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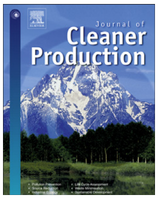

Review

Urban mining for asphalt pavements: A review

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ABSTRACT

The increasing consumption of natural resources for road construction and generation of urban waste materials are two global ecological problems. Urban mining aims to convert waste materials into raw materials for industrial production, and as a result, address both problems simultaneously. This study explores the potential of urban mining for asphalt pavement surface courses. In the first part, as each country/region has its unique challenge with waste materials, a screening method taking the EU and Switzerland as case studies is employed to select waste materials that potentially qualify for asphalt surface courses. The second part presents a review of laboratory studies regarding the performance of asphalt mixtures with selected waste materials. Based on the industrial experience, the third part discusses the technology, specifications and cost considerations of asphalt surface courses with waste materials. Furthermore, the technical maturities for using waste materials are estimated in terms of technology readiness level (TRL). Overall, the paper demonstrates that various categories of waste materials can be potentially used in asphalt surface courses, revealing urban mining opportunities. The selected waste materials may improve the performance of asphalt mixtures with optimization of several factors, such as the fraction size and amounts of waste materials for addition or replacement. The TRL results showed that using crumb rubber (wet process) and steel slag are currently more mature than using other waste materials in asphalt surface course.

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1. Introduction

Roads continue to play the dominating role among various modes of inland transport. In the European Union (EU) for example, 76.4% of 2016 inland freight was transported by roads (Eurostat, 2019). Amongst various road surfaces in Europe, asphalt surface course accounts for more than 90% (EAPA, 2019). This leads to large amount of asphalt mixtures being produced, requiring significant consumption of natural aggregates and asphalt binder. With the increasing number of heavy vehicles on the road network, additives are also required to improve the mechanical properties of pavements. These realities result in multi-dimensional challenges for the road industry, such as the scarcity of natural resources, rising environmental burdens and increasing cost by using performance additives. On the other hand, landfilling waste materials, their toxic emissions and their use as secondary resources are also emerging societal topics (Islam et al., 2020). Compared with the amounts of waste materials generated, the quantity and quality for recycling are still insufficient. For example, the average rate of waste recycling in the EU was ca. 40% in 2016, and the number in Switzerland, although relatively better, was also less than 70% (Eurostat, 2018; FOEN, 2018c). Large amounts of waste materials are being landfilled, uneconomically incinerated and down-cycled, calling for continuous efforts to provide new solutions.

Urban mining aims to convert urban waste materials into raw materials for industrial production, reducing the consumption of natural resources while enhancing the recycling of waste materials. An example from the road industry is the use of reclaimed asphalt pavement (RAP) in new road constructions (EAPA and Eurobitume, 2011). Different layers of asphalt pavements have different specifications, with surface course having the most stringent. As such, using waste materials in asphalt surface course is still not prevalent. However, other advantages warrant the development of asphalt surface courses with waste materials. Firstly, surface course requires regular maintenance during its service life, resulting in considerable consumption of materials. Urban mining can be a potential solution to lower the consumption of virgin materials. Secondly, since surface course has the highest technical and economic values for pavements, we can potentially avoid the down-cycling of waste materials and justify the cost of waste treatments (Huang et al., 2007).

Previous studies have tried to summarize the use of waste materials in asphalt surface course. For example, Huang et al. (2007) reviewed the treatments of four waste materials in the UK and the performance of surface course with those waste materials. The review by Poulikakos et al. (2017) further included the criteria for screening waste materials, as well as the analysis of cost and sustainability. The present paper aims to make following contributions: (1) Further development of criteria to select suitable waste materials for asphalt surface course; (2) Providing an overview of studies with focus on the performance, technology, specifications and cost considerations of surface course with waste materials; (3) Based on available laboratory and field experience, the technical maturities for using different waste materials in surface course are estimated in terms of technology readiness level (TRL). It should be noted that reclaimed asphalt pavement (RAP) is not discussed since it has been investigated in detail in our previous studies and the works from other researchers (Dinis-Almeida et al., 2016; Valdés et al., 2011; Zaumanis et al., 2020; Zaumanis et al., 2014).

2. Selection of waste materials for asphalt surface course

In order to select waste materials that are potentially qualified for asphalt surface course, the following four criteria are proposed:

(1) The performance of asphalt mixtures with the candidate waste material should be comparable to that using virgin materials (results from scientific and industrial experience are taken as reference);
(2) The candidate waste material should be generated locally with enough quantity to make up a considerable portion of raw materials for asphalt surface course;
(3) If the candidate waste material is being recycled by other industries, its application in asphalt surface course should have equivalent or better economic and environmental benefits to that of the current use.
(4) The use of candidate waste material should not be banned by local legislation.

Since the conditions mentioned above may differ from region to region, the present paper takes Switzerland and the EU as case studies to implement the criteria. Same procedures can be carried out for other regions. By applying criterion (1), several waste materials including waste glass, waste textiles, bottom ash, end-of-life tires (ELT), recycled concrete aggregates (RCA), waste ceramics, waste plastics and steel slag can be considered. However, as specified by criteria (2), (3) and (4), the candidate materials should also meet the requirements of availability, legislation and economic/environmental benefits. The material specific analysis is described as follows:

Waste glass: According to Haupt et al. (2017), various modes of glass recycling exist in Switzerland for producing packaging glass, foam glass and glass sand. The environmental benefits of using waste glass in asphalt surface course are comparable to that in glass sand, while these are less than that of packaging and foam glass. Thus criterion (3) is not satisfied. In the EU, 26% of packaging glass is currently landfilled, implying 4 Mt of waste glass that can be potentially recycled (FEVE, 2016).

Waste textiles: Although certain types of waste textiles are suitable for asphalt mixtures, there are also fibers such as cotton that are unsuitable due to their degradable property (Abtahi et al., 2010). The unqualified fibers are usually blended with suitable fibers in many postconsumer textiles, making it complex and costly to separate (Rengel, 2017). In this case criterion (3) is not satisfied for Switzerland and the EU.

Bottom ash: Bottom ash is usually found as residues from municipal incineration plant. Its use in Switzerland is forbidden due to the high content of heavy metals. In the EU, bottom ash aggregates have been used in base/subbase course in the countries such as Germany, Denmark and the Netherlands (CEWEP, 2019). However, considering the leaching aspects, specific regulations need to be legislated for its use in surface courses. Thus criterion (4) is not fulfilled for both case studies.

End-of-life tires (ELT): All the ELT in Switzerland are currently used in terms of energy recovery and material recycling (ETRMA, 2018). Using ELT in asphalt surface course is as competitive as other applications, thus it is possible to consider ELT for Swiss road industry (USTMA, 2018). In the EU, 0.2 Mt of ELT are disposed by storage or landfill, implying recycling opportunities (ETRMA, 2018).

Recycled concrete aggregates (RCA): According to Gauch et al. (2016), the amount of RCA in Switzerland was 6.58 Mt in 2015, of which 0.99 Mt was landfilled. For the EU, Monier et al. (2011) estimated that the recycling rate of C&D waste, in which RCA is the largest group, is ca. 46%. Due to the considerable available amounts, the recycling of RCA is challenging for both Switzerland and the EU. Asphalt surface course can be a potential solution to this problem.

Waste ceramics: In Switzerland and the EU, ca. 30–40% of waste ceramics is not recycled, indicating the possibilities for urban mining (AWEL, 2010; Juan et al., 2010).

Waste plastics: As indicated by FOEN (2018a), every year 0.78 Mt of waste plastics are disposed as waste in Switzerland and 0.7 Mt is used for energy recovery. In the EU, ca. 69% of waste plastics was not recycled in 2016 (PlasticsEurope, 2018). The high rate of incineration and landfill are challenges for the management of waste plastics, leading to potentials for recycling in asphalt surface course.

Steel slag: The annual productions of steel slag are ca. 0.17 and 21.8 Mt in Switzerland and the EU, respectively (EUROSLAG, 2012; FOEN, 2018b). 24% of them is temporarily stored or landfilled in Europe, implying noticeable amounts that can be used in asphalt surface course (EUROSLAG, 2012).

Based on the analysis above, Table 1 summarizes the amounts of qualified waste materials in Switzerland and the EU. "–" refers to the fact that the criteria are not satisfied for the region. It can be seen that RCA has the largest available amount amongst all the qualified materials, followed by waste ceramics, waste plastics and steel slag.

3. Laboratory studies on using waste materials in asphalt surface courses

By applying the criteria in Section 2, the candidate waste materials can be evaluated based on the properties of asphalt mixtures where they are incorporated in. However, the methods to evaluate the properties may vary and need to be clarified as much as possible. In this section, a review of laboratory results for using selected waste materials in asphalt mixtures is presented. The discussed performance includes rutting resistance, moisture resistance, stiffness modulus and fatigue resistance. Although the thermal cracking resistance is also an important concern, it is seldom mentioned in the publications addressing asphalt mixtures with waste materials, thus it is difficult to compare materials using this property. Considering the fact that the performance of asphalt mixtures is closer to field performance than that of binder or aggregates alone, the publications that only study binder or aggregates are not included. In addition, a supplementary document is attached to summarize the information on waste materials, asphalt mixtures and testing methods mentioned by each paper. Since the conditions in Switzerland are mainly focused in this study, waste glass, waste textiles and bottom ash that fail to satisfy the local criteria are not discussed.

3.1. End-of-life tires (ELT)

For the application in asphalt mixtures, ELT is generally processed into crumb rubber (CR). CR can be incorporated by either wet or dry process (Cao, 2007; Poulikakos et al., 2019). In wet process, binder is modified by blending and interacting with CR before mixing with aggregates. In dry process, CR is directly added into aggregates before mixing with binder. Considering the difference between these two methods, the review is presented for wet and dry processes separately. The CR for discussion is not pretreated, unless indicated.

3.1.1. Using CR by wet process

Rutting resistance: Several studies indicated that the rutting resistance of asphalt mixtures can be improved by using CR-modified binder (Kim et al., 2014; Qiu et al., 2011; Shirini and Imaninasab, 2016). In these papers, the content of CR ranged from 5 to 20% by mass of binder and the size of CR was less than 0.6 mm. Additionally, Qiu et al. (2011) and Kim et al. (2014) focused on dense-graded asphalt mixtures while Shirini and Imaninasab (2016) investigated porous asphalt mixtures.

Moisture resistance: Qiu et al. (2011) showed that higher tensile strength ratio (TSR) of asphalt mixtures can be achieved by adding 5–15% CR (by mass of binder), compared with the control specimen with straight run binder. Opposite conclusions were drawn by Kim et al. (2014), in which 8–12% CR (by mass of binder) led to decreased TSR of asphalt mixtures. Pérez and Pasandín (2017) added 10% CR (by mass of binder) and similar TSR results were found between modified and control specimens. However, in their study the air voids content of modified specimens (6%) was higher than that of the control (4.5%). Since high air voids content generally affects the TSR of asphalt mixtures negatively, this weakness might be offset by adding CR, thus similar TSR results were measured. For porous asphalt mixtures, Shirini and Imaninasab (2016) showed that up to 15% CR (by mass of binder) can improve the TSR of specimens, whereas the benefits cannot be seen by adding 20% CR.

Stiffness modulus: Gallego et al. (2007) showed that by incorporating 10% CR (by mass of binder), the stiffness modulus of asphalt mixtures at temperatures from −15 to 40 °C were lower than that of the control. In their study, the air voids content of modified specimen (6.9%) was higher than that of the control (3.8%). This may also lead to low stiffness modulus of modified specimen. Kök and Çolak (2011) prepared the specimens with constant air voids content (ca. 4%) and incorporated 4–10% CR (by mass of binder). Compared with the control specimen, their results revealed that the stiffness modulus of modified specimen was

Table 1
Generated and recycled quantities of waste materials in Switzerland and the EU (MSW: municipal solid waste, CH: Switzerland).

Waste materials		Collected waste		Recycled as materials[a]		Landfilled/Other[b]
		Mt/year	Reference	Mt/year	Reference	Mt/year
Waste glass (MSW)	CH	–	–	–	–	–
	EU[c]	15.7	FEVE (2016)	11.6	FEVE (2016)	4.1
Waste textiles (MSW)	CH	–	–	–	–	–
	EU	–	–	–	–	–
Bottom ash (MSW)	CH	–	–	–	–	–
	EU	–	–	–	–	–
ELT (Other waste)	CH	0.045	ETRMA (2018)	0.02	ETRMA (2018)	0.025
	EU	2.95	ETRMA (2018)	1.75	ETRMA (2018)	1.2
RCA (C&D waste)	CH	6.58	Gauch et al. (2016)	5.59	Gauch et al. (2016)	0.99
	EU	320–380	Monier et al. (2011)	147.2–174.8	Monier et al. (2011)	145.2–172.8
Waste ceramics (C&D waste)	CH[d]	<1.17	FOEN (2015, 2016)	<0.7	AWEL (2010); FOEN (2015, 2016)	<0.47
	EU	200	Juan et al. (2010)	144	Juan et al. (2010)	56
Waste plastics (C&D waste, MSW)	CH	0.78	FOEN (2018a)	0.08	FOEN (2018a)	0.7
	EU	27.1	PlasticsEurope (2018)	8.4	PlasticsEurope (2018)	18.7
Steel slag (Other waste)	CH	0.17	FOEN (2018b)	0.13	EUROSLAG (2012)	0.04
	EU	21.8	EUROSLAG (2012)	16.6	EUROSLAG (2012)	5.2

[a] Quantities that are incinerated for energy generation are not included.
[b] Quantities of wastes that are landfilled, incinerated, stored and exported.
[c] Only packaging glass is considered.
[d] The total amount of waste ceramics/flat glass/gypsum is listed.

higher at 25 °C. Qiu et al. (2011) investigated the stiffness modulus of asphalt mixtures at temperatures from −20 to 10 °C. They reported that the modified specimens with 5–15% CR (by mass of binder) had lower stiffness modulus than the control.

Fatigue resistance: Gallego et al. (2007), Kök and Çolak (2011) and Kim et al. (2014) demonstrated that adding CR improved the fatigue resistance of asphalt mixtures. These results were determined by 3-point-bending test or indirect tensile fatigue test at 20 or 25 °C.

3.1.2. Using CR by dry process

Rutting resistance: Similar to wet process, several studies reported that using CR by dry process can improve the rutting resistance of asphalt mixtures (Cao, 2007; Hassan et al., 2013; Kedarisetty et al., 2018; Lastra-González et al., 2016; Moreno et al., 2014). In these papers, either straight run binder or polymer-modified binder was used for the control specimens.

Moisture resistance: Moreno et al. (2014) and Cetin (2013) showed that adding CR by dry process led to decreased TSR of asphalt mixtures. In the study of Kedarisetty et al. (2018), CR was pretreated into reacted and activated rubber (RAR). The contents of RAR in asphalt mixtures were from 2 to 4% (by mass of mixture). Their results of modified Lottman test showed that the TSR of modified specimens (ca. 90%) was comparable to that of the control (91%).

Stiffness modulus: Lastra-González et al. (2016), Moreno et al. (2014) and Navarro and Gámez (2012) reported that the CR-modified specimens presented higher stiffness modulus than the control. The test temperatures in these papers ranged from 0 to 40 °C.

Fatigue resistance: The 4-point-bending test performed by Lastra-González et al. (2016) showed that at 20 °C, the fatigue resistance of asphalt mixtures was improved by using CR. Moreno et al. (2014) conducted the same test at 10 °C and reported that at low strain levels (<100 μm/m), CR improved the fatigue resistance of asphalt mixtures; while at higher strain levels (>100 μm/m), the modified specimen had worse fatigue resistance than the control. Kedarisetty et al. (2018) reported that at 25 °C, using reacted and activated rubber improved the fatigue life of asphalt mixtures at 450 kPa stress level.

In summary, CR can be used as alternative aggregates or binder modifier. However, it should be noted that the porous structure of CR may absorb the lighter fractions in the binder, leading to swelling of CR (Wang et al., 2020). Possible solutions are using additional binder to assure proper coating of aggregates, or using pretreated CR to refrain swelling (Kedarisetty et al., 2018).

3.2. Recycled concrete aggregates (RCA)

RCA are the products of waste concretes after crushing and grading. In the articles presented in this review, RCA are generally not pretreated, unless indicated.

Rutting resistance: Motter et al. (2015) and Radević et al. (2017) replaced 15–100% of coarse aggregates by RCA. Their results of wheel tracking test showed that the rutting resistance of asphalt mixtures were improved when RCA content was below 75% (by mass of coarse aggregates). Similar results were found by Mikhailenko et al. (2020), in which the specimens with 12, 24 and 32% RCA (by mass of total aggregates) had better rutting resistance than the control. However, Albayati et al. (2018) reported different conclusions by replacing 20–100% of coarse aggregates by RCA. Their results showed that the rutting resistance of all the modified specimens were worse than that of the control, although the RCA were pretreated (by soaking in hydrated lime slurry for 24 h and subsequent drying at 110 °C for 4 h). Mills-Beale and You (2010) and Radević et al. (2017) used RCA to substitute both coarse and fine aggregates. They concluded that RCA can aggravate the rutting of asphalt mixtures. Different results were reported by Ossa et al.

(2016), in which the rutting resistance of asphalt mixtures were improved by using RCA to replace 30–40% of total aggregates. In addition, Chen et al. (2011) showed that the RCA filler can improve the rutting resistance of asphalt mixtures, while Mikhailenko et al. (2020) found the performance similar.

Moisture resistance: Mills-Beale and You (2010), Ossa et al. (2016), Kareem et al. (2018) and Mikhailenko et al. (2020) concluded that the replacement of course and fine aggregates by RCA led to a decrease in the moisture resistance of asphalt mixtures, while Albayati et al. (2018) showed that the TSR of asphalt mixtures can be improved by using pretreated RCA to replace all the coarse aggregates. Chen et al. (2011) reported that the moisture resistance of asphalt mixtures was improved by using RCA filler, while Mikhailenko et al. (2020) found that the performance of using RCA filler is same as using control filler.

Stiffness modulus: The dynamic modulus test performed by Mills-Beale and You (2010) showed that at 5–40 °C, the stiffness modulus of asphalt mixtures decreased when 25–75% of total aggregates were replaced by RCA. Similar conclusions from the testing at 5–25 °C can be found in Radević et al. (2017). However, Arabani and Azarhoosh (2012) showed that at 25 °C, the stiffness modulus of asphalt mixtures increased when all the fine aggregates were replaced by RCA. In the study of Kareem et al. (2018), RCA was coated with cement slag and bitumen water-proofing membrane to reinforce its weak particles and reduce binder absorption. The coarse aggregates of asphalt mixtures were replaced by this pretreated RCA (20–60% by mass of total aggregates). Their results showed that at 40 °C, the stiffness modulus of asphalt mixtures increased for the replacement of 20–40%. Whereas at 25 °C, all the modified specimens had lower stiffness modulus than the control. As filler, RCA presented no effects on the stiffness modulus of asphalt mixtures (Chen et al., 2011).

Fatigue resistance: Several studies reported positive effect of RCA on the fatigue resistance of asphalt mixtures (Albayati et al., 2018; Arabani and Azarhoosh, 2012; Chen et al., 2011; Nejad et al., 2013; Pasandín and Pérez, 2017), while negative conclusion can also be found in Wu et al. (2017).

The reviewed studies indicated that RCA can be used as an alternative to conventional aggregates. Nevertheless, the porous structure of RCA can absorb the binder that may lead to low effective binder content in asphalt mixtures.

3.3. Waste ceramics

Using waste ceramics in asphalt mixtures is similar to the use of RCA. Herein, waste ceramics are generally not pretreated, unless indicated.

Rutting resistance: Wang et al. (2018) used waste ceramics to replace 25–100% of coarse aggregates by volume. Their results showed that all the modified specimens were more resistant to rutting than the control. Opposite conclusions were drawn by Feng et al. (2013), in which waste ceramics replaced 20–80% of coarse aggregates by mass. It should be noted that the polymer-modified binder used in Feng et al. (2013) and unmodified base binder used in Wang et al. (2018) could be a significant contributing factor to the different results. When both fine and coarse aggregates were replaced by waste ceramics, several papers reported that the rutting resistance of asphalt mixtures can be improved (Che et al., 2018; Eisa et al., 2018; Silvestre et al., 2013).

Moisture resistance: According to Muniandy and Aburkaba (2010) and Che et al. (2018), using waste ceramics as filler or fine aggregates resulted in poor moisture resistance of asphalt mixtures. Muniandy and Aburkaba (2010) replaced 100% of virgin filler and Che et al. (2018) replaced 20–100% of fine aggregates by waste ceramics. Different conclusions were drawn by Feng et al. (2013), in which 20–40% of coarse aggregates by mass was replaced by waste ceramics. Their results showed that the moisture resistance of modified specimens was improved. Silvestre et al. (2013) prepared porous asphalt mixtures with 30% waste ceramics (by mass of total aggregates). Their results showed that the TSR of modified specimens was lower than that of the control. Kofteci and Nazary (2018) replaced all the virgin filler and part of fine aggregates by waste ceramics. They reported that only the specimens with 25% waste ceramics (by mass of total aggregates) had higher TSR than that of the control, while the TSR was lower for other modified specimens (with 12.5, 37.5 and 50% waste ceramics).

Stiffness modulus: Muniandy and Aburkaba (2011) and Muniandy and Aburkaba (2010) showed that at 25 °C, the stiffness modulus of asphalt mixtures increased when all the virgin filler (10% by mass of mixtures) was replaced by waste ceramics. Muniandy et al. (2018) reported that at 25 °C, the asphalt mixtures with 20% waste ceramics (by mass of fine aggregates) presented higher stiffness modulus than the control.

Fatigue resistance: In the study of Muniandy and Aburkaba (2011), the size of filler was classified into three groups: 100% of filler passing 0.020 mm sieve; 50/50% passing 0.075/0.020 mm sieve; 100% passing 0.075 mm sieve. They concluded that for the first two groups, using 100% waste ceramics as filler led to a decrease in the fatigue resistance of asphalt mixtures; while for the third group, waste ceramics filler enhanced the fatigue resistance of asphalt mixtures. It shall be noted that previous publications seldom focused on the effect of waste ceramics on the fatigue resistance of asphalt mixtures, thus more research is required.

In short, waste ceramics can be used as alternative aggregates, while the high crushing value and high acicular content may limit the amounts of waste ceramics that are incorporated.

3.4. Waste plastics

Based on the composition, waste plastics can be classified into various categories such as polyethylene (PE), polyethylene terephthalate (PET), polyvinyl chloride (PVC) and polypropylene (PP) with different physical properties. This may affect the methods for adding them in asphalt mixtures. As a result, the review is presented in terms of each category.

3.4.1. Polyethylene (PE)

PE is the first commercially produced vinylic polymer. Its early products were known as low density polyethylene (LDPE) for packaging. Later the high density polyethylene (HDPE) was developed mainly for use in molding (Hocking, 2006). The melting point of PE (ca. 130 °C) is below the asphalt mixing temperature (ca. 160 °C), thus it can be added by either wet or dry process.

3.4.1.1. Using waste PE by wet process. *Rutting resistance:* Punith and Veeraragavan (2007) prepared asphalt mixtures with 2.5–10% waste LDPE (by mass of binder). Their results of dynamic creep tests showed that at 30–60 °C, all the modified specimens suffered less permanent deformation compared to the control. Moghadas Nejad et al. (2014) added 5% HDPE by mass of binder. By conducting dynamic creep tests at 40 and 50 °C, the modified specimens presented better rutting resistance than that of the control.

Moisture resistance: Several studies reported that adding waste PE by wet process can improve the moisture resistance of asphalt mixtures (Al-Hadidy and Tan, 2009; Al-Hadidy and Yi-qiu, 2009; Attaelmanan et al., 2011; Köfteci, 2016; Nouali et al., 2019). In these papers, the contents of waste PE ranged from 0.7 to 10% (by mass of binder).

Stiffness modulus: Punith and Veeraragavan (2007), Attaelmanan et al. (2011) and Nouali et al. (2019) showed that the stiffness modulus of PE-modified asphalt mixtures was higher than that of the control. In these studies, the test temperature ranged from 5 to 25 °C. The PE contents were between 0.7 and 10% (by mass of binder).

Fatigue resistance: The indirect tensile fatigue test performed by Moghadas Nejad et al. (2014) showed that at 15 and 20 °C, 5% HDPE (by mass of binder) can improve the fatigue resistance of asphalt mixtures. To conclude further, more research is required in this area.

3.4.1.2. Using waste PE by dry process. *Rutting resistance:* According to Lastra-González et al. (2016) and Giri et al. (2018), using waste PE by dry process can improve the rutting resistance of asphalt mixtures. The PE contents in two studies were 1% (by mass of total aggregates) and 2% (by mass of mixtures), respectively. Sangita et al. (2011) incorporated waste PE together with CR. The overall content of waste materials was 8% by mass of binder, in which the ratio between waste PE and CR was 4 : 1. Their results of wheel tracking test showed that the rutting depth of modified specimens was ca. 40% less than that of the control.

Moisture resistance: Sangita et al. (2011), Moghadas Nejad et al. (2013) and Giri et al. (2018) concluded that the TSR of asphalt mixtures can be improved by adding waste PE. The PE contents in Moghadas Nejad et al. (2013) ranged from 0.43 to 0.48% by mass of total aggregates.

Stiffness modulus: Lastra-González et al. (2016) showed that at 20 °C, the stiffness modulus of PE-modified asphalt mixtures were higher than that of the control; while Moghadas Nejad et al. (2013) concluded that the stiffness modulus of modified and control specimens were similar at 25 °C. The dynamic modulus test performed by Giri et al. (2018) revealed that the effect of waste PE was temperature dependent: at high temperatures, the stiffness modulus of modified specimen was higher than that of the control; however, at low temperatures, the effect was reversed.

Fatigue resistance: For dry process, studies regarding the fatigue resistance of PE-modified asphalt mixtures are limited in number. One reference can be found in Lastra-González et al. (2016), in which the results of 4-point-bending test at 20 °C showed no effect of waste PE on the fatigue resistance of asphalt mixtures.

3.4.2. Polyethylene terephthalate (PET)

Waste PET is mainly incorporated by dry process due to its high melting point (ca. 240 °C). In the following review, dry process was used by all the papers except Ameri and Nasr (2017).

Rutting resistance: Baghaee Moghaddam et al. (2014), Al-Jumaili (2018) and Ameri and Nasr (2017) reported that PET-modified asphalt mixtures were more resistant to rutting than the control. Specifically, PET (<2.36 mm) with contents from 0.2 to 1% (by mass of total aggregates) were used in Baghaee Moghaddam et al. (2014). PET with higher contents (3–12% by mass of total aggregates) and larger size (2.36–4.75 mm) were incorporated by Al-Jumaili (2018).

Moisture resistance: In the study of Taherkhani and Arshadi (2019), aggregates were firstly mixed with binder for 5 min, then PET was added and mixed for 2 min. Moreover, PET was sorted into two groups by size, with contents from 2 to 10% by mass of binder. Their results showed that for large size PET (1.18–2.36 mm), the TSR of asphalt mixtures can be improved by adding 2–4% PET. For small size PET (0.297–0.595 mm), the TSR of asphalt mixtures can be improved by adding up to 6% PET. Similar conclusions were drawn by Usman et al. (2019b), in which 0.3–1% PET (by mass of mixtures)was incorporated. Their results of modified Lottman test showed that the PET contents from 0.3 to 0.5% led to an increase in the TSR of asphalt mixtures.

Stiffness modulus: Baghaee Moghaddam et al. (2012) added 0.2–1% PET (by mass of total aggregates) and conducted indirect tensile stiffness modulus test at three stress levels (250, 350 and 450 kPa at 20 °C). Their results showed that the horizontal tensile stiffness modulus of asphalt mixtures depended on both the PET content and stress level: at 250 kPa, specimens with 0.2% PET had higher tensile stiffness modulus than the control; at 350 kPa, specimens with 0.2–0.4% PET had higher tensile stiffness modulus; at 450 kPa, all the modified specimens had higher tensile stiffness modulus. Usman et al. (2019a) reported that the PET contents from 0.3 to 0.7% (by mass of mixtures) led to an increase in the tensile stiffness modulus of asphalt mixtures.

Fatigue resistance: According to Baghaee Moghaddam et al. (2012), Modarres and Hamedi (2014) and Dehghan and Modarres (2017), asphalt mixtures with PET presented better fatigue resistance than the control. The PET contents in Modarres and Hamedi (2014) and Dehghan and Modarres (2017) were 10% and 0.5–2% (by mass of binder), respectively. The test temperatures were 5 and 20 °C. Usman et al. (2019a) performed stress-controlled indirect tensile fatigue test at 500, 600 and 700 MPa at 20 °C. Their results showed that at all the stress levels, the fatigue resistance of asphalt mixtures with 0.3–0.5% PET (by mass of mixtures) were better than that of the control, while the PET contents from 0.7 to 1% led to a decrease in the fatigue resistance of asphalt mixtures.

3.4.3. Polyvinyl chloride (PVC)

PVC has a wide range of melting temperatures between 100 and 260 °C, as a result it is possible to use this material by both wet and dry processes. However, the performance of asphalt mixtures with waste PVC was seldom investigated. Herein, three papers using wet process are discussed. Behl et al. (2012) incorporated 3 and 5% (by mass of binder) waste PVC (2–4 mm). Their results showed that the TSR of PVC-modified asphalt mixtures were higher than that of the control. Similarly, Ziari et al. (2019) incorporated 5 and 10% (by mass of binder) waste PVC (2–3 mm). All the PVC-modified specimens presented higher TSR than the control. Small size waste PVC (<0.297 mm) was used by Arabani and Yousefpour Taleghani (2017). The contents ranged from 1 to 5% (by mass of binder). Their results of repeated load axial tests revealed that waste PVC can improve the rutting resistance of asphalt mixtures. Similar conclusions was also drawn by Ziari et al. (2019).

3.4.4. Polypropylene (PP)

PP has a melting temperature between 160 and 166 °C, thus it can be incorporated by both wet and dry processes. Al-Hadidy (2018) and Karmakar et al. (2018) added waste PP by wet process. Al-Hadidy (2018) attempted to demonstrate whether PP can improve the binder resistance to ageing. The PP content was 5% (by mass of binder) and both modified and control specimens were prepared after a 48 and 96 h' ageing. Their results revealed that the TSR of PP-modified asphalt mixtures (ca. 91% for 48 h' ageing and 86% for 96 h' ageing) were higher compared to that of the control (ca. 87% for 48 h' ageing and 81% for 96 h' ageing). Various PP contents (0.5–4.5% by mass of binder) were employed by Karmakar et al. (2018) without ageing. Their results showed that for PP contents from 0 to 2% (by mass of binder), the TSR of asphalt mixtures increased from 82.55 to 105.53%; while for PP contents from 2 to 4.5%, the TSR decreased from 105.53 to 80.55%, implying 2% was the optimum PP content. Additionally, dry process was applied by Lastra-González et al. (2016), in which 1% (by mass of total aggregates) waste PP (>6.3 mm) was incorporated. Their results revealed that PP-modified specimens presented better rutting resistance (at 60 °C), higher stiffness modulus (at 20 °C) and similar fatigue resistance (at 20 °C) compared to the control.

It can be seen that depending on the melting point, waste plastics can be added as alternative aggregates or binder modifier.

Nevertheless, different densities of plastics in comparison to base binder may lead to instability of modified binder, restricting the storage stability.

3.5. Steel slag

As the byproduct of steel production, steel slag contains free calcium and magnesium oxides that may expand due to hydration reactions. As a result, pretreatments such as moist curing are generally required to minimize the risk. In the articles presented in this review, steel slag are generally pretreated, unless indicated.

Rutting resistance: Chen and Wei (2016) and Amelian et al. (2018) replaced 100% of coarse aggregates by basic oxygen furnace (BOF) slag. Their results of Hamburg wheel tracking tests showed that the modified specimens had better rutting resistance than the control. Pattanaik et al. (2019b) prepared porous asphalt mixtures with various contents of electric arc furnace (EAF) slag (25, 50, 75, 100% by mass of coarse aggregates). They concluded that all the slag contents can improve the rutting resistance of porous asphalt mixtures and the specimen with 75% slag had the best performance.

Moisture resistance: Chen and Wei (2016) and Amelian et al. (2018) reported that the moisture resistance of asphalt mixtures was improved by using 100% BOF slag as coarse aggregates. Bocci (2018) employed fine ladle furnace (LF) slag as filler. They reported that the TSR of modified specimens (92.7%) was comparable to that of the control (90.3%). As indicated by Pattanaik et al. (2019a), the moisture resistance of porous asphalt mixtures can be improved by using up to 100% EAF slag as coarse aggregates.

Stiffness modulus: Bocci (2018) and Pattanaik et al. (2019b) showed that the stiffness modulus of asphalt mixtures with steel slag was higher than that of the control at 20 °C. Kim et al. (2018) performed dynamic modulus test at various temperatures (−10, 5, 20, 40, 54 °C). They concluded that steel slag led to an increase in the stiffness modulus of asphalt mixtures at all the test temperatures.

Fatigue resistance: Qazizadeh et al. (2018) reported that using up to 100% EAF and BOF slag as coarse aggregates can improve the fatigue resistance of asphalt mixtures. Pattanaik et al. (2019b) showed that the porous asphalt mixtures with EAF slag had better fatigue resistance than the control. Bocci (2018) showed that under stress-induced loading, using LF slag as filler improved the fatigue resistance of asphalt mixtures; while under strain-induced loading, the fatigue resistance of modified and control specimens were similar.

In short, steel slag can be used as alternative aggregates. The removal of free calcium and magnesium oxides, or the passing of expansion test, should be carried out before use.

3.6. Summary and analysis

Based on the review presented above, it can be seen that the effects of waste materials on the performance of asphalt mixtures depend on several factors, such as the fraction size and amount of waste materials, type and amount of binder, air voids content of asphalt mixtures, test temperature and stress/strain level. Since the overall effect is the interactive actions of various factors, it is difficult to summarize these effects both briefly and comprehensively. Therefore, two summaries are made by this study: in the main text, a simplified summary is made in Table 2; while in the supplementary document, a detailed summary regarding different factors are presented in a number of tables for each waste material. In Table 2, vertical arrows (in green or red) are used when all the reviewed papers have similar comments on the effect of subject waste material on certain performances. Specifically, the green arrow means: (1) better resistance to rutting; (2) better resistance to moisture; (3) higher stiffness modulus (which is not always positive for asphalt mixtures); (4) better resistance to fatigue. The meaning of the red arrow is opposite to that of the green. When a paper presents both positive and negative results due to changing the fraction size or amount of waste material, the green arrow is still used. When there are conflicting conclusions from different papers on the same waste material, the double arrow in yellow is used. Some conflicts can be attributed to the differences in mix design or testing method, which are mentioned in the review above. When the performance of asphalt mixtures is not affected by waste materials, the horizontal arrow in grey is used. When there is no paper studying the corresponding performance, the cross mark " × " is used. It can be seen that waste PE (wet process) and steel slag present consistent abilities to improve the performance of asphalt mixtures, followed by CR, waste plastics (except PE) and waste ceramics. The performance of RCA is relatively inconsistent compared to other waste materials.

4. Field practice for using waste materials in asphalt surface course

Laboratory study is the first step to evaluate the potential for using waste materials. The feasibility should be ultimately demonstrated by field applications. This section presents a review of worldwide practices for using waste materials in asphalt surface course. Most articles in this review were documented in the news, technical reports, scientific papers and specifications from industrial or governmental agencies.

4.1. End-of-life tires (ELT)

In the U.S., the California Department of Transportation (Caltrans) is one of the pioneering agencies reporting the field performance of rubberized asphalt concretes pavements (Zhou et al., 2014). By using wet process, Caltrans showed that the gap-graded rubberized surface course with half thickness can last as long as the conventional dense-graded surface course with full thickness (Rust et al., 1993). For new construction, Caltrans suggested that the gap-graded rubberized surface course should be placed on conventional hot mix asphalt rather than unbounded base layer (Caltrans, 2006). As to economic aspects, Caltrans indicated that the initial cost of rubberized asphalt mixtures ranged from 6.6% less to 13.7% more compared to that of the control, depending on the category of projects (Caltrans, 2019). The specification of wet process in California can be found in Caltrans (2018), referring to the requirements of material production and road construction. According to Heitzman (1992), the early dry process in the U.S. (PlusRide™ technology) prescribed the CR content between 1 and 3% (by mass of mixtures), the CR size being from 2 to 4.2 mm, the air voids content of asphalt mixtures being from 2 to 4% and binder content being from 7.5 to 9%. The projects applying PlusRide™ in California presented varied field performance in the 1980's (Van Kirk, 1991). In Ontario, Canada, eight pilot projects using dry process showed unsatisfactory short term performance (Swearingen et al., 1992). Due to inconsistent performance and lack of standardization, the field application of dry process is limited compared to wet process (Hassan et al., 2014). However, the improved technology such as liquid surface treatment for CR is being developed, making it reliable to use dry process (AsphaltPlusLLC, 2017). According to the producer, this technology has been applied in rubberized asphalt pavements of 12 states in the U.S. (AsphaltPlusLLC, 2018).

In Europe, Spain has seen continuous efforts to promote the use of CR in surface course since 1996. As indicated by Alonso et al.

Table 2
Summary of the effects using waste materials in the asphalt mixture at laboratory scale.

Waste material	Rutting resistance	Moisture resistance	Stiffness modulus	Fatigue resistance
CR from ELT (wet process)[a]	↑	↕	↕	↑
CR from ELT (dry process) [b]	↑	↓	↑	↕
RCA[c]	↕	↕	↑	↕
Waste ceramics[d]	↕	↕	↑	↑
Waste PE (wet process) [e]	↑	↑	↑	↑
Waste PE (dry process) [f]	↑	↑	↕	→
Waste PET[g]	↑	↑	↕	↑
Waste PVC[h]	↑	↑	×	×
Waste PP[i]	↑	↕	↑	→
Steel slag[j]	↑	↑	↑	↑

[a] Gallego et al. (2007); Kim et al. (2014); Kök and Çolak (2011); Pérez and Pasandín (2017); Qiu et al. (2011); Shirini and Imaninasab (2016).
[b] Cao (2007); Cetin (2013); Hassan et al. (2013); Kedarisetty et al. (2018); Lastra-González et al. (2016); Moreno et al. (2014); Navarro and Gámez (2012).
[c] Albayati et al. (2018); Arabani and Azarhoosh (2012); Chen et al. (2011); Kareem et al. (2018); Mikhailenko et al. (2020); Mills-Beale and You (2010); Motter et al. (2015); Nejad et al. (2013); Ossa et al. (2016); Pasandín and Pérez (2017); Radević et al. (2017); Wu et al. (2017).
[d] Che et al. (2018); Eisa et al. (2018); Feng et al. (2013); Kofteci and Nazary (2018); Muniandy and Aburkaba (2011); Muniandy and Aburkaba (2010); Muniandy et al. (2018); Silvestre et al. (2013); Wang et al. (2018).
[e] Al-Hadidy and Tan (2009); Al-Hadidy and Yi-qiu (2009); Attaelmanan et al. (2011); Köfteci (2016); Moghadas Nejad et al. (2014); Nouali et al. (2019); Punith and Veeraragavan (2007).
[f] Giri et al. (2018); Lastra-González et al. (2016); Moghadas Nejad et al. (2013); Sangita et al. (2011).
[g] Al-Jumaili (2018); Ameri and Nasr (2017); Baghaee Moghaddam et al. (2012); Baghaee Moghaddam et al. (2014); Dehghan and Modarres (2017); Modarres and Hamedi (2014); Taherkhani and Arshadi (2019); Usman et al. (2019a); Usman et al. (2019b).
[h] Arabani and Yousefpour Taleghani (2017); Behl et al. (2012); Ziari et al. (2019).
[i] Al-Hadidy (2018); Karmakar et al. (2018); Lastra-González et al. (2016).
[j] Amelian et al. (2018); Bocci (2018); Chen and Wei (2016); Kim et al. (2018); Pattanaik et al. (2019a); Pattanaik et al. (2019b); Qazizadeh et al. (2018).

(2018), almost 300 rubberized asphalt pavements with a total length of 1600 km have been constructed in Spain, consuming 17 000 t of CR. Wet process was applied in 87% of total length and the rest was constructed by dry process. Most trial sections showed satisfying performance with the passing of years and adverse conditions. Alonso et al. (2018) also estimated that the unit cost of asphalt rubber binder was ca. 22% lower than that of polymer-modified binder. Along with pilot projects, specific regulations were also developed in Spain, such as "Circular Order 21/2007 on the specifications that must be met by binders and mixtures containing rubber from ELT" (OrdenCircular, 2007). Pilot projects can also be found in other European countries such as Portugal, Sweden and Italy (Antunes et al., 2000; Nordgren and Preinfalk, 2009; Sangiorgi et al., 2018). As a follow up of a recently completed project, three Swiss Cantons are constructing test sections implementing CR-modified asphalt mixtures using dry process. In Asia, China started the construction of rubberized asphalt pavements since 2004, initially motivated by the positive field experience of California and Arizona (Way et al., 2015). Up to now, localized specifications and guidelines have been published in various regions such as Jiangsu, Beijing and Tianjin (Beijing, 2006; Jiangsu, 2006; Tianjin, 2006). In Africa, the technology of Arm-R-Shield™ was introduced from Arizona to South Africa in 1983. In the following years the resulting rubberized asphalt pavements presented outstanding performance (Renshaw et al., 2007). The Southern African Bitumen Association have also published the guidelines for using asphalt rubber binder in asphalt pavements (Sabita, 2015).

4.2. *Recycled concrete aggregates (RCA)*

Compared to the practice of CR, the field application of RCA is very limited in asphalt surface course. This can be explained by the inconsistent performance of RCA-modified asphalt mixtures, as depicted in the review of laboratory studies in Section 3.2. Even in base/subbase course, using RCA may still be challenging due to insufficient trust in RCA quality (Toop, 2019), the restriction of legislation (Redling, 2020) and the concern over cost (Caulfield, 2020).

4.3. *Waste ceramics*

Similar to the case of RCA, using waste ceramics in asphalt surface course is mainly at laboratory level. For the field practice, base/subbase course and light traffic roads are still the preferred options for using waste ceramics in pavements (Mazzoni, 2012; Shinn, 2020).

4.4. *Waste plastics*

The road industry in the U.S. used postconsumer PET to develop a stabilizer for RAP (TechniSoil, 2019). By mixing crushed RAP with this stabilizer, they were able to pave a surface course with 100% RAP and achieve satisfying field performance (Hajj et al., 2017). This technology was recently applied in the repaving work of downtown Los Angeles (Peters, 2019). The chemical industry in the U.S. also developed plastic-modified binder in place of conventional polymer-modified binder (DowChemical, 2019b). The plastic binder was applied to construct two ca. 2600 feet (792 m) pavements in Freeport, Texas, using 1686 pounds (ca. 765 kg) of recycled linear LDPE and meeting the requirement of PG 70–22 (DowChemical, 2019a). In Europe, the binder modifier with waste plastics was developed and applied in several regions of UK such as Durham, Coventry and Cumbria (Barrett, 2019; Cumbria, 2019; Durham, 2018) Moreover, this technology is spread internationally to the regions such as Persian Gulf and Australia (Graham, 2019). In

2019, a trial section using this technology was also constructed in Zermatt, Switzerland (Frost, 2019). In Asia, India began the construction of plastic-modified pavements since 2002. The technology is based on dry process, mixing heated aggregates with shredded plastics within 30–60 s, then adding hot binder to produce asphalt mixtures (Thiagarajan, 2018). This technology has been applied in several states of India with a total length more than 10 000 km. In 2015, a governmental order was issued to make it mandatory to use waste plastics in road construction (Menon, 2016).

4.5. Steel slag

In the U.S., at least 16 states were reported to use steel slag as aggregates for asphalt pavements, mostly in surface course (Stroup-Gardiner and Wattenberg-Komas, 2013). In 1994, a trial section was constructed in Oregon using 30% steel slag. Parameters such as rutting, skid resistance and roughness were tested after five years' service. Their results indicated that the pavement with steel slag had similar performance to the conventional pavement (Hunt and Boyle, 2000). In an Illinois example, an intersection had a problem of low durability due to high traffic loads from trucks. An effective solution was demonstrated by using stone matrix asphalt (SMA) surface treatment with steel slag. The modified surface course significantly improved the durability from a few months to more than five years due to enhanced rutting resistance and friction (NSA, 2001). Considering the existence of calcium and magnesium oxides in steel slag, the specifications of many states require one to six months' moist curing and/or expansion tests in advance (WSDOT, 2015). As to economic concerns, the experience of Illinois and Iowa showed that the cost of local steel slag was normally equivalent to the cost of importing high friction aggregates. However, it would be uneconomical when long distances were required to transport steel slag (WSDOT, 2015).

In Europe, Germany had trial sections as early as 1980s (Motz and Geiseler, 2001). Their projects reported strong bearing capacity of steel slag and high polishing resistance of modified surface course (Motz and Geiseler, 2001). Their experience also showed that it is possible to apply steel slag in low noise pavements, which require high quality aggregates to prepare open-graded surface course (Thomé-Kozmiensky, 2014). Another example can be found in Croatia, where a 200 m trial section with 70% steel slag (by mass of total aggregates) was placed. Their field tests indicated that the trial section had better resistance to rutting compared to the control (Rastovčan-Mioč et al., 2010). In Australia, some surface treatments have suffered short durability due to heavy transportation. In 1992, the local Roads and Traffic Authority started using 14 mm dense-graded surface courses with steel slag. Specifically, steel slag accounted for 87.9% by mass of mixtures and C320 binder with 5% gilsonite was used. The modified surface course performed well until it was replaced in 1998. Based on the successful experience, steel slag was also applied in 20 mm dense-graded and 10 mm open-graded surface courses (ASA, 1999).

4.6. Summary and analysis

Based on the review above, a summary is made in terms of following aspects:

Mechanical performance: Asphalt surface course with ELT, waste plastics and steel slags were demonstrated to have superior or competitive field performance compared to the control. Using ELT by traditional dry process may result in unqualified performance. However, recent technology is remedying the shortcomings and presents good prospects. It is difficult to reach conclusive results on using RCA and waste ceramics due to insufficient field applications.

Economics: Asphalt rubber can be economical compared to polymer-modified binder. High market value can also be achieved for waste plastics if they are able to substitute the virgin polymer in asphalt. The cost of steel slag depends on its source. It is suggested to use local steel slag avoiding long distance hauling. Inferior mechanical performance can shorten the lifespan of surface course, which in turn increases the consumption of materials during a certain period of time and offsets the cost reduction by using waste materials.

Sustainability: Urban mining is expected to maintain the availability of natural resources and lower the environmental burdens of virgin material production and waste disposal. However, using waste materials may have complex environmental impacts when its whole value chain is considered. The burdens may not be really eliminated, while are shifted from one process to another (Hellweg and Milà i Canals, 2014). Therefore, it is suggested to assess the impacts of waste materials in surface course from "cradle to grave" and analyze case by case.

Table 3
Estimated TRL for using waste materials in asphalt surface course (CH: Switzerland).

Waste Material	Region	TRL	References
CR (wet process)	World	7–9	Alonso et al. (2018); Caltrans (2018); Sabita (2015); Way et al. (2015); Zhou et al. (2014)
	CH	1–4	Loderer et al. (2018)
CR (dry process)	World	5–7	Alonso et al. (2018); AsphaltPlusLLC (2017); Hassan et al. (2014); Swearingen et al. (1992)
	CH	1–4	Rodríguez-Fernández et al. (2020)
RCA	World*	1–4	Caulfield (2020); Redling (2020); Toop (2019)
	CH	1–4	Mikhailenko et al. (2020)
Waste ceramics	World*	1–4	Mazzoni (2012); Shinn (2020)
	CH	<1	N.A
Waste plastics	World	5–7	Graham (2019); Hajj et al. (2017); Thiagarajan (2018)
	CH	5–7	Frost (2019)
Steel slag	World	7–9	ASA (1999); Hunt and Boyle (2000); Motz and Geiseler (2001); Rastovčan-Mioč et al. (2010); WSDOT (2015)
	CH	<1	N.A

[*] Laboratory studies can be found in Table 2.

5. Technology readiness level (TRL)

The current technical maturities for using waste materials in asphalt surface course are evaluated in terms of TRL, in order to find the relation between laboratory and field experience, as well as the gap between current progress and complete industrial application. TRL was initially proposed by the U.S. National Aeronautics and Space Administration (Banke, 2017). The latest evaluation system includes nine levels with increasing maturities (NASA, 2017). To reduce the subjectivity of authors' judgements, this article simplified the nine-level-system into four groups: "< 1″ infers that the topic has not been investigated; "1 to 4″ refers to the progress at laboratory scale or lower; "5 to 7″ indicates that pilot projects have been implemented in the field; "7 to 9″ infers that the application is partially or completely industrialized. TRL results are shown in Table 3, indicating that using CR (wet process) and steel slag present the highest maturities with wide acceptance, legislation permits and developed specifications at worldwide scale. This is followed by using CR (dry process) and waste plastics, with gaps of limited acceptance and incomplete specifications. Using RCA and waste ceramics have the lowest TRL. The reasons can be attributed to insufficient reliable performance, legislative restrictions and economic concerns. TRL results at Swiss scale are generally lower than the worldwide values, implying more barriers for using waste materials in asphalt surface course. According to the communication between authors and Swiss industrial partners, the primary reason of low TRL is lack of economic motivation due to sufficient capital and abundant natural aggregates. Another reason is the preference for closed-loop recycling, which impedes using waste materials across different industries. Lastly, the uncertainties of environmental impacts and regulations also limit asphalt surface course with waste materials (Eberhard, 2020).

6. Conclusions

This study discussed the potential waste materials that can be used in asphalt surface courses. The conclusions are drawn as follows:

(1) Waste materials including waste glass, ELT, RCA, waste ceramics, waste plastics and steel slag have the potential to be used in asphalt surface courses in the EU. These waste materials are also suitable for Switzerland except waste glass. Waste textiles and bottom ash are currently not suitable for both regions due to cost and legislation concerns;

(2) Based on the review of laboratory studies, the selected waste materials may improve the performance of asphalt mixtures when various factors are optimized. These factors include the fraction size and amount of waste materials, type and amount of binder, air voids content of asphalt mixtures and suitable testing methods. In some cases pretreatments are also required;

(3) The review of laboratory and field experience presented varied maturities for using waste materials. The TRL results indicated a wider industrial acceptance for using CR (wet process) and steel slag. In contrast, RCA and waste ceramics are seldom applied in the field. The reason can be explained by weak performance, legislative restrictions, uncompetitive costs and incomplete specifications;

(4) Compared with the worldwide developments, waste materials are seldom used in Swiss asphalt surface courses, implying a gap in experience but also a potential for recycling certain materials in roads. The reason can be attributed to lack of economic motivation, preference for closed-loop recycling and strict environmental regulations.

In future studies, two aspects need further investigation: (1) Finding engineering solutions to use waste materials in asphalt surface courses, including relevant test methods; (2) Assessing the economic and environmental viabilities of asphalt surface courses with waste materials. For this purpose, the methodologies of life cycle assessment and life cycle cost assessment would be relevant.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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