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Potential use of crushed waste glass and glass powder in sustainable pervious concrete: A review

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ABSTRACT

This review explores the innovative use of crushed waste glass and glass powder in sustainable pervious concrete, emphasizing their potential to enhance mechanical properties and environmental benefits. Pervious concrete, characterized by its high porosity and permeability, is crucial in stormwater management and reducing urban heat. However, its inherent low compressive strength necessitates the incorporation of supplementary materials. This study highlights the pozzolanic activity of glass powder, which improves strength and durability while reducing the overall cement content, thereby lowering the carbon footprint associated with concrete production. The review addresses the challenges of using high glass powder replacement levels, including potential compressive strength reductions and increased susceptibility to freeze-thaw cycles. Future research directions include optimizing mix designs and investigating hybrid approaches that combine glass powder with recycled aggregates. Ultimately, this review underscores the vital role of waste glass in promoting sustainable construction practices and contributing to the circular economy within the pervious concrete industry.

1. Introduction

Pervious concrete (PC) is a specialized type with a highly porous and permeable structure that lets water flow quickly. The distinctive characteristics of PC make it a precious material for various applications, especially in stormwater management and sustainable construction. The porous nature of the material allows rainwater to percolate through the concrete and recharge groundwater, reducing surface runoff and mitigating the risk of flooding (Subramaniam and Sathiparan, 2023). This makes PC an environmentally sustainable solution, as it helps to replenish natural water resources and reduce the urban heat island effect (Tsatsou et al., 2023). In terms of its expected properties, it typically exhibits a porosity, or void space, ranging from 15 % to 35 % of its total volume, allowing for high water flow rates of 280–700 liters per minute per square meter (Li et al., 2021a, 2021b). However, this porous structure also results in a lower compressive strength compared to traditional concrete, typically ranging from 3.5 to 28 MPa (Shen et al., 2021). The open pore structure can also make PC more susceptible to weathering, freeze-thaw cycles, and potential clogging, requiring more maintenance over time.

Higher cement content in PC is primarily driven by the need to compensate for the material's inherent porous structure and low overall density. The open-pore design of PC results in a lower compressive strength compared to traditional concrete, requiring a higher cement content to achieve the necessary strength for applications such as pedestrian walkways and low-volume vehicle areas (Sathiparan et al., 2024). Additionally, the porous nature of the material makes it more challenging to achieve adequate workability and cohesion during the mixing and placement process, necessitating more cement to improve these properties (AlShareedah and Nassiri, 2021). However, the reliance on excessive cement in PC can have adverse environmental impacts. Cement production is a highly energy-intensive and carbon-intensive process, contributing significantly to the overall carbon footprint of the construction industry (Sathiparan, 2021). Excessive use of cement in PC can partially negate the sustainability benefits of this porous material, as it can diminish its ability to manage stormwater and recharge

Abbreviations: Agg/B, aggregate to bibder ratio; C-S-H, calcium silicate hydrate; C.A, aggregate content; C.C, cement content; C.S, compressive strength; CWG, crushed waste glass; GP/B or WGP/B, waste glass powder to binder ratio; PC, pervious concrete; SAI, strength activity index; SCM, supplementary cementitious material; WGP, waste glass powder; CWG /Agg, waste glass to aggregate ratio; W/B, water to binder ratio.

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groundwater effectively (Lamichhane et al., 2024).

To address this challenge, alternative approaches can be explored to lower the cement in PC. One such approach is using supplementary cementitious materials (SCMs) such as fly ash, metakaolin or silica fume as partial substitutes for cement. These SCMs can help improve the concrete's strength, durability, and sustainability while reducing the cement requirement (Juenger and Siddique, 2015). Additionally, incorporating recycled concrete aggregates or other waste materials as the coarse aggregate component can further contribute to a more circular and sustainable approach to PC production (Jahami and Issa, 2023; Qaidi et al., 2021; Qaidi et al., 2022). Table 1 summarizes the materials used as SCMs and compares embodied energy and CO_2 emission with cement. Compared to other SCMs, rice husk ash and waste glass powder (WGP) have less embodied energy and CO_2 emission.

WGP as an SCM to replace cement in PC offers several compelling advantages compared to other traditional SCM options. Table 2 provide a quantitative comparison of waste glass powder with other commonly used supplementary cementitious materials (SCMs), highlighting its advantages in terms of mechanical performance, workability, and durability. The comparative analysis demonstrates that WGP not only enhances the compressive strength of pervious concrete at lower replacement ratios but also provides significant workability benefits due to its fine particle size. Furthermore, WGP exhibits superior durability characteristics, particularly in resisting chemical attacks, which is crucial for sustainable construction practices.

One of the primary benefits of WGP is its pozzolanic solid activity. WGP allows them to react with the calcium hydroxide released during the cement hydration. This reaction forms an additional calcium silicate hydrate (C-S-H) gel, the primary binding agent in concrete (Jiang et al., 2022; Matos et al., 2024). This pozzolanic reaction helps improve the PC mixture's overall strength and long-term performance. In addition to its pozzolanic properties, WGP can also enhance the workability and flowability of the PC, making it simpler to place and compact the material into a uniform, stable structure. This is particularly advantageous for PC, where the porous nature of the material can sometimes pose challenges in terms of workability (Omran et al., 2018). Furthermore, the fine, spherical particles of WGP can help refine the porous structure of the PC. This can reduce the risk of water penetration and improve the resistance to various forms of deterioration, such as sulphate attack and alkali-silica reactions (Abed et al., 2024). This enhanced durability can lead to a longer service life for PC installations.

From a sustainability perspective, using WGP as a cement substitution offers significant environmental benefits. WGP is often a byproduct or waste material from the glass manufacturing industry, making it a more sustainable option than traditional cement production, with a significant carbon footprint (Bostanci, 2020). Additionally, the widespread availability and potentially cost-effective nature of WGP make it an attractive SCM choice for PC applications (Matos et al., 2024). The usage of WGP as cement replacement or crushed waste glass (CWG) as aggregate in PC has been the focus of widespread research, yielding promising results. Studies have shown that incorporating ground WGP as a partial substitute for cement can effectively improve the compressive strength, flexural strength, and durability of PC while reducing the cement content (Li et al., 2021a, 2021b). Some researchers have taken a hybrid approach, investigating the combined use of WGP as a cement replacement and CWG as a coarse aggregate in PC mixes. These combined strategies have shown promising results in terms of enhancing the characteristics of PC. The synergistic effects of using both WGP and CWG can provide a better comprehensive solution for lessening the ecological effect of PC (Shen et al., 2020).

A comprehensive review of the usage of WGP as a cement replacement and CWG as an aggregate in PC is crucial for several compelling reasons. Firstly, cement manufacturing is highly energy-intensive and carbon-intensive, contributing significantly to the construction industry's carbon footprint. Employing waste materials like WGP and CWG can enhance the sustainability of PC by reducing its environmental footprint. Moreover, repurposing CWG in PC can contribute to the circular economy and reduce the volume of waste sent to landfills or incineration. This review can help quantify the potential for CWG utilization in PC and identify the most effective methods for its

Table 2
A quantitative comparison of waste glass powder with other commonly used supplementary cementitious materials.

SCM	Compressive Strength	Workability	Durability
Waste Glass Powder	30–40 % improvement at 10–15 % replacement (Li, et al., 2021a,b)	Improved due to fine particle size (Moura et al., 2021)	Excellent resistance to sulfate attack and alkali-silica reaction (Li, et al., 2021a,b)
Fly Ash	25–30 % improvement at 20–30 % replacement (Sathiparan et al., 2024)	Moderate, dependent on fineness (Saha, 2018)	Good, but less effective under harsh conditions (Saboo et al., 2019)
Silica Fume	50–60 % improvement at 10–15 % replacement (Sathiparan and Subramaniam, 2024)	Generally high due to pozzolanic activity (Adil et al., 2020)	High, with significant resistance to chemical attacks (Adil et al., 2020)
Metakaolin	40–50 % improvement at 15–20 % replacement (Mansour and Al Biajawi, 2022)	Good, but may require higher water content (Singh and Murugan, 2022)	Good, with some susceptibility to alkali-silica reaction (Singh and Murugan, 2022)

Table 1
Overview of cement and materials used as supplementary cementitious materials and their embodied energy and CO_2 emission.

SCMs	Chemistry	Process	Embodied energy (MJ/kg)	CO_2 emission ($kgCO_2$/kg)	Ref.
Cement	Ca-Si	The clinker is then ground with gypsum and other additives	4.5–5.3	0.73 – 0.91	(El-Hassan and Kianmehr, 2017; ICE, 2011)
Copper Slag	Fe-Si	A by-product from copper smelting	0.36–0.50	0.02–0.04	(Chaitanya and Kumar, 2022; Jin and Chen, 2022; Motz and Geiseler, 2001; Prem et al., 2018)
Fly ash	Si-Al	A by-product from coal-fired power plants	0.1	0.008	(Hemalatha and Ramaswamy, 2017; ICE, 2011; Saha et al., 2018)
Glass powder	Si	Finely ground waste glass	0.06 – 0.14	0.007 – 0.016	(Letelier et al., 2019)
Ground granulated blast furnace slag	Si-Ca-Al	A by-product of iron and steel production	1.6	0.067	(Ahmad et al., 2022; ICE, 2011; Özbay et al., 2016)
Metakaolin	Si-Al	A calcined clay material	3.48	0.33 – 0.40	(Mansour and Al Biajawi, 2022; Meddah et al., 2018; Park et al., 2021; Singh, et al., 2023a,b; Zhan et al., 2020)
Red mud	Fe-Ca-Al	A waste product from the aluminum industry	0.2–0.5	0.8–1.0	(Niu and Lin, 2024; Tang et al., 2019)
Rice husk ash	Si	A by-product of burning rice husks	0.008	0.005	(Olatoyan et al., 2023; Pode, 2016; Sathiparan, 2021; Sathiparan et al., 2023)
Silica fume	Si	A by-product of the silicon and ferrosilicon industry	0.1	0.014	(Chishi and Gautam, 2023; He and Wang, 2014; Kuruscu and Girgin, 2014; Singh et al., 2023a, 2023b)

incorporation, thereby addressing the challenges of resource efficiency and waste reduction. A comprehensive review can help determine the optimal mix designs, proportions, and application methods to maximize the benefits of these alternative materials in PC. This information can then inform the development of standardized guidelines and specifications, ensuring PC mixtures' consistent and reliable performance incorporating these alternative materials. Finally, a thorough review of the current research can help identify areas for further investigation, such as long-term performance, optimal mix designs, or the impact of different glass particle characteristics. By highlighting these research gaps, future studies can be directed towards addressing the remaining challenges and advancing the practical application of WGP and CWG in PC. This knowledge can then inform the development of more environmentally friendly and resource-efficient PC solutions.

Extensive research has been conducted to investigate the impact of different SCMs on the properties and performance of PC. These SCMs include fly ash (Khankhaje et al., 2023), silica fume (Ghosh et al., 2015; Jadeja and Dhandha, 2017; Sathiparan and Subramaniam, 2024), rice husk ash (Ghosh et al., 2015; Jadeja and Dhandha, 2017; Talsania et al., 2015), furnace slag (Ghosh et al., 2015; Jadeja and Dhandha, 2017) and ceramic waste (Ghosh et al., 2015; Talsania et al., 2015). Despite extensive research on PC, a comprehensive review explicitly focusing on using WGP or CWG as constituents has not been conducted to the authors' knowledge. This study investigates the impact of replacing cement with WGP and aggregates with waste glass on PC's hydraulic and mechanical properties. This includes evaluating porosity, permeability, strength attributes, and freeze-thaw resistance. A research methodology chart outlining the approach for this review study is presented in Fig. 1.

2. Overview of past studies

The data selection began by defining the objectives, which focused on evaluating how CWG and WGP could enhance sustainability in PC. Next, the relevant papers were identified by searching sources such as Scopus, Google Scholar, ScienceDirect, and the ASCE Library, using keywords like "pervious concrete," "waste glass," "waste glass powder," and "sustainability," while employing Boolean operators for refinement. The articles were screened by reviewing the titles and abstracts using a PRISMA flowchart. Data extraction then gathered key information from the selected studies with standardized forms. Important data points

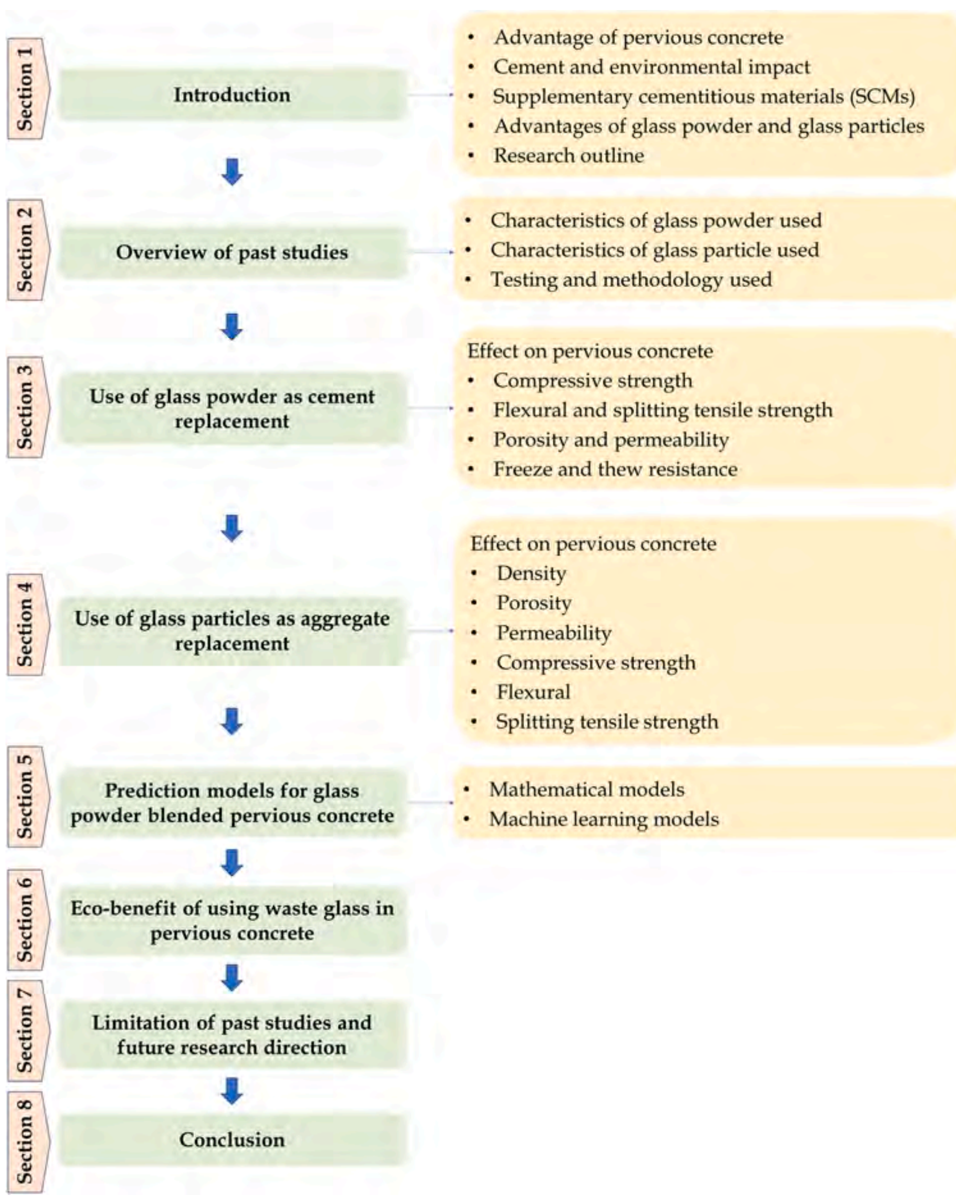

Fig. 1. Methodology chart of the review.

included the types and proportions of WGP or CWG used, the properties of the PC, environmental benefits, and any challenges encountered in utilizing CWG. The extracted data was organized in a structured format using tables and figures. The compiled data was analyzed to identify trends, benefits, and limitations associated with using CWG in PC, considering both qualitative and quantitative aspects.

Fig. 2 shows that the keyword analysis for the study of WGP and CWG use in PC provides valuable insights into the key focus areas and the interconnections between various concepts. The keyword "pervious concrete" has the highest occurrence, indicating that it is the central topic of the study. Other frequently occurring keywords include "compressive strength", "permeability", "recycled aggregates", "glass powder", and "waste glass", suggesting that the research is focused on the physical and mechanical characteristics of PC, as well as the utilization of recycled materials. The total link strength, which represents the strength of the relationships between keywords, also highlights the interconnectedness of the research. The keywords with the highest total link strength are "pervious concrete", "compressive strength", "glass", "mechanical permeability", "recycling", "water permeability", "concrete", and "sustainable development". These strong connections indicate that the study is examining the influence of incorporating WGP and CWG on PC characteristics, as well as the prospective for these materials to contribute to the sustainability of concrete production and construction.

The analysis of publication trends regarding glass waste-based pervious concrete reveals a significant increase in research activity over the past few years. As shown in Table 3, the number of articles published has steadily risen, with a notable spike in 2024, where 11 articles were published. This marks a substantial increase from 2023, which saw 7 publications, and reflects a growing interest in sustainable materials in construction. The year 2022 also demonstrated a robust output with 8 articles, highlighting a consistent upward trajectory in research activity since 2019, which recorded 6 articles. This trend illustrates an emerging focus on integrating waste materials, particularly

Table 3
Publication numbers on glass waste based pervious concrete with year of publication.

Year of publication	No of articles
2024	11
2023	7
2022	8
2021	4
2020	1
2019	6
2018	7
2017	1
2016	2
< 2016	6

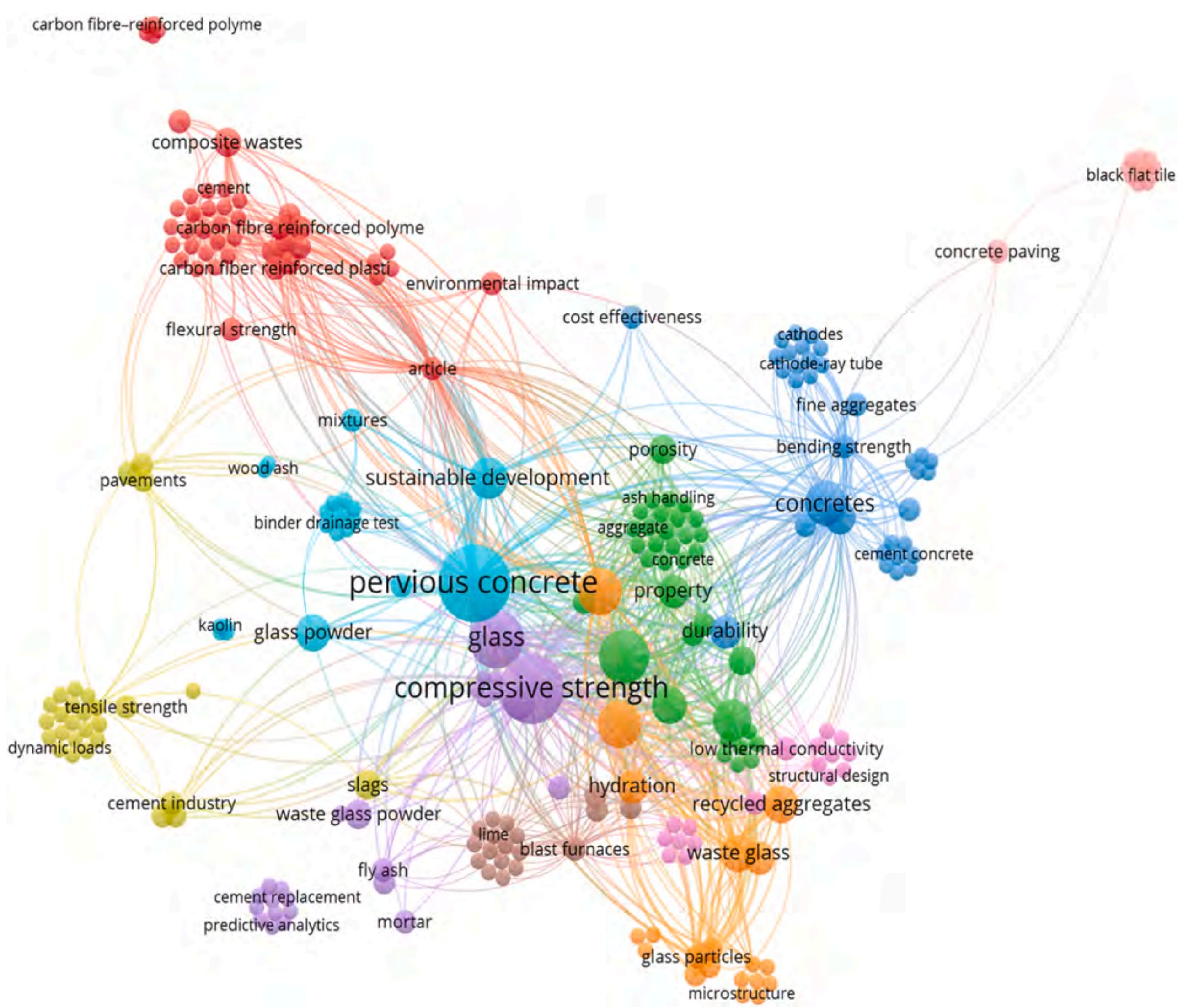

Fig. 2. A co-occurrence network of the keywords for study on WGP and CWG in pervious concrete.

glass, into construction practices, driven by the need for sustainable solutions and the circular economy. The temporal evolution of research in this area not only signifies the maturation of the field but also points to an expanding knowledge base that can inform future studies and practical applications.

2.1. Characteristics of glass power and glass aggregates

Table 4 presents the physical properties of WGP and CWG that have been investigated as potential cement and aggregate replacements in PC. The low water absorption values for WGP and glass particles indicate that the glass particles may be more suitable as cement and aggregate replacements, as they would not significantly increase the water demand of the concrete mixture. The density of the glass particles ranges from 1330 to 1517 kg/m^3 , which is lower than the typical range for natural aggregates (around 2500–2800 kg/m^3), suggesting that the usage of glass particles as an aggregate substitution could result in a decrease in the overall density of the PC.

The specific gravity of WGP ranged from 2.29 to 2.80. At the same time, glass particles had a specific gravity between 2.50 and 2.65, generally within the range of common cementitious materials and aggregates used in concrete. This suggests that glass could be a suitable replacement material for concrete. The BET-specific surface area of the WGP was reported in a few studies, ranging from 0.342 m^2/g to 0.635 m^2/g, which is higher than the typical range for cement (around 0.3–0.5 m^2/g), indicating the potential for improved pozzolanic reactivity and strength development when used as a cement substitute. Overall, the physical properties of the CWG materials, including low water absorption, relatively low density, and high specific surface area, suggest that they could be viable options for substituting cement and aggregates in PC production, potentially leading to improved performance and sustainability.

Table 5 shows that WGP is primarily composed of silicon dioxide (SiO_2), which makes it appropriate for usage as a partial substitution for cement in cementitious material production. The general requirements for the chemical composition of high-reactivity pozzolans are typically specified in standards like AASHTO M 321 (AASHTO-M321, 2013) as crucial requirements are as follows: the combined content of SiO_2, Al_2O_3 and Fe_2O_3 should be greater than or equal to 70 % by mass, the sulfur trioxide (SO_3) content should be less than or equal to 3 % by mass, the loss on ignition (LOI) should be less than or equal to 3 % by mass. The ASTM C168 (ASTM-C168, 2022) and IS 3812 (IS-3812, 2013) also provide similar requirements for the chemical composition of high-reactivity pozzolans. The research on WGP in PC satisfied the standard specifications.

Table 4
Physical properties of the WGP and CWG.

Replacement type	Ref.	Water absorption (%)	Density (kg/m^3)	Specific gravity	BET specific area (m^2/g)
WGP	Ferrada (2024)	7.5	-	-	-
	Khadgi et al. (2022)	-	-	2.50	-
	Moura et al. (2021)	-	-	2.80	0.631
	Pradeep et al. (2019)	-	-	2.50	-
	Talsania et al. (2015)	-	-	2.50	-
	Yavuz et al. (2024)	-	-	2.29	0.342
	Shen et al. (2020)	-	-	2.48	0.635
CWG	Ahmad et al. (2024b)	0.045	1517	2.65	-
	Lu et al. (2019)	2.63	1360	2.54	-
	Shen et al. (2020)	-	1330	2.54	-
	Chen et al. (2023)	-	-	2.50	-
	El-Hassan et al. (2023)	0.1	1472	2.50	-

2.2. Test on pervious concrete

Table 6 summarizes the research conducted on WGP as a cement substitute and glass particles as aggregates in PC. The studies have explored various mix design parameters and performance characteristics. Several researchers have investigated the impact of replacing 0–20 % of the cement with WGP while varying the aggregate-to-binder ratio from 3.0 to 5.0 and the water/cement ratio from 0.20 to 0.45. When glass particles were used as aggregate substitutes in PC, the studies investigated a variety of binder compositions, including cement, cement with silica fume, cement with silica fume and WGP, and cement with ground-granulated blast-furnace slag (GGBS). The aggregate-to-binder (Agg/B) ratios ranged from 2.95 to 5.00, while the water-to-binder (W/B) ratios varied from 0.14 to 0.45. The researchers tested a broad spectrum of CWG replacement levels, ranging from 0 % to 100 %. The waste glass particle sizes varied, with some studies using finer particles in the range of 0–4.75 mm, while others utilized coarser particles between 2.36 and 12.5 mm. Some studies utilized chemical admixtures, while others did not.

The specimen sizes for testing vary, with standard dimensions being 150 mm cubes, 100 mm cubes, and 150 × 300 mm cylindrical samples. The studies have followed various standards, such as ACI 522 R (ACI-522R, 2010a), ASTM C39 (ASTM-C1754/C1754M, 2012), ASTM C78 (ASTM-C78, 2009), ASTM C496 (ASTM-C496, 1996), ASTM C1701 (ASTM-C1701/1701M (2017)), ASTM C1754 (ASTM-C1754/C1754M, 2012), GB/T50081 (GB-T50081, 2002), GB/T50082 (GB-T50082, 2009), and JIS A 5371 (JIS-A-5371, 2016), to conduct these tests and characterize the performance of PC.

3. Use of glass powder as cement replacement in pervious concrete

WGP can be used in PC due to its sustainability and waste utilization benefits, pozzolanic properties that enhance strength and durability, and ability to maintain the high permeability and porosity required for PC applications. Their effect on the characteristics of PC is discussed below.

3.1. Compressive strength

Fig. 3(a) presents the usage of WGP to replace cement in PC and indicates several exciting trends in compressive strength. Generally, the data suggests that low to moderate replacement ratios, typically in the range of 0.1–0.15, can maintain or even slightly improve the compressive strength. This trend can be attributed to the pozzolanic reaction between the cement hydration products and WGP, which can help to densify the microstructure and enhance the overall strength (Muhedin and Ibrahim, 2023). The pozzolanic activity of WGP plays a crucial role in enhancing the mechanical properties of pervious concrete. The primary chemical mechanism involves the reaction of WGP with calcium hydroxide ($Ca(OH)_2$), a byproduct of the cement hydration process. When cement hydrates, it releases $Ca(OH)_2$, which can react with the amorphous silica present in WGP to form additional calcium silicate hydrate (C-S-H) gel, the main binding phase in concrete. This reaction

Table 5
Chemical composition of WGP.

	CaO	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	MgO	K_2O	SO_3	LOI
Li et al. (2021)	7.6	71.2	3.12	0.54	11.23	2.49	0.068	0.016	-
Shen et al. (2020)	10.8	70.2	2.46	0.56	13.9	1.50	0.12	0.10	-
Talsania et al. (2015)	11.50	66.56	1.02	-	12.32	3.02	1.06	-	-
Yavuz et al. (2024)	8.55	70.1	1.57	0.12	12.50	4.25	0.14	0.08	0.70

can be represented by the equation (de Moura et al., 2019):

$$SiO_2 + Ca(OH)_2 \rightarrow C\text{-}S\text{-}H + H_2OSiO_2 + Ca(OH)_2 \rightarrow C\text{-}S\text{-}H + H_2O \quad (1)$$

The formation of C-S-H contributes to the densification of the microstructure, thereby improving the compressive strength and durability of the concrete mixture. Moreover, the presence of alkali ions (such as Na_2O and K_2O) in the waste glass can enhance the reactivity of the silica, leading to a more efficient pozzolanic reaction (Zheng, 2016). The optimized particle size distribution of WGP also plays a role; finer particles increase the surface area available for reaction, facilitating a greater extent of pozzolanic activity. The compressive strength tends to decrease at higher replacement ratios, above 0.15–0.2. This is likely due to the reduction in the cement content, which plays a crucial role in forming the cementitious matrix that provides the concrete's structural integrity. The decreased cement content can lead to a less dense and cohesive microstructure, reducing compressive strength.

However, the studies by Li et al., 2021a, 2021b suggest that the water-to-binder (W/B) ratio can influence the performance of PC containing WGP. They found that lower W/B ratios (0.26 and 0.28) were more favorable in maintaining compressive strength at higher replacement ratios. This can be attributed to the improved workability and particle dispersion at higher W/B ratios, which can help to compensate for the reduced cement content and promote a more uniform and stable microstructure. The optimal replacement ratio balances the beneficial pozzolanic effects of the WGP at lower replacement levels and the detrimental effects of the reduced cement content at higher replacement levels. By carefully selecting the appropriate replacement ratio and adjusting the W/B ratio, it is possible to maintain or even improve the compressive strength. It is important to note that the specific performance of a PC with WGP can vary depending on the characteristics of the WGP, the mix design, and the curing conditions.

Fig. 3(b) illustrates the trend between the strength activity index (SAI = strength of WGP replaced PC/ strength of control PC) and WGP replacement level. The trend shows a quadratic relationship between the SAI and the WGP replacement level, as shown in Eq. (2).

$$SAI = -4.817\ (WGP/B)^2 + 1.125(WGP/B) + 0.916 \quad (2)$$

The negative coefficient of the squared term (-4.817) indicates a parabolic trend, where the strength activity index initially increases with the WGP replacement and reaches a maximum. Then, it decreases as the substitution level further increases. This optimal substitution level and the associated strength activity index indicate that incorporating WGP at around 11.7 % can increase the compressive strength compared to the control mix (0 % replacement). However, as the replacement level increases beyond this optimal point, the compressive strength will decrease.

The specific optimal replacement level and the corresponding strength activity index may depend on the WGP characteristics, the mix design, and other factors. The aggregate-to-binder (Agg/B) ratio is a key factor affecting PC's compressive strength. The collective influence of the Agg/B ratio and the WGP replacement level on the compressive strength of PC is illustrated in Fig. 4. At lower Agg/B ratios (higher cement content), the beneficial effects of the WGP replacement can be less pronounced. Although the higher cement content can better accommodate the pozzolanic reactions, the increased cement gel also leads to a stronger bond between the aggregates. As a result, the benefit gained from the additional pozzolanic reactions is relatively less pronounced (Isaia et al., 2003). As the Agg/B ratio increases (lower cement content), the compressive strength becomes more sensitive to the WGP replacement level. The optimal combination of the Agg/B ratio and the WGP replacement level is crucial to achieve the desired balance between the beneficial and detrimental effects on compressive strength. For a higher Agg/B ratio, there is significantly less calcium hydroxide (CH) to accommodate the pozzolanic reaction.

As shown in the figure, with an Agg/B ratio of 4.0, the PC could tolerate a higher WGP replacement level (20–25 %) while maintaining satisfactory compressive strength. However, when the Agg/B ratio is higher (e.g., 5.0), the optimal WGP replacement level should be lower (e.g., 10–15 %) to prevent a substantial reduction in compressive strength. The interplay between the A/C ratio and the WGP replacement level emphasizes the significance of careful mix design and optimization to achieve the desired PC performance characteristics for specific applications.

When WGP is used to replace cement in PC partially, the observed trend of the strength ratio at various curing ages is illustrated in Fig. 5. At early curing ages, the strength ratio (7/28 and 14/28th day) does not change significantly with the increase in WGP substitution level. This is because the initial cement hydration process is the dominant contributor to the early-age strength development of concrete. The pozzolanic reaction between the WGP and the calcium hydroxide released during cement hydration is relatively slower and takes time to contribute to the strength gain (Lin et al., 2023). Therefore, substituting WGP does not considerably affect the early-age strength ratios, as the cement hydration process is still the primary driver of strength development.

At later curing ages, the strength ratio (56/28 and 112/28th day) tends to increase with the increase in WGP replacement level. Over time, the pozzolanic reaction between the WGP and the calcium hydroxide becomes more pronounced, forming an additional calcium silicate hydrate (C-S-H) gel. The secondary C-S-H formation from the pozzolanic reaction gradually contributes to the long-term strength development of the concrete (Shi et al., 2005). As the WGP replacement level increases, the available silica from the WGP can react with the calcium hydroxide more effectively, leading to a more significant long-term strength gain. This results in a higher strength ratio at the 56-day and 112-day curing ages compared to the 28-day strength, as the pozzolanic reaction continues contributing to the strength development. Also, the secondary C-S-H formation from the pozzolanic reaction helps to densify the concrete microstructure, reducing porosity and improving the overall strength characteristics.

3.2. Flexural and splitting tensile strength

Figs. 6 and 7 illustrate the variation in flexural strength and splitting tensile strength with the WGP/B ratio. Based on the results, the general trend observed is that as the replacement ratio of WGP in cement increases, the concrete mixture's flexural strength and splitting tensile strength tend to decrease in some cases and increase in others. It is indicated that the specific trends and the range of replacement ratios where the flexural strength and splitting tensile strength are optimized can vary depending on various factors, such as the material properties of the WGP, the water-to-binder ratio, and the curing conditions, as observed in the data from different studies (Li, et al., 2021a,b; Pradeep et al., 2019; Talsania et al., 2015; Yavuz and Yazıcı, 2023). WGP is a pozzolanic material that can react with the calcium hydroxide (Ca

Table 6
Summary of the research conducted on WGP as cement replacement in pervious concrete.

Ref.	Replacement type	Size	Agg/B	WGP/B	CWG/Agg	W/B	Admixture used	Test conducted	Specimen size	Standard used
Ferrada (2024)	Cement	< 75 μm	5.0	0–0.20		0.35	No	Permeability	150 × 300 mm cylindrical	ACI 522 R (2010a)
								Compressive strength	150 × 300 mm cylindrical	ASTM C39 (2012)
Khadgi et al. (2022)	Cement	-	3.0	0–0.20		0.45	No	Compressive strength	150 mm cube	-
Li et al. (2021)	Cement	45 μm	3.2–3.5	0–0.25		0.22–0.28	Yes	Porosity	100 mm cube	CJJ/T253 (2016)
								Permeability	100 mm cube	CJJ/T135 (2009)
								Compressive strength	100 mm cube	GB/T50081 (2002)
								Flexural strength	100 × 100 × 400 mm	GB/T50081 (2002)
								Splitting tensile strength	100 × 100 × 400 mm	GB/T50081 (2002)
								Freeze-thaw	100 mm cube	GB/T50082 (2009)
Moura et al. (2021)	Cement	< 75 μm	3.2–4.5	0–0.34		0.20–0.28	Yes	Density	-	-
								Permeability	-	ACI 522 R (2010a)
								Compressive strength	-	ABNT NBR 5739 (2018)
Pradeep et al. (2019)	Cement	< 90 μm	4.0	0–0.20		0.35	No	Compressive strength	150 mm cube	IS: 516 (1959)
								Flexural strength	150 mm cube	IS: 516 (1959)
Talsania et al. (2015)	Cement	< 75 μm	4.0	0–0.20		0.30–0.40	No	Compressive strength	150 mm cube	IS: 516 (1959)
								Flexural strength	150 mm cube	IS: 516 (1959)
Yavuz et al. (2024)	Cement	-	4.8	0–0.20		0.35	No	Density	150 mm cube	-
								Porosity	-	-
								Permeability	100 × 200 mm cylindrical	ACI 522 R (2010a)
								Compressive strength	150 mm cube	-
								Flexural strength	100 × 100 × 400 mm	-
								Splitting tensile strength	100 × 200 mm cylindrical	-
Ahmad et al. (2024b)	Coarse agg.	9.5–12.5 mm	4.77		0–0.5	0.34	No	Permeability	100 mm cube	ASTM C1701 (2017)
								Compressive strength	100 × 200 mm cylindrical	ASTM C39 (2012)
								Flexural strength	100 × 100 × 400 mm	ASTM C78 (2009)
Lu et al. (2019)	Coarse agg.	2.36–5.0 mm	5.00		0–1.0	0.29–0.45	No	Porosity	200 × 100 × 60 mm	ASTM C1754 (2012)
								Permeability	75 × 60 mm cylindrical	JIS A 5371 (2016)
								Compressive strength	200 × 100 × 60 mm	ASTM C39 (2012)
Shan et al. (2020)	Coarse agg.	2.36–5.0 mm	3.00		0–1.0	0.14	Yes	Porosity	70 mm cube	ASTM C1754 (2012)
								Permeability	100 × 50 mm cylindrical	JIS A 5371 (2016)
								Compressive strength	70 mm cube	ASTM C39 (2012)
Chen et al. (2023)	Fine agg.	0–4.75 mm	4.17		0–1.0	0.30	No	Compressive strength	150 mm cube	ASTM C39 (2012)
El-Hassan et al. (2023)	Fine agg.	0–5.0 mm	2.95		0–1.0	0.30	No	Permeability	150 × 300 mm cylindrical	ACI 522 R (2010a)
								Compressive strength	150 mm cube & 150 × 300 mm cylindrical,	ASTM C39 (2012) & BS EN 12390–3 (2019)
								Flexural strength	150 × 150 × 450 mm	ASTM C78 (2009)
								Splitting tensile strength	150 × 300 mm cylindrical	ASTM C496 (1996)

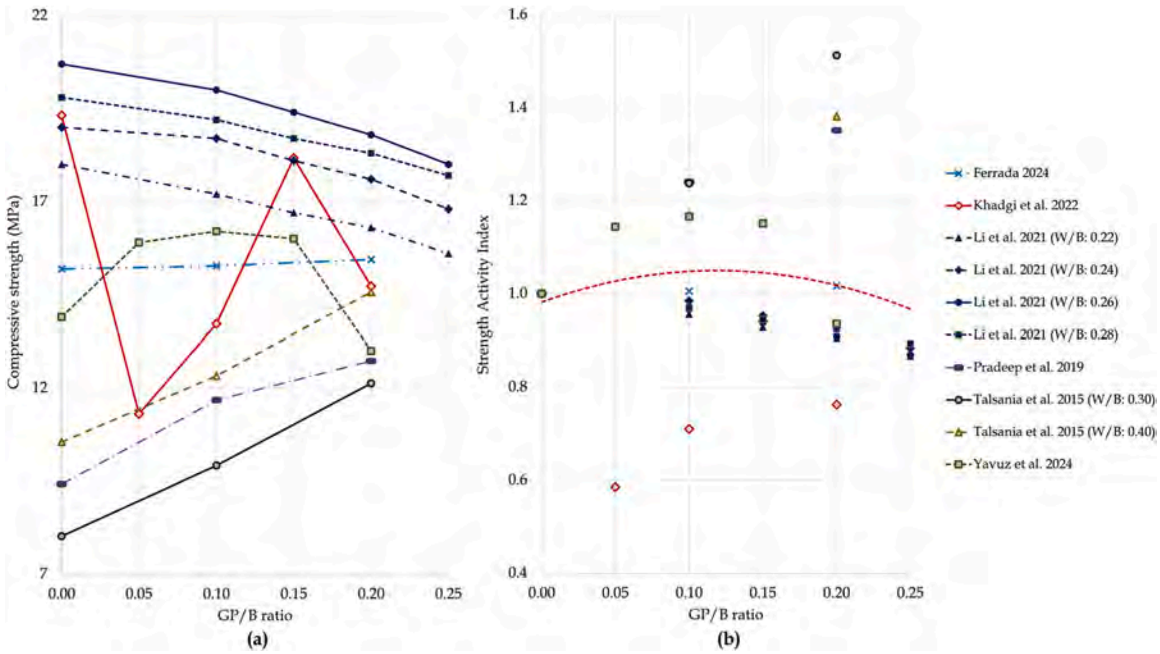

Fig. 3. (a) Compressive strength and (b) strength activity index variation with WGP/B ratio.

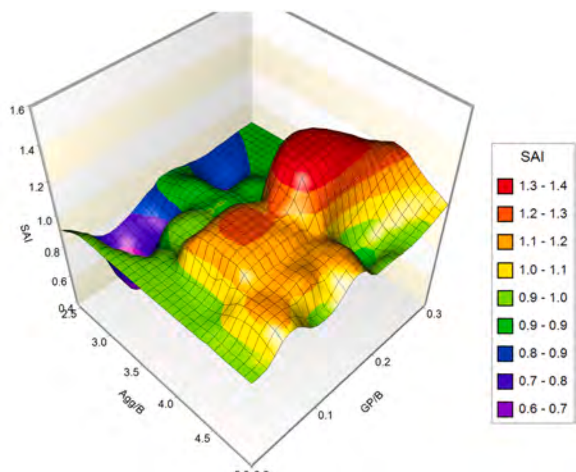

Fig. 4. Combine the effect of aggregate to binder and WGP/B ratio on the compressive strength of pervious concrete (Figure prepared from data collected form reference listed in Table 6).

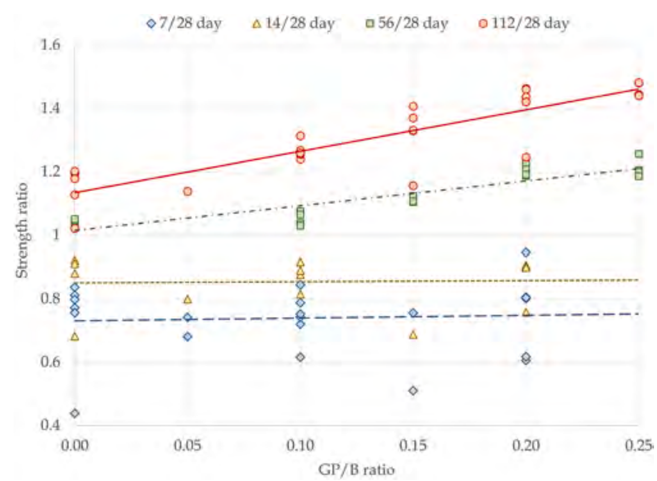

Fig. 5. Strength ratio at different curing ages with 28th day compressive strength of pervious concrete for different WGP/B ratio (Figure prepared from data collected form reference listed in Table 6).

$(OH)_2$) released during cement hydration. This pozzolanic reaction produces additional calcium silicate hydrate (C-S-H) gel, the primary binding agent in concrete. However, the pozzolanic reaction is slower than the initial cement hydration. As the replacement ratio of WGP increases, the amount of cement in the mixture decreases. This "dilution" of cement content leads to a reduction in the overall strength-providing compounds, such as C-S-H gel, which are the primary contributors to the flexural strength of concrete (Shayan and Xu, 2006). Including WGP, which has a different particle size distribution compared to cement, can affect the particle packing and the overall workability of the concrete mixture. Depending on the specific particle size distribution and the replacement ratio, the concrete mix may become less workable, leading to incomplete compaction and reduced flexural strength. The Interfacial transition zone (ITZ) between the cement paste and the aggregates (including the WGP particles) plays a crucial role in the concrete's overall strength. As the WGP replacement ratio increases, the ITZ may become weaker, reducing the concrete's flexural strength (Elaqra et al., 2019).

The data suggests that there may be an optimal replacement ratio, typically around 10–15 %, where the flexural strength and splitting strength are maximized. Beyond this range, the reduction in cement content and the potential challenges in the pozzolanic reaction and particle packing can lead to a more significant decrease in the flexural strength of the concrete.

As shown in Fig. 8, the general trend observed is that as the Agg/B ratio and the WGP/B ratio increase, the concrete mixture's flexural strength activity index (SAI) exhibits complex behavior. The results suggest an optimal combination of Agg/B (between 3.5 and 4.0) and WGP/B ratios (between 0.20) that can maximize the flexural strength of the concrete. At lower A/B ratios, the reduction in SAI was observed due to the increase in the WGP/B ratio. At higher A/B ratios (around 4.0), the increase in the WGP/B ratio can partially offset the negative impact of the Agg/B ratio, leading to a less significant rise in SAI. The combined effect of the Agg/B ratio and the WGP/B ratio on the SAI of PC is a

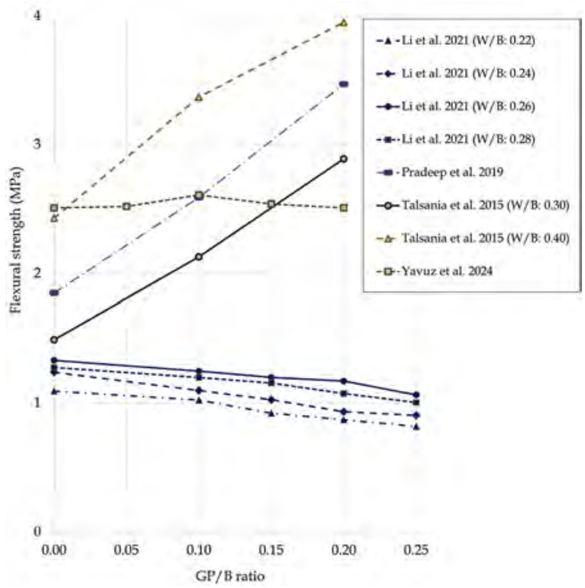

Fig. 6. Flexural strength variation with WGP/B ratio.

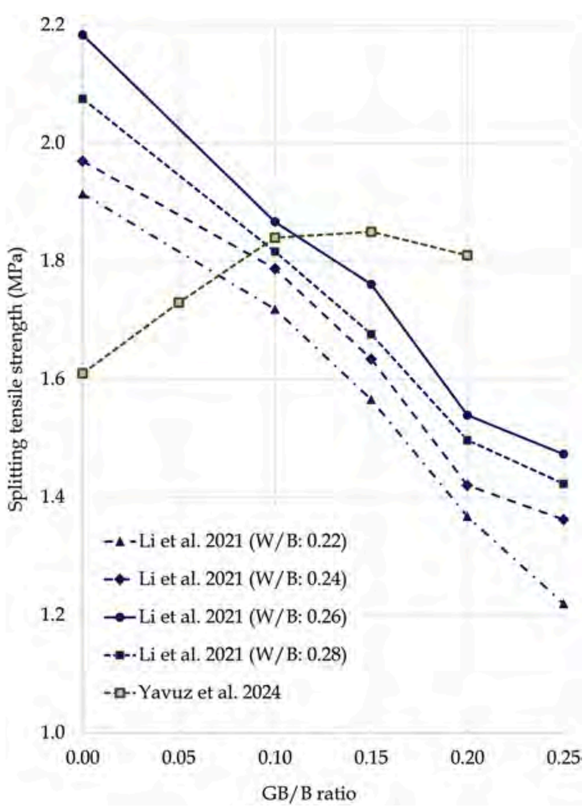

Fig. 7. Splitting tensile strength variation with WGP/B ratio.

complex interplay between the positive contribution of the WGP and the negative impact of the Aggregate.

3.3. Porosity and permeability

Porosity is critical for PC as it significantly influences the material's rheological, hydraulic, and mechanical properties (Ridengaoqier and Hatanaka, 2021). A higher porosity is desirable in PC to achieve high water permeability, a key requirement for many applications. However, excessively high porosity can compromise the material's strength and

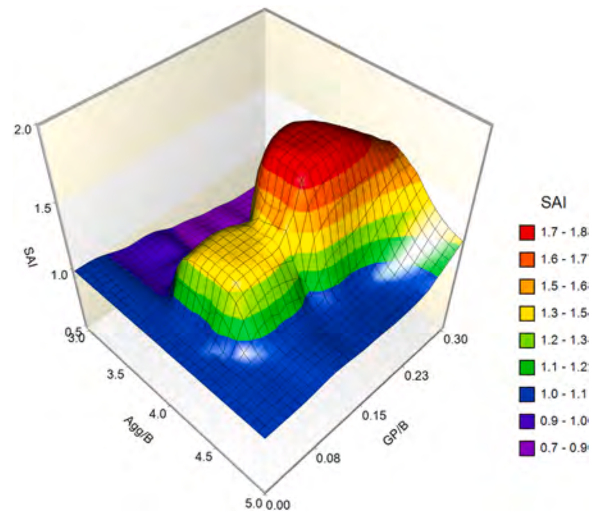

Fig. 8. Combine the effect of aggregate to binder and WGP/B ratio on the flexural strength of pervious concrete.

structural integrity (Li et al., 2019). The relationship between porosity and permeability in pervious concrete is influenced by several microstructural changes, primarily driven by the inclusion of waste glass powder (WGP) and the configuration of the void spaces within the concrete matrix. As WGP is added, it participates in the pozzolanic reaction with calcium hydroxide produced during cement hydration, leading to the formation of additional calcium silicate hydrate (C-S-H) gel (Mejdi et al., 2019). This reaction can enhance the density of the microstructure, which may influence the distribution and connectivity of pore spaces. The incorporation of WGP can modify the pore size distribution within the pervious concrete. Studies indicate that finer particles, such as WGP, fill the larger voids, potentially creating a more uniform pore structure. This uniformity can enhance permeability by allowing water to flow more freely through interconnected voids while maintaining sufficient porosity (Li et al., 2022). The configuration of voids is crucial in determining permeability. Higher porosity often correlates with increased permeability; however, if the voids are not well-connected, permeability may be compromised (Hommel et al., 2018). The presence of WGP can enhance the interconnectivity of the pores by refining the pore structure, thereby improving water flow through the concrete. Fig. 9 illustrates the effect of WGP addition on the permeability of PC. The results show that the porosity and permeability decrease as the WGP/B ratio increases. Adding WGP as a cement replacement can initially reduce the porosity of PC by improving the packing density and reducing the formation of large pores. The decrease in permeability with increasing WGP/B ratio is likely due to the reduction in the size and interconnectivity of the pore network. Also, Maura et al. reported that the water content (or W/B ratio) also plays a crucial role, as it can affect the workability and compaction of the concrete mix, which in turn can influence the porosity

According to the guidelines set by the American Concrete Institute Committee 522, the recommended permeability range for PC to facilitate proper drainage is 1.4–12.2 mm/s (ACI-522R, 2010b). In contrast, the Chinese National Standard (CJJ/T-135, 2009) suggests limiting the maximum permeability for PC to 0.5 mm/s. However, a Chinese National Standard (CNS-14995, 2006) recommends a minimum permeability of 0.1 mm/s for pedestrian pavements. The existing literature indicates that incorporating WGP as a cement replacement can reduce the permeability of PC. However, the available research shows that the reduced permeability values resulting from using WGP still fall within the allowable range specified by the various standards and guidelines.

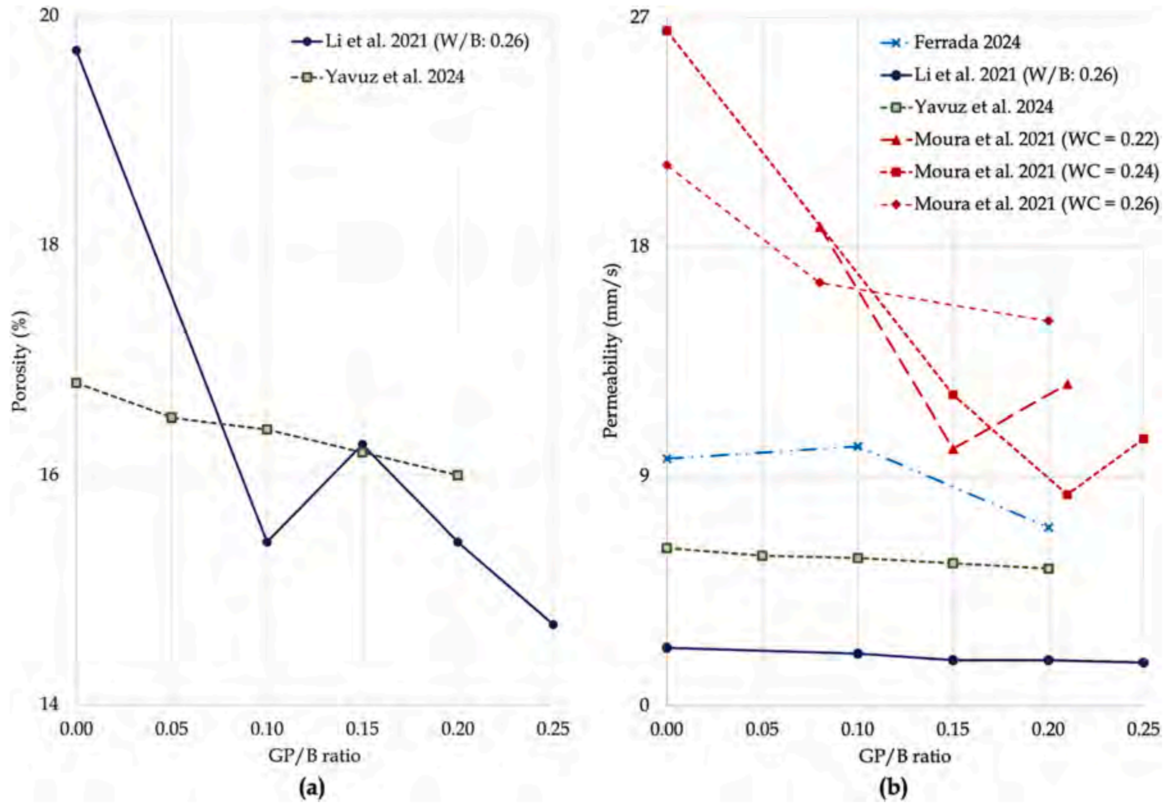

Fig. 9. (a) Porosity and (b) permeability variation with WGP/B ratio.

3.4. Freeze and thaw resistance

Fig. 10 represents the results of a study by Li et al. (Li, et al., 2021a,b) on the effect of WGP substitution in PCs subjected to freeze-thaw cycles. As the percentage of WGP substitution increases, the weight loss generally increases as well. The weight loss increases with the number of freeze-thaw cycles, indicating that the PC is becoming more vulnerable to deterioration. The freeze-thaw cycles cause expansion and contraction of the concrete matrix, leading to the development of microcracks and pores (Wang and Gupta, 2021). The WGP replacement, while improving certain properties of the PC, can also make the concrete more vulnerable to freeze-thaw damage. the different coefficients of thermal expansion among the cement paste and the WGP can create internal stresses during the freeze-thaw cycles, leading to increased weight loss.

Similar to weight loss, the strength loss increases as the percentage of WGP replacement and the number of freeze-thaw cycles increase. Also, the strength loss is generally higher for higher WGP replacement percentages. The freeze-thaw cycles can cause the formation of microcracks and the concrete matrix's deterioration, reducing the concrete's overall strength. The WGP replacement, while potentially improving the early-age strength of the concrete, can make the concrete more vulnerable to freeze-thaw damage over time. The development of microcracks and

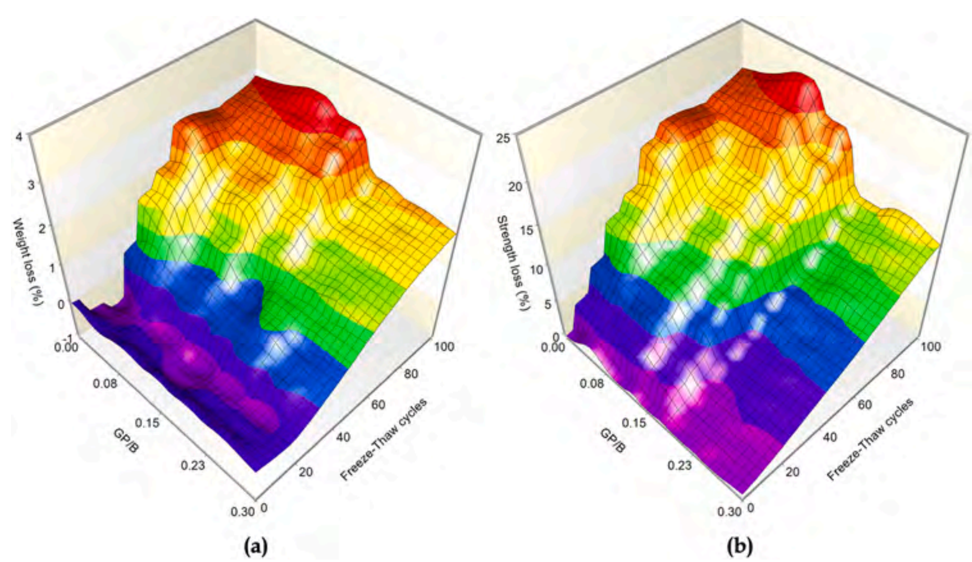

Fig. 10. Effect of WGP/B ratio and freeze and thaw cycle on (a) weight loss and (b) strength loss of pervious concrete.

pores in the concrete can lead to a decrease in the load-bearing capacity and the overall compressive strength of the PC (Luo et al., 2022).

Given the susceptibility of pervious concrete to freeze-thaw cycles, several design modifications can enhance durability. Adding fibers (such as polypropylene or steel) can improve the tensile strength and crack resistance of PC, thereby mitigating damage from freeze-thaw cycles (Zhou et al., 2024). Incorporating air-entraining agents can create microscopic air pockets within the concrete, which provide space for water expansion during freezing, reducing internal pressure and subsequent cracking (Cheung et al., 2018). Reducing the water-to-binder ratio while maintaining workability through the use of superplasticizers can enhance the overall density and reduce porosity, which is critical for freeze-thaw resistance. Also, selecting aggregates with proven freeze-thaw resistance can also contribute to the overall durability of the concrete mix. In addition, applying water-repellent sealants or coatings on the surface of the pervious concrete can minimize water absorption, further protecting against freeze-thaw deterioration (Jahandari et al., 2023).

3.5. Optimal replacement ratio and performance targets

The optimal replacement ratio of waste glass powder (WGP) in pervious concrete (PC) is vital for achieving a balance between mechanical performance and sustainability. For applications that demand high compressive strength, such as vehicular roads or high-traffic areas, a lower WGP replacement ratio (approximately 10 %) is recommended. This ensures that the concrete maintains sufficient strength to withstand heavy loads. In contrast, for pedestrian walkways or low-traffic areas, a higher replacement ratio (up to 15–20 %) may be feasible, as the structural demands are less stringent.

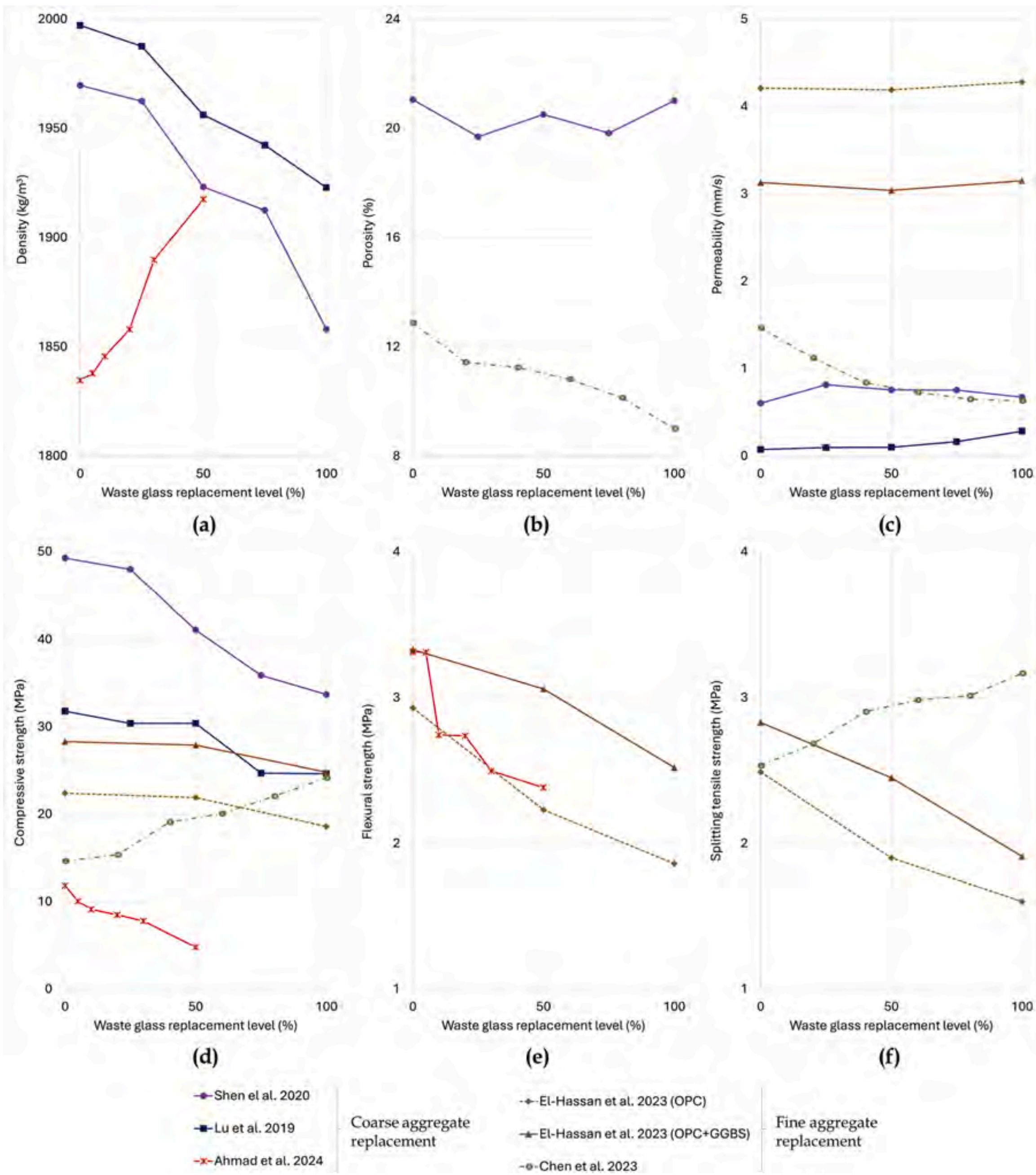

Fig. 11. Effect of CWG as aggregate replacement on (a) density, (b) porosity, (c) permeability, (d) compressive strength, (e) flexural strength and (f) splitting tensile strength of PC.

If the primary objective is to enhance the permeability of the concrete to support effective stormwater management, increasing the WGP replacement ratio can be beneficial. Ratios of 15–20 % can lead to improved water flow rates while maintaining adequate mechanical properties if other mix design parameters are optimized. It is essential to monitor the water-to-binder ratio and workability when increasing the replacement level to ensure that the concrete can still be effectively placed and compacted.

For environments prone to freeze-thaw cycles or other harsh conditions, careful attention must be paid to the WGP replacement ratio. A balance should be struck between enhancing durability and maintaining mechanical performance. A moderate replacement ratio of around 10–15 % may be optimal, combined with design modifications (e.g., air-entraining agents, fibers) to enhance freeze-thaw resistance. Each application may have unique requirements based on environmental conditions, load characteristics, and intended use. Therefore, it is essential to conduct preliminary trials to determine the most effective WGP replacement ratio for specific scenarios.

4. Crushed waste glass as aggregate in pervious concrete

Incorporating CWG as a coarse aggregate or fine aggregate replacement in PC offers several key advantages. Environmentally, it reduces the demand for natural resources and diverts CWG from landfills, promoting a more sustainable construction practice. Economically, CWG is often available at a lower cost compared to traditional aggregates, potentially reducing the overall material expenses. From an aesthetic perspective, the unique visual characteristics of CWG can enhance the appearance of the PC, providing a decorative and reflective effect. Lastly, the utilization of CWG in PC can expand the application opportunities for this sustainable construction material.

Fig. 11 demonstrates the effects of replacing coarse and fine aggregates with CWG particles on the properties of PC. As the CWG replacement percentage for coarse aggregate increases, PC density decreases. This is likely due to the lower density of CWG compared to the traditional coarse aggregates used in PC. The porosity of PC generally decreases as the CWG replacement percentage increases. The changes in porosity can be attributed to the influence of the CWG particles on the pore structure and interconnectivity within the PC matrix. The permeability of PC generally remains the same or slightly decreases as the CWG replacement percentage increases. CWG particles have a different shape and surface texture than traditional coarse aggregates like gravel or crushed stone. Incorporating CWG can alter the pore structure and interconnectivity within the PC matrix. Depending on the specific characteristics of the CWG, it may create a more tortuous or less interconnected pore network, which could lead to a slight decrease in permeability.

The compressive strength and flexural concrete of PC decreases as the CWG replacement percentage increases. Traditional coarse aggregates, such as gravel or crushed stone, typically have higher compressive strength compared to CWG particles. Replacing these stronger aggregates with weaker CWG leads to a reduction in the overall compressive strength of the PC. The Interfacial Transition Zone (ITZ) between the CWG particles and the cement paste can be a source of weakness. If the bonding between the CWG and the cement paste is less strong than the bonding between the traditional aggregates and the cement paste, it can decrease compressive strength. The irregular shape and surface texture of CWG particles may not provide as effective interlocking and load transfer mechanisms as the angular and rough-textured traditional coarse aggregates, leading to a decrease in strength. It's important to note that the reduction in compressive and flexural strength can vary depending on factors such as the specific characteristics of the CWG and the mix design proportions.

When CWG particles are used to replace fine aggregates in PC, the material's properties undergo notable changes. The density of the PC slightly decreases as the CWG replacement percentage increases, which can be attributed to the lower specific gravity of the CWG compared to traditional fine aggregates. Interestingly, the permeability of the PC increases with the increase in CWG replacement. This can be attributed to the higher porosity of the CWG particles, which contributes to a more interconnected pore structure within the PC mixture. The overall porosity of the material also increases with the CWG replacement, further enhancing the permeability.

The PC's compressive, splitting tensile, and flexural strengths exhibit a decreasing trend as the CWG replacement increases. This can be explained by the weaker bonding between the cement paste and the smooth surface of the CWG particles, resulting in a less effective stress transfer mechanism than the better mechanical interlocking with natural sand.

5. Prediction model for properties of glass powder blended pervious concrete

Prediction models for WGP blended PC are crucial for optimizing mix design, evaluating performance, assessing sustainability, and guiding practical application. These models help quantify the effects of incorporating WGP on crucial properties like strength, porosity, and permeability, enabling the development of cost-effective and environmentally friendly PC solutions.

Li et al. (2021) established a series of models to predict the effect of the water to cement ratio (w/c) and WGP to cement ratio (WGP/c) content on the porosity, permeability and compressive strength of PC using a non-linear surface fitting method. The w/c ranges from 0.22 to 0.28, and WGP/c ranges from 0 to 0.25. Based on the experiment results, the equations for predicting the porosity (v), permeability (k) and compressive strength (f_c) were established, as shown in Eqs. (3)-(5).

$$v = -94.2 + 928.8(w/c) - 0.47(WGP/c) - 1906.2(w/c)^2 + 0.003(WGP/c)^2 + 0.998(w/c)(WGP/c) \quad (3)$$

$$k = -26.05 + 227.32(w/c) - 0.05(WGP/c) - 457.2(w/c)^2 + 0.0001(WGP/c)^2 + 0.115(w/c)(WGP/c) \quad (4)$$

$$f_c = -82.52 + 799.59(w/c) - 0.34(WGP/c) - 1502.8(w/c)^2 + 0.004(WGP/c)^2 + 0.58(w/c)(WGP/c) \quad (5)$$

The R^2 was 0.958, 0.965 and 0.951 for porosity, permeability and compressive strength, respectively, indicating that the proposed equation has a high degree of accuracy and is a good fit. However, these models have some limitations, such as the researchers only tested a relatively narrow range of water-cement ratios and WGP contents. Also, the proposed models agreed well with the experimental results, but it needs to provide more information about the model validation process. Without an independent validation dataset, it isn't easy to fully assess the predictive capabilities and generalizability of the models. The models only consider the effects of w/c and WGP content. Still, there may be other factors (e.g., curing conditions, aggregate properties, mix design proportions) that could also influence the properties of PC.

Ahmad et al. (2024a) developed linear regression, non-linear regression, and artificial neural network (ANN) models to predict the compressive strength of PC containing WGP. Authors considered water to binder ratio (w/b), cement content (C.C in kg/m^3), waste glass powder content (WGP in kg/m^3), Coarse aggregate content (C.A in kg/m^3) and curing period (T in days) as input parameters. They gathered 99 compressive strength datasets from various published literature on PC and proposed the models based on that. From these data points, 75 data points were used for the training and the remaining 24 data were used for the testing of the models. Based on the analysis, they proposed the Eqs. (6) and (7) for compressive strength (C.S) prediction for LR and NLR models.

$$C.S = 65.35 - 30.28(w/b) + 0.01(C.C) - 0.01(WGP) - 0.03(C.A) + 0.102(T) \quad (6)$$

The linear regression (LR) model showed moderate prediction accuracy as the coefficient of determination (R^2) was equal to 0.77 and 0.79 for the training and testing datasets, respectively. The corresponding root mean squared error (RMSE) values are 2.721 and 2.725 MPa for the training and testing datasets.

$$C.S = -16.2(w/b)^{0.37} + 0.1(C.C)^{0.1} - 0.1(WGP)^{0.1} - 0.696(C.A)^{0.096} + 14.48(T)^{0.191} \quad (7)$$

For the non-linear regression (NLR) model, the R^2 and RMSE are equal to 0.82 and 2.394 MPa, 0.89 and 1.370 MPa for the training and testing datasets, respectively. Although the NLR model performed better than the LR model, its performance is still moderate.

Among the models tested, the artificial neural network (ANN) with a configuration of two hidden layers, five neurons, a momentum of 0.2, a learning rate of 0.1, and 5000 iterations demonstrated the highest accuracy in predicting compressive strength. Both the training and testing datasets showed excellent accuracy as R^2 equals 0.99 and RMSE value equals 0.53 and 0.49 MPa for the training and testing datasets, respectively. The study's main limitation is the limited scope of the dataset used for model development and validation. The proposed models may not be suitable for datasets with different characteristics or distributions.

The prediction models presented in this study offer valuable insights for practitioners looking to optimize pervious concrete mix designs incorporating WGP. To facilitate effective application of these models in real-world scenarios, several key strategies can be employed. Incorporating the developed prediction models into existing concrete mix design software can streamline the process for practitioners. By providing user-friendly interfaces that allow for input of material properties and desired performance outcomes, practitioners can easily generate optimized mix designs. Clear guidelines should be established for selecting the appropriate input parameters for the models. This includes recommendations on the types and proportions of WGP, as well as considerations for environmental conditions and intended applications. Such guidelines will help practitioners make informed decisions based on specific project requirements. Also, establishing a feedback loop between researchers and practitioners will ensure that the models are continuously refined and updated based on field performance data. Practitioners can provide insights into the challenges faced during implementation, which can inform future research and model enhancements. In addition, encouraging practitioners to monitor the performance of concrete mixes designed using the prediction models will provide valuable data for further validation and refinement. By tracking metrics such as compressive strength, permeability, and durability over time, practitioners can assess the models' effectiveness and make necessary adjustments. By implementing these strategies, practitioners can effectively leverage the prediction models to enhance the sustainability and performance of pervious concrete mixes.

6. Eco benefit

WGP as a cement replacement and CWG as an aggregate in PC offers several sustainability benefits. Cement production is highly energy-intensive and carbon-intensive, contributing significantly to global greenhouse gas emissions. Replacing a portion of cement with WGP can help reduce the overall cement consumption in PC mixes, lowering the environmental impact of cement manufacturing. Fig. 12 shows the challenges in managing waste glass disposal and the potential advantages of using it in pervious concrete.

The economic feasibility of incorporating WGP into pervious concrete involves evaluating both processing and transportation costs compared to traditional SCMs such as fly ash, silica fume, and slag. The production of WGP typically involves crushing and grinding waste glass, which can be cost-effective, especially if sourced from local recycling facilities. The energy required for processing is generally lower than that for traditional SCMs, as the glass can often be processed at existing facilities designed for glass recycling. Materials like fly ash and slag usually require transportation from power plants or steel production

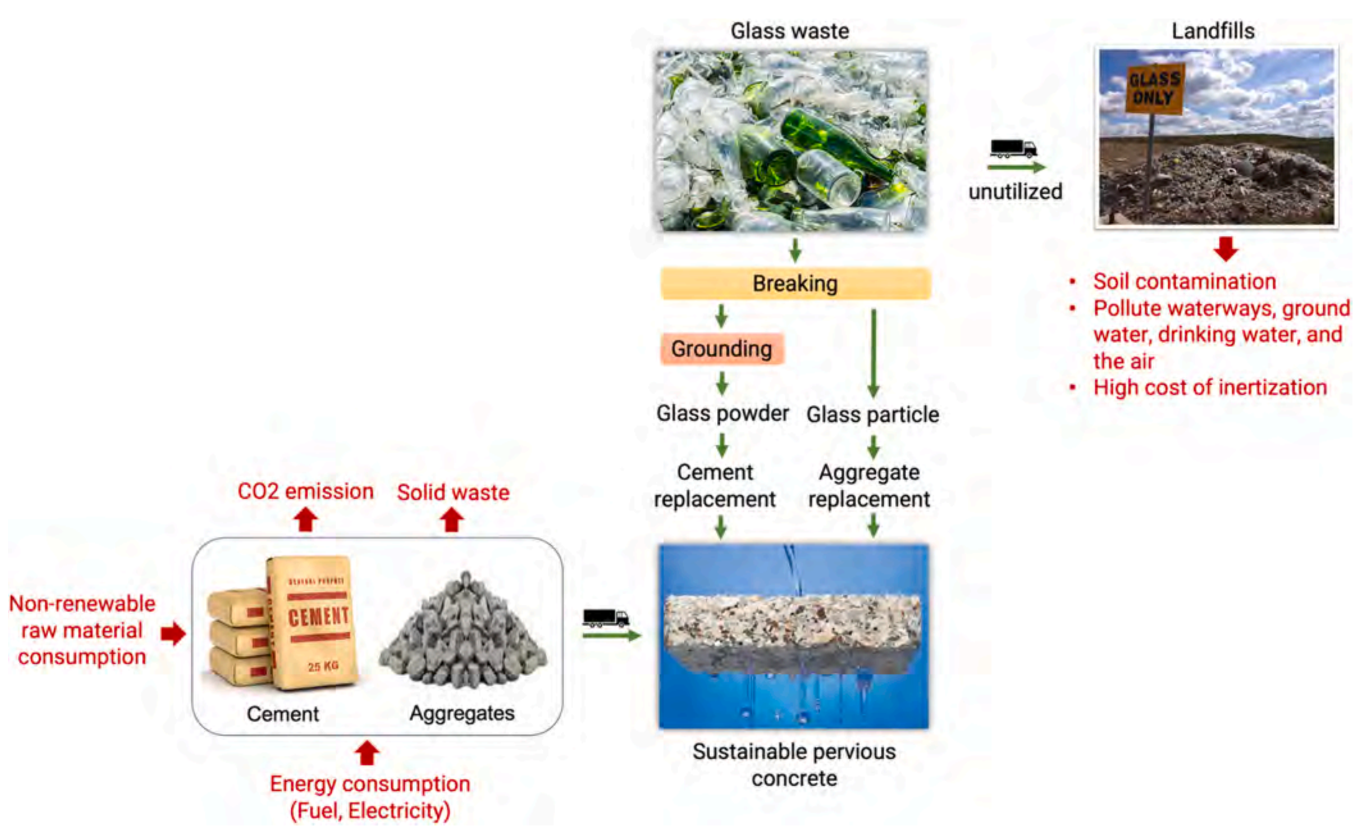

Fig. 12. Challenges in managing waste glass disposal and the potential advantages of using it in pervious concrete.

facilities, which adds to their overall costs. The processing of these materials can also involve additional steps such as drying or grinding, increasing their cost.

As WGP is often sourced locally from recycling centers, transportation costs can be minimized. Local availability reduces the carbon footprint associated with long-distance transportation, enhancing the sustainability profile of WGP. Many traditional SCMs are transported over significant distances, which can substantially increase costs. For example, fly ash and slag may need to be transported from remote industrial sites, increasing the overall price per ton due to fuel and handling expenses. A preliminary cost analysis indicates that WGP can be competitive with traditional SCMs when considering both processing and transportation. While specific costs can vary by region and market conditions, initial estimates suggest that WGP could reduce concrete production costs by approximately 10–15 % compared to traditional SCMs, depending on local availability and processing efficiency.

The results from the life cycle analysis of glass recycling conducted by British Glass provide valuable insights into the energy consumption and CO_2 emissions associated with grinding and segregating glass. The grinding and segregation process consumes between 3 and 15 kWh per ton of glass, indicating a significant energy requirement that varies depending on the specific processing conditions and technology used. The Table 7 data on various sizes of WGP and their corresponding energy consumption and CO_2 emissions (Letelier et al., 2019). The data illustrates that finer grinding requires more energy, which in turn can lead to higher CO_2 emissions if sourced from fossil-fuel-heavy energy grids. This suggests a trade-off between particle size and processing energy efficiency. The variation in CO_2 emissions based on country reflects the differing energy sources used in electricity production. Countries relying more on renewable energy sources will have lower associated CO_2 emissions for the same amount of electricity consumed. Understanding the energy and emissions profiles of different glass recycling processes can guide policy decisions and investments towards more sustainable practices. It underscores the need for improving energy efficiency and transitioning to low-carbon energy sources in the glass recycling sector.

This study investigates the environmental benefits of utilizing waste glass powder (WGP) in previous concrete production based on mixed design proposed by Yavuz et al. (2024). The focus lies on the life cycle assessment (LCA) of mortar production, specifically its energy consumption and CO_2 emissions. Following the guidelines outlined in ISO-13315–2 (2014), the pervious concrete mortar production life cycle is divided into three stages:

- Raw Material Production: This stage considers the embodied energy and CO_2 emissions associated with extracting and processing the raw materials used in mortar production. Data for these values are obtained from established sources like the Bath Inventory of Carbon and Energy (ICE) (2011) and relevant research studies (Letelier et al. (2019) and Seddik Meddah (2017)). Table 8 summarizes the energy consumption and CO_2 emissions per kilogram of each raw material. This data serves as the basis for calculating the total embodied energy and CO_2 emissions for this stage.
- Transportation: This stage accounts for the environmental impact of transporting raw materials to the production facility. The ICE database (2011) provides reference values for road transportation, the most common method. Here, embodied energy is estimated at 2.4 MJ/ton.km and CO_2 emissions at 0.15 kg/ton.km. The total environmental impact of transportation is determined by multiplying these values by the specific distance each raw material travels.
- Manufacturing: The final stage considers the energy consumption and CO_2 emissions generated during the on-site mixing, casting, and curing of mortar at the production facility. Research by Gonzalez Stumpf et al. (2014) suggests that dedicated mixers consume approximately 0.002 MJ/kg of mortar for this process. Electricity, typically used as the primary energy source, contributes roughly 0.59 kg of CO_2 emissions per kilowatt-hour (kWh) consumed (equivalent to 3.6 MJ) (Gonzalez Stumpf et al., 2014). These values are used to calculate the total environmental impact of the manufacturing phase.

Table 7
Energy consumption and CO_2 associated with WGP grinding time (extracted from Letelier et al. (2019)).

WGP Size (μm)	Time (hrs)	Energy consumption (kWh)	CO_2 emission[a] ($kgCO_2$/ton)
38.1	2.54	38.09	0.30 – 35.27
44.5	2.16	32.47	0.26 – 30.06
73.7	1.11	16.66	0.13 – 15.43

[a] CO_2 emission varied based on country

Table 8
Energy embodied and CO_2 emission for the raw material (per kg).

Material	Cement	WGP	Aggregates	Water
Raw material production				
Embodied energy (MJ/kg)	4.5	0.137	0.093	0.01
CO_2 emission (CO_2.kg/kg)	0.73	0.035	0.008	0.001
Transportation				
Distance (km)	200	50	200	20
Embodied energy (MJ/kg)	0.48	0.12	0.48	0.048
CO_2 emission (CO_2.kg/kg)	0.03	0.0075	0.03	0.003
References	(ICE, 2011)	(Letelier et al., 2019)	(Seddik Meddah, 2017)	(ICE, 2011)

The embodied energy and CO_2 emissions associated with mortar production were evaluated and presented in Fig. 13. These calculations were based on the mixed design proposed by Yavuz et al. (2024). The incorporation of Waste Glass Powder (WGP) as a partial cement replacement strategy resulted in a significant reduction in both embodied energy and CO2 emissions. As the WGP content increased, the reduction in embodied energy became more pronounced, reaching 3.1 %, 6.1 %, 9.2 %, and 12.3 % for replacement levels of 5 %, 10 %, 15 %, and 20 %, respectively. This substantial decrease can be attributed to the lower embodied energy associated with WGP production compared to Ordinary Portland Cement (OPC). Similarly, the inclusion of WGP as a cement replacement had a more pronounced effect on CO2 emissions. The CO_2 footprint decreased proportionally with increasing WGP content. Reductions of 3.7 %, 7.5 %, 11.2 %, and 15.0 % were observed for WGP replacement levels of 5 %, 10 %, 15 %, and 20 %, respectively. These findings highlight the potential of WGP to contribute to a more sustainable construction industry by reducing the CO2 emissions associated with mortar production.

Additionally, glass waste is a significant source of environmental pollution, as it is not easily biodegradable and can accumulate in landfills. Incorporating WGP and CWG particles as aggregates in PC can help divert these waste materials from landfills, contributing to a more circular economy and reducing the need for virgin raw materials. WGP and CWG aggregates can also enhance the durability of PC, including its resistance to freeze-thaw cycles and weathering, which can extend the service life of PC pavements and reduce the need for frequent maintenance and replacement.

Furthermore, PC, with its inherent ability to allow water infiltration, can help manage stormwater runoff more effectively, reducing the burden on municipal storm drainage systems, preventing localized flooding, and promoting groundwater recharge, contributing to sustainable water management practices. PC's porous structure can also help reduce the urban heat island effect by allowing evaporative cooling

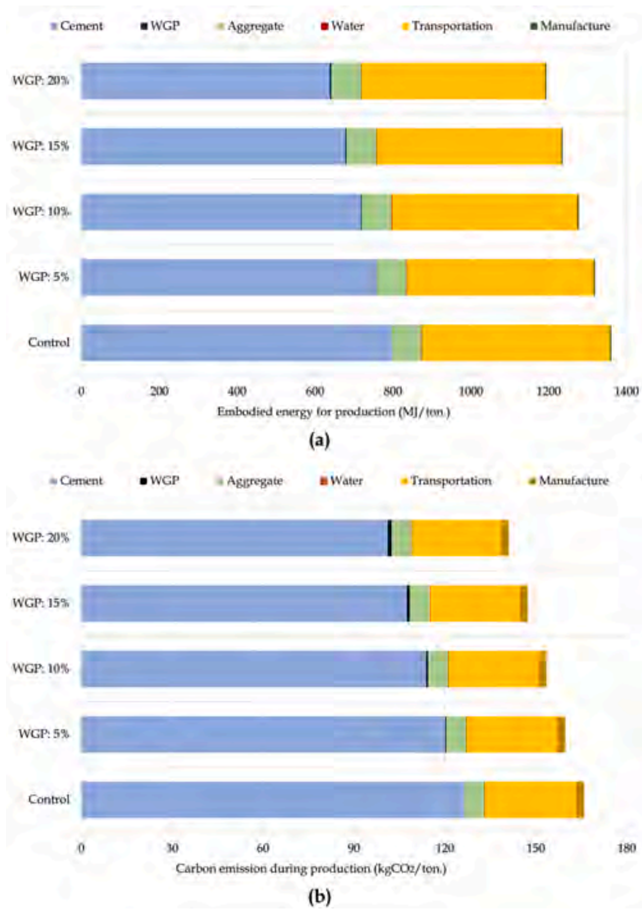

Fig. 13. (a) Embodied energy and (b) carbon emission for the production of one ton of pervious concrete mortar.

and reducing surface temperatures, leading to energy savings for cooling buildings and improved thermal comfort in urban environments, enhancing the overall sustainability of the built environment. By incorporating WGP as a cement replacement and CWG as an aggregate in PC, the construction industry can advance towards more sustainable construction practices, reduce the environmental footprint, and contribute to a more circular economy.

7. Limitations of the past studies and future research direction

The review of the existing literature has highlighted the promising results of using WGP and CWG in PC mixes. Researchers have documented improved mechanical properties, increased porosity and permeability, and reduced environmental impact compared to conventional PC. However, the review has also revealed several limitations and knowledge gaps that require further investigation to fully harness the potential of these waste materials in PC applications.

- Limited research on combined use of WGP and CWG: Most previous studies have focused on using either WGP as a cement replacement or CWG as an aggregate replacement in PC. More research is needed on the combined use of these two waste materials to maximize the benefits of a single PC mix. Therefore, more research is required to evaluate the synergistic effects on mechanical properties, durability, and overall sustainability, including the potential for improved strength, permeability, and reduced environmental impact.
- The long-term durability and performance of PC mixes containing WGP and CWG have yet to be thoroughly investigated. More research is needed to assess the resistance to weathering, freeze-thaw cycles, and potential clogging over an extended service life.
- The optimal mix design proportions for combining WGP and CWG in PC have yet to be established. Further investigation is required to determine the most effective ratios of these materials to achieve the desired mechanical, durability, and sustainability properties. Identify the optimal ratios of these materials to maximize the benefits in terms of mechanical properties, durability, and overall sustainability.
- The impact of different glass particle characteristics, such as size, shape, and composition, on PC performance has yet to be extensively explored. Understanding the influence of these parameters can help guide the effective utilization of WGP and CWG in PC. So, further research is required to comprehensively understand how these parameters influence the properties, behavior, and long-term performance of PC containing WGP and CWG.
- The need for standardized guidelines and specifications for using WGP and CWG in PC can hinder the widespread adoption of these sustainable solutions. Establishing such guidelines can provide a framework for consistently and reliably implementing these materials in PC applications. These guidelines should address mix design, testing procedures, performance requirements, and installation practices to facilitate the widespread adoption of these sustainable solutions.
- Also, past researches mainly focus on the mechanical characteristics of PC, and the cost and eco-benefit of including WGP or glass waste in PC are considered. So, there is a need to conduct comprehensive studies to quantify the economic and environmental benefits of using WGP and CWG in PC, including the potential cost savings and reduction in carbon footprint compared to traditional concrete mixes. This information can help drive the widespread adoption of these sustainable materials.
- There needs to be more study on combination with other supplementary cementitious materials. Explore the potential for combining WGP and CWG with other supplementary cementitious materials or innovative admixtures to enhance the performance and sustainability of PC further. This could involve investigating synergistic effects, optimizing mix designs, and evaluating the overall benefits of these multi-component systems.

While the study identifies key knowledge gaps, providing specific methodological recommendations can enhance the clarity and focus of future research efforts. To effectively address these gaps, the following experimental approaches are recommended:

- Long-Term Performance Studies: Conduct field trials to evaluate the durability and longevity of glass-modified pervious concrete under varying environmental conditions. This could include monitoring performance over several years to assess factors like compressive strength, permeability, and resistance to freeze-thaw cycles.
- Optimized Mix Design Experiments: Implement systematic mix design experiments utilizing design of experiments (DOE) methodologies. This can help identify optimal ratios of glass powder and crushed waste glass, considering variables such as water-to-cement ratios and aggregate sizes.
- Life Cycle Assessment (LCA): Perform comprehensive LCAs comparing traditional pervious concrete with glass-modified variants. This should include metrics on carbon footprint, energy consumption, and waste generation throughout the material lifecycle.
- Standardized Testing Protocols: Develop and standardize testing protocols for assessing the performance of glass-modified pervious concrete. This could include tests for mechanical properties, permeability, and environmental impact assessments that are consistent across different studies.
- Hybrid Material Investigations: Explore the synergistic effects of combining glass powder with other supplementary cementitious

materials (SCMs), such as fly ash or slag. Experimental designs should focus on understanding how these combinations can further enhance strength and sustainability.
- Field Application Studies: Initiate pilot projects in urban settings to evaluate the performance of glass-modified pervious concrete in real-world applications. Collect data on stormwater management effectiveness, urban heat island mitigation, and overall community impact.

By addressing these limitations and pursuing the identified future research directions, the scientific community can contribute to developing more environmentally-friendly and resource-efficient PC solutions that effectively utilize CWG materials, ultimately leading to more sustainable construction practices.

8. Conclusion

The review outlines the significant advantages of using CWG and WGP in PC. These materials offer a sustainable construction approach, enhancing environmental and mechanical properties. From the review, the following key points were drawn.

- Incorporating CWG and WGP significantly reduces reliance on traditional cement and natural aggregates. By utilizing these recycled materials, the construction industry can promote better waste management practices, diverting materials from landfills and contributing to a more sustainable future.
- WGP and recycled glass aggregates enhance PC's compressive and flexural strength, particularly at low to moderate replacement levels. Additionally, the pozzolanic activity of WGP improves the durability and long-term performance of the concrete, making it a viable alternative to conventional materials.
- Despite the benefits, there are challenges to consider. Higher replacement levels of WGP may reduce compressive strength, while the PC's susceptibility to freeze-thaw cycles could compromise its integrity over time. Addressing these challenges is crucial for the effective implementation of these sustainable materials.
- Future research should focus on optimizing mix designs to maximize the performance of PC containing WGP and CWG. Moreover, exploring hybrid approaches that combine WGP with CWG could yield even better results. Investigating these materials' long-term performance and durability will also be essential for their broader application in construction.
- The use of WGP and CWG in PC not only supports environmentally friendly construction practices but also aids in reducing the volume of waste sent to landfills. This approach promotes a circular economy within the concrete industry, emphasizing the importance of resource efficiency and sustainability in modern construction practices.

Ethics

Not applicable

Patient consent statement

Not applicable

Permission to reproduce material from other sources

Not applicable

Clinical trial registration

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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.

Data Availability

Data will be made available on request.

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