permanent materials published as of today, and to review critically their definitions. A synthetic assessment of the permanent quality of soda-lime glass according to such definitions will also be carried out.

2. Review of the existing definitions of permanent materials

The first mention of the term Permanent Materials in European legislation dates back to 2012, when in a resolution for a *Resource Efficient Europe* the following words were used: *"… whereas a future holistic resource policy should no longer merely distinguish between 'renewable' and 'non-renewable' resources, but should also extend to* ***permanent materials****…"*

In the text no explicit definition of the concept was given, probably because it was deemed self-evident, at least in its broadest meaning; since then, no harmonized definition has been proposed yet at any legislative or official level.

In recent years, several international (but non-legislative) documents have dealt with the concept of Permanent Materials, proposing their own definitions of the term and developing critics and assessments over the classification of existing materials in the light of this new category. Among the most recent and relevant documents published on the subject, the following two were taken into consideration for the present study:

- *British standard BS 8905:2011 "Framework for the assessment of the sustainable use of materials – Guidance"*, the first document to ever propose a definition of Permanent Materials;
- *Carbotech Final Report 2014 "Permanent materials, scientific background".*

2.1 British standard BS 8905:2011 : "Framework for the assessment of the sustainable use of materials – Guidance"

The British standard BS 8905:2011, titled *Framework for the assessment of the sustainable use of materials – Guidance*, sets the guidelines for the sustainability assessment of materials usage throughout the production chain, from suppliers to end users.

In extreme synthesis, the standard describes a series of procedures that could support designers and other stakeholders in making well grounded decisions regarding the selection of the optimal material for a certain application or product, taking into account both the social, economic and environmental aspects of resource sustainability.

Before entering into detailed descriptions of the algorithms for evaluating the impact of every step of the materials life cycle (sourcing, manufacture, service life, end of life, etc), for drawing cross comparisons between different solutions, etc, the standard sets the definitions for several properties of materials, among which the "permanent" quality is found. The following definition is reported in section B2, dealing with material sourcing (page 20):

> ***Permanently available materials*** *are those for which efforts are made to retain for use in society the energy and raw materials invested in their production at the end of the product life, either through reuse or recycling, with no loss of quality no matter how many times the material is recycled. »*

From a *Sustainable Development* point of view, the first three lines of this definition might (and should) actually apply also to every material within the framework of the *Circular Economy*, because no waste of energy or resource is to be tolerated, and recycling, even if possible only partially or with loss of quality (down-cycling), is always to be promoted.

The key feature of *Permanent Materials* is mentioned in the last dozen of words of the definition, "with no loss of quality no matter how many times the material is recycled": indeed, what renders permanent some types of recyclable materials is their capability of being recycled over and over again without loss of intrinsic properties or quality, potentially allowing completely closed loop recycling of products (e.g. glass bottles to glass bottles) without the need of integration of new raw materials.

However, this definition could be improved from several points of view:

- firstly, a clearer distinction between permanent and non permanent materials could be achieved if the definition also covered the chemical, thermodynamic and micro-structural features that render “permanent” a material, that is that allow endless same-quality-recyclability;
- secondly, the definition should also take into consideration the application of the material, especially for what concerns its availability for recycling after service life (e.g. aluminum used in cans can be recovered, but aluminum used in explosives cannot).
- Moreover, an explicit mention of the fact that permanent materials in principle do not require addition of new primary raw materials at each recycling step in order to maintain the same quality level would be beneficial in highlighting the core benefit of their exploitation.
- Finally, a useful addition to the definition given by the standard BS 8905:2011 would be a distinction between potentially permanent materials, that is materials whose intrinsic chemical features can allow endless closed-loop recyclability, and effectively permanent materials, that is potentially permanent materials for which separate collection of wastes, sorting and reprocessing technologies are already sufficiently developed end established to allow feasible closed-loop recycling.

2.2 Carbotech Final Report 2014: “Permanent materials; scientific background”

Carbotech is a research and consulting company that carried out an in depth study on the concept of Permanent Materials, to build a better scientific ground for its definition.

The study proposes different synthetic definitions depending on the scientific skill of the recipients, enhancing the possibility of achieving a straight, clear and precise communication at every level.

In particular, two definitions are given for Permanent Materials (**PeM** acronym in the text):

> *“**Explanatory definition**: A permanent material is one for which the inherent properties do not change during use, regardless of repeated recycling into new products. Its recycling does not necessarily require the addition of primary material or additive to enable the basic material function / properties”*

> *"**Scientific definition**: A material is defined as permanent if its inherent properties do not change during use, and through solid-liquid transformation it can revert to its original state. This is the case when the material consists of basic component, which are either chemical elements or robust chemical compounds, making repeated use and recycling possible without change of inherent material properties"*

The explanatory definition centers its target of being easily understandable by anyone, people lacking a scientific background included, and of taking into consideration the cornerstone features of permanent materials, which are the endless recyclability without loss of quality and the no need of integration (at least in principle) of primary resources for successful same-quality-level-recycling. Moreover, it also explicitly state that PeM's must not suffer a degradation of their intrinsic / inherent properties during service life.

The scientific definition provides a more technical qualification of Permanent Materials, even though some points remain not perfectly clear: for example, the "robustness" of chemical compounds can hardly be considered a clearly identified and measurable physico-chemical property, upon which discriminating the permanent quality of a material.

The study by Carbotech explicitly acknowledges that chemical features alone do not enable a material to be automatically considered permanent, but a series of other conditions must also be respected. First of all, the specific application is crucial, in that it must allow the recovery of the material for recycling purposes after its service life: for ex. Al, is generally permanent when used for containers or in mechanical engineering, but it is not when used in explosives.

Moreover, even if the application is suitable, a series of other requirements are still necessary for an effective translation of chemical permanency into an industrial reality, namely: compliance of the specific use to the relevant legislation; existence of suitable collection, separation, treatment, etc. technologies and facilities; and positive contribution of the recycling process to sustainable development from the economic, ecologic and social points of view. All these aspects are summarized together by Carbotech into the single term "material *Stewardship*".

Therefore, two tiers of material permanency are introduced: mere chemical permanency, depending only on the intrinsic nature of the material (i.e. type and strength of bonds, microstructure, etc) and addressed with the acronym of *PeM* ("Permanent Materials"), and effective, practical permanency from the Sustainable Development point of view, addressed as *CPeM* ("Concept of Permanent Materials"), and requiring both chemical permanency and material *Stewardship*.

The following materials and relative applications are reported to be CPeM by Carbotech: Aluminiun (motors, cans, windows frames); steel (stainless steel, galvanized steel, tin cans); glass (bottles); copper (construction, electrical and communication; electronics); Manganese (die-cast). On the contrary, the following materials are not considered CPeM: aluminum when used in explosives; paper and cardboard; natural fibers (cotton, silk, wool); wood; thermoplastic and thermoset polymers.

3. Fundamental features of Permanent Materials

The definitions of "Permanent Materials" reported in both the documents reviewed in Section 2 introduced some piece of valuable insight on the concept of permanency, highlighting the fundamental features that a material must possess to be part of this new category.

In particular, in order to be considered effectively ***Permanent***, a material:

- must **not degrade during service life**, at least not up to the point of compromising its original functions.
- must allow **endless recycling without degradation** of intrinsic/inherent properties; in an implicit way, this statement comprises also the following two derived features:
  - must allow **same-quality-level recycling**, that is recycling of old products to manufacture new products of the same type of the original, or whose quality still potentially allows at a later stage the recycling into the original form; e.g. used glass bottles crushed into cullet and molten to produce new bottles, or jars, or goblets, etc.
  - must allow completely **closed-loop recycling**, i.e. in principle it does not require addition of primary raw materials at each reprocessing step to enable the recycling into products of the same quality level; e.g. aluminum cans can be melted to produce recycled aluminum sheets (which can later be formed into new cans) without need of primary aluminum integration.
- must be **available for recycling after service life**, which in turn implies that:
  - suitable technologies must exist for its effective recycling, especially including the removal of external impurities;
  - suitable and widespread facilities must exist for the separate collection of wastes or for the sorting of mixed waste streams.
- must give a **positive contribution to Sustainable Development** (e.g. resource savings, energy savings, less gaseous emissions, etc) through its **industrial scale recycling process**.
- the usage of the material, its recycling process and its eventual disposal (to be avoided as much as possible) all **comply with the existing legislation**.

If all the aforementioned conditions are respected, the material can actually be considered Permanent, and its usage should be encouraged in all the suitable applications, in order to achieve the maximum advantages from its specific positive features.

4. Glass as a Permanent Material

Taking into consideration all the fundamental features detailed in the preceding section, glass probably represents one of the best examples of Permanent Materials nowadays in use, thanks to its intrinsic physic-chemical and structural properties, to the material "Stewardship" already established, to the maturity of the recycling chain (separate collection, treatment, supply), to the awareness of the consumers regarding its endless recycling potential, etc.

4.1 Glass as a Permanent Material - Chemical and Structural Properties

From the structural and chemical point of view, soda-lime glass is constituted by a disordered tridimensional highly interconnected silicate network, whose basic unit is the SiO_4^{4-} tetrahedron: 4 atoms of Oxygen (O) placed at the 4 vertexes of a tetrahedron, bonded to a central atom of Silicon (Si).

These tetrahedrons are connected to each other by their vertexes, which means that most Oxygen atoms are shared between two contiguous tetrahedra, forming Si─O─Si bonds, and are for this reason named "bridging Oxygens". The presence of alkali ions such as Na^+ and K^+ in the composition of soda-lime glasses modifies the network, breaking locally its continuity and creating several $Si─O^-\cdots M^+$ bonds, i.e. "non bridging Oxygens"; the presence of alkali earth ions such as Ca^{2+} and Mg^{2+} has similar, but less disrupting effect. The relative spatial distribution of the SiO_4^{4-}tetrahedra and of modifier cations in the tridimensional network does not exhibit any long range order, therefore the material is not crystalline, but is amorphous.

The very high degree of interconnection between tetrahedra, the great majority of bridging Oxygens with respect to non bridging ones, the strength of the Si─O bonds, etc render soda-lime glass an highly inert material, that **does not undergo any appreciable degradation during normal service life**.

Soda-lime glass is produced by high temperature (T > 1450°C) melting of a mixture of primary raw materials (quartz sand, soda ash, limestone, dolomite, sodium sulfate, etc) and secondary raw materials (glass cullet, glassy sand, recycled filter dust, etc); in its molten state, glass is still made up of SiO_4^{4-}tetrahedra connected to each other, even though, compared to its solidified state, the network is fragmented into smaller, more linear and less interconnected domains, which explains the less viscous, but still honey-like (viscosity around 100 - 1000 poises) nature of glass in its molten form. Upon cooling down, the silicate chains spontaneously bond again to each other, rebuilding the interconnected tridimensional network of solid glass without any need of external intervention, addition or catalysis.

The capability of the network to be partially fragmented during the melting phase (or re-melting in case of glass cullet), and then to spontaneously reform again in a completely reversible way is one of the features that render glass a *Permanent Material*, allowing **endless recycling without any loss of intrinsic properties or quality**. In fact, thanks to the strength and stability of the Si—O bonds, the network does not undergo any permanent thermodynamic change upon re-melting, that is it receives no "damage" that cannot be spontaneously "healed" during the cooling phase.

This is a radical difference, for example, with respect to polymers: also thermoplastics can indeed be re-melted by simply raising their temperature above a suitable value, which brakes the **inter**-molecular Van der Waals bonds between macromolecular chains and reduces the viscosity of the material to ranges suitable for new forming; but the process introduces also permanent damages to the macromolecular chains themselves, reducing their average length due to irreversible cracking of **intra**-molecular bonds (e.g. C—C bonds).

This in turn reduces the performances of the recycled material, closely linked to the average molecular weight of its chains, substantially preventing direct same-quality-level recyclability for polymers; on the other hand, restoring these bonds to "repair" the macromolecules would imply a re-polymerization reaction, that would require the addition of new monomers and catalysts in suitable temperature and pressure conditions, and this would violate the requirement of "no need of primary raw materials addition", again barring for polymers the classification into the Permanent Materials category.

On the contrary, used glass bottles can be recycled into new glass bottles in a **closed loop**, with absolutely **no need of integration of primary raw materials**, at least from the **thermodynamic point of view**: the transformation can be viewed as a reduction of viscosity caused by high temperature heating (re-melting), followed by a shaping step accompanied by a controlled increase of viscosity back to the original values (forming and annealing). All these processes take place without degradation of the intrinsic structure of the material and without appreciable loss of mass, so the whole recycling is completely reversible from the theoretical point of view, and thus supports the inclusion of soda-lime glass into the category of **Permanent Materials**.

A very similar argument could be developed in principle also for most metals, whose solid crystalline lattice and microstructure are destroyed during the melting step of the recycling process, but are then either spontaneously rebuilt in the same original fashion upon solidification, or can be obtained back from the direct solidification structure through suitable thermo-mechanical treatments, without addition of new raw materials.

4.2 Glass as a Permanent Material - Material Stewardship

In Europe soda-lime container glass ***Stewardship*** is nowadays a well established reality, thanks to the joint efforts made in the past decades by the European Union, Member States, glass producers, cullet producers, machinery suppliers, Education, Media, etc, down to beverage final consumers:

- Separate collection of waste has been intensively promoted by Media, in Schools, by Municipal Solid Waste management companies, etc, therefore at present used glass containers are **easily available for recycling** all over Europe.
- The existing **technologies** for wastes **sorting** and subsequent **elimination of impurities** like ferrous and non-ferrous metals, organic matter, ceramics, Lead crystal glass, glass-ceramics, etc are quite **mature**, and capable of producing “furnace-ready” glass cullet of good quality with good efficiency.
- Recycling of glass cullet produces **great benefits for the environment**, since it reduces the exploitation of non-renewable mineral resources, the emissions of CO_2 into the atmosphere by carbonated primary raw materials, the energy consumption for the melting process (and thus CO_2 emissions by fuel burning and electrical energy production), the use of landfills, etc.

Based on FEVE data, in some Member States like Denmark, Sweden or Belgium, the recycling rates for container glass have surpassed the 95% level, that is **industrial closed loop recycling has been practically achieved** at the national scale. This demonstrates that, if proper measures are undertaken by all the stakeholders of the glass production and recycling chain, from common citizens to policy-makers, glass can translate its intrinsic Permanent quality (from the chemical and structural point of view) into a practical, industrial reality, rendering **soda-lime glass containers** completely **compliant** with the concepts of **Sustainable Development**, **resource Stewardship and Circular Economy**.

5. Conclusions and Future Developments

The capability of being endlessly recycled without loss of inherent properties or quality which characterizes Permanent Materials is a paramount asset for *Sustainable Development*, since it allows to greatly reduce the rate at which non-renewable resources are extracted and depleted from the Earth’s Crust, and minimizes the exploitation of landfills for final disposal of wastes.

In recent years, several international (but non-legislative) documents have dealt with the concept of Permanent Materials, proposing their own definitions of the term and developing critics and assessments over the classification of existing materials in the light of this new category.

On the basis of such definitions, to be considered Permanent a material must possess a series of suitable chemical and structural features, that render it non-degradable neither during service life, nor during recycling processes; moreover, to translate this intrinsic potential for Permanency into an industrial reality, a suitable material *Stewardship* must also exist, that is the available technologies, facilities, legislation and social background must enable an efficient closed-loop recycling.

Taking into consideration the available definitions, glass probably represents one of the best examples of Permanent Materials nowadays in use, thanks to its intrinsic physic-chemical and structural properties, to the material "Stewardship" already established, to the maturity of the recycling chain (separate collection, treatment, supply), to the awareness of the consumers regarding its endless recycling potential, etc.

As a final remark, it may be worth noting that the definitions of "*Permanent Material*" available at present are all quite close to each other, but they are not completely identical; therefore, the formulation of a unique, clear and comprehensive definition might be a very important step for the worldwide acknowledgment of this new categorization.

Moreover, fostering a cross-sector technical and scientific debate over Permanent Materials, their definitions, the identification and quantification of their distinctive features, the evaluation of their potential contribution to Sustainable Development, etc would be a perfect head start in spreading awareness on this relatively new concept .

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