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A review on pavement porous concrete using recycled waste materials

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Abstract. Pavements porous concrete is a noble structure design in the urban management development generally enabling water to be permeated within its structure. It has also capable in the same time to cater dynamic loading. During the technology development, the quality and quantity of waste materials have led to a waste disposal crisis. Using recycled materials (secondary) instead of virgin ones (primary) have reduced landfill pressure and extraction demanding. This study has reviewed the waste materials (Recycled crushed glass (RCG), Steel slag, Steel fiber, Tires, Plastics, Recycled asphalt) used in the pavement porous concretes and report their respective mechanical, durability and permeability functions. Waste material usage in the partial cement replacement will cause the concrete production cost to be reduced; also, the concretes' mechanical features have slightly affected to eliminate the disposal waste materials defects and to use cement in Portland cement (PC) production. While the cement has been replaced by different industrial wastes, the compressive strength, flexural strength, split tensile strength and different PC permeability mixes have depended on the waste materials' type applied in PC production.

Keywords: Pavements Porous Concrete (P.P.C); waste materials; pavements porous concrete; glass waste; recycled crushed glass; steel slag; steel fiber; tires waste; plastic waste; recycled asphalt; Pervious concrete

1. Introduction

There is a growth in the amount and type of waste materials across the population increment. Majority of waste materials such as stockpiles, landfill material or illegally dumped (Bhargava *et al.* 2003, Sharbatdar 2008, Aghaee and Foroughi 2013, Aghaee *et al.* 2014, Abedini *et al.* 2017, Ji *et al.* 2017, Bao *et al.* 2016) have been remained no decayed in the environment for long years (Sakhaeifar *et al.* 2015, Nobakht *et al.* 2017) causing a waste disposal crisis and environmental pollution specifically in dense populated areas (Batayneh *et al.* 2007).

Pervious concrete (PC) with a high void content has been potentially used to decline the rain-water runoff defined as porous, permeable and no fine concrete (Joshaghani 2016); moreover, according to ACI522R-10, PC has compromised almost the least slump, open-graded material with Portland cement, course aggregates, the least fine aggregates, admixtures, and water (ACI , Kacha).

The solid waste amount and its distribution within the disposal method and the activity type have indicated the total solid (85%), waste (20%), glass, plastic, so the concrete (1721.8 tons/year) has belonged to the building construction with 90% dumped, flowingly, the nomination of other disposal methods is an essential (Benazzouk *et al.* 2006, Olivier *et al.* 2012). While the cement production has produced 8% greenhouse (Talsania *et al.* 2015), the production of 1-ton Portland cement applied in civil engineering (Ghataora *et al.* 2004, Ganjian *et al.* 2015) has released approximately 1-ton carbon dioxide contributing to the greenhouse, moreover, the Portland cement has greatly demolished the environment. The Portland cement less production and its replacement by non-carbon dioxide has produced cementitious products with low carbon concrete products with the least impact to its durability and other physical properties (Ghataora *et al.* 2004, Ganjian *et al.* 2015).

In the recent years, few studies have focused on the cement and concrete product conversion with the aim of using waste glass, recycled crushed glass (RCG), steel slag, steel fiber, tires and plastics in pervious concrete (PC) to eliminate the disposal problems and develop the PC mechanical features (Shah and Pitroda, Bazzaz 2018b). However, due to the lack of the superior strength and durability in conventional PC pavement, material engineering has focused on its physical, structural and mechanical features development. Also, considering the PC pavement's voids and porosity (Ramadhansyah *et al.* 2014, Shakrani *et al.* 2017), obtaining great strength through the ordinary materials and their mixtures are almost impossible. Consequently, adding materials such as admixture and

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superplasticizer cement or aggregates replacements besides few waste materials and Nano-materials have been applied to increase the properties of PC pavement (Huang *et al.* 2007). This study has reviewed the waste materials (Recycled crushed glass (RCG), Steel slag, Steel fiber, Tires, Plastics, Recycled asphalt) used in the pavement porous concretes and report their respective mechanical, durability and permeability functions.

2. Recycled waste materials

Waste materials with large fractions have been applied in the road or building projects. Align with the current study in waste glass, steel slag, tires and plastics description, the outer layers including the surface and binder course of the asphalt pavements are used commonly (Edwards and Schelling 1999, Gonzalez-Torre *et al.* 2003, Krivtsov *et al.* 2004).

2.1 Glass

Since the container recycling rate and flat glass is 36% and 30%, therefore, 1.1 Mt (33%) of waste glass has been recycled, when 0.73 Mt (66%) has belonged to glass container products and 0.14 Mt (13%) is for secondary aggregate. Finally, 2.3 Mt (67%) of waste glass has been buried (Driscoll and Slutter 1961). The recycling phenomena have served both as a recyclable waste passive container and a common recycling habit motivation. Glass has been recycled with no product quality losing; in great quantities, changing the recycled cullet to a glass-making plant has saved energy and mineral resources (Brinkler 2004). Waste glass (aggregate) has not saved great energy or minerals than the glass making (Chesner *et al.* 1998), however, the color disharmony of waste glasses has provoked to find diverse opportunities in aggregates usage (Turgut and Yahlizade 2009). The use of concrete recycled glass has been performed by the alkali-silica reaction (ASR) due to the reactive content of silica in the glass (≥70%) (slag 2001). The waste glass used as an aggregate in asphalt road construction might carry few technical features.

2.2 Recycled crushed glass (RCG)

On waste glass application in construction, it should be crushed and screened to provide the most proper design gradation (Kalyoncu 2001). In a proper size and process, crushing the glass or cullet has exhibited properties similar to the gravel or sand.

2.3 Steel slag

Considering the stable process and the consistent slag generation rate, the steel production processing outcome has estimated the amount of steel slag. Based on US NSA (National Slag Association), steel slag is (7.5–15)% of produced steel (Hird *et al.* 2002) and the marketable slag through USGS (US Geological Survey) is (10–15)% steel production (Hird *et al.* 2002). The recycling steel slag has been gathered from a few steel plants providing more effective set than the other solid waste materials. Thus the controlling and achieving of waste materials consistent quality is more applicable. The steel slag 100% recycling has been prioritized in asphalt pavements.

2.4 Steel fiber

The Steel fiber of Krampe Harex has hooked ends 35 mm in length and 0.5 mm in diameter (DE 35/0.55N) with a tensile strength of roughly 1250 N/mm^2.

2.5 Tires

While tires are shredded (21%) and considered as the raw materials, some have been used for energy recovery (22%), and some in landfills, stockpiles or illegal dumps (34%) (Group 2001, Tiernan 2005). In the last decade, around 40,000 t (or 9%) is combusted in cement kilns due to the scrap tires' energy value to coal used as fuel in cement production (Shulman 2000). The high processing cost, according to Transport Research Laboratory (TRL) (guidance which is related to recycling in transport infrastructure), has belonged to the unregulated tires disposal developing. Waste tires' transportation cost is averagely around £1/ton/km based on European Tire Recycling Association (ETRA) (Shulman 2000). Despite the technical viable the scrap tires usage in asphalt or pavements has been subsidized to compete with conventional aggregates (Patel 2000) providing the technical requirements of asphalt pavements.

2.6 Plastics

Majority of plastics recycling has been maintained by domestic industrial and commercial sources (e.g., bottles), considering economic barriers (Hassan *et al.* 2004). Any recycling growth depends on the effective mixed plastic through the robust environmental assessment method (Parry 2004). Likewise, the rubber, recovery plastic waste is to gain the thermal content (38 MJ/kg), comparing the coal (31 MJ/kg) and CO2 emissions (greenhouse). Accordingly, recycled plastics have been routinely applied in public, insulation, ducts and piping but less in pavement construction (WRAP 2003c). Like glass, the low Packaging Waste Recovery (PRN) is regarded for low recycling levels (WRAP 2003b). Despite the plastic packaging in the majority of plastic recycling, Poly Vinyl Chloride (PVC) has been used as the lowest recycling rate (Pratik and Patel 2014). The common opinion has leaned more on the financial incentives than the specifications that affect the recycling activity (Sriravindrarajah *et al.* 2012), so the plastics of asphalt pavements have provided crucial materials' outlet.

2.7 Recycled asphalt materials

Reclaimed or recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) have been widely used in Hot Mix Asphalt (HMA) in Texas. The possible use of RAP and RAS in Portland Cement Concrete (PCC) not only would help dispose of excess RAP and RAS, but also provide a cost reduction for aggregates in hydraulic cement concrete. The asphalt paving engineering community has always advocated recycling, including RAP, RAS, tires, etc. (Bazzaz 2018a, Bazzaz *et al.* 2018, Bazzaz 2018b). This promotes substantial cost savings and conservation of aggregates and asphalt.

The increasing maintenance and rehabilitation actions lead to considerable amounts of RAP left in stockpiles in the United States. The possible use of RAP in PCC as aggregate replacement not only would help dispose of excess RAP stockpiles, but also provide a reduction in virgin aggregate consumption in PCC, which brings significant benefits from both economic and environmental standpoints.

RAP contains mainly aggregate with adhering aged asphalt film and can be successfully reused for new constructions. A research in 2013 conducted surveys of RAP usage in the United States (Hansen and Copeland 2013). Their results show that the overwhelming majority of RAP is used in MHA or WMA (Warm Mix Asphalt), which is considered to be an effective way to reduce RAP stockpiles. However, most department of transportations (DOTs) only allow the RAP fraction in the HMA up to 20%, because the addition of too much RAP is likely to cause serious reduction in pavement performance. Besides HMA/WMA application, RAP can also be used in the base and cold mix. RAP has been put into landfills as well, but those amounts are fairly small (Fig. 1).

Recycled Asphalt Shingles (RAS) are other recycled materials that have been successfully used in the HMA construction. Two main types of RAS are used in roof construction based on their base compositions: organic cellulose and fiberglass. Table 1 lists their composition

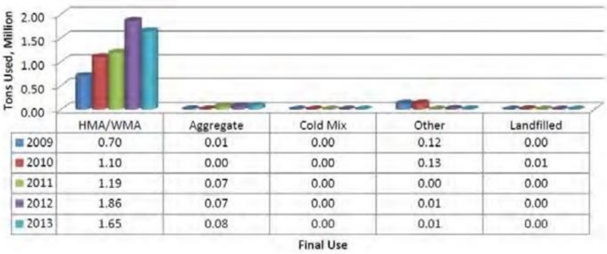

Fig. 1 RAP with Different Usage (Million Tons) (Hansen and Copeland 2013)

Table 1 Composition of RAS

Organic	Asphalt	(30~35)%
	Mineral fiber	(5~15)%
	Mineral and ceramic-coated granules	(30~35)%
Fiberglass	Asphalt	(15~20)%
	Felt	(5~15)%
	Mineral filler	(15~20)%
	Mineral and ceramic-coated granules	(30~35)%

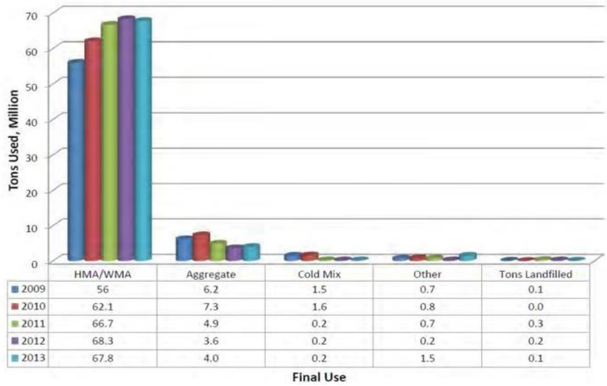

Fig. 2 RAS with Different Usage (Million Tons) (Hansen and Copeland 2013)

RAS can be classified as manufacturer waste shingles and tear off shingles based on the source they are from. Manufacturer waste is known as roofing shingle tabs or punch-outs, and it includes out-of-spec, miscolored, or damaged shingles (Griffiths and Krstulovich 2002).

Similar to RAP, RAS is also mainly used in producing HMA and WMA. RAS materials generally contain 15 to 35% of asphalt binder. As a result, RAS can serve as a good source of asphalt binder and this could provide an annual savings of $1.1 billion for asphalt industry (Council 2011).

The use of negligible amount of RAS in cold mix, landfill and base was also reported as shown in Fig. 2 (Hansen and Copeland 2013).

The major conclusions from this project are:

1) The coarse RAP with suitable gradation containing sufficient intermediate size particles can help make dense graded concrete. The dense graded RAP-PCC showed better workability and mechanical properties compared to the other gap graded RAP-PCC.

2) The major weak point of the RAP-PCC system is the asphalt. Asphalt cohesive failure (i.e., crack easily propagate through the asphalt layer around the RAP particles) is the major failure mechanism.

3) Compared with the material production for plain PCC pavement, the production of materials for constructing RAP-PCC pavements (either full-depth or two-lift) was more economical and consumed less amounts of energy. It released less amounts of air pollutants, greenhouse gases, and toxic materials. It also led to less land use and water withdrawals.

4) The idea of using RAP-PCC as the bottom lift in a two-lift.

PCC pavement can maximize the RAP usage without compromising the pavement performance or compromise within the permissible limits (Mukhopadhyay and Shi 2017).

3. Literature on pavements porous concrete

The PC properties by replacing the cement with fly ash (20%) and silica fume (10%) have been examined in the presence of A/C (4:1) and W/C (0.30, 0.35 & 0.40) by Patel *et al.* (2014), then the W/C growth from 0.30 to 0.40, the compressive strength, flexural and split tensile strength have also been raised, however, permeability has stepped down in the previous concretes containing 20% fly ash and 10% silica fume (Pratik and Patel 2014).

Another study have focused on the PC in cement replacement (35% and 70%) with ground granulated blast furnace slag (GGBFS) indicating that on GGBFS increasing, the compressive strength might have shown an increasing but decreasing in permeability (Jain and Chouhan 2011). Accordingly, the permeability and compressive strength have depended on the particle size and A/C ratio. Through the use of A/C (ratio 6:1, 8:1 & 10:1), A/C (6:1) has shown the highest compressive strength compared to the A/C (8:1 & 10:1); Therefore, the combination of prior A/C ratios with greater A/C ratio (8:1 & 10:1) have been ratified in the pavement requiring low compressive strength and high permeability rate. Thus, the coarse aggregates small sizes might be capable to provide a greater compressive strength and more permeability rate (Jain 2011). Meanwhile, the permeability has been determined by the water-cement ratio, aggregate shape and size. In all PC mix aggregates, the produced small aggregates have shown a greater compressive strength (Ravindrarajah and Yukari 2010). Following, the permeability has highly dependent on W/C ratio and aggregate size. Thus, the produced smaller aggregate size has provided less permeability compared to the mix one gained in the larger aggregate size (Zhang *et al.* 2017). The PC physical attributes have been investigated by replacing 20% and 50% of cement with fly ash through the usage of A/C (4:1) and W/C (0.35) (Ravindrarajah and Yukari 2010). The results have shown that the water permeability has no major impact if 1) 50% of the cement has been covered by fly ash and 2) the compressive strength has been declined on fly ash raising (Hager *et al.* 2017).

4. Previous research review based on recycled waste materials

In another study, it was investigated that the recycled aggregates (RA) produced by mechanical shredding from discarded concrete and clay bricks have been applied to maintain the recycled aggregates PC (RAPC) to verify the effects of crushing index on its features. Following, the compressive strength, elasticity modulus, flexural strength, permeability coefficient, and total void ratio have been examined with the freeze and thaw cycle test. RAPC results have shown that the compressive and flexural strength and elasticity modulus of 28 days has declined from 36% to 28% and 21%, while the crushing index has raised from 9% to 37%, also, the strength losing rate has raised from 6.6% to 18.7%, meanwhile, the mass-losing rate has inclined from 2.3% to 8.5% (Thomas *et al.* 2016). According to the results, the crushing index growth is significantly effective compared to the strength, elasticity modulus, flexural strength and RAPC freeze thaw (test) durability and the high integration with crushing index of recycled aggregates. Align with a crushing index more than 24%, a PC with recycled aggregates has shown low mechanical features and durability, while the crushing index effects on the permeability coefficient have grown and RAPC total void rate has been removed.

A study has investigated the performance of a waste incorporated pervious concrete pavement (PCP) system through the eleven mini-mixtures usages to represent the spectrum of design recommendations. The outcomes have led to a base mixture design including the structural and hydrological requirements. The test has been conducted by using 20% cement replacing in Class C or Class F fly ash cement in the mixture crushed recycled PC as the underlying coarse aggregate in 10% sand replacement with crushed glass on the fine aggregate layer (Thomas *et al.* 2014). PCP test has confirmed the structural and hydrological requirements then the water quality test has been done on the effluent storm-water in PCP compared to the asphalt portion surface runoff in the same parking lot.

It was found some friendly products such as Ground Granulated Blast Furnace Slag (GGBS), cement bypass dust (BPD), run of station ash (ROSA), basic oxygen slag (BOS), plasterboard gypsum (PG), incinerator bottom ash aggregate (IBAA), recycle crushed glass (RCG), recycled concrete aggregate (RCA), recycled bricks (RB), steel fiber and Poly Vinyl Alcohol (PVA) Fiber and the combinations of binary and ternary cementations blended in different mixes. The outcomes have indicated that a concrete paving mix with GGBS (6.3%), BPD (0.7%) and OPC (7.0%) is able to lessen Portland cement content by 30% compared to the common applying with no effect to the paving blocks' strength or durability produced on BS EN 1338;2003 (Skripkiūnas *et al.* 2010).

Another study has been performed on the chloride penetration depth, resistance attack and macro-cell corrosion of rubberized concrete (Skripkiūnas *et al.* 2010). The results have indicated that the concrete chloride penetration depth with (2.5-7.5)% crumb rubber is less or the same amount to the control mix concrete. A major weight and compressive strength losing have been occurred in the control mix concrete than the rubberized concrete when the acid attacks. Thus the rubberized concrete has obviously resistance to the hard locations with the chance of acid attack.

The natural river sand has been replaced partially by the waste tire rubber effectiveness in cement concrete (Thomas *et al.* 2014). In the presence of water cement, the concrete M30 grade is based on IS 10262: 2010 (0.4). The substitution of fine aggregates ranging from 0% to 20% has been performed in 2.5% multiples with discarded tire rubber (crumb rubber). Tests have been conducted to define the compressive and flexural strength, abrasion resistance, microstructure, water permeability, and sorptivity in concrete specimens (Skripkiūnas *et al.* 2010). The results have indicated that the crumb rubber might be replaced partially in common fine aggregate (up to 7.5%) with no favorable strength reduction that has confirmed the rubberized concrete as the proper replacement (Skripkiūnas *et al.* 2010).

Another study has replaced cement by ceramic waste powder (30% by weight) for M25 grade concrete indicating that the compressive strength has been fulfilled up to 30% ceramic waste powder replacement with no effect to the M 25 strength and no significant change in flexural strength (Gesoğlu *et al.* 2014).

A study have examined on a constant water to the cement (ratio 0.27) with the cement content of 450 kg/m^3, then the tire chips, crumb rubber and fine crumb rubber replacement have produced rubberized PCs in a crumb rubber sieving from 1 mm sieving at two diverse contents (10% & 20%). Accordingly, the mix of two types of tire chips crumb rubber and tire chips fine crumb rubber have been used in the rubberized processing within the same content. PC samples in the presence and absence of tire rubber have been examined for flexural strength, abrasion and freezing-thawing resistance (Patil and Murnal 2014). The outcome has indicated that rubber has significantly affected the abrasion and freezing- thawing resistance when the PC flexural strength has been decreased as follows:

Despite the rubber application defects like durability, the rubber usage has provided well resistance in PC; therefore, the rubber' usage in various sizes or amount have improved the PC surface property by offering acceptable outcomes in abrasion resistance regarding wear deepness leading to a common use in parking, walkway and road shoulder etc. (Patil and Murnal 2014).

The cement replacement (0%, 20%, 30% and 40%) with glass powder has also been investigated. When the particle size is lower than 75 μm, the tensile strength of compressive and split in the concrete have been raised up to 20% replacement followed by a sharp decline (Kuo *et al.* 2013).

In another research, washed municipal solid waste incinerator bottom ash (MSWIBA) as a substitution for common aggregate in PC has been analyzed. Accordingly, the permeability, compressive strength, bending and split tensile strength tests have been also conducted (Bhutta and Tsuruta 2010). The outcomes have indicated that the concrete unit weight obtained from MSWIBA is around 1653–2080 kg/m3 and rose in the cement paste ratio filling. On a linear alignment between the connected porosity and permeability coefficients, both have been decreased when the filling ratio has been increased (Bhutta and Tsuruta 2010).

The open and closed air pores volume size, air pores distribution and freezing- thawing test have been studied. The results have shown that additional rubber waste aggregate has raised the cement matrix closed porosity. Also the attacked concrete by the freezing and thawing cycle has improved the concrete durability (Bhutta and Tsuruta 2010).

A research have analyzed that the rubber particles included of tire chips, crumb rubber and a mixture of rubberized concrete with course rubber particles have been declined in the rubber concentration raising, so there is no fast failing case with no separation in the specimen's elements (Ganjian *et al.* 2009). The response of the combined mixture's stress strain has presented that the ultimate stress of the combined tire rubber concrete is separate from the fine aggregates' concentration and the curve shape of the stress strain has depended on the coarse aggregates concentration (Ganjian *et al.* 2009).

Two sets of concrete specimens have been performed in 2008. While in the first set, different chipped rubber weights have been replaced by the coarse aggregates, in the second set, a scrap tire powder has been replaced by cement. After the mechanical and durability tests conduction, the results have shown a replacement up to 5% in both sets has brought no significant effect on concrete properties, however, any replacement ratio growing has brought remarkable changes (Ghosh *et al.* 2015). The strength of compressive and tensile concrete has been reduced in rubber replacement for aggregate or cement. The rubber replacement has raised the depth of water permeability in the concrete mixture and has grown the water absorption in case of the coarse aggregate replacement but reduced the water absorption in cement replacement.

Another study on the wasted rubber as a fine aggregate to develop the lightweight construction materials has been performed. The rubber content raising has declined the sample unit weight with a high strength reduction and the composites' elastic modulus. Rubbers in cement paste have enhanced the composite hardness and increased the materials' strain potential (Lucke *et al.* 2015).

Another study has focused on the aerated cement composite with wasted rubber. It has been found that the presence of air voids has reduced the elasticity dynamic modulus indicating high composite sound insulation range (Lee *et al.* 2013).

A group of researches has worked on re-using decayed concrete, glass and plastic in ordinary Portland cement (OPC). Concrete ground plastics and glass have been applied to replace the fine aggregates in the concrete mixes (up to 20%), when the crushed concrete has been applied to replace the coarse aggregates (up to 20%) (Lee *et al.* 2013). At the prime aggregates supplement, the cost variation among the crushing glass, plastic and concrete have been considered in which the glass application has indicated no significant effect in the slump, then the plastic and crushed concrete have been applied in the concrete (up to 20%). The concrete strength has shown less compressive and splitting tensile strength than the common concrete with common aggregate (Lee *et al.* 2013).

5. Conclusions

The growth of rubber particles application as concrete aggregates has encouraged researchers to look at the performance of rubberized pervious concrete especially in term of durability as it has a low or limited value of strength resistance and the results indicated the pervious concrete incorporated with rubbers had a lower splitting tensile strength, modulus of elasticity, compressive strength of 3-30 MPa, and permeability of 0.025-0.61 cm/s.

According to the literature, waste materials usage in the pavement porous concrete has played a beneficial role to surpass the PC pavement properties despite few defects in features. Waste material usage in the partial cement replacement in PC, the whole concrete production cost has been reduced; also, the priority of recycled aggregate to natural aggregate has provided a remarkable increment in the permeability coefficient. However, the concretes' mechanical features have slightly affected 1) to eliminate the disposal waste materials defects and 2) to use cement in PC production. While the cement has been replaced by different industrial wastes, the compressive strength, flexural strength, split tensile strength and different PC permeability mixes have depended on the waste materials' type applied in PC production. Thus, the integration of the aforementioned waste materials into the pavements porous concrete is adequately favorable for roads and public areas.

References

Abedini, M. *et al.* (2017), "Evaluation of concrete structures reinforced with fiber reinforced polymers bars: a review", *J. Asian Sci. Res.*, **7**(5), 165-175.

ACI, A. "522R-10. 2010." Report on pervious concrete. ACI Committee 522: 38.

Aghaee, K. and Foroughi, M. (2013), "Mechanical properties of lightweight concrete partition with a core of textile waste", *Adv. Civil Eng.*, 1-7.

Aghaee, K. *et al.* (2014), "Mechanical properties of structural lightweight concrete reinforced with waste steel wires", *Mag. Concrete Res.*, 6**6**(1), 1-9.

Bao, Y. *et al.* (2016), "Concrete pavement monitoring with PPP-BOTDA distributed strain and crack sensors", *Smart Struct. Syst.*, **18**(3), 405-423.

Batayneh, M. e*t al.* (2007), "Use of selected waste materials in concrete mixes", *Waste Manage.*, **27**(12), 1870-1876.

Bazzaz, M. (2018a), "Experimental and analytical procedures to characterize mechanical properties of asphalt concrete materials for airfield pavement applications", Ph.D., University of Kansas.

Bazzaz, M. *et al.* (2018), "A Straightforward procedure to characterize nonlinear viscoelastic response of asphalt concrete at high temperatures", *Transport. Res. Record*, 0361198118782033.

Bazzaz, M. e*t al.* (2018b), "A Straightforward procedure to characterize nonlinear viscoelastic respinse of asphalt concrete at high temperatures", *Transport. Res. Record*: *Transport. Res. Board*.

Benazzouk, A. *et al*. (2006), "Physico-mechanical properties of aerated cement composites containing shredded rubber waste", *Cement Concrete Compos.*, **28**(7), 650-657.

Bhargava, K. *et al*. (2003), "Analytical model of corrosion-induced cracking of concrete considering the stiffness of reinforcement", *Struct. Eng. Mech.*, **16**(6), 749-769.

Bhutta, M. and Tsuruta, K. (2010), "Evaluation of properties of workable porous concrete", *Proceedings of the 35th conference on our world in concrete and structures*.

Brinkler, K. (2004), CARE report on automotive glass recycling. 2004 update, london: consortium for automotive recycling. (The consortium represents the United Kingdom's main motor vehicle manufacturers, importers, and dismantlers.).

Chesner, W.H. *et al.* (1998), User guidelines for waste and by-product materials in pavement construction.

Council, N.R. (2011), Asphalt shingles waste management in the Northeast fact sheet.

Driscoll, G. and Slutter, R. (1961), Research on composite design at Lehigh University, Month.

Edwards, D. and Schelling, J. (1999), "Municipal waste life cycle assessment: Part 2: Transport analysis and glass case study", *Process Saf. Inviron. Protection*, **77**(5), 259-274.

Ganjian, E. *et al.* (2015), "Using waste materials and by-products to produce concrete paving blocks", *Constr. Build. Mater.*, **77**, 270-275.

Ganjian, E. *et al*. (2009), "Scrap-tyre-rubber replacement for aggregate and filler in concrete", *Constr. Build. Mater.*, **23**(5), 1828-1836.

Gesoğlu, M. *et al.* (2014), "Abrasion and freezing–thawing resistance of pervious concretes containing waste rubbers", *Constr. Build. Mater.*, **73**, 19-24.

Ghataora, G. *et al.* (2004), "Summary project report on the utilization of recycled aggregates generated from highway arising and steel slag fines", University of Birmingham, Birmingham, UK.

Ghosh, S.K. *et al*. (2015), "A review on performance of pervious concrete using waste materials", *Int. J. Res. Eng. Technol.*, **4**(13), 105-115.

Gonzalez-Torre, P.L. *et al.* (2003), "Some comparative factors regarding recycling collection systems in regions of the USA and Europe", *J. Environ. Manage.*, **69**(2), 129-138.

Griffiths, C.T. and Krstulovich, J.M. (2002), Utilization of recycled materials in Illinois highway construction, Illinois. Dept. of Transportation.

Group, U.T.W. (2001), "Fifth annual report of the used tyre working group", Internet Site: www. tyredisposal. co. uk.

Hager, A. *et al.* (2017), Sustainable design of pervious concrete pavement systems.

Hansen, K.R. and Copeland, A. (2013), Annual asphalt pavement industry survey on recycled materials and warm-mix asphalt usage, 2009-2012.

Hassan, K. *et al.* (2004), Development of new materials for secondary and recycled aggregates in highway infrastructure.

Hird, A.B. *et al*. (2002), "Tyre waste and resource management: a mass balance approach", Viridis Report VR2.

Huang, Y. *et al*. (2007), "A review of the use of recycled solid waste materials in asphalt pavements", *Resour. Conserv. Recy.*, **52**(1), 58-73.

Hylands, K. and Shulman, V. (2003), Civil engineering applications of tyres. Viridis Report VR5. Crowthome, TRL Limited.

Jain, A. and Chouhan, J. (2011), "Effect of shape of aggregate on compressive strength and permeability properties of pervious concrete", *Int. J. Adv. Eng. Res. Stud.*, **1**, 120-126.

Jain, A.K., Chouhan, J.S. and Goliya, S.S. (2011), "Effect of shape and size of aggregate on permeability of pervious concrete", *J. Eng. Res. Studies*, **2**(4), 48-51.

Ji, X. *et al.* (2017), "Anchorage properties at the interface between soil and roots with branches", *J. Forestry Res.*, **28**(1), 83-93.

Joshaghani, A. (2016), "The effects of zeolite as supplementary cement material on pervious concrete", *Proceedings of the International Concrete Sustainability Conference*, Washington, DC.

Kacha, S.A.P.S. (2016), "Utilization of waste materials in the production of pervious concrete–A", *Int. J. Sci. Res. Development.*, **4**(9),442-449.

Kalyoncu, R.S. (2001), "Slag–iron and steel", US geological survey minerals yearbook 2001.

Krivtsov, V. *et al.* (2004), "Analysis of energy footprints associated with recycling of glass and plastic—case studies for industrial ecology", *Ecological Modell.*, **174**(1), 175-189.

Kuo, W.T. *et al.* (2013), "Use of washed municipal solid waste incinerator bottom ash in pervious concrete", *Cement Concrete Compos.*, **37**, 328-335.

Lee, M.J. *et al.* (2013), "Purification study of pervious concrete pavement", *IACSIT Int. J. Eng. Technol.*, **5**(5), 532-535.

Lucke, T. *et al.* (2015), "A simple field test to evaluate the maintenance requirements of permeable interlocking concrete pavements", *Water*, **7**(6), 2542-2554.

Mukhopadhyay, A. and Shi, X. (2017), Validation of RAP and/or

RAS in Hydraulic Cement Concrete: Technical Report.

Nobakht, M. *et al.* (2017), "Selection of structural overlays using asphalt mixture performance", *J. Mater. Civil Eng*., **29**(11), 04017209.

Olivier, J.G. *et al*. (2012), "Trends in global CO2 emissions; 2012 Report, The Hague: PBL Netherlands Environmental Assessment Agency", Joint Research Centre, Ispra.

Parry, T. (2004), "Briefing: Development of asphalt and concrete products incorporating alternative aggregates", *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*, Month.

Patel, M.T.N., Jochem, E. and Worrell, E. (2000), "Recycling of plastics in Germany", *Resour. Conserv. Recy*., **29**, 65-90.

Patil, P. and Murnal, S.M. (2014), "Study on the properties of pervious concrete", *Int. J. Eng. Res. Technol*., ISSN: 2278-0181.

Pratik, P. and Patel, M.E.T. (2014), "Evaluation of strengths and permeability of pervious concrete", Department Of Civil Engineering.

Ramadhansyah, P. *et al.* (2014), Porous Concrete Pavement Containing Nano-silica: Pre-Review, Advanced Materials Research.

Ravindrarajah, R.S. and Yukari, A. (2010), "Environmentally friendly pervious concrete for sustainable construction", *Proceedings of the 35th Conference on Our World in Concrete & Structures*.

Sakhaeifar, M.S. *et al.* (2015), Selection of Long Lasting Rehabilitation Treatment Using Life Cycle Cost Analysis and Present Serviceability Rating: 1-264.

Shah, D.S. and Pitroda, J. (2013), "Assessment for use of gravel In pervious concrete", *Int. J. Eng. Trend. Technol.*, **4**(10), 4306-4310.

Shakrani, S.A. *et al.* (2017), "Applications of waste material in the pervious concrete pavement: A review", P*roceedings of the AIP Conference*.

Sharbatdar, M.K.B. *et al.* (2008), "Behavior of fiber concrete under impact and explosive load", *Proceedings of the 14th International Civil Engineering Student Conference*, Semnan, Iran.

Shulman, V.L. (2000), "Tyre recycling after 2000: status and options".

Skripkiūnas, G. *et al.* (2010), "Porosity and durability of rubberized concrete", *Proceedings of the 2nd International Conference on sustainable construction materials and technologies*.

Slag, S. (2001), "A premier construction aggregate", NSA.

Sriravindrarajah, R. *et al*. (2012), "Mix design for pervious recycled aggregate concrete", *Int. J. Concrete Struct. Mater.*, **6**(4), 239-246.

Talsania, S. *et al*. (2015),"A review of pervious concrete by using various industrial waste materials".

Thomas, B.S. *et al.* (2014), "Strength, abrasion and permeation characteristics of cement concrete containing discarded rubber fine aggregates", *Constr. Build. Mater.*, **59**, 204-212.

Thomas, B.S. *et al*. (2016), "Recycling of waste tire rubber as aggregate in concrete: durability-related performance", *J. Clean. Prod*., **112**, 504-513.

Tiernan, J. (2005), Cement producing system incorporating a waste derived fuel suspension burner for a down draft calciner, Google Patents.

Turgut, P. and Yahlizade, E.S. (2009), "Research into Concrete Blocks with Waste Glass".

WRAP (2003c), "Survey of applications, markets & growth opportunities for recycled plastics in the UK".

WRAP. (2003b), "Standards and specifications affecting plastics recycling in the UK".

Zhang, Z. *et al.* (2017), "Influence of crushing index on properties of recycled aggregates pervious concrete", *Constr. Build. Mater*., **135**, 112-118.

CC

Acronyms and abbreviations:

Mt	million tones
ASR	Alkali-Silica Reaction
US NSA	US National Slag Association
USGS	US Geological Survey
TRL	Transport Research Laboratory
ETRA	European Tyre Recycling Association
PRN	Packaging Waste Recovery
PVC	Poly Vinyl Chloride
A/C	Aggregate/Cement
W/C	Water/Cement
GGBFS	Ground Granulated Blast Furnace Slag
RA	recycled aggregates
RAPC	recycled aggregates pervious concrete
PCP	pervious concrete pavement
GGBS	ground granulated blast furnace
BPD	cement by-pass dust
ROSA	run-of-station ash
BOS	basic oxygen slag
PG	plasterboard gypsum
IBAA	incinerator bottom ash aggregate
RCG	recycle crushed glass
RCA	recycled concrete aggregate
RB	recycled bricks
MSWIBA	municipal solid waste incinerator bottom ash
OPC	Ordinary Portland Cement
HMA	Hot Mix Asphalt
PCC	Portland Cement Concrete
WMA	Warm Mix Asphalt