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Review

Harvesting the unexplored potential of European waste materials for road construction

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ABSTRACT

This paper demonstrates how a considerable amount of waste produced in the urban and peri-urban environment can be recycled in asphalt roads. The example presented is from Europe, however, the barriers and conclusions are universal. It was shown that various waste materials such as glass, asphalt, concrete, wood, plastics etc. have a potential for re-use in asphalt roads. The available quantities of the European target waste materials that would otherwise be incinerated or disposed in landfills were considered. It was shown that there is high potential in Europe for recycling in road construction, in particular, under the hypothetical scenario where 33% of new roads would be made of the target waste materials (excluding RAP which is already recycled), it is estimated that 16% of the available waste quantities could be recycled in roads. Four hypothetical roads were analysed showing a considerable savings in costs, CO2 and energy in comparison to conventional asphalt mixtures using all virgin components.

Contents

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1. Introduction

It is well established that industrial countries are producing a considerable amount of waste (Sousa and Way, 2000; Proparco; Solid Waste Management) and a major part of the resources are wasted through the mainly linear process of material use in our economies. Materials are extracted, used or further processed into products where they are used and then disposed of in landfills and incinerators. There is a clear need to improve EU resource efficiency and reduce climate and environmental impacts, through promoting waste reuse and recycling and by phasing out disposal or incineration of waste, according to the waste hierarchy of the European Waste Framework Directive 2008/98/EC (European_Parliament, 2008). A significant share of waste materials is recycled back into the same product where they came from (closed-loop recycling). However, despite considerable progress in recycling of waste materials generated in the urban environment, in several instances their quality or technical requirements do not allow for the materials to be recycled into the same product and as a result the waste materials are landfilled or incinerated. This provides a substantial opportunity to recycle wastes produced as precious raw materials for example in road pavements.

Roads are the dominating transport infrastructure in Europe and an important contributor to the economy. The total inland freight transport in the EU-28 was estimated to be close to 2′100 billion tonne-kilometres (tkm) in 2012; three quarters (75.1%) of it transported by roads (http://ec.europa.eu/eurostat/statistics-explained/index.php/Freight_transport_statistics, assessed 11.12.2015). Similarly, every year a considerable amount of new and rehabilitated roads are built amounting to a total of 4.7 million kilometres (Mkm) corresponding to the production of more than 276.4 Mt of asphalt mixtures (EAPA, 2012). This entire road network demands a substantial amount of aggregates, bituminous and cementitious binders and performance enhancing additives to withstand the ever increasing demands in terms of axle loads and frequency of traffic. At the same time, with the increase of heavy vehicles on the road and scarcity of raw materials depending on the region, the road pavement industry is facing new challenges in terms of resources and mechanical performance that have to be met.

Various types of waste materials have been successfully used in road pavements. However, as the literature search that follows shows, this use has remained for the most part at the research level or limited to some countries and therefore, there is an urgent need to develop and broadly demonstrate such solutions in real-life environments in order to promote widespread market uptake. A survey on the barriers impeding the use of recycled materials in the construction industry revealed that the number one reason why companies don't use recycled materials is cost followed by lack of education, while less frequently stated reasons referred to the product quality (Bolden et al., 2013).

This article aims to facilitate the use of waste materials for road construction by giving an overview of the urban and peri-urban waste problem and present a solution in terms of recycling in roads. Furthermore the paper demonstrates, by presenting some examples, what types of materials have shown to work and their use should be encouraged through a combination of proper standardization, legislation and incentives. The paper gives the waste statistics in European urban and peri-urban environment as an example, however the results and conclusions are universal.

2. Waste materials suitable for recycling in road pavements

Asphalt concrete is a complex three phase material consisting of aggregates, a binder and air voids. In addition, performance enhancing additives such as fibers and polymers are used as modifiers.

The motivation for recycling in pavements is two-fold: either to save resources or to improve material properties. In the resource category, re-use of old pavement or non-pavement materials such as construction and demolition (C&D) or marginal materials which are low quality, in new pavements can be named. Regarding material improvement, the following can be listed: replacing traditional components such as bitumen with polymers; tailoring pavement performance using selected materials to fulfil increase in performance requirements; using traditional materials to pool different properties.

In this article, certain waste materials have been chosen as substitutes for traditional virgin raw materials. In order to have any real impact on the reduction and re-use of urban waste through recycling in roads and, at the same time, producing standard quality roads, the following criteria were used to choose the waste materials: (i) demonstrated comparable performance in road pavements compared to virgin materials; (ii) available quantity; (iii) absence of higher value alternatives for their exploitation; (iv) waste collection systems in place enabling secure access and (v) high treatment and disposal costs. A review of the selected waste materials is provided below.

2.1. Concrete

Concrete is one of the most important construction materials nowadays and its production has reached 25 billons tons a year (World Business Council for Sustainable Development (WBCSD, 2007). This in turn produces more than 900 million tons of concrete waste that are produced each year worldwide (Wimala et al., 2011). As a result, crushed concrete is one of the main materials obtained from C&D waste, together with bricks or milled asphalt pavement. Usually, this waste is disposed of in land-fills or recycled as construction material.

The use of recycled waste concrete for construction has been a topic for several decades (Schulz et al., 1992; Sangiorgi et al., 2015). Particularly, this type of waste has been used for the construction of pavements, primarily crushed as coarse aggregate, mostly in base and sub-base layers with good results. For example, Bennert et al. (2000) studied the performance of recycled concrete aggregate in base and sub-base courses and concluded that a mixture of 25% of recycled concrete aggregates with 75% of natural aggregate has the same resilient response and permanent deformation properties as standard dense-graded aggregates in base courses. Results of the study conducted by Brooks and Cetin (2012) confirms that using 30% recycled demolition waste and cement klint dust to strengthen the subgrade and to prepare the subbase, helps reducing the overall thickness of the pavement. Other research works focused on the performance of asphalt mixtures with construction and demolition waste, showing that mixing the right amount of recycled and natural aggregates can lead to a superior performance (Arabania et al., 2013). Furthermore, the use of the fine fraction of the waste as filler can help increasing the dynamic modulus and reducing the dynamic creep of asphalt mixtures (Wong et al., 2007). To summarize, using this type of waste on the construction of pavements could help decreasing the amount of land-fills while reducing the use of natural resources and increasing the performance of a pavement. To that end, further research in this field is encouraged.

2.2. Reclaimed asphalt pavement

Reclaimed asphalt pavement (RAP) provides high quality aggregates and binder and can be recycled up to 100% in new roads. As it will be shown in the last section (Fig. 2), there are considerable savings in materials related costs even if rejuvenating agents are used to restore the properties of the old asphalt binder. According to the recorded statistics 47Mt of RAP are recycled in Europe but the rate of recycling in Europe varies greatly with Germany at 97% and Switzerland at 24% (EAPA, 2012). Research by the authors has shown that asphalt concrete containing very high amounts of RAP (60% in the example) can have mechanical performance that is similar to mixture made of all virgin components (Poulikakos et al., 2014). Here an asphalt concrete mixture and a high modulus mixture were investigated.

2.3. Glass

Glass is one of the major waste products in all urban areas worldwide. The quantity is substantial for example recent data indicates that Europe generated ca. 17 million tons of glass. Its re-use in glass bottle production is hindered by the presence of debris from C&D waste and coloured glass particles (Disfani et al., 2011). Regarding applications in road construction the important parameters are shape, size and surface properties. Glass waste in asphalt concrete can be used in the form of fibers, large or small particles and powder. The particular particles' morphology (flat and elongated grains) of the glass wastes could represent a problem during the compaction of the mixtures. Some concerns about stripping phenomena for glass wastes have been noted (Pasetto and Baldo, 2013). Glass powders were adopted as the replacements of traditional stabilizer and filler. Basalt glass powder performed better than lime rock powder, as the filler of asphalt composite (Lou et al., 2013). Diatomite-glass fiber modified asphalt concrete had a better capacity to resist fatigue damage (Cheng et al., 2012). The study by Disfani et al. (2011) on medium (<9.5 mm) and fine (<4.75 mm) sized recycled glass indicate that they exhibit geotechnical behaviour similar to natural aggregates and could be used as fines for road construction applications. Coarse recycled glass (CRG) was however found to be unsuitable for geotechnical engineering applications. The use of crushed glass in road applications has also been promoted through national regulations is some countries.

2.4. Scrap tyres

Tyre-derived products can be used to replace conventional construction materials in roads (Sousa, 2012; Sousa and Way, 2000). The benefits of using tyre chips are, amongst others, reduced density, improved drainage properties and good thermal insulation. However, most cost effective developments have been done using crumb rubber (CR) modified mixtures which can improve hot mix asphalt performance properties significantly. In addition CR can be used for Cold and Warm mixtures (Dondi et al., 2014). Many laboratory investigations have shown promising results for CR modified asphalt. Addition of CR can be done directly in the hot bitumen (wet process) or in the mixture (dry process). For example, Liang et al. (2015) have shown a significant improvement in viscoelastic characteristics and viscosity compared with neat asphalt as a result, a better resistance to permanent deformation in roads. The fabrication of the road has to be swift as sedimentation of the CR particles can occur. The positive experience with these products led to a mandate by California Legislature to use asphalt modified mixtures in 35% by the weight of the mixtures placed in California roads. More recently California Department of Transportation has decided to use, CR modified mixtures in all surface courses. In fact with these mixtures, when CR is properly introduced in the mixture, layer thickness can be reduced in half. This is due to the improved fatigue and cracking characteristics of the mixtures which in turn leads to great savings in CO_2 emissions during the construction phase and during the maintenance phase during the service life of a road. An additional advantage of using CR in pavements is the noise reduction properties. Using CR in the pavement results in the muffling of generated vibrations from the tyre-pavement interactions which are the dominant mechanisms in the noise from tyre–road interaction (Bueno et al., 2014).

2.5. Plastics

Many studies are available on the use of various waste polymers in roads, such as polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), polyurethane (PU), ethylene vinyl acetate (EVA), polyvinyl chloride (PVC) and different fibers (Kalantar et al., 2012).

2.5.1. PET

Polyethylene terephthalate (PET) is a thermoplastic polymer resin of the polyester family, biodegradable and semi-crystalline. The majority (around 60%) of PET production is for synthetic fibers, whereas PET bottle production is responsible for 30% of the production. Table 3 shows that there is a total of 4.5 Mt/y of waste plastics including PET that is produced in Europe of which 0.4 Mt/y could be used as additive for asphalt concrete as discussed further in the next section.

Though a considerable amount of PET is recycled into new products, PET is still responsible for a significant amount of materials that go into landfills. For example, Hassani et al. (2005) states that due to the large number of PET bottles more than 1 million m^3 of landfill space is needed for disposal of PET in Iran every year. The research on the use of recycled PET for flexible road pavements dates back to the beginning of the 1990′s (Ledesma and Isaacs, 1991). Recycled PET in road construction is mainly used as follows.

- PET granules to replace aggregates in mixtures

Substitution of up to 25% by weight of the asphalt mixture with granule sizes from 1.2 mm to 2.4 mm was achieved (Hassani et al., 2005). In addition, it was shown that the addition of PET to mastics asphalt (SMA) mixtures increased the stiffness modulus as well as the fatigue resistance (Moghaddam et al., 2012) and an aggregate replacement of 20% results in increased resistance to permanent deformation (Rahman and Wahab, 2013; Moghaddam et al., 2014).

- PET fibers as bitumen modifier and mix reinforcement

The primary advantage of adding PET fibers as a binder modifier is to reduce costs for production of polymer modification (PmB) by using inexpensive polymers (i.e. waste polymers). Polymer modification is required for high porosity asphalt concrete such as porous asphalt (Bhosale, 2006). The content of PET ranged from 2% to 8% by total binder mass. The temperature susceptibility of the modified binder was improved, the rutting resistance increased, as well as the high Performance Grade (PG) of the binder. Other studies found that an optimal amount of PET fibers was found to range from 4% to 6% by bitumen mass in terms of SMA performance (Chen et al., 2008). The modified SMA showed improved resistance to permanent deformation, increased stiffness and lower binder drainage (Ahmadinia et al., 2011, 2012).

- Chemically processed recycled PET as bitumen modifiers and anti-stripping agents

Studies show the use of recycled PET flakes which are depolymerized to monomers and higher oligomers, since monomers can be used as building blocks with other polymers. One alternative is the use of Depolymerized PET to improve the asphalt mixture quality (Brebeanu et al., 2003). Another approach is chemical recycling as the mixing of PET with pentaerythrytol (PENTE) also showed potential as binder additive (Mendes et al., 2011).

2.5.2. PE

Hinishoglu and Agar (2004) tested high density PE (HDPE) modified binder in terms of asphalt mixture performance using the industry standard mechanical Marshall tests. The results showed that Marshall Stability and quotient increased. The latter increased by 50% compared to the control mix. Casey et al. (2008) show that 4% recycled HDPE gives most promising results when blended with a pen graded binder. Wheel tracking (permanent deformation) and fatigue tests on hot mix asphalt (HMA) revealed that the HDPE modified product performed better than a regular polymer modified binder. Moreover, Khurshid et al. (2013) found that the addition of 8% of HDPE was the optimum modifier amount to increase stability and rutting resistance. However, it has been reported that the low-temperature performance increases more when using low-density PE (LDPE) with wider molecular weight distribution compared to HDPE narrow distribution (Ho et al., 2006). More examples can be found in Fang et al. (2008) who combined waste PE and rubber for modifying bitumen. Their results show that softening point and ductility increased and penetration decreased in comparison to non-modified binders. Furthermore, Jeong et al. (2011) worked with waste PE as bitumen modifier and characterized mechanical performance. Results showed a better rutting resistance. Sangita et al. (2011) show a study on waste polymers (nitrile rubber and PE) as binder modifier. The optimum waste polymer content was found to be 8% by weight of bitumen leading to a considerable improvement of mechanical properties of asphalt mixtures tested. Fang et al. (2012) worked with organophilic montmorillonite together with PE as bitumen modifiers. Standard properties such as penetration, softening point and ductility markedly improved. Furthermore, the aging behaviour of waste PE modified bitumen were studied and concluding that the properties of aged modified bitumen were improved (Fang et al., 2013, 2014).

2.5.3. EVA

A study on the rheology of polymer-modified binders with recycled EVA has found that this modification improved the properties in the low- and high temperature ranges (Garcia-Morales et al., 2004a, 2004b). Moreover, Benrachedi et al. (2008) investigated bitumen modified with ozonated recycled EVA showing that the modified bitumen had good penetrability and higher softening point. In these cases, the correct choice of crosslinking agents and catalysts is stated to be of crucial importance (Fang et al., 2009b).

2.5.4. Polyurethane (PU)

Polyurethane (PU) is used in a wide variety of applications in the food cold chain, in upholstered furniture and mattresses, shoes, cars, medical devices as well as for the thermal insulation of buildings and technical equipment. When PU reaches its end of life after many decades in use, it is mainly landfilled or incinerated (90%) and only a small percentage (10%) is recycled or incinerated (Zevenhoven, 2004). Together with a large quantity of excavation waste, construction and demolition waste it accounts for about 30% of all waste generated in the European Union. Its lifetime is closely linked to the buildings renovation cycles. One problem is related to the contamination by others in its use phase (bitumen, adhesives, rust, render, etc.). Different end-of-life options for PU insulation are focused on (i) its re-use in less demanding applications, i.e. transforming it into packaging material or new products, (ii) chemical recycling by hydrolysis, aminolysis and glycolysis to produce polyols for further second life applications, (iii) recovery into energy for municipal incinerators that generate electricity and, increasingly, heat for use in buildings and industrial processes or (iv) simply landfill, since PU waste is free of ozone depleting substances and is not classified as hazardous waste. Nevertheless, innovative applications to divert end-of-life options have been investigated including some involving bituminous materials. Although it is known that PU is not compatible with bitumen as a consequence of the instability of the resulting system (Bukowski and Gretkiewicz, 1982), this issue has been overcome either by synthesizing a network in the presence of plasticizers or by pre-treating bitumen with modified clay, maleic anhydride or dibasic acids. For example, PU pre-polymer has been used as a bitumen improver in the manufacturing of waterproofing coatings/sealing compounds for construction uses (Singh et al., 2006). Another case also studied the effect of PU as reactive polymer with functional groups able to chemically interact with bitumen compounds for obtaining polyurethane modified bitumen (Carrera et al., 2010). Again, bitumen modification with PU takes place by reaction of the isocyanate groups (–NCO) of the pre-polymer with functional groups containing active hydrogen atoms (mainly, –OH), typically present in the asphaltene micelles. This modification of bitumen also involves the addition of water leading to production of a foamed binder that can be potentially employed in those applications where a bituminous material with low viscosity is required. These authors also analysed the influence of the molecular weight and isocyanate content on the rheology of polyurethane bituminous binders (Carrera et al., 2014). Moreover, this application is described in another work where PU is evaluated as effective bitumen additive for bituminous foam due to the well-known ability of isocyanate compounds to be foamed (Izquierdo et al., 2012). In this

Table 1
Properties of Carbon Black.

Oil Content%	2.94	Vikr-%	
Density 20 °C	490	kg/m3	
Calorific value (Gross)	22.22	MJ/kg	ASTM D240
Chlorine	0.098	Vikr-%	ASTM D808
Sulphur EN-ISO8754%	2.23	Vikr-%	ASTM D1552

study, the authors aimed at combining waterproofing properties of bituminous membranes with thermal and acoustic insulation of sprayed polyurethane foams in a novel product with enhanced mechanical and chemical properties by modification with a reactive polymer. In addition, another more practical example can be found in a recent Spanish patent where the use of PU foamed waste in an asphalt mixture replacing part of the mineral filler is explained (ES 2 386 116 (2012)). The inventors claim that an improvement of the plastic deformation is achieved with this new material. Moreover, they assure that, since polyurethane is a thermostable polymer, there is no degradation at high temperature and thus, no emission of hazardous substances during fabrication process.

2.5.5. Carbon black

The use of plastics as a raw material in the production of fuels has become a growing trend because it promotes energy self-sufficiency, reduces vulnerability to fluctuations in fuel prices as well as the environmental impact generated in two ways: the scarcity of energy resources and pollution and ecosystem damage as a result of landfill deposition. Between 15% and 25% of the municipal waste in Europe consist of mixed plastic, which reached over than 35 million tonnes per year. Pyrolysis is used to produce liquid fuel similar to diesel from residual waste from municipal waste treatment plants, especially plastics waste. Processing mixed waste plastics through pyrolysis produce synthetic oils, carbon rich powder and gas. Carbon black, is produced continually during 24 h with continued removal of carbon rich solid form of fine powder from the processing unit. It is removed from the reactor by a conveyor screw and stored in 1 ton quantities in large bags. It is characterized by high hydrocarbon content (mostly plastics and tyres) with contaminations of sand and inorganics (Table 1). Char may be used as a solid fuel or as a precursor for activated carbon manufacture but carbon black has a potentially important end-use as an additive for road bitumen. The addition of carbon black in asphalt is found to improve its mechanical and rheological properties. In addition, carbon black, was employed to design and prepare electrically conductive asphalt mixtures for deicing or self-monitoring purposes (Wen and Chung, 2004; Wu et al., 2005). It was demonstrated that the conductivity of asphalt concrete is proportional to the volume of conductive graphite or fibers added until the percolation threshold is reached. However, excess conductive additives above a certain level does not reduce the resistivity anymore, but strongly influences the mechanical strength or the workability of the mixture.

2.5.6. Other polymers and blends

Various other kinds of polymers have been used successfully as modifiers for asphalt concrete; the sequel lists some of the experiences reported. Micronized PVC was employed successfully by Singh et al. (2003) as a soft filler for asphalt mixtures. PP was used by Sabina et al. (2009) for bitumen modification (8% and 15% by binder weight). Marshall Stability and indirect tensile strength as well as rutting resistance increased. Suresha et al. (2010) summarized a lab investigation on porous asphalt modified with cellulose fibers and waste plastics. Modifiers showed significant reduction in moisture-induced damages. Shredded waste plastics were found potentially useful for porous asphalt layers. The investigation on bitumen modification by waste plastic and maleic anhydride (MA) grafted waste polymers (MA-g-WP) showed enhanced storage stability and performance compared to normal WP (Naskar et al., 2012). In this context, the strongest increase in binder performance was found by combining LDPE and EVA for binder modification (Murphy et al., 2000, 2001). Garcia-Morales et al. (2006) also presented a study on bitumen modification with waste from EVA, EVA/LDPE, crumb tyre rubber and ABS. Blends with EVA and LDPE display also promising results in the high temperature regime with higher rutting resistance than non-modified binders. Fuentes-Auden et al.'s (2007) worked with synthetic binders where polymers, resins and oils were mixed to create bituminous like binders. It was found that recycled polymer/oil blends behaved like thermo-rheologically complex materials with a gel-like performance (Kajal et al., 2007).

2.6. Ceramics

Excess stocks and defective products generate a large volume of waste in the ceramic tile industry (Statistisches Bundesamt, 2012). Chemical and mechanical characteristics of ceramic wastes make these materials a good source of alternative aggregates for the pavement industry. Recycled aggregates obtained from ceramic industry wastes were largely used in the recent past in road construction for sub-base courses on low-volume roads as well as in the production of concrete pavements (Koyuncu et al., 2004; Huang et al., 2009; Pacheco-Torgal and Jalali, 2010). Alternatively, ceramic materials, from different manufactural origin, were used as filler for Hot Mix Asphalt. Muniandy and co-workers (Muniandy et al., 2012, 2013) observed significant improvement in term of stiffness and rutting resistance of Stone Mastic Asphalt (SMA) mixtures when incorporating ceramic waste as filler (10% in mixture weight) with respect to conventional limestone filler.

Larger ceramic particles, obtained from of sanitary wastes, were also successfully used in asphalt mixtures (Krüger and Solas, 2008). Van de Ven et al. (2011) studied the feasibility of adding ceramic aggregates from electrical insulators in a base course mixture. No water sensitivity was detected, while a decrease in Marshall Stability could be observed associated with the smoother ceramic particles. Feng et al. (2013) evaluated the performance and thermal conductivity in asphalt pavements with different percentages of crushed ceramic waste. The addition of lower percentage of recycled aggregates reduced the thermal conductivity and rutting potential. The authors concluded that asphalt mixtures with up to 40% substitution of natural aggregate by recycled ceramic aggregate could satisfy the wearing performance requirements.

2.7. Municipal solid waste incineration (MSWI) bottom ash

The incineration of MSW results in reduction in quantity of 65–80% in mass and 85–90% in volume. However, the resulting residues have different characteristics and are divided into bottom ashes and fly ashes (FAs). MSWI FAs are fine particles and have normally a high content of chlorides and significant amounts of toxic substances (such as heavy metals or organic compounds). Fly ash can be used in general as partial replacement for Portland cement. Their disposal in landfills is achieved by treating in a cementitious, organic or vitreous matrix. MSWI bottom ashes however have coarser dimensions, several tens of millimetres in size, with much lower hazardous material content (Bertolini et al., 2004). About 16 Mt of MSWI are produced in Europe each year which are landfilled (Table 3). MSWI bottom ash is an atypical granular material because it may include industrial by-products that result from the incineration of domestic waste. Furthermore, bottom ash from MSWI consists of a mix of inert materials as the combustion process cleans and separates metals and inert components, which could not otherwise be recycled. MSWI bottom ash has shown promising results for the partial substitution of natural aggregates in road construction with enhanced mechanical strength (Becquart et al., 2009). Particular attention has to be made to the heterogeneous nature of this material as this depends on the incinerated material.

2.8. Steel slag

Steel slag has been successfully used as a road construction material because of its advantageous characteristics and mechanical properties. For example, road surface layers constituted of Blast Furnace (e.g. crystallized and vitrified) granulated slag (BF) and Basic Oxygen steel slag (BO) are commonly used in European countries such as England and France (Dunster, 2002; Rockliff et al., 2002; Pascal et al., 2009; Morone et al., 2014). An alternative source of artificial aggregates is given by Electric Arc Furnace (EAF) steel slags which are obtained after a specific industrial production process, (Ellis, 1999; Morone et al., 2014).

The use of steel slag was recently investigated in a numbers of studies. Sofilic et al. (2010) evaluated the feasibility of using EAF steel slag as alternative aggregate source in asphalt pavement by performing a number of micro-structure analyses such as Scanning Electron Microscopy (SEM) showing that this material can be used for asphalt pavement construction and surface treatments. Liapis and Likoydis (2012) evaluated the field response of asphalt mixtures prepared with EAF steel slag demonstrating satisfactory performance in terms of skid resistance and surface texture. The possibility of using EAF steel slag for preparing Warm Mix Asphalt (WMA) mixtures (mixtures prepared at lower temperatures) in substitution for natural limestone was investigated by Mahmoud et al. (2013). Their results show enhanced resilient modulus and tensile strength, as well as reduced moisture sensitivity and permanent deformation for mixtures containing steel slag.

More recently, steel slags such as Linz-Donawitz (LD) slag, were used for preparing porous asphalt (PA) and SMA mixtures (Cannone Falchetto and Moon, 2015) and for partially or entirely replacing the conventional aggregate skeleton (Grönniger et al., 2015). The experimental results indicated that asphalt mixtures prepared with slag are suitable for asphalt pavement construction and that, in most cases they perform better than conventional asphalt mixtures prepared with natural aggregates.

2.9. Textiles

The annual world production of textiles, nonwovens as well as fiber reinforced composite materials amounts to about 90 Million tons (CIRFS, 2014). Due to increased ecological awareness and more stringent legislations, disposal of textile waste is increasingly avoided through the use of recycling technologies. Over 60% of the world production of textiles consists of Synthetic products, while 30% of natural fibers like wool and cotton.

With respect to the recycling process of textiles, two material sources can be identified: industrial waste and consumer waste (Bartl et al., 2005). Industrial waste – derived either during the processing of fibers or during the production of textiles can be easily recycled. The recycling of consumer waste is more complex, because it commonly consists of unknown fiber mixtures and often contains non-fibrous materials such as buttons or other metals.

In the EU, 12.2 Mt of textiles are discarded every year, with only 2.8 Mt (23%) of these post-consumer textiles being recycled while 3.9 Mt is landfilled or burnt in municipal waste incinerators (JRC, 2010).

The use of textiles in road constructions is discussed by Abtahi et al. (2010) who provided a comprehensive overview on the history of fiber reinforcement in pavement. In general the use of fibers in asphalt concrete materials has been investigated with three different targets: improvement of the mechanical response, preparation of electrically conductive mixtures, and establishing of a new market to manage the waste fibers. According to Abtahi et al. (2010) different types of fibers including Polypropylene, Polyester, Cellulose, Carbon, and Nylon were successfully recycled in asphalt concrete materials. It is stated that in general, fibers change the viscoelasticity of mixture; improve dynamic modulus, moisture susceptibility, creep compliance, rutting resistance and freeze–thaw resistance; in addition they help reducing reflective cracking phenomena. Furthermore in the particular case of porous asphalt fibers are used to reduce drain down of the binder.

2.10. Wood

To date waste wood is not commonly used in pavement construction. Two types of use can be identified so far: the use of waste wood as a chemical additive in bitumen and the use of waste wood chips as aggregate substitute (Kandhal, 1993). Bio-oils derived from waste wood resources are thought to be a potential alternative for petroleum asphalt binders in asphalt pavements. In the study conducted by Yang et al. (2013), three types of bio-oils were used at three contents (0%, 5%, 10%). Laboratory and field tests were conducted to identify the properties and perform a durability assessment of a sidewalk pavement containing wood chips. It was shown that this material can be made by crushing construction waste and the by-products of harvested wood and combining it with polyurethane resin. Urethane-to-wood-chip weight ratios of 0.5, 0.75, and 1.0 were used in the laboratory tests. Furthermore, the sidewalk pavement manufactured with wood chips was tested to identify its tensile strength, elasticity, permeability, flammability, and elution. The tensile strength of the pavements containing air-dried wood chips was between 0.2 N/mm^2 and 1.1 N/mm^2, and smaller amounts of urethane resin increased the pavement's strength reduction during flooding. The coefficient of permeability was between 0.5 and 0.8 mm/s and satisfied the 0.1 mm/s specification required for the construction of permeable pavements. The golf ball and steel ball coefficients tended to increase with an increase in the use of resin. A combustible gas torch experiment indicated no problems associated with flammability, and the measured skid resistance (BPN 72 to 77) of the wood-chip pavement satisfied the requirement for the minimum skid resistance value (BPN > 50) of sidewalk pavements. The field construction of sidewalk pavement using wood chips was also executed, and the results of a follow-up study conducted for 6 months after construction showed deterioration of the wood chips, especially for smaller resin ratios. It was found that the changes in surface height, elasticity, and permeability coefficient of pavements with resin ratios of 0.6 and 0.8 satisfied the reference requirements.

3. Sources of target waste materials

Various waste stream sources containing the target waste materials, listed in Section 2, for reuse and recycling in the road construction industry have been identified in the urban and peri-urban environment, as listed below.

3.1. Construction and demolition (C&D) waste

C&D has been identified by the EU as a priority waste stream for reuse and recycling, as the amounts of waste generated per year reach 461Mt, accounting for approximately 25–30% of all waste generated in the EU. However, the current level of its recycling and re-use is estimated to be 46% on average, with significant variations between Member States (<10% to >90%). In some of the member states, this waste stream is to a large extent disposed of, using up valuable space in landfills (ECDGENV, 2011). Increasing costs and new restrictions for landfilling create needs for sustainable reuse and recycling solutions for C&D waste. According to the EU waste framework directive 2008/98/EC, preparing for reuse, recycling and other material recovery of non-hazardous C&D waste must be increased to a minimum of 70% by 2020. C&D in Europe contains many of the necessary target waste materials for roads, as it consists of 12–40% concrete, 8–54% masonry, 4–26% asphalt and 2–4% wood (Fischer and Werge, 2009), and smaller waste fractions of glass (0.66%) (Glass for Europe, 2010), textiles and polyurethane. There is high potential for diverting C&D concrete waste from landfills as approximately 75% of concrete waste could be recycled in road construction (Wahlström et al., 2014). Ceramic wastes from C&D (bricks, tiles) may be re-used/recycled, although the majority of this stream is landfilled (Juan et al., 2010). Almost 100% of the reclaimed asphalt (RAP) may be recycled in-situ for road construction (Wahlström et al., 2014). From the overall generation of C&D wood waste, on average 35% is landfilled and 34% is incinerated while the rest is recycled into timber products (Wahlström et al., 2014). Flat glass waste from C&D, requires considerable cleaning/processing in order to be recycled into glass products (Glass for Europe, 2010). Therefore, a significant part may be diverted from landfills in order to be used as an aggregate substitute. Textile waste from C&D debris constitute 16% of the overall amount of textile waste generated, with the majority of this waste stream being landfilled and incinerated (JRC, 2010; FoEE, 2013).

As it can be seen from the above and the discussion in Section 2, a significant amount of C&D waste may be re-used or recycled in roads, and thus significantly minimize the amount of C&D waste landfilled or incinerated.

3.2. Bulky waste

Bulky waste is a specific type of waste from households including furniture, fixtures, electrical appliances, plasterboards, carpets and green waste. In general, bulky waste constitutes a considerable amount of waste generated in the urban environment which is usually destined for landfills, although there are insufficient data on the quantities generated and their composition in Europe. Indicatively it is mentioned that bulky waste collection in Denmark constituted 26% of municipal waste in 2005 (Larsen et al., 2011). In some of the old EU members, recycling of bulky waste is significant (15% of the total MSW recycling), while in other countries and especially in the new members, recycling rates are much lower (Fischer and Werge, 2009). The output of a study on bulky waste composition of a municipality in Denmark (Larsen et al., 2011) was used to indicatively estimate the potential to use the target waste materials found in bulky waste. If it is assumed that this case is representative of the EU situation, it can be said that approximately 20Mt of bulky waste (∼30%) at EU level consist of waste materials that could be recycled in roads (Table 3).

3.3. Material recovery facilities (MRF)

At the MRFs recyclable waste are separated into the different recyclable waste streams, baled and sent to the recycling industries for further recovery. However, as the necessary recycling infrastructure or the relevant industrial production facilities is not available in all EU countries, significant amounts of these separately collected waste streams are exported for recycling or landfilled. The waste streams that could be recycled locally in road construction are plastics, wood and glass packaging waste (PW) as well as textile waste. With respect to the abovementioned packaging waste streams, Eurostat (2016a) reports that in 2012, 30% (4.5 Mt) of generated plastic PW, 30% (3.5 Mt) of wooden PW and 0.3% (0.04 Mt) of glass PW, were recovered but not recycled probably due to their lower quality for recycling into the same materials, and therefore these amounts remained unexploited.

3.4. End-of-life vehicles (ELVs)

Every year, ELVs generate approximately 6–7 Mt of waste in the EU (Eurostat, 2016b) which should be managed correctly. European Directive 2000/53/EC on ELVs sets quantified targets for their re-use and recovery at a rate of 95% by 2015. While considerable progress has been made in the last decade concerning recycling and reuse of ELVs in several EU countries, there is still room for improvement for achieving the targets, by recycling other vehicle components apart from metal parts, such as tyres, glass, PU and textiles in road construction. In particular, in 2010 about 3.3 Mt of used tyres were generated in Europe (ETRMA, 2011). With respect to the treatment methods applied to this waste stream, it is mentioned that in 2012, 47% was recycled and re-treated (38% and 9% respectively) while a significant amount was incinerated with energy recovery (38%), exported for incineration (6%) and landfilled (9%) (ETRA, 2013). The amounts of waste tyres disposed in landfills were significantly decreased recently, as the European Landfill Directive 1999/31/EC banned landfilling of tyres from 2006. However, this resulted in significant amounts of tyre waste being exported outside EU, thus transferring the problem of their management to other countries. The automotive glass represents approximately 3% (by mass) of the total composition of a car (Glass for Europe, 2010), thus resulting in the generation of approximately 0.2 Mt of ELV glass every year. Due to the fact that the current methods applied for glazing dismantling of this waste stream are complex, the majority of ELV glass is landfilled if not recycled as aggregate substitute (Glass for Europe, 2010). With respect to the PU content in vehicles, this constitutes 10–15% of the average plastic content which is approximately 150–120 kg/car (ISOPA, 2012a), resulting in 0.1 Mt of PU ELV waste generation each year. Finally, ELV textile waste constitutes 2% of the overall textile waste generated each year (or 0.1 Mt) (JRC, 2010; FoEE, 2013).

3.5. Waste appliances

Polyurethane rigid foam (PUR) is the insulating material which is most widely used for refrigerators and freezers. In the EU, it is estimated that around 18 million waste refrigerators and freezers are generated every year, containing 5–10 kg PUR each (Becker, 2008). PUR parts may be dismantled manually and either recycled or used as fuel, depending on national infrastructures (ISOPA, 2012b). However, the majority of PUR waste is still disposed in landfills. An increase in PUR recycling is expected though, as according to the European Waste Electrical and Electronic Equipment WEEE Directive 2012/19/EU, at least 75% and 80 % of large household appliances (incl. refrigerators and freezers) shall be recycled by 2015 and 2019 respectively.

3.6. Thermal waste treatment plants

It is estimated that Waste-to-Energy plants generate 0.23 Mt of bottom ash for every tonne of waste incinerated. In 2009 about 449 Waste-to-Energy plants were operating in Europe with a total generation of 16 Mt of bottom ash (CEWEP, 2010). While in some EU countries landfilling is the dominant management method of bottom ash from the incineration of municipal solid waste (MSWI), in some other EU countries significant quantities (50–100%) of MSWI bottom ash are utilized for road construction and similar purposes (Crillesen and Skaarup, 2006). In addition, waste pyrolysis plants produce substantial quantities of carbon black that can be recycled in roads instead of landfilled.

Table 2
Asphalt concrete components, their percentage in the mixture and possible waste substitutes.

AC Component	% in Mixture by weight	Possible amount[a] [Mt]	Possible Waste Substitutes
Aggregates	90	82.1	Concrete
			Ceramics
			Steel Slag
		44.6	RAP
Filler	3	2.7	Ceramics
			Glass
			Bottom Ash
Binder Addi-tives	2	1.8	Plastics
			PU
			Crumb Rubber
			Wood
			Textiles
			Carbon Black
Binder	5	2.3	RAP
Total	100	133.6	with RAP
		86.7	without RAP

[a] Possible amount is calculated based on 33% of yearly total production of asphalt concrete in Europe.

3.7. Steel and ceramic industries

The amount of steel slag produced by steel industries in Europe totalled about 21.8 Mt in 2010. About 48% of the produced slag was used as aggregates for road construction, 6% for cement production, 10% was used internally for metallurgical purposes, 12% was recycled into other applications, 11% was temporarily stored and 13% was taken to a final deposit (EUROSLAG/EUROFER, 2012). It is therefore considered that about 72% of the produced slag may be recycled in road construction.

Furthermore, it is estimated that the ceramic waste produced by the ceramic industries in Europe account for 30% of their daily production. However, the majority of these wastes cannot be recycled into the current ceramic products and processes and as a result, is destined to landfills (Senthamarai and Manoharan, 2005).

4. Discussion

4.1. Use of waste in roads- a possible scenario

The latest figures regarding the production of asphalt concrete in Europe indicate that 276.4 Mt were produced in 2012, of which 47 Mt (or 17%) was made of reclaimed asphalt pavement (RAP) (Fig. 1, left). Fig. 1 (right) indicates the high potential of using the proposed urban waste materials, if hypothetically 50% of the annually produced asphalt concrete in Europe was replaced by a combination of these waste materials and RAP. As it can be seen, an additional 33% (or 86.7 Mt) of the annually produced asphalt concrete (excluding RAP) could be made up of waste substitutes, under this scenario. This estimate is made as the use of waste is limited by national standards. For example the use of CR is allowed in Spain but not in Switzerland. Or the use of RAP in the surface courses is not allowed in some countries.

In Section 2 the target waste materials and their use were discussed and in Section 3 the source of these target materials was outlined. As explained previously, road pavements consist of coarse and fine mineral aggregates, a binder such as bitumen that acts as glue to keep the composite material together and performance enhancing additives. The literature review listed in the previous sections has shown that the individual components replaced by waste products could improve or have the same performance as all virgin components. Table 2 lists these target materials and their potential use in roads. The composition of an average asphalt concrete such as for example AC11 is approximately 90% aggregates, 3% filler, 2% additives and 5% binder as shown in Table 2. This will results in potentially 82.1Mt waste aggregates, 2.7 Mt waste filler, and 1.8 Mt waste additives as shown in Table 2. Of particular importance is the amount that is listed as percentage in the total mixture as well as the tonnage assuming that 33% of roads would be made of waste components. This table shows what materials could be potentially substituted for aggregates, filler and binder additives. The table does not suggest that they should be combined. Whether or not these components can be combined has to be investigated considering the particular waste components used.

As can be seen from Table 2, in terms of quantity of waste the aggregate substitutes with 82.1 Mt have the most potential. However, from the point of view of the asphalt mixing plant the material costs play a crucial role in the decision making process. Fig. 2 summarizes the calculation results for a US example showing the materials related costs in using RAP in asphalt concrete (Zaumanis,

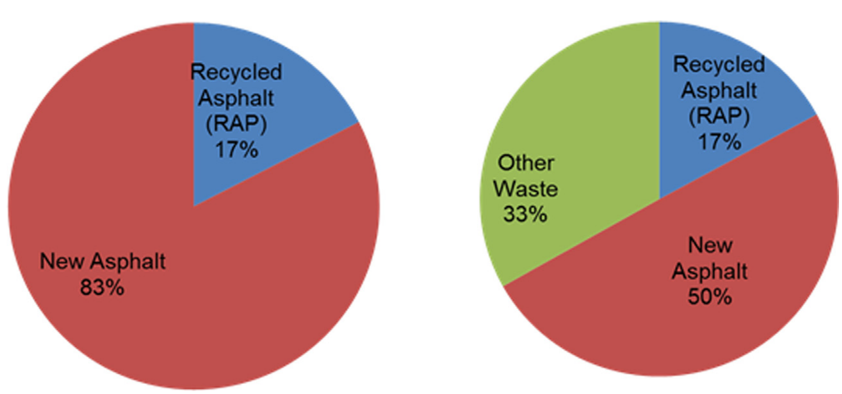

Fig. 1. Left: Current asphalt concrete composition in Europe; Right: possible future scenario.

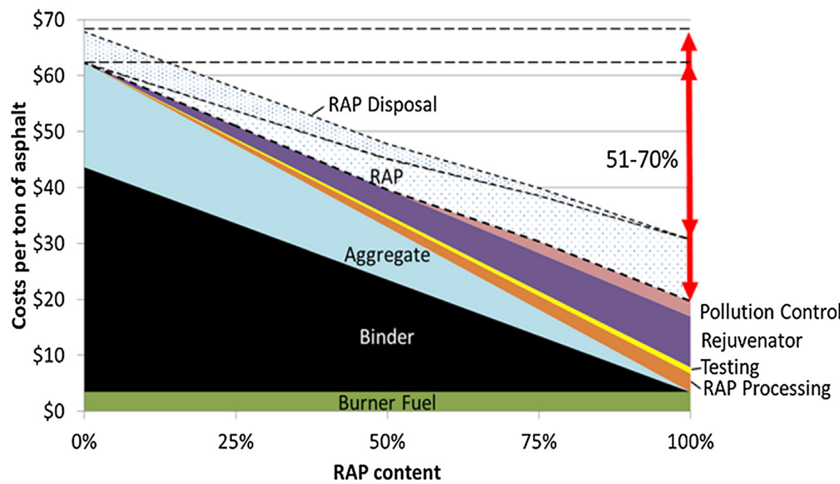

Fig. 2. Material related costs of hot mix recycling (Zaumanis, 2014).

2014). As can be seen from this figure, the bulk of the initial materials costs are from the binder followed by aggregates. The figure shows that although by using RAP additional costs incur such as RAP processing, testing and addition of rejuvenators to name a few, overall the potential for cost reduction when using RAP is 51–70%.

In Table 3 the available quantities of the European target waste materials that would otherwise be incinerated or disposed in

Table 3
Available quantities of target waste materials in Europe and potential for utilization in road construction.

Waste materials	Sources	Generated amount in Europe		Available amount (Mt/y)[a]		Potential for utilization in roads [b]	
		Mt/y	References	Mt/y	References	(Mt/y)	(%)
Concrete	C&D waste	350.0	ECDGENV, 2011	262.5	Wahlström et al., 2014	34.3	13.1
Asphalt	C&D waste	47.0	ECDGENV, 2011	47.0	Wahlström et al., 2014	47[c]	100
Ceramics	C&D waste	200.0	Juan et al., 2010	160.0	Juan et al., 2010	32.1	19.5
	Bulky waste	11.0	Larsen et al., 2011	4.4	Fischer and Werge, 2009[e]		
	Ceramic industry	N.A	–	N.A	–	–	–
Glass	C&D waste	3.0	Glass for Europe, 2010; ECDGENV, 2011	2.6	Glass for Europe, 2010, 2014[d]	1.5	43
	ELVs	0.2	Glass for Europe, 2010; Eurostat, 2016b				
	Bulky waste	1.3	Larsen et al., 2011	0.5	Fischer and Werge, 2009[e]		
	MRF	15.7	Eurostat, 2016a	0.4	Eurostat, 2016a		
Plastics	MRF	15.1	Eurostat, 2016a	4.5	Eurostat, 2016a	0.4	9
PU	C&D waste	N.A.	–	0.3	Zevenhoven, 2004	0.3	100
	Bulky waste	0.1	Larsen et al., 2011				
	ELVs	0.1	ISOPA, 2012a,b; Eurostat, 2016b				
	WEEEs	0.1	Becker, 2008				
Textiles	C&D waste	0.9	JRC, 2010; FoEE, 2013	3.9	JRC, 2010	0.3	7.7
	Bulky waste	2.8					
	ELVs	0.1					
	MRF	1.3					
Tyres	ELVs	3.3	ETRMA, 2011	1.8	ETRA, 2013	0.3	17
	Bulky waste	0.1	Larsen et al., 2011				
Wood	C&D waste	15.0	ECDGENV, 2011	10.4	Wahlström et al., 2014	0.3	2.6
	Bulky waste	5.3	Larsen et al., 2011	1.8	Fischer and Werge, 2009[e]		
	MRF	12.0	Eurostat, 2016a	3.5	Eurostat, 2016a		
Steel slag	Steel industry	21.8	EUROSLAG/EUROFER, 2012	15.7	EUROSLAG/EUROFER, 2012	15.7	100
MSWI bottom ash	Thermal waste treatment plants	16	CEWEP, 2010	16	Crillesen and Skaarup, 2006	1.2	8
Carbon Black		N.A	–	N.A	–	0.2	–
Total		700.4		535.3	With RAP	133.6	24.9%
					Without RAP	86.7	16.1%

[a] Quantities of waste produced that are currently (i) landfilled, incinerated, stored and exported outside the EU or (ii) are already recycled in road construction.
[b] Under the hypothetical scenario of using 50% waste in European roads including RAP.
[c] This amount is not added to the total amount being recycled in the current scenario because it is already recycled in roads.
[d] Based on the statement of the references that the majority of these waste streams are used as aggregate substitute or sent to landfill, it is assumed that 80% of the generated waste quantity is available.
[e] An average of 50% collection and recovery is assumed. The percentage of amount that is available is considered to be the same with that of the respective waste material from C&D.

Table 4
Cost, CO2 and energy savings for four possible asphalt mixtures containing waste products.

	Average standard asphalt		WASTE4ROADS 1		WASTE4ROADS 2		WASTE4ROADS 3		WASTE4ROADS 4	
	Costs		Costs		Costs		Costs		Costs	
	[€/ton mat.]	[€/ton asphalt]	[€/ton mat.]	[€/ton asphalt]	[€/ton mat.]	[€/ton asphalt]	[€/ton mat.]	[€/ton asphalt]	[€/ton mat.]	[€/ton asphalt]
Cost savings	Material costs	82.2	Material costs	67.9	Material costs	70.5	Material costs	70.9	Material costs	86.4
			Savings by material [€]	14.3	Savings by material [€]	11.7	Savings by material [€]	11.3	Savings by material [€]	-4.2
			Savings by material [%]	17.4%	Savings by material [%]	14.3%	Savings by material [%]	13.7%	Savings by material [%]	-5.1%
			Savings by waste [€]	11.5	Savings by waste [€]	14.2	Savings by waste [€]	16.6	Savings by waste [€]	11.2
			Savings by waste [%]	14.0%	Savings by waste [%]	17.2%	Savings by waste [%]	20.2%	Savings by waste [%]	13.6%
			TOTAL SAVINGS [€]	25.8	TOTAL SAVINGS [€]	25.9	TOTAL SAVINGS [€]	27.9	TOTAL SAVINGS [€]	7.0
			TOTAL SAVINGS [%]	31.4%	TOTAL SAVINGS [%]	31.5%	TOTAL SAVINGS [%]	33.9%	TOTAL SAVINGS [%]	8.5%

	Average standard asphalt		WASTE4ROADS 1		WASTE4ROADS 2		WASTE4ROADS 3		WASTE4ROADS 4	
	kg CO2 (GWP)		kg CO2 (GWP)		kg CO2 (GWP)		kg CO2 (GWP)		kg CO2 (GWP)	
	[CO2/ton mat.]	[CO2/ton asphalt]	[CO2/ton mat.]	[CO2/ton asphalt]	[CO2/ton mat.]	[CO2/ton asphalt]	[CO2/ton mat.]	[CO2/ton asphalt]	[CO2/ton mat.]	[CO2/ton asphalt]
CO2 (GWP) savings	Material CO2	29.0	Material CO2	15.1	Material CO2	17.8	Material CO2	23.1	Material CO2	27.2
			Savings by material [CO2]	13.9	Savings by material [CO2]	11.3	Savings by material [CO2]	6.0	Savings by material [CO2]	1.9
			Savings by material [%]	47.9%	Savings by material [%]	38.8%	Savings by material [%]	20.6%	Savings by material [%]	6.4%
			Savings by waste [CO2]	122.9	Savings by waste [CO2]	114.6	Savings by waste [CO2]	56.7	Savings by waste [CO2]	182.1
			Savings by waste [%]	812.1%	Savings by waste [%]	645.1%	Savings by waste [%]	245.7%	Savings by waste [%]	670.2%
			TOTAL SAVINGS [CO2]	136.8	TOTAL SAVINGS [CO2]	125.8	TOTAL SAVINGS [CO2]	62.6	TOTAL SAVINGS [CO2]	184.0
			TOTAL SAVINGS [%]	860.0%	TOTAL SAVINGS [%]	683.9%	TOTAL SAVINGS [%]	266.3%	TOTAL SAVINGS [%]	676.7%

	Average standard asphalt		WASTE4ROADS 1		WASTE4ROADS 2		WASTE4ROADS 3		WASTE4ROADS 4	
	Non-renewable Energy		Non-renewable Energy		Non-renewable Energy		Non-renewable Energy		Non-renewable Energy	
	[MJ/ton mat.]	[MJ/ton asphalt]	[MJ/ton mat.]	[MJ/ton asphalt]	[MJ/ton mat.]	[MJ/ton asphalt]	[MJ/ton mat.]	[MJ/ton asphalt]	[MJ/ton mat.]	[MJ/ton asphalt]
N.-r. energy savings	Material Energy	2725.1	Material Energy	1361.9	Material Energy	1633.4	Material Energy	2168.4	Material Energy	2667.8
			Savings by material [MJ]	1363.2	Savings by material [MJ]	1091.7	Savings by material [MJ]	556.7	Savings by material [MJ]	57.3
			Savings by material [%]	50.0%	Savings by material [%]	40.1%	Savings by material [%]	20.4%	Savings by material [%]	2.1%
			Savings by waste [MJ]	355.0	Savings by waste [MJ]	335.6	Savings by waste [MJ]	301.1	Savings by waste [MJ]	313.4
			Savings by waste [%]	26.1%	Savings by waste [%]	20.5%	Savings by waste [%]	13.9%	Savings by waste [%]	11.7%
			TOTAL SAVINGS [MJ]	1718.2	TOTAL SAVINGS [MJ]	1427.3	TOTAL SAVINGS [MJ]	857.8	TOTAL SAVINGS [MJ]	370.7
			TOTAL SAVINGS [%]	76.1%	TOTAL SAVINGS [%]	60.6%	TOTAL SAVINGS [%]	34.3%	TOTAL SAVINGS [%]	13.9%

landfills is listed. It can be seen that there is high potential in Europe for recycling in road construction, in particular, under the hypothetical scenario where 33% of new roads would be made of the target waste materials (excl. RAP which is already recycled), it is estimated that 16.1% of the available waste quantities could be used excluding RAP and 24.9% with RAP. The individual components were calculated using Table 2 in conjunction and considering the total tonnage of asphalt concrete produced. For example as indicated in Table 3 there is 262.5 Mt of C&D waste if 33% of all new roads contained waste and a percentage of the aggregates used were substituted by C&D waste then the used C&D aggregates in asphalt concrete would be 34.3 Mt/yr or 13.1% of available amounts. In some cases the available amount of that particular waste was the limiting factor not the potential of its use in roads.

4.2. Sustainability consideration

To demonstrate the economic and environmental potentials of the asphalt products that could be produced using waste, the costs, the CO2 emissions (Global Warming Potential – GWP in kg CO2 equivalents) and the non-renewable energy demand of an average European asphalt product has been estimated. Such information can provide vital information for the decision makers, as only through an LCA/LCC analysis can we make the right decisions in terms of viability of using waste for roads. The calculations show clearly that there are economic and environmental advantages to using waste in roads. Four possible asphalt mixtures (WASTE4ROADS 1 to 4) containing various waste products were compared to the results of the average asphalt mixture. Firstly, the savings caused by the application of waste materials was analysed. The determination of the cost savings was based on data provided by the industry. Thereby, the raw material prices were used for the calculation of the production costs. The difference between prices of treated waste and raw material prices were applied to determine the cost savings by avoiding waste disposal. For the calculation of CO2 and non-renewable energy savings it was assumed that waste materials, which were already applied frequently as recycling raw material within building materials (i.e. ceramic, concrete and steel slag aggregates as well as RAP), were afflicted with environmental impacts (stemming from the upgrading process to applicable recycling material), because their application can be seen similar to the application of primary raw materials. Wastes, which are so far not utilized frequently within building materials (i.e. glass, PET, PU, CR, etc.), enter the analyses by introducing the environmental burden free, because the upgrading are assumed to be end-of-life processes for the primary use of these materials. Furthermore, also the savings caused by avoiding waste disposal are determined. Table 4 shows the estimated cost, CO2 and non-renewable energy savings of the four asphalt products applying wastes as raw materials. For example in one of the products that uses CR, avoiding the disposal of crumb rubber in a municipal waste incineration mainly causes the high savings of CO2 emissions. As it can be seen in Table 4 for four types of roads using combined waste products the material costs are reduced (8.5% to 33.9%) and benefit for society in terms of reduced greenhouse gases (266.3% to 860%) and saved non-renewable energy (13.9% to 76.1%) is increased considerably.

5. Conclusions

It was shown that the use of various waste materials in roads is a viable option that needs to be exploited further. The technical readiness level (TRL) among the investigated materials varies greatly. The use of some materials such as crumb rubber is very advanced technically as well as legislatively as demonstrated by the example in California USA whereas, CR finds obstacles in France, Italy and Spain because of local national legislations and sometimes lack of trust in scientific research. The use of other materials such as waste wood needs to be explored further. In order to achieve this efficiently, the involvement of various stakeholders is needed. On the one hand, the waste management professional needs to direct the waste to be used for road construction and, on the other, the road construction professionals have to have access to knowledge regarding handling, preparation and costs as well as the resulting quality associated with the use of such materials. Furthermore the scientific community needs to make a more significant effort to bring the acquired knowledge to the practicing professionals. Last but not least appropriate legislation and standards need to be in place to guide the professionals on the use of waste for road construction. Using four possible scenarios for using waste products in roads it was demonstrated that a significant savings in costs, CO2 and energy can be derived from using waste products in road in comparison to mixtures made of all virgin components.

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