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REVIEW ON THE POST–CONSUMER PLASTIC WASTE RECYCLING PRACTICES AND USE THEIR PRODUCTS INTO SEVERAL INDUSTRIAL APPLICATIONS

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Abstract: The global plastic production has increased immensely during the last decades and the plastics have become an essential part of our modern lifestyle. This has contributed greatly to the increasing quantity of plastic–related waste. Numerous plastic waste materials are generated both from production and from the population, plus a few other special waste streams, such as packaging. The increasing awareness about the environment has tremendously contributed to the concerns related with disposal of the generated wastes. Reuse of waste and recycled plastic materials in several application as an environmental friendly by–products has drawn attention of researchers in recent times, and a large number of studies reporting new developments in this area. This paper presents a conceptual overview related to the plastic products categories (easily recyclable and rarely recyclable plastics), plastic materials recycling (mechanical recycling, chemical mechanical recycling and energy recovery), and recycling of the post–consumer plastic waste. Also, the paper presents the most important applications of the recycled plastic materials.
Keywords: plastic waste, types of plastic, waste hierarchy, post–consumer waste, recycling & reuse of plastics

INTRODUCTIVE NOTES

Plastics, also called polymeric materials, allow the obtaining in large manufacturing series of different sizes product, rigid or flexible, transparent or coloured. The plastic products are characterized by the diversity of processing processes, under the conditions of a high productivity compared to the traditional materials.[1–6] Most polymers have low densities, around 1 g/cm3 (polypropylene is 0.90 g/cm3, polycarbonate is 1.2 g/cm3, polyethylene varying from as low as 0.912 g/cm3 to as high as 0.975 g/cm3), compared to traditional materials (7.8 g/cm3 for steel, 2.7 g/cm3 for aluminium and 2.54 g/cm3 for glass), which ensures light products with satisfactory qualities especially in the field of consumer goods.[1–6] To the obvious qualities, noted above, the advantages conferred by the pleasing appearance and colouring or by the resistance to corrosion are not infrequently added. The combined action of the above advantages often determines the preferential use of plastics, being light, strong and resource–efficient.[1–9]

The needs of a modern society, which stimulated the intensive development of the plastic's production, determined the consecration of activities directly or indirectly related to their production, use and strictly management.[1–12] The consumption of plastic materials is increasing worldwide, with dozens of types of plastics being known. Of these, several types are used in the manufacture of packaging, other types in manufacturing of several consumer goods, in automotive related industry, in construction industry etc.[2–7,13–16]

Most of the world's plastic production, however, is transformed into polluting waste.[1–17] Every year, large quantities of waste are generated both from production and from the population, plus a few other special waste streams, such as packaging.[1–12] The plastic packaging reaches the first to the garbage dump (Figure 1) or to the collection centres.[2,4–7,12–16] Annually, over 8 million tonnes of plastic of all categories end up in the environment and then in the oceans.[1–18]

Figure 1. Large quantities of plastic waste

Due to the wide variety of plastic waste as well as their increasing quantities, their collection, recycling and processing has become an acute problem lately.[1–18] Thus, large quantities of waste occupy large areas of land, and the respective wastes are highly resistant to natural degradation factors.[3–5,11,13–16] Given that the volume of waste deposited in landfills needs to be stabilized or reduced, increasing the volume of

waste highlights the importance of ensuring new waste treatment capacities (recycling, reuse, co–incineration, etc.).[1–18]

Of the most harmful polymers, we mention the category of thermoplastic materials, which include polystyrene (PS), polycarbonate (PC), polyamides (PA) and polyvinyl chloride (PVC) or those found in packaging (container body, bags), such as polyethylene terephthalate (PET), polyethylene (PE) – low density polyethylene (LDPE) and high density polyethylene (HDPE) – and polypropylene (PP).[1,4,5,14]

The share of packaging waste (which also includes plastic packaging, Figure 2) from the total municipal solid waste generated has increased significantly in recent years, following the increasing trend of the quantities of packaging placed on the market.[1,3,7,11] Some statistics say that packaging waste accounts for up to 15–20% of the municipal waste stream, and polyethylene terephthalate (PET) waste accounts for about 3–5% of this quantity.[1–17]

Figure 2. Plastic packaging products

The wide range of different plastics with different properties and applications makes the collection and sorting of plastics much more complex than for most other basic materials such as metals, paper or glass.[4,5,7–11] In some cases, it can work reasonably well, e.g. in the collection and recycling of PET bottles. In other cases, there are no set systems – such polystyrene (PS) and polyvinyl chloride (PVC) from construction – or the existing system is simply not working well enough.[4–9] Globally only 9% of plastic ever produced has been recycled, whilst 79% can now be found in landfills, dumps or the environment and 12% has been incinerated (Figure 3). Plastics are all around us, a large part is incinerated or much of its value is lost once a plastic object has been used just once. Almost 50% of the plastic waste generated globally was single–use packaging.[17,18]

Figure 3. Globally plastic waste recycled, landfilled and incinerated

The rate of plastic production has grown faster than that of any other material.[3,5,17,18] Researchers estimate that about 60% of that plastic has ended up in either a landfill or the natural environment.[3,7,9,17,18] We need to slow the flow of plastic at its source, but we also need to improve the way we manage plastic waste, because a lot of it ends up in the environment.[1–18] By efficiently managing plastic waste (including the packaging waste), the amount of waste that is deposited at landfills is significantly reduced. Also, the recovery of plastics from post–consumer waste can lead to the saving of crude oil (basic raw material) and some of the energy used in manufacturing processes.[2,9,11,13–18]

The world is already struggling with its plastic waste and recycling issues. Therefore, the recycling of post–consumer plastic waste is increasingly promoted as the means to achieving circular economy. It converts plastic waste into a secondary material that can be fed back into the system, for use in the same or new products, with similar or lower functionality.[1–37] However, this is not so simple. The wide variety of polymers currently used is a major obstacle to the recycling of all plastics.

RECYCLING PACKAGING MATERIALS

The environmental aspects of the use of packaging are of great importance.[17–24,26–37] For a particular packaged product, the most appropriate approach must be chosen, which can be described as follows:[2,5–11,16–37]

- the volume and mass of the packaging must be minimized and redesigned the current packaging size to optimize it for space, maintaining the required levels of safety, hygiene and acceptability for the packaged product and its user;
- the packages must be manufactured in such a way as to allow reuse according to the rules in force;
- the packages must be manufactured in such a way as to allow the recovery of materials, energy recovery or composting, in accordance with the norms in force.

The most effective way to reduce waste is to not create it in the first place. Making a new product requires a lot of materials and energy – raw materials must be extracted from the earth, and the product must be fabricated then transported to wherever it will be sold.[4,5,7–11] As a result, reduction and reuse are the most effective ways you can save natural resources, protect the environment and save money.
Specific measures regarding the prevention and / or reduction of the quantities of waste resulting from each container and packaging products production and use can be achieved by implementing policies and practices such as:

- efficient management of materials destined to packaging (paper and corrugated paperboard, glass, steel, aluminum, plastics, wood, and small amounts of other materials);
- reducing packaging quantities through new packaging solutions and strategies;
- efficient management of all packaging waste.

Basically, there is no ideal ecological solution for packaging, being only a multitude of measures that can be taken.[16–24] One of them is recycling, processing of empty packaging, so that it is brought to their original form or a similar model. Some materials are very suitable for recycling. Others, although theoretically are recyclable, they require complicated procedures and technologies.
Some packaging materials are not suitable for recycling. Because of this, other storage methods must be found for them, not just garbage pits. One solution might be burning, but some materials become very polluting in this process. Landfill process has several disadvantages such as wastes have great volumes, decrease of the areas in which the wastes are stored, high cost and contamination of water and soil. Due to these reasons, the process of landfill should be preferred in a situation when the process of recycling cannot be performed.[19,25–27]

Figure 4. The waste hierarchy

REDUCTION (Figure 4) is the first and most important step in material efficiency practices and the prevention of packaging waste formation.[2,6–9,12–16,19–11] It is the essential element of this problem, because it involves the actions of eliminating or reducing the toxicity of the materials before they reach the landfill. The reduction of raw materials includes the following actions:

- reducing the use of non–recyclable materials;
- replacing available materials and products with reusable materials and products;
- reducing the amount of generated waste;
- increasing the efficiency of the use of all packaging destined materials.

REUSING (Figure 4) is the next step in the efficiency of materials and in the prevention of waste formation. The actual reuse preserves the original structures of the material. In fact, the reusing is the practice of using a product, whether for its original purpose (conventional reusing) or to fulfil a different function (creative reusing or repurposing).[12,21]
RECYCLING (Figure 4) is the third step of this hierarchy, which involves converting the waste into a raw material for re–manufacturing. By replacing natural materials with recycled natural resources, natural resources and energy are conserved. In fact, by transforming waste into usable resources, recycling offers a way of managing waste by reducing pollution, conserving energy and developing more competitive manufacturing industries.[12,21–37]
RECYCLING differs from REUSE in that it transform wastes into new raw materials which are then used to make new product, as opposed to reusing the intact waste. As this extra processing requires energy, and therefore, REUSE is environmentally preferable to RECYCLING.[12,21]
Over the last decades, the plastic fraction of plastic waste is treat by incineration or landfilling, although the recycling is possible, their mechanical properties making them adequate to produce constructive components like bricks, synthetic coarse aggregates for concrete or armouring fiber for a concrete mixture in building materials sector.[27] Thus, plastic fraction of waste could be used to develop novel recycled materials.[19–37]

PLASTIC PRODUCTS CATEGORIES

Today the plastic materials are produced from fossil based chemicals that are put together into long fibers, molecular chains. Currently, petrochemical plastics such as polyethylene terephthalate (PET), polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyamide (PA) have a relatively low cost and a good cost, mechanical performance, such as breaking resistance, ensures heat tightness, etc. Given that the accumulation of large quantities of these materials in the environment has serious and irreversible ecological consequences, the current global approaches are focused on the use of efficient recycling strategies and practices.[19–37]

Figure 5. Plastic products categories
PET/PETE, plastic products of category # 1; HDPE, category # 2 plastic products; V or PVC, plastic products of category # 3; LPDE, plastic products of category # 4; PP, plastic products of category # 5; PS, plastic products of category # 6; OTHERS, plastic products of category # 7

Of the 7 types of plastic (Figure 5) we meet on the market, each is composed of different substances that must be treated individually. The first step to knowing how to recycle or reuse plastic is to easily identify the waste category:

— Polyethylene Terephthalate (PET, plastic products of category # 1) is one of the most used types of plastic and is found in most colourless or colour water and soft drinks bottles or other containers used for consumer goods. It is intended for single use only. It is a lightweight, durable and easily recyclable material that can be transformed into polyester fibres or foil. In the recycling process, the plastic is crushed into flakes which are then reprocessed to create new products. PET must be recycled, but not reused (Figure 6).

— High Density Polyethylene (HDPE, category # 2 plastic products) is a rigid type of plastic from which detergent canisters are produced, is the most frequently recycled type of plastic and is considered among the least dangerous plastic forms. HDPE products are reusable and recyclable (Figure 6).

— Polyvinyl Chloride (PVC, plastic products of category # 3) is a soft and flexible type of plastic used for food packaging or for the production of plastic products. PVC is cheap, durable, easy to handle, but it is a major threat to the environment as it is very difficult to reuse, difficult to recycle and requires high costs in the recovery process. PVC products are not recyclable, and many of them are not reusable (Figure 8).

— Low Density Polyethylene (LPDE, plastic products of category # 4) is a type of plastic often found in heat–insulating packaging, in shopping bags, but also in some clothes and furniture items. This type of plastic is considered to be less toxic than others, but it is not normally recycled that LDPE recycling products are not very resistant. LDPE products are reusable, but not usually recyclable (Figure 7).

— Polypropylene (PP, plastic products of category # 5) is a type of hard and light plastic that has excellent qualities of heat resistance. It is used for packing food, for making the bottle caps. PP products are considered safe for any reuse, but their recycling is done only under certain conditions (Figure 7).

— Polystyrene (PS, plastic products of category # 6) is a cheap, lightweight plastic with a wide variety of uses: from disposable products to building materials. It is one of the most used plastics, found in expanded, extruded or foam forms. PS products should be avoided where possible, as their recycling is quite difficult (Figure 8).

— The plastic products of category # 7 are made from a combination of the other types of plastics or from less commonly used plastics (such as PC–polycarbonate or unlabelled plastic) and are difficult to recycle because they do not fall into a fixed category. These plastic products are not recommended for reuse (Figure 8).

Packaging containers (PET–polyethylene terephthalate) and their caps (PP–polypropylene) are among the most polluting plastic articles found in nature, analysing the quantities of waste they produce, as well as the existing recovery options. The management modalities (according to the waste hierarchy) are multiple such as reuse, recycling, reuse as raw material, incineration or final storage. Although most thermoplastic polymers can be recycled, recycling PET containers is much more practical.

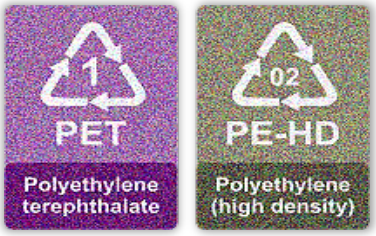

Figure 6. Always recyclable plastics

Figure 7. Sometimes recyclable plastics

Figure 8. Rarely recyclable plastics

Polyethylene terephthalate (PET, category # 1 plastic products) appears in waste from the packaging of non–alcoholic or soft drinks, water (flat or carbonated) or beer. Containers for bottles stained with liquid detergent, cosmetics or shampoo are high density polyethylene products (HDPE, plastic products of category # 2). The caps of these containers are made of polypropylene (PP, plastic products of category # 5). They are not suitable for reuse (although they are reused), but they are easily recyclable in many products.

Figure 9. Easily recyclable plastics

All these plastic products (categories # 1, 2, 4 and 5, Figure 9) although they could be recycled, do not always reach the collection system. However, according to numerous researches, there are alternatives.[19–37]

PLASTIC MATERIALS RECYCLING

Household refuse and industrial disposal of plastic materials is a major environmental concern.[15] Because of legal requirements, which have been enforced to protect the environment, there is a pressing need to develop methods to recycle plastic waste.

RECYCLING (Figure 10) is an important key factor to get plastics into a circular economy, as we above–mentioned. Plastics recycling is the process of waste plastic reprocessing into useful by–products.[19–37] Since the majority of plastic materials are non–biodegradable, the recycling actions are an important part of global efforts to reduce plastic in the waste stream.[1–37] Mechanical recycling has emerged as the most economical, as well as the most energetic and ecologically efficient option. (Figure 10)

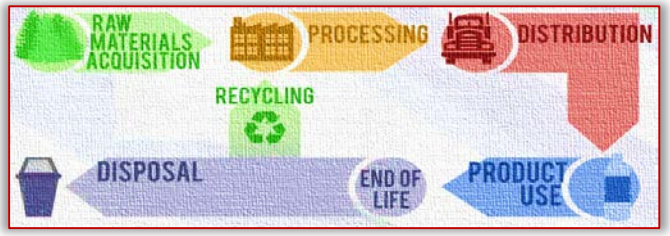

Figure 10. Recycling into a circular economy – a concept

Energy recovery is a valuable alternative for plastics–rich waste fractions that cannot be sustainably recycled.[16] Some plastics cannot be recycled in an eco–efficient manner. For these plastics, energy recovery (Figure 11) is the most resource–efficient solution available when compared to landfilling.[16]

Therefore, there are two major ways to recycle plastic products, including the packaging plastics:

- MECHANICAL RECYCLING, where the plastic is washed, ground into flakes and melted, and
- CHEMICAL RECYCLING, where the plastic is broken down into basic components.

MECHANICAL RECYCLING where the plastics are sorted, grinded, washed and then reused in the production to partly or fully replace virgin polymers.[13–16,19] Key requirements for successful mechanical recycling are large, homogenous streams with constant and even quality. To achieve this, the design of the packaging is very important for recycling and waste management with collection of sorted waste at the households to avoid contamination (Figure 11).

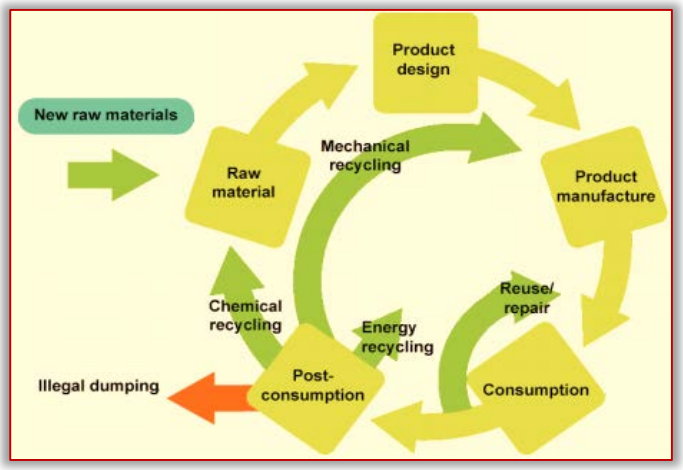

Figure 11. Recycling and reuse of plastics [13]

CHEMICAL RECYCLING (Figure 11) is a complementary technology, that can help diverting from landfill certain plastic waste which cannot be sustainably recycled by mechanical recycling.[16] Examples of suitable streams for feedstock recycling include laminated and composite plastics, low quality mixed plastics streams and contaminated plastics. Chemical recycling (or feedstock recycling) is much less developed to industrial scale and means a process where the polymers are degraded back to monomers to be used as raw material to produce new polymers.[16] In fact, processes as gasification and pyrolysis break down plastic waste to produce synthesis gas (syngas) as well as other liquid and semi–liquid products.[16]

MECHANICAL RECYCLING of plastics refers to the processing of plastics waste into secondary raw material or products without significantly changing the chemical structure of the material.[16] Before recycling, most plastic products are sorted according to their resin type, resin identification code or are separated by color before they are recycled. After sorting, for mechanical recycling the plastic recyclables are then shredded. These shredded fragments then undergo processes to eliminate

impurities like paper labels. This sorted plastics are melted and often extruded into the form of pellets which are then used to manufacture other by–products.[16]

Analysis has shown that 84% of the plastic packaging waste originates from polyolefins and polyethylene terephthalate (PET).[25] The polyolefin group comprises polyethylene (PE) and polypropylene (PP) polymers. PET is the most recycled plastic packaging material and today the PET bottle recycling is the only true circular stream in large scale where post–consumer packaging becomes packaging again in recycled bottle to new bottle or bottle–to–new by–product applications.

PVC is a universal polymer which can be processed into a wide variety of short–life or long–life products.[26] As a result of increasing consumption of PVC–made products in recent years, the quantity of used PVC items entering the waste stream is gradually increased. Currently, there is a considerable public concern about the problem of plastic wastes, from which PVC has not escaped and the material or energy recycling may be a suitable way to overcome this problem.[26]

The scrap of polycarbonate – PC can be used in several civil engineering applications as addition in cementitious materials, as an aggregate to prepare concrete mixtures or as a substitute for sand in cement mortars.[28–30] Thus, polycarbonate aggregates can provide good energy absorbing materials which are especially interesting in structures subjected to dynamic or impact efforts. Also, the scrap of polycarbonate can be used in several road and urban applications as partial substitution of natural coarse or fine ingredients in a bituminous mix.[33–37]

When different types of plastics are melted together, which cause structural weakness in the resulting material, meaning that polymer blends are useful in only limited applications. Plastic solid waste, such as polypropylene (PP) and polyethylene (PE), is creating new challenges, which in today's scenario are major research concerns. The two most widely manufactured plastics, polypropylene (PP) and polyethylene (PE) – low density polyethylene (LDPE), high density polyethylene (HDPE) – and polypropylene (PP) and polyethylene terephthalate (PET), behave this way, which limits their utility for recycling.

How plastic waste is processed remains extremely variable from country to country, and recycling remains considerably under–used.[4–8,10–14] Yet recycling is the best solution for processing plastic waste because it limits environmental impact and generates significant socio–economic gains. However, at every stage of the plastic life cycle, there remain a large number of impediments to the development of recycling.[14]

APPLICATIONS

There is low utilisation of plastic waste and only a fraction of plastic materials go back into production processes through reuse and recycling practices, despite of their recycling potential.[2–6,10–11] Now, an important plastic fraction of waste is treat by incineration or landfilling, although the recycling is possible, their mechanical properties making them adequate to produce new by–products.[2–6,10–11] The use of waste products in several industrial applications not only makes it economical, but also helps in reducing disposal problems.[2–6,10–11] One such waste is plastic, which could be used in various applications and new by–products. However, efforts have also been made to explore its use in several application, several of them being below presented:

- The main application in this sense is the polyethylene terephthalate (PET) bottle recycling. In the recycling industry, this is referred to as "post–consumer PET". In this sense, the collected post–consumer PET containers are sorted into different color fractions and they are washed and flaked (or flaked and then washed). This sorted post–consumer PET waste is crushed, chopped into different size flakes, pressed into bales, and offered for reusing (Figure 12). PET flakes are used as raw material for a range of products that would otherwise be made of polyester.

Figure 12. PET waste and crushed PET flakes

Figure 13. Recycling PET waste into polyester fibres

- One use for this PET flakes is to create polyester fibres (a base material for production of clothing, pillows, carpets, bags etc.). The

recycled PET thread or yarn (Figure 13) can be used either alone or together with other fibers to create a very wide variety of fabrics;

— Other major outlets for recycled PET are new containers (bottles and food or non–food–contact packages);

Figure 14. Recycling PET waste into new bottles

(a)

(b)

Figure 15. Armed concrete blocks (a) and floor tiles (b)

— Also, the PET products can be easily used in the construction sector, as reinforcement in armed concrete blocks or paving slabs, for consolidation their structure or as substitute of sand and gravel sorts from the aggregate;

— High–density polyethylene (HDPE) is a commonly recycled plastic, being easily extruded or injection molded and turned into brand new pipe. Often it is typically downcycled into plastic lumber or and other durable products like detergent or shampoo bottles;

— LDPE is not often recycled but can be recycled into lumber, landscaping ties or floor tile;

— PP (polypropylene), found in some containers and medicine bottles or caps, is gradually becoming more accepted by recyclers and offered for reusing for plastic lumber or custom–made products;

— Several plastic products are recovered from the waste stream, are not landfilled or burned, and successfully recycled into much larger products for industrial applications such as plastic composite railroad ties (Figure 16) or used as rain resistant recycled plastic (aggregate, bitumen or asphalt);

— Most polystyrene products are not recycled, altrough their scrap can easily be added to products such as insulation sheets for construction applications, metal casting operations or for producing insulating concrete forms;

Figure 16. Plastic composite railroad ties

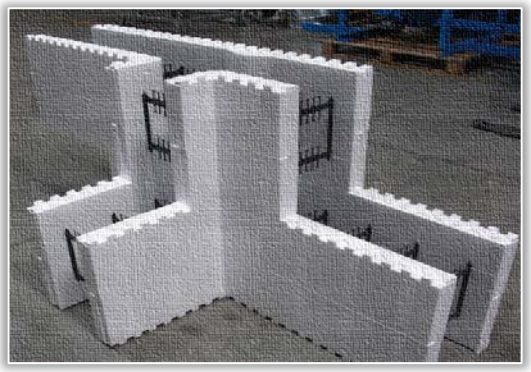

Figure 17. Insulating concrete forms

— Recycled plastic lumber (RPL) is a wood–like material made from recycled plastics that aims to diminish the environmental pollution resulting from plastic wastes. This material is used in different kinds of nonstructural and structural applications. Recently, the recycled plastic lumber (Figure 18) has been proposed as a suitable material to develop structural walls that comprise the seismic resistant system of housings;

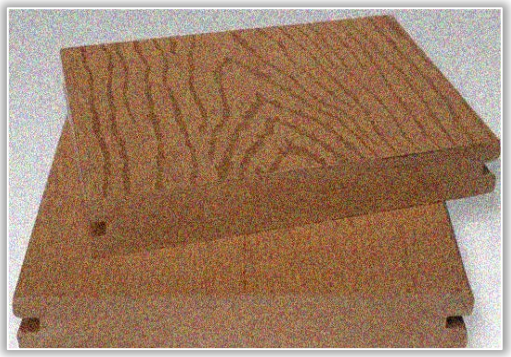

Figure 18. Recycled plastic lumber

— Plastic pipe producers are forced by various initiatives to increase the content of recycled material in their products. The performance of the recycled material is worse than the performance of the virgin material, but it would be theoretically possible to use the recycled material in pressure applications as a part of multilayer pipes.

— Commingled, mixed or contaminated plastic materials – including some material groups such as thermosets or mixed plastics which were labeled as un–recyclable – can all be used as feed stock, and,

therefore, composite products can be produced of 100% waste plastics. Developping a non–traditional (but patented) processes, virtually any plastic waste can be economically recycled into useful composites for nearly endless recycled content product applications.[38] The main advantage is that materials need no separation, cleaning, or pre–processing other than size reduction into chips or flakes. This allows heavy, solid, and durable recycled content products to be produced economically without concern for material cost.

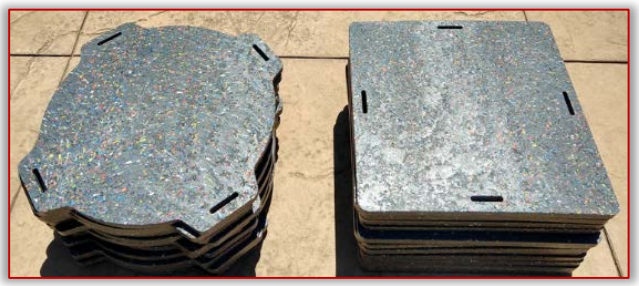

Figure 19. Composite products from 100% waste plastics (commingled, or mixed plastic materials) [38]

CONCLUSIONS

A large variety of materials fall into the category of plastics. These versatile materials have found their way into almost every aspect of daily life. Often described as durable materials they unfortunately spend the majority of their long life in a landfill.

The building and construction industry has a key role to play in sustainability of the built environment by promoting plastics recycling, a large percentage of plastics being recycled into extended–lifetime construction products (building blocks, roof tiles, insulation, panels etc.). Other areas include paving bricks production and roads or bridge construction. Also, recycled waste plastics have been found to replace aggregates in road construction and landscape.

One of the advantages of products made from recycled plastic is the cost of manufacturing cheaper than those made from virgin raw materials. The benefits of using recycled plastic are:

- disposal of the quantities of waste deposited in garbage dumps or collected systematically, and
- saving the energy quantities needed to produce raw materials for various industries.

Increased recycling will reduce the need for fossil feedstock but due to downgrading of plastics in the use and recycling phases there will be a continued need for virgin material. Therefore, contributing to the conservation and reuse of existing resources is more than a good civic policy, it is an imperative.

The efficiency of the materials and the prevention of the formation of waste imposes a more cyclical approach than the typical linear one, for the processing and use of resources. The world is heading for an era of natural resource conservation, of which recycling is an integral part. Without recycling, the circuit of materials in nature would become a series of events without a logical resolution. Any useful materials would become dispensable and would not be retained as a possible resource. The use of already processed materials implies substantial energy savings compared to the use of raw materials, and the by–products are less polluting than the raw materials.

According to the environmental legislation it is necessary to save natural resources, to reduce the management costs and to apply effective solutions to diminish the impact on the environment, by recovering waste. Currently, unused waste is mostly stored, although if we could use waste as a valuable resource. In this context, unused waste is also a potential loss.

The application of recycled wastes inevitably lead to develop green construction materials. Therefore, promoting the sustainable and affordable development of green concrete and mixtures by incorporating different plastic wastes in the road construction and building materials industries can solve partly, of course, the impasses of degradation of natural restricted aggregate resources as well as contaminations of environment, due to landfilling.

References

[1] MacArthur, E., Beyond plastic waste (2017) 843–843
[2] European Commission, A European Strategy for Plastics in a Circular Economy, Brussels (2018)
[3] Geyer, R., Jambeck, J.R., Law, K.L., Production, use, and fate of all plastics ever made. Science advances, 3(7), (2017) e1700782
[4] Merrington, A.. Recycling of plastics, in Applied plastics engineering handbook William Andrew Publishing (2017) 167–189
[5] Scheirs, J., Polymer recycling: science, technology and applications, Vol. 132, New York: Wiley (1998)
[6] Allwood, J.M., Squaring the circular economy: the role of recycling within a hierarchy of material management strategies. In Handbook of recycling (2014) 445–477
[7] Hopewell, J., Dvorak, R., Kosior, E. Plastics recycling: challenges and opportunities. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526), (2009) 2115–2126
[8] Lazarevic, D., Aoustin, E., Buclet, N., Brandt, N., Plastic waste management in context of a European recycling society: Comparing results and uncertainties in a life cycle perspective. Resources, Conservation & Recycling, 55(2) (2010) 246–259
[9] Gharfalkar, M., Court, R., Campbell, C., Ali, Z., Hillier, G., Analysis of waste hierarchy in the European waste directive 2008/98/EC. Waste management, 3 (2015) 305–313
[10] Shen, H., Pugh, R.J., Forsberg, E., A review of plastics waste recycling and the flotation of plastics, Resources, Conservation and Recycling, 27(3) (1999) 285–286

[11] Mwanza, B.G., Mbohwa, C., Drivers to sustainable plastic solid waste recycling: a review. Procedia Manufacturing, 8, (2017) 649–656.
[12] Huysman, S., De Schaepmeester, J., Ragaert, K., Dewulf, J., De Meester, S., Performance indicators for a circular economy: A case study on post–industrial plastic waste. Resources, Conservation and Recycling, 120 (2017) 46–54
[13] STEPS – Annual Report 2016–17, Plastic waste – A Challenge for the entire value chain, (STEPS) Sustainable Plastics and Transition Pathways (2017)
[14] d'Ambrières, W., Plastics recycling worldwide: current overview and desirable changes, Field ACTions Science Reports (FACTS), Special Issue 19: Reinventing Plastics (2019) 12–21
[15] Maris, J., Bourdon S., Brossard J–M, Cauret, L., Fontaine, L., Montembault, V., Mechanical recycling: Compatibilization of mixed thermoplastic wastes, Polymer Degradation and Stability, Vol. 147 (2018) 245–266
[16] Plastics Europe: Recycling and energy recovery – Zero plastics to landfill (2020), https://www.plasticseurope.org/
[17] UNEP, Single–use plastics – A roadmap for sustainability, United Nations Environment Programme, 2018
[18] UNEP, The state of plastics – World Environment Day Outlook, United Nations Environment Programme, 2018
[19] Ragaert, K., Delva, L., Geem, K., Mechanical and chemical recycling of solid plastic waste, Waste Management, 69 (2017) 24–58
[20] Tam, V.W., Tam, C.M., A review on the viable technology for construction waste recycling. Resources, conservation and recycling, 47(3) (2006) 209–221
[21] Brems, A., Baeyens, J., Dewil, R., Recycling and recovery of post–consumer plastic solid waste in a European context. Thermal Science, 16(3) (2012) 669–685
[22] Singh, N., Hui, D., Singh, R., Ahuja, I. P. S., Feo, L., Fraternali, F., Recycling of plastic solid waste: A state of art review and future applications. Composites Part B: Engineering, 115 (2017) 409–422
[23] Malik, N., Kumar, P., Shrivastava, S., Ghosh, S. B., An overview on PET waste recycling for application in packaging. International Journal of Plastics Technology, 21(1) (2017) 1–24
[24] Jankauskaite, V., Recycled polyethylene terephthalate waste for different application solutions. Environmental Research, Engineering and Management, 72(1) (2016) 5–7
[25] Jinghua, W., Recycling of polyolefin plastics waste. China Plastics Industry, 33(1) (2005) 40–45
[26] Sadat, M., Gholam, S., Bakhshandeh, R., Recycling of PVC wastes, Polymer Degradation and Stability, 96(4) (2011) 404–415
[27] Buekens, A., Yang, J., Recycling of WEEE plastics: a review, Journal of Material Cycles and Waste Management, 16(3), (2014) 415–434
[28] Rebeiz, K.S., Craft, A.P., Plastic waste management in construction: technological and institutional issues. Resources, conservation and recycling, 15(3–4) (1995) 245–257
[29] Rebeiz, K.S., Fowler, D.W., Paul, D.R., Recycling plastics in polymer concrete systems for engineering applications. Polymer–Plastics Technology and Engineering, 30(8) (1991) 809–825
[30] Saikia, N., De Brito, J., Use of plastic waste as aggregate in cement mortar and concrete preparation: a review, Construction and Building Materials, 34 (2012) 385–401
[31] Siddique, R., Khatib, J., Kaur, I., Use of recycled plastic in concrete: A review. Waste management, 28(10), (2008) 1835–1852
[32] Chavan, M.A, Use of plastic waste in flexible pavements, International Journal of Application or Innovation in Engineering and Management, 2(4) (2013) 540–552
[33] Hassani, A., Ganjidoust, H., Maghanaki, A.A., Use of plastic waste (poly–ethylene terephthalate) in asphalt concrete mixture as aggregate replacement. Waste Management & Research, 23(4) (2005) 322–327
[34] Mathew, P., Varghese, S., Paul, T., Varghese, E. Recycled plastics as coarse aggregate for structural concrete. International Journal of Innovative Research in Science, Engineering and Technology, 2(3), (2013) 687–690
[35] Louie, M.L., Sustainable solutions for railroad trackwork. In Urban Public Transportation Systems (2013) 338–346
[36] Krishnaswamy, P., Lampo, R., Recycled–plastic lumber standards: From waste plastics to markets for plastic–lumber bridges. Standardization News, 2 (2001)
[37] Najafi, S.K., Use of recycled plastics in wood plastic composites–A review. Waste management, 33(9) (2013) 1898–1905
[38] Commingled plastic recycling and molding, http://goodinnovation.com

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