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Review Article

Recycling wastes to develop permeable blocks

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Waste management has become a significant challenge for developing countries, driven by urbanization and increased per capita waste generation. Recycling has been recognized as an effective solution to reduce waste by transforming it into value-added products. However, less than 20% of global waste has been recycled, indicating that waste hierarchy principles and circular economy approaches have not yet made a substantial impact. In the construction sector, several innovative practices have been explored, including the adoption of advanced technologies for waste reduction, the use of alternative materials, and the application of concepts like life cycle assessments and circular economy strategies. Globally, municipal solid waste generation has been projected to reach 3.4 billion tonnes by 2050, with the construction sector contributing around 31%. Efforts have been made to recycle construction and demolitionwaste, such as concrete aggregates, waste bricks, and industrial by-products like fly ash, as partial replacements for cement and aggregates. Permeable pavements have emerged as a sustainable solution in urban areas, enabling runoff water to infiltrate and recharge groundwater. This paper has summarized the development of permeable paver systems, highlighting recent advancements using waste materials. It has discussed their potential and suggested that waste-derived pervious blocks could play a key role in building a sustainable future.

Keywords: Bricks, Compressive strength, Green infrastructure, Hydraulic performance, Sustainability, Waste recycling

1 Introduction

Urbanization has driven the growth of many countries, with cities becoming centres of economic activity, innovation, and higher income generation. However, this rapid growth has placed immense pressure on natural resources such as water bodies, land use patterns, water management systems, solid waste generation, and air quality[1,2]. Concretization has impaired natural drainage systems, as paved surfaces like roads and building premises have increased stormwater volumes and reduced natural groundwater infiltration. As a result, stormwater runoffs have found their way into rivers and seas, leading to flooding, channel widening, habitat loss, erosion, and streambed alteration[3,4].

It is estimated that approximately 3% of the Earth's surface has been paved[5,6]. Furthermore, the urban heat island effect, caused by higher temperatures in densely populated areas, has intensified precipitation patterns, particularly in the form of increased rainfall[7,8]. To address these challenges, sustainable strategies such as runoff volume reduction, infiltration, and stormwater treatment have been promoted. These approaches, including Sustainable Drainage Systems (SUDs), Stormwater Best Management Practices (BMPs), and Low-Impact Development (LID) systems, have been widely adopted [9,10]. Practices like permeable pavements, infiltration trenches, and detention reservoirs have also been developed to support these systems [11].

The Permeable Pavement System (PPS) has been increasingly adopted worldwide in recent years. It was first implemented in the U.S., Japan, and Europe in the early 1980s[12]. In urban areas, the concept has gained importance due to the growing incidence of the urban heat island effect and water logging during monsoons. PPS has been designed to allow water to pass through its structure by utilizing concrete with little or no fine aggregate. It typically consists of paver blocks, an aggregate-based base and sub-base system, and a geosynthetic liner.

PPS has also been acknowledged by certification systems such as LEED (Leadership in Energy & Environmental Design), the Indian Green Building

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Council (IGBC), and the Green Rating for Integrated Habitat Assessment (GRIHA).

Reports from organizations like the US EPA and UNEP have emphasized its role in reducing the urban heat island effect and supporting green infrastructure management for water[13].Guidelines have been developed for field and laboratory testing of permeable pavements, assessing their impact on water quality, and understanding the basics of pervious pavement systems and materials[14].

Additionally, pervious blocks have been reported to provide benefits such as noise reduction due to porosity, skid resistance from surface texture, and minimized water ponding. Other properties, including lower thermal conductivity and a reduced Solar Reflectance Index (SRI), have also been documented[15]. Various permeable paver types, including Open Grade Pavers, Plastic Grid Systems, Porous Asphalt, Porous Concrete, and Permeable Interlocking Concrete Pavers, have been made available as seen in Fig. 1. These systems use cement, water, and coarse aggregates with gaps filled by pea gravel to facilitate water infiltration into the ground. The base and sub-base layers consist of aggregates that filter surface runoff, aiding groundwater recharge. While the construction sector has consumed significant natural resources and virgin materials, PPS has provided a sustainable approach to mitigate these impacts.

It has been estimated that cities worldwide generate approximately 1.3 billion tonnes of solid waste annually[16]. This figure is projected to rise to 2.2 billion tonnes by 2025[17]. India has emerged as the second-largest producer of construction and demolition (C&D) waste globally, generating around 530 million tonnes annually, second only to China[18]. C&D waste primarily comprises soil, sand, gravel, bricks, masonry, concrete, metals, wood, and other materials[19]. With the ongoing expansion of urban areas, recycling and reusing C&D debris have gained attention as sustainable alternatives to natural resources like sand and gravel.

The construction sector has placed significant pressure on natural resources, including clay, sand, soil, and aggregates, while also contributing to greenhouse gas emissions. Heavyweight concrete, for instance, has been reported to emit approximately 903 kg of CO_2 equivalent per cubic meter[20]. These environmental concerns have made recycling of C&D waste increasingly critical.

Several countries have steadily improved their recycling rates for C&D waste, as illustrated in Fig. 2. Notable examples include South Korea[21], Czech Republic[22], Estonia[23], Japan[24], Austria, Germany[25], Denmark, Netherlands[23], Ireland, and United Kingdom[27]. These efforts underline the growing global emphasis on sustainable construction practices.

The majority of recycled construction and demolition (C&D) waste has been utilized as backfill material, sub-base road material, and as a substitute for natural aggregates in concrete[23,26]. In addition to C&D waste, other municipal and industrial wastes, including fly ash, incinerated bottom ash, rubber, chitosan, ground blast furnace slag, ceramic wastes,

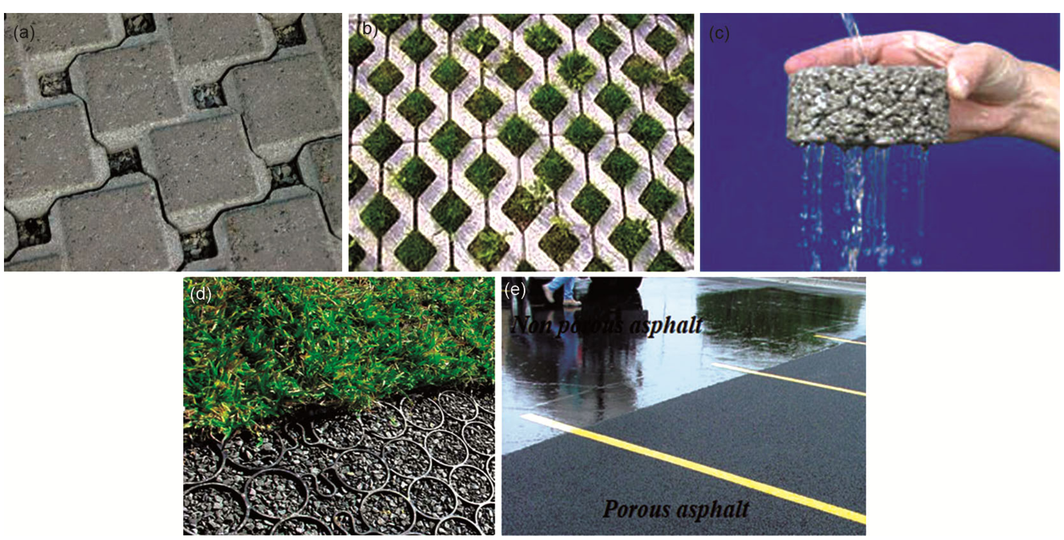

Fig. 1 — Types of permeable pavers; (a) Permeable interlocking concrete pavers, (b) Open grade pavers, (c) Pervious concrete, (d) Plastic grid pavers, and (e) Porous asphalt.

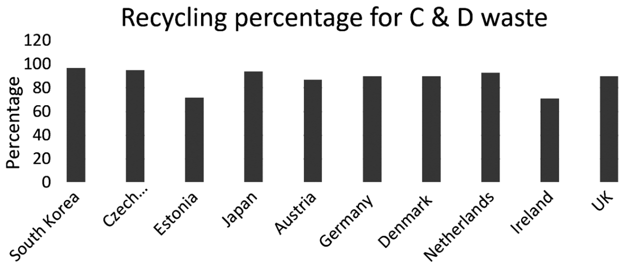

Fig. 2 — Recycling percentage of C&D waste globally.

water treatment plant sludge, waste diatomite, and clay brick waste, have been incorporated in the development of permeable pavers.

This paper discusses recent advancements in permeable pavement systems, highlighting permeable pavers as a vital tool for better urban runoff water management and a key component of green infrastructure. The paper also explores new approaches for creating permeable pavers using alternative materials, particularly waste materials from various sectors. Furthermore, it addresses the research needs, knowledge gaps, and key findings from studies conducted by multiple researchers in the field.

2 Materials and Methods

2.1 Work done and methodology adopted for developing permeable pavement system

One of the US EPA's earliest studies highlighted the first field-scale application study of porous asphalt permeable systems. The study highlighted that the peak runoff rates on the parking lot sites in Rochester, New York were reduced by 83% with no damage to the structural integrity of porous asphalt[27]. Surface runoff reduction and pollutant removal study was carried out for car park runoff. In this work, the Pollution Mitigation Index (PMI) of five systems–Filter strip, Swale, Bioretention cell, Retention Pond, and Permeable paver was measured for parameters like Total suspended solids (TSS), Total Petroleum Hydrocarbons (TPH), and Zinc (Zn). It was found that Bioretention had the highest relative capability to remove all three pollutants followed by permeable pavers[28]. The thermal performance of permeable pavements and the Urban Heat Island effect have also been considered. Permeable pavements made of industrial wastes showed surface temp lowered by almost 25°K, while the use of peat moss and bottom ash in pervious concrete reduced surface temp by 18°K and in another case, the use of steel by-products such as water holding filler reduced the surface temp by 0.6°K; all of these above materials were compared with traditional asphalt surface while these also show lesser reflectance and lower thermal inertia. However, it should be noted that this was observed only upon precipitation and more focus should be given to understanding their effect on the urban canopy layer microclimate, energy consumption, and pedestrian thermal stress[29,30]. The performance of permeable pavement has generated a lot of curiosity and many studies have been conducted to understand the same. Clogging in permeable pavements due to degradation of pavement, deposition of debris from the road dumped by vehicles, and surrounding vegetation were highlighted by Kia[31]. While a review study[32]documented shows that on-field application of pervious concrete is efficient in reducing the tire pavement noise, increased safety in driving due to quick removal of stormwater and calls for the need for developing mixture design and measurement of parameters with a standard approach specific to Pervious Concrete. Application on high volume roads, calculation of life cycle cost analysis, better characterization and adoption of standard procedures for field application and quality control will be useful in making a sustainable pavement construction material.

Recently China has undertaken steps to implement Sponge City concept in its urban regions. The main aim of this urban water management strategy is to absorb, store, treat, reuse & recycle stormwater for both public and environment purpose through Green Infrastructure applications such as green roofs, permeable pavement systems and bioretention systems. Green infrastructure can be defined as 'use of plant or soil systems, permeable surfaces or substrates, that can harvest stormwater for reuse, or landscaping to store, infiltrate in the ground, or evapotranspiratein order to reduce the flow to the sewer systems or other surface water bodies (US EPA).Permeable concrete performs better than pervious asphalt and Permeable interlocking concrete pavers without considering clogging issue. Converting impermeable surfaces to permeable is one of the major goals of this new concept[33]. Japan has also undertaken the initiative to install permeable pavements in the form of interlocking paver blocks. These are effective inthe removal of stormwater from roadways thereby increasing safety factors, reducing hydroplaning, noise reduction, removal of total suspended solids, total nitrogen, and total phosphorus from the runoff water, draining of runoff formed from de-icing, to being citizen-friendly. The Japan Interlocking Pavement Engineering Association (JIPEA) recommends PICBP to have permeability of 0.01 cm/sec, minimum flexural and compressive strength of 3 MPa and 20 MPa respectively[34]. Studies on fluid transport processes in permeable pavements show that the highest evaporation rate is seen in green pavers, followed by porous pavers. However, this particular area of understanding evaporation rates in PPS is challenging as there are no proper methods of measurement and less literature is available on the effect of sub base layers on evaporative cooling[35]. One of the recent reviews on permeable pavement highlighted the multi-functionality of porous concrete. The study highlights that hydraulic performance, mechanical performance, skid resistance, sound absorption, temperature mitigation and air quality improvement were widely studied parameters for researchers. It was also noted that conflicting technical results show lack of confidence in their efficiency and performance leading to limited large-scale implementation on field. The study concludes that it is possible to design high performing porous concrete targeted for specific application and to develop optimized mix design with hydraulic and mechanical requirements making them more feasible[15].

Green roofs and permeable pavements are a few of the widely studied sustainable urban drainage (SUD) systems in the European Union to manage urban floods. Most of the studies recorded have been performed at experimental sites only confined at local and institutional levels, while lacking at governance and policy levels. Also, further understanding is required of other components of SUDs at distinct geographical areas and at all scales. Within EU, transitioning to SUDs have been observed in the U.K, Denmark and Sweden while no academic work is observed in eastern and southern European regions[36].

It is evident that permeable pavement system is now recognized as one of the better urban drainage systems that can combat urban issues of flooding, receding groundwater levels, water shortage, and urban heat island effect along with other benefits. However, these studies also highlight gaps commonly seen throughout such as lack of standard method for mix design and testing of permeable pavers, lifespan and related information, real large-scale application on field, understanding the efficiency of the system in different geographical regions and climatic conditions.

2.2 New approaches in permeable paver/bricks

Until now, the construction sector has been very efficient in creating solid, high-strength, load-bearing products from virgin materials. However, rapid industrialization and advancement also led to waste generation to such an extent that major countries are facing the issue of waste treatment and disposal. This has led to an added interest in reutilizing these waste materials by turning them into useful products that can have a better life cycle than the conventional route of disposal in landfills. The findings of published views have been summarised in Table 1.

2.2.1 Industrial wastes

High-performance permeable bricks were made from ceramic waste as aggregate, fly ash and clay. The bricks obtained had a strength of 6.8 MPa, porosity of 28%, and permeability of 3.0×10^{-2} cm/sec under optimal conditions. The bricks made with dimensions of 140 × 140 × 80 mm were fired at 1100 -1200°C for 1 hr. Sodium silicate was used as the high temperature binder along with fly ash, cement and clay to improve the plasticity of the mixture. The permeable bricks were tested on a pilot and industrial scale for the production of 10,000 bricks per batch and the energy consumption per unit of permeable bricks was calculated to be about 1.4MJ/Kg[37]. A lightweight floatable and permeable geopolymer block was developed from fly ash. The compressive strength of the foamed geopolymer blocks was 0.55 ± 0.08 MPa, dry density of 0.37 g/cm^3, permeability to water coefficient was 0.35 cm/s and the BET surface area was 67.62 m^2/g. Geopolymerization method was employed to make these lightweight blocks. Sodium hydroxide and sodium silicate solution were used to make the alkaline activating solution that acted as the binder for the mixture. Oleic acid and hydrogen peroxide was added to the mix to induce the formation of foam and pores with open cell structure. Small cubes with 33 mm sizes were made and sealed in plastic bag before curing at 80 °C for 10 h in oven. The porous geopolymer block show higher adsorption capacity for methylene blue viz. 50.7 ± 0.7 mg/g and thus can be used as a replacement for zeolites for wastewater treatment process[38]. Permeable block from bottom ash

Table 1 — Summary of Literature on permeable products made from wastes.

Type of product developed	Raw material	Performance	Targeted Application	Method	References
Permeable bricks	Ceramic waste, fly ash, clay, sodium silicate	6.8 MPa compressive strength, permeability of 3.0 × 10^{-2} cm/sec, porosity28%	Sponge city – potential material	sintering	Yang *et al.*[20]
Light weight floatable, permeable block	Fly ash, Sodium silicate, sodium hydroxide, hydrogen peroxide solution, oleic acid	Foamed geopolymer compressive strength– 0.55 MPa, permeability 0.35 cm/sec	Replacement for zeolites and adsorbent	geopolymerization	Y. Liu *et al.*[38]
Permeable bricks	Bottom ash slag, fly ash, carboxymethyl cellulose, ceramic gravel, clay, grog	compressive strength range 300-475 Kgf/cm^2, permeability 0.046-0.063 cm/sec	Footpath material	sintering	Nishigaki[39]
Permeable brick	Bottom ash, water treatment plant sludge	compressive strength 256 Kg/cm^2, permeability 0.016 cm/sec		sintering	C. F. Lin *et al.*[50]
Porous ceramics	Waste diatomite, water treatment plant sludge	compressive strength – 18.3 MPa, water absorption 49.9%	pavements	sintering	K. L. Lin *et al.*[51]
Pervious concrete	Fly ash, nano silica, cement, sodium hydroxide	compressive strength 15.1 MPa at 7th day, permeability 4.5 mm/sec	pavement	Curing	Hwang *et al.*[40]
Pervious concrete	Modified organoclay bentonite, cement	compressive strength 47-68 MPa, permeability of 1.5-1.7 cm/sec	pavement	curing	Shang & Sun[52]
Pervious concrete bricks	Bottom ash, cement	compressive strength 10-20 MPa, permeability range 0.01-0.1 cm/sec, porosity range 19-30%	Pavement	curing	Wu *et al.*[41]
Permeable paver	Chitosan, rubber crumbs, sodium tripolyphosphate solution	compressive strength 502 KPa to 2.6 MPa		Cross-linking	Murray *et al.*[53]
Concrete	Fly ash, clay brick waste	Permeability 5.1 to 14.5% range			Zong *et al.*[42]
Porous geopolymer	Metakaolinite, sodium silicate, sodium hydroxide	14 MPa compressive strength	Best remedial measure for urban heat island effect	geopolymerization	Okada *et al.*[54]
Water retaining porous ceramics	Vermiculite, allophane	compressive strength 1-3 MPa, water absorption 37 to 63%,	Useful in combating with urban heat island effect	sintering process	Okada *et al.*[55]
Paver block	Blast furnace slag, cement, admixture	compressive strength 1.6 to 2.7 MPa at 7th day, water absorption > 65%	Pavement	Curing in water	Takahashi[43]
Concrete paver blocks	Carbon negative aggregates, cement	compressive strength range 18.48 – 68.80 MPa, water absorption 1.66% - 9.17%	Permeable pavement	Curing	Monrose[44]
Filler material for permeable pavement	C & D waste – crushed bricks. Recycled concrete aggregates, reclaimed asphalt pavement, non-woven geotextiles		Filler materials in permeable pavement system		Rahman *et al.*[56]
Pervious concrete	Recycled concrete aggregates. Silica fume, nano clay, steel fibres, waste plastic fibres		Structural application		Toghroli *et al.*[57]
Permeable bricks	Gangue, tailings, waste ceramic	compressive strength range 5-40 MPa, permeability 0.065-0.08 cm/sec		sintering	Zhu *et al.*[45]
Paver blocks	Tire derived aggregates, polyurethane-based binder,	compressive strength of 1.24-1.41 MPa	Permeable surface		Raeesi *et al.*[58]
Permeable ceramics	Silica sand tailing, coal gangue, steel slag	compressivestrength range – 42.83 to 72.39 MPa, permeability range 4.68×10^{-2} cm/sec	Sponge city concepts	Sintering	Huang *et al.*[46]
Pervious material	Ceramic waste, natural sand, polyurethane-based binder	Permeability range - 70 × 10^{-4} to 90 × 10^{-4} m/s, compressive strength 6.25 MPa	Pavement material		Lu *et al.*[59]

slag and fly ash was produced using surface-melting and plasma melting furnace. The bricks obtained shows compressive strength in the range of 300-475 Kgf/cm^2; density in the range of 1.84-1.94 g/cm^3 and permeability of 0.046-0.063 cm/sec. The bricks were sintered at 1200-1230°C for 80 hours. Water solution of carboxymethylcellulose (CMC) was used for moulding and clay, ceramic gravel and grog were added additionally in the mixture. The study was tested at trial site to pave footpath highlighting the reuse of incineration residue in an effective way[39].

Pervious concrete pavement made from fly ash and Nano silica along with bamboo bioretention basins were developed and assessed for volume reduction and pollution removal. The pervious concrete paver showed 7th day compressive strength of 15.1 MPa and targeted permeability of 4.5 mm/sec. Cement was used as the binder in the study and the specimens were cured in lime saturated water under ambient conditions. Tap water along with treated effluent, fertilizer solution and coolant solution were used as sources for faecal coliform, phosphate and COD pollutants, respectively. Greater removal of faecal coliforms (~99%) and phosphates (~50%) was observed compared to COD (~53%) in comparison with bamboo bioretention system. The study concludes that pervious concrete pavement along with bamboo bioretention basin makes a better combination for tackling effective urban stormwater management[40]**.** Pervious concrete bricks with incineration bottom ash in place of sandstone has also been explored. The bricks obtained show compressive strength in the range of 10 to 20 MPa, water permeability in the range of 0.01-0.1 cm/sec, water absorption range from 4 to 15% and average porosity range of 19-30%. Cement was used as the binder in the study and the bricks were cured under water immersion. The experimental specimen using bottom ash aggregate size #4 and a water-to-cement ratio of 0.55 demonstrated the maximum compressive strength, and holds the most promise for future applications in pavement[41]. Clay brick waste as recycled aggregates and fly ash to make pervious concrete has also been explored. The results show that addition of recycled aggregates (RA) reduced density of the mix, compressive and flexural strength was reduced by 16%, 27%, 44% and 16%, 22%, 33% respectively for 30, 40 and 50% recycled aggregate content while increased water permeability was observed in the range of 5.1 to 14.5 %. Fly ash and cement was used as binding agents. Microstructure analysis shows presence of pores and voids in the loose structure indicating increased porosity due to the addition of recycled aggregate. The study concludes that mix containing 30% RA performed best and was more economical for practical application[42].

A water retentive material was developed at JFE Steel, using blast furnace slag, cement and admixture to form paver block. The 7thday compressive strength of the material varied from 1.6 to 2.7 MPa with water absorption greater than 65%. The max temperature difference between dense-graded asphalt and water retentive pavement was more than 10 °C. The material was also tested by actually applying it in parking area within the premises for three summers and no change in its properties was observed. The study concludes that road cool material made from blast furnace slag can be used to supress the urban heat island phenomenon[43].

Carbon negative aggregates (CNA) were used as a replacement to natural aggregates to develop concrete paver blocks in permeable pavements. The 28-day compressive strengths and densities ranged from 18.48 to 68.80 MPa and from 2236 to 2612 kg/m^3, respectively. The 28-day splitting tensile strengths and water absorption percentages ranged from 1.23 to 3.84 MPa and from 1.66% to 9.17%, respectively. Microstructural studies revealed good bonding results for both the Carbon Negative Aggregates and Natural Aggregates[44].

Permeable bricks by sintering method were explored by using mining wastes like gangue and tailings. At optimised conditions of, 60-70% gangue, 20% tailings and 10-20% waste ceramic, brick with compressive strength more than 30 MPa and water permeability of about 0.03 cm/sec were obtained. The bricks were obtained by sintering at 1180-1200°C for 45 mins. Tailings were used as a binder for the bricks instead of clay and the sintered gangue and waste ceramic was used in place of aggregates. The study concludes that aggregate – type, size and content along with sintering temperature affect the characteristics of permeable brick, inverse relation was observed between permeability and compressive strength and strength of aggregates have greater impact on the brick[45].

Permeable ceramics have been developed from silica sand tailing, coal gangue and steel slag by sintering method. At the optimum conditions of silica sand tailing 55%, steel slag 20%, and coal gangue 25%, compressive strength of the produced ceramics was 42.83 MPa, bending strength 6 .87 MPa and permeability 4.68×10^{-2} cm/sec. The ceramics were sintered at 1000 -1170°C for 2 hours. If the sintering temperature is increased, then increase in compressive strength and increase in water permeability of bricks was observed. The study concludes that developing permeable ceramics entirely from industrial waste is possible and should be explored especially in sponge city concepts[46].

Industrial wastes have also been studied to obtain pervious concrete. Pervious concrete using ground steel slag powder as binder and crushed steel slag as aggregate were explored as a potential material for sponge city concept. Highest compressive strength of 82.6 MPa with 2.5% phosphogypsum content was achieved. The binder was also partially substituted by phosphogypsum and cured in carbonation box for CO_2 curing. The carbonated steel slag pervious concrete specimens with higher porosity were successfully tested for plantability of tall fescue which showed savings of 75.8% in cost of materials with absorption of about 100 Kg/m^3 of carbon dioxide[47].

In another study, steel slag was used as a replacement to natural aggregates in making pervious concrete. Highest compressive strength (~17.6 MPa) was obtained with 100% replacement of natural aggregates with steel slag along with increased connected porosity (~28%) and water permeability (~13 mm/sec). Portland cement was used as a binder in the process. Positive effects of steel slag are also seen on tensile strength and flexural strength of the specimens. The study concludes that steel slag can be used in place of natural aggregates in making pervious concrete[48].

Water permeable geopolymer specimen was prepared using fly ash, slag and metakaolin in a study. The 1-day compressive strength of the specimen was 30 MPa which increased to 49 MPa on 28-day of curing. The permeability of the specimens was 1.70 cm/sec and void ratio was 27.6%. Alkaline activator made of sodium silicate solution and sodium hydroxide were used as binder and curing was done at 20°C with 95% relative humidity[49].

2.2.2 Water treatment plant sludge

In another study, incinerator bottom ash slag was used along with water treatment plant sludge to produce water permeable bricks. The bricks produced with 20% bottom ash content show compressive strength of 256 Kg/cm^2, water absorption of 2.78% and permeability of 0.016 cm/sec.The bricks were obtained by sintering method at 1150°C for 360 mins. Water treatment plant sludge ratio was varied from 75-98%, while bottom ash ranged from 2-25%, specimens were subjected to moulding pressure of 110 kg/cm^2 per block and sintered at temp. range of 900 to 1200 deg. C for time period of 1-max. 6 hrs. The use of bottom ash and sludge promotes the formation of beehive structure and voids in the structure[50].Porous ceramics have also been explored from waste diatomite and water treatment plant sludge. The produced bricks showed high compressive strength of 18.3 MPa and water absorption rate of 49.9%. Varying proportions of the raw materials (80-100% diatomite and 0-20% sludge) was done to produce bricks sintered at temp. of 1000-1270°C for 2 hrs.The use of wastes reduced CO_2 emissions by 23.8% due to fuel reduction was observed[51].

2.2.3 Other wastes

Studies focussing on removing the contaminants from stormwater using multi-functional green pervious concrete developed from modified organoclay bentonite were carried out. The pervious concrete compressive strength and permeability ranged from 47-68 MPa and 1.5-1.7 cm/sec respectively. Cement was used as the binder and modified organoclay bentonite as an amendment additive. Enhanced removal of naphthalene was observed in pervious concrete with modified bentonite due to its higher adsorption and retardation capacity than conventional pervious concrete. The isothermal batch tests reveal that the addition of a small amount of modified organoclay gave higher removal thus concluding that, green pervious concrete developed from modified Organoclay shows to be a potential pavement material for contaminant removal[52].

Chitosan has also been tested as a binder for making permeable pavement materials using rubber crumbs. Chitosan affects the mechanical stability of the specimen. The specimens show compressive strength in the range of 502 KPa to 2.6 MPa. Chitosan and sodium tripolyphosphate solution were used in the binder solution as the cross-linking agent. The permeable paver developed showed the removal of particulate and dissolved pollutants namely zinc from the water. The pavers were highly porous and brittle but showed mechanical fragility[53].

Porous water-retaining geopolymers were developed from metakaolinite. The highest pore size of 390 nm was observed at the highest H_2O/Al_2O_3

ratio of 19.5. Lowest H_2O/Al_2O_3 ratio geopolymers showed highest mechanical strength of 14 MPa. The samples were made by geopolymerization process. Sodium silicate and sodium hydroxide were used as the binding agents and the samples were cured at 40℃ for 4 days. The ranges for sodium hydroxide solution ranged from 6 to 14M, Na_2O/Al_2O_3 ratio varied from 0.92-1.08 range and H_2O/Al_2O_3 ratio 14.2 to 19.5.The study concludes that lower H_2O/Al_2O_3 ratio geopolymers are desirable as they have mechanical strength, small pore size and thus release water at a lesser rate making them one of the best suitable remediation measures for Urban Heat Island Effect [54].Porous ceramics were developed from known water retainer materials – vermiculite and allophane. Max compressive strength of 2.2 MPa was recorded for samples with Vermiculite: Allophane ratio of 10:90. The samples obtained show compressive strength in the range of 1-3 MPa and higher water absorption in the range of 37 to 63%. The samples were obtained via the sintering process at 800℃. The study concludes that vermiculite and allophane can be used in water retentive ceramics as they slowly release water, and thus, can be potentially used to combat 'urban heat island effect'[55]. Permeable pavements as filter media have also been explored by some researchers. Natural aggregate substitution with C & D wastes like crushed bricks (CB), recycled concrete aggregates (RCA) and reclaimed asphalt pavement (RAP) with non-woven geotextile as a filter media has also been studied. Constant head hydraulic conductivity tests showed that RAP showed highest permeability followed by RCA and then crushed bricks. CB showed highest removal efficiency while RAP showed the least for removal of pollutants – Total Phosphorus, Total Nitrogen and Total Suspended Solids. The study concludes that C&D materials can be used as alternative filler materials in permeable pavement system[56].

In another extensive study, the effects of replacing natural aggregates (RNA) with recycled concrete aggregates (RCA), silica fume (SF) and Nano-clay (NC) as partial replacement to cement and steel fibres (STF) and waste plastic fibres (WPF) as reinforcement in making pervious concrete mixes were studied. At 100% RCA in a mix with SF as partial replacement to cement, the compressive strength for 7 days increased by 115% than its counterpart without SF. The compressive strength of the samples was reduced with increasing RCA content though the addition of SF revered the effect. The density of mixes reduced with increasing RCA content while porosity increased. SF and NC increased the density but contributed to the reduction in the porosity of the samples. The study concludes that the pervious concrete with 100% RCA can be used without compromising in strength if pozzolanic filler such as silica fume and steel fibers are added to the mixes for use in structural applications[57].

3 Results and Discussion

The study undertaken throws a light on the following research gaps observed from the literature reviewed:

- A wide variety of waste materials have been tested for developing permeable pavers. However, it is important to note that the composition and availability of these materials is inconsistent and may affect the desired outcome.
- Lack of standard methods for making pervious concrete has an impact, as customized methods made by individual researchers vary and increase the unreliability of the permeable paver application. It is important to have process optimization for the mix design to ensure validation of the targeted mixes.
- While there are studies on use of novel materials for making permeable pavements that are mentioned in this paper, not all studies cover other important structural parameters. Most focus on the compressive strength of the specimens, other parameters like thermal conductivity, threshold hydraulic conductivity, water quality and noise reduction can also be studied. User needs can be analysed, based on the multiple data sets for its wider implementation. Such findings will be helpful in the further advancement of processes and actual implementation.
- Less literature is available on understanding the evaporation rate from permeable pavement systems. Inadequate understandingofthe measurement of evaporative cooling can be further improved.
- Limited field studies for permeable pavers were found. Replacement of conventional materials with wastes also triggers concerns for the safety and durability of the product. More such studies with demonstrations are required to encourage the recycling of suitable waste materials in permeable pavers.

- Limited work on the costs of permeable pavers can be another aspect of hesitation in its use. More research work is needed that can document the economics of using wastes in permeable pavers and thus help in actual on-field applications of this technology. Life Cycle Costs of waste utilization and their benefits analysis will provide ample reasons for better adoption of innovative solutions.
- Clogging behaviour of permeable pavers is another area that needs more studies. Long-term in-depth investigation on the clogging of permeable pavers, restoring infiltration capacity, and mechanisms to remove the same along with maintenance should be carried out. These studies can encourage the application and on-field trials of the permeable pavers.
- The behaviour of paver block under different climatic conditions can be explored through modelling and advanced characterization of the specimens to assess their usefulness in given conditions
- It has been observed that the use of green methods such as geopolymerization for making permeable pavers shows promising outcomes. More studies undertaking such ecofriendly methods of making pavers are needed to change the mindset of using traditional construction materials that are not only energy-intensive but also cause a great strain on natural resources along with the contribution of CO_2 emission.

4 Conclusion

With growing demand for infrastructure development and focus on sustainability, use of permeable pavers in place of impervious pavers can, not only, help in reduction of noise and the urban heat island effect but also provide the country with better transport environment and technology up gradation. Permeable pavers can be used in areas that are prone to flooding. They can also act as filter media for removing suspended and organic matter from the stormwater system and allow it to reach deeper layers of soil and help in recharging the groundwater table. The use of waste materials in place of virgin resources is the need of the hour. Although lack of homogeneity in the wastes can make them quite unreliable for large-scale use, however, specific areas can be delineated for their possible use.Their use can be aimed atnon-structural and non-load-bearing purposes. Promising aspects towards the use of organic binders in place of cement and clay and the use of green methods like geopolymerization for developing permeable pavers can help in the reduction of cost and emissions. Likewise, the government must offer incentives and legislation that would promote the use of secondary materials in the construction field thereby also fulfilling the targeted SDG-12 goal of sustainable consumption and responsible production pattern. Research institutes can also help in transferring the technology for on-field application and aim at resolving the issues faced by the construction industry which will invariably benefit all stakeholders involved as well as the environment.

Recent developments and innovations about the use of waste materials in making permeable pavers have been discussed in this paper. The existing scientific information related to thermal performance, water quality and clogging behaviour is limited. As, the recycling of waste materials is currently one of the active areas of research, the progress on developing eco-friendly low-cost pavers from waste needs to progress faster with complete documentation of properties that can help in better understanding and application of this technology.

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