Waste-Infused Geopolymer Concrete: A Systematic Literature Review with Meta-Analysis

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Abstract

The cement industry is the major source of producing the most abundant green-house gas, CO2. Hence, the research world is on the hunt to unravel the mystery of replacing ordinary cement with equivalent but environmentally sustainable substances. Here arises the context of Geopolymer Concrete (GPC). The very word 'geopolymer' in GPC refers to the class of different alumino-silicate materi-als that are chemically dissimilar from traditional cement. These materials are al-kali-activated with natural minerals, such as quartz and feldspar, or various indus-trial or agricultural by-products, including construction and demolition (C&D) waste. Because of its eco-friendliness, it paves the way to the emergence of alter-native management of different types of harmful solid waste. This review article is based on the utilisation of different types of waste materials like fly ash, poly-vinyl alcohol fibre (PAF), Palm oil fuel ash (POFA), oil Palm shell (OPS), glass powder, recycled aggregates, agro-waste, C&D waste, etc., infused in GPC. These wastes are incorporated into GPC not only to reduce environmental impact but also to advance research in finding GPC with enhanced mechanical and other properties. Methodologically, PRISMA has been followed to construct this sys-tematic literature review. In this piece, articles from the last 10 years in the Indian subcontinent and Southeast Asian context have been reviewed.

Keywords: Geopolymer concrete, waste, concrete, PRISMA, metadata analysis.

Abbreviation

POA: Palm oil ash, RS: Reinforced steel, BMW: Biomedical waste ash, BCW: Bone China waste, PF: Polypropylene fibers, CSF: Crimped steel fiber, TB: Turmeric bulb, GP/ GWP: Glass powder, CR: Crumb rubber, GF/GFRC/G/GFRP/AGF: Glass fiber, SF: Steel fiber, , CS: Copper slag, MS: Metal swarf, QD: Quarry rock dust/ Quarry dust, LF: Lignocellulosic fiber, SS: Steel slag, BMWA: Bio-medical waste ash, RCA: Recycled coarse aggregate, SBA: Sugarcane bagasse ash, RFA: Recycled fine aggre-gate, BA: Bamboo ash, GP: Glass powder, A: Alcofine, CCA: Coral coarse aggregate, LWA: Lime waste Aggregate, RHA: Rice husk ash, RGW: Recycled granite waste, GW: Granite waste, EE: External exposure, AD/ AC: Air dry, OD/ OC/HC: Oven dry, VPD: Volcanic pumice dust, GSA: Groundnut shell ash, RBA:

Recycled bricks aggre-gate, SLS: Sewage sludge, BWSP: Bethamcherla waste stone powder, MHA: Millet husk ash, WSA: Wheat straw ash, POC: Palm oil clinker, OPS: Oil palm shell, FA: Fly ash, GGBS: Ground granulated blast furnace slag, LCWA: Low calcium waste wood ash, WRF: Waste rubber fiber, EW: Electronic waste, WGP: Waste glass powder, UFS: Ultra fine slag, CF: Carbon fiber, CFRP: Carbon fiber reinforce polymer, PVA: Poly-vinyl alcohol fiber, BR: Bauxite residue, BA: Bottom ash, FS: Foundry sand, EPP: Eco-Processed pozzolan, AAS: Alkaline activated slag, WFS: Waste foundry sand, BF: Basalt fiber, COCS: Crude oil contaminated sand, LA: Laterite aggregates, PW: Plastic waste, BLA: Bamboo leaf ash

1 Introduction

Every year, different categories of waste are generated from the industry, agricultural, mining sector, urban & semi-urban municipal waste, etc., in huge amounts. These are dumped in landfills, river water & riverbanks near industrial areas. The River Ganga is one of the most polluted water bodies in India [1, 2]. The growing quantity of waste every year can cause a serious deficit in landfill areas and depletion of the Earth’s natural resources [3].
Management of these wastes through construction is, perhaps, one of the best initiatives for managing waste materials. ‘Waste-infused geopolymer concrete’ has proved to be a better substitution for OPC, which can result in a reduction of CO2 generated by the production of OPC [4]. GPC is produced using industrial by-products and activated by an alkaline solution. Encapsulating waste as a fine & coarse aggregate or as a binder material in GPC can pave a new path in managing waste material. Proper curing and appropriate selection of waste materials may enhance the mechanical, durability, physical, and chemical properties of GPC [5, 6].
This piece presents a systematic literature review of articles from the last 10 years in the context of the Indian Subcontinent and Southeast Asia. The review provides a detailed overview of the wastes encapsulated in GPC, along with a comparison of mechanical properties and durability with traditional concretes. The paper also high-lights the outcome of meta-data analysis of this literature review

2 Materials and Methodology

PRISMA method (Preferred Reporting Items for Systematic reviews and Meta-Analyses) has been followed (Fig. 1) in this study. The keywords ("Geopolymer concrete") AND ("waste material" OR "solid waste") have been given as the input under the field of TITLE-ABS-KEY in both the index, i.e., Scopus and ScienceDirect. Initially, 939 articles have been collected. After screening and sorting meticulously, it has come down to 101, which was further finessed to 65. This review has focused on the articles published in the Indian subcontinent and Southeast Asia, or authored by researchers belonging to that region, over the past decade. The review has been done to have an idea of the contextual regional advancement of sustainable building materials.

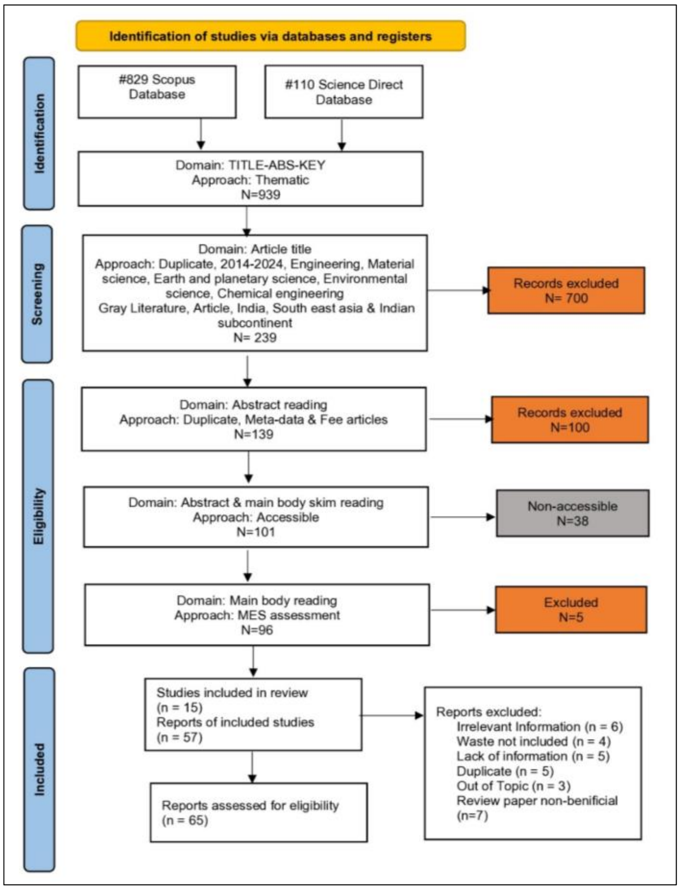


Fig. 1. PRISMA Table (Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71)

3 Results

3.1 Bibliometric analysis and involvement of waste and countries

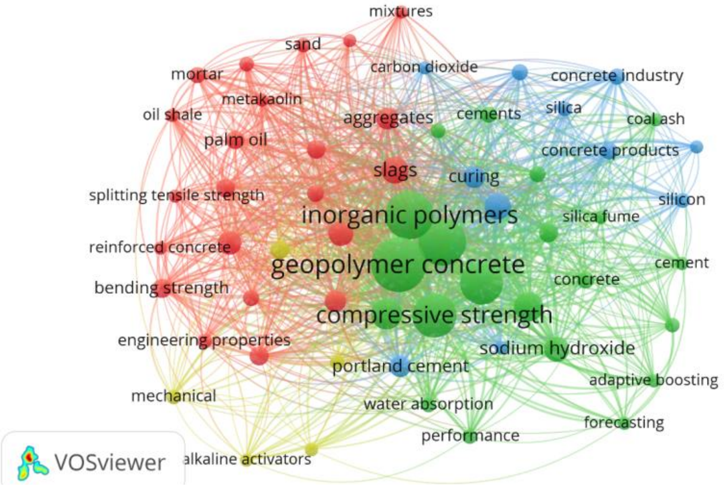


Fig. 2. Keyword Co-occurrence Network (Total Link Strength based)

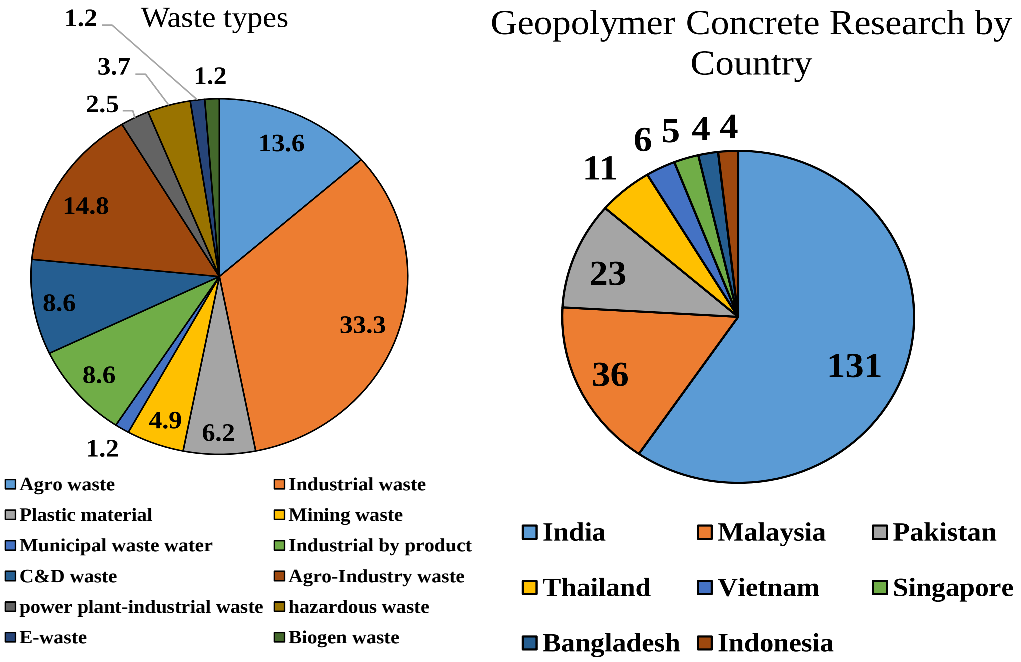
From the perspective of critical observation, this field is technically developed in strength and mix design, but lacks addressing the effect of this concrete in environmental and societal domains. Keywords like “sustainable development” and “carbon dioxide” exist at the periphery, indicating a lesser concentration in these matters, and are not emphasised by the researchers. This research creates a gap in integrating life cycle assessment, pollution mitigation, and carbon footprint analysis into the mainstream of geopolymer studies.

The networks also reflect the absence of industrial adoption or strong health-related keywords, i.e. “occupational exposure”; such keywords are not prominent. This shows the lack of attention to practical implementation and workers' safety.

The peripheral position of AI/ML related keywords, i.e “forecasting” and “adaptive boosting”, indicates rare use of technologies like digital and predictive modelling revolution. Through this, it is clear that the missing opportunity is how simulation could accelerate mix design and sustainability optimisation.

Another point of reflection is the absence of strong health-related or industrial adoption keywords. For example, “occupational exposure” is not prominent, suggesting that while the materials are being optimised in labs, practical implementation and worker safety considerations are not getting proportional attention.

The peripheral placement of AI/ML-related keywords like “adaptive boosting” and “forecasting” implies that the digital and predictive modelling revolution has barely touched this domain — a lag-behind scenario given how simulation could accelerate mix design and sustainability optimisation



(a) (b)

Fig. 3. (a) Percentage of waste types from literature; (b) Publication count from the Indian Subcontinent and Southeast Asia

Fig.3a illustrates that Industrial waste (33.3%) is by far the most researched waste type in the reviewed literature, suggesting its significant environmental presence and possibly higher potential for reuse in industrial applications. Power plant industrial waste (3.7%), mining waste (4.9%), hazardous waste (1.2%), and plastic material (6.2%) have notably low representation, despite their high environmental impact. This suggests a research gap in these waste categories that could be explored further. The spread is heavily skewed toward industrial and agricultural origins, indicating literature bias towards large-scale, high-volume waste sources rather than smaller but hazardous streams. Fig. 3b illustrates the development of countries in the field of research related to sustainable materials. According to the pie chart, India dominates the domain of waste management with 131 papers/publications. Pakistan (23 pa-pers) and Malaysia (36 papers) are the runners-up in this domain, potentially due to the growing industrialisation and challenges related to waste in these countries. Along with that, Singapore (5), Vietnam (6), Thailand (11), Bangladesh (4), and Indonesia (4) show the poorer results. The pie chart heavily focuses on industrial wastes in Fig. 3a, clearly dominated by developing countries (India, Malaysia).

3.2 Workability and mechanical strength

It can be observed in Fig.5 that the combinations of industrial byproducts such as BA, FS, BWSP, RHA, and composite wastes like PF+CSF, BR+G yield the highest compressive strength, showcasing their excellent pozzolanic activity and filler effects. Conversely, agricultural wastes, infused in geopolymer concrete, such as GF, POA, and AGF, showed lower strength. SSL and POC resulted in significantly lower com-pressive strength, indicating a limited pozzolanic contribution and a possible negative impact on concrete matrix densification. Along with that, the GPCs of (12M - 16M) alkaline solution had significantly increased compressive strength.

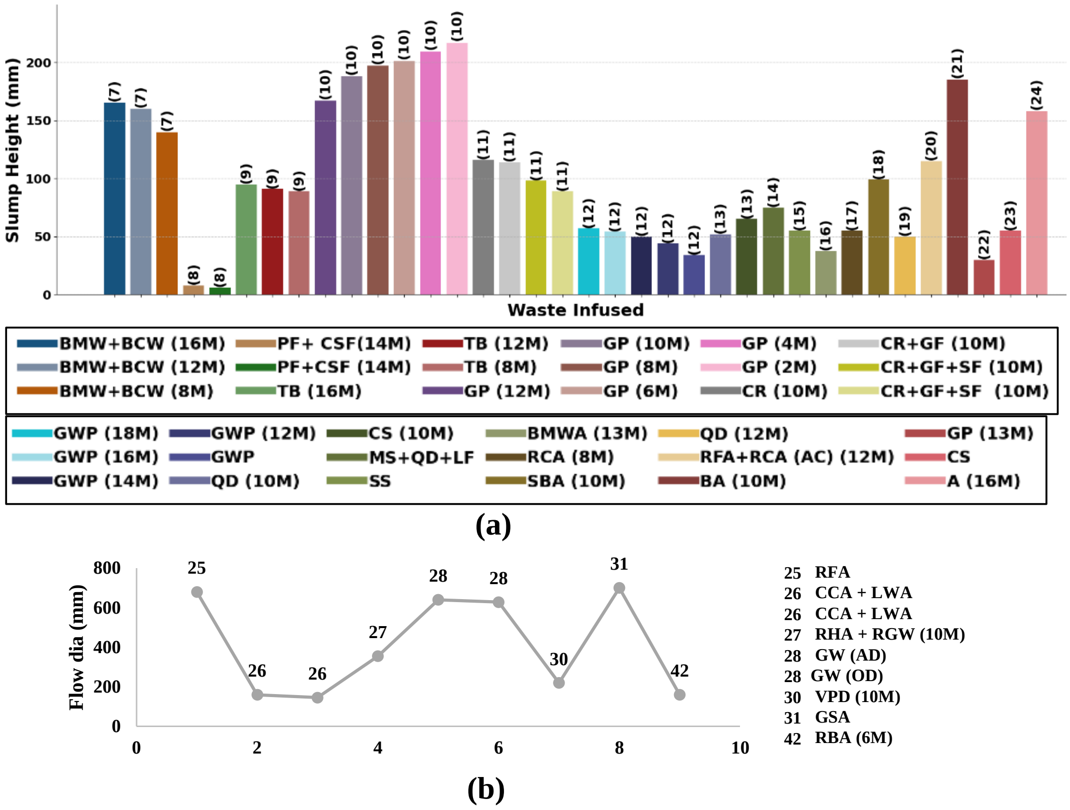


Fig. 4. Keyword Co-occurrence Network (Total Link Strength based)

In Fig.6, the graph of split tensile strength, BWSP-infused-GPC, showed the highest strength, about 9.9 MPa. But since only one datum is available, further studies should be conducted to confirm the repeatability. On the other hand, POC showed a weak split tensile strength. POC may reduce carbon footprint, but a drastic reduction in tensile strength. In Fig.7 it can be observed that CR alone yielded the lowest flexural strength (0.48 MPa), showing its unsuitability in the structural aspect on its own. However, in a hybrid system with glass fibre & steel fibre, it jumped to 7.13 MPa — almost a 15-fold increase. It has appeared thrice: 3.5 MPa, 6.6 MPa, 7.2 MPa. Bio-medical waste ash reached up to 8.3 and 5.9 MPa, performing above average.

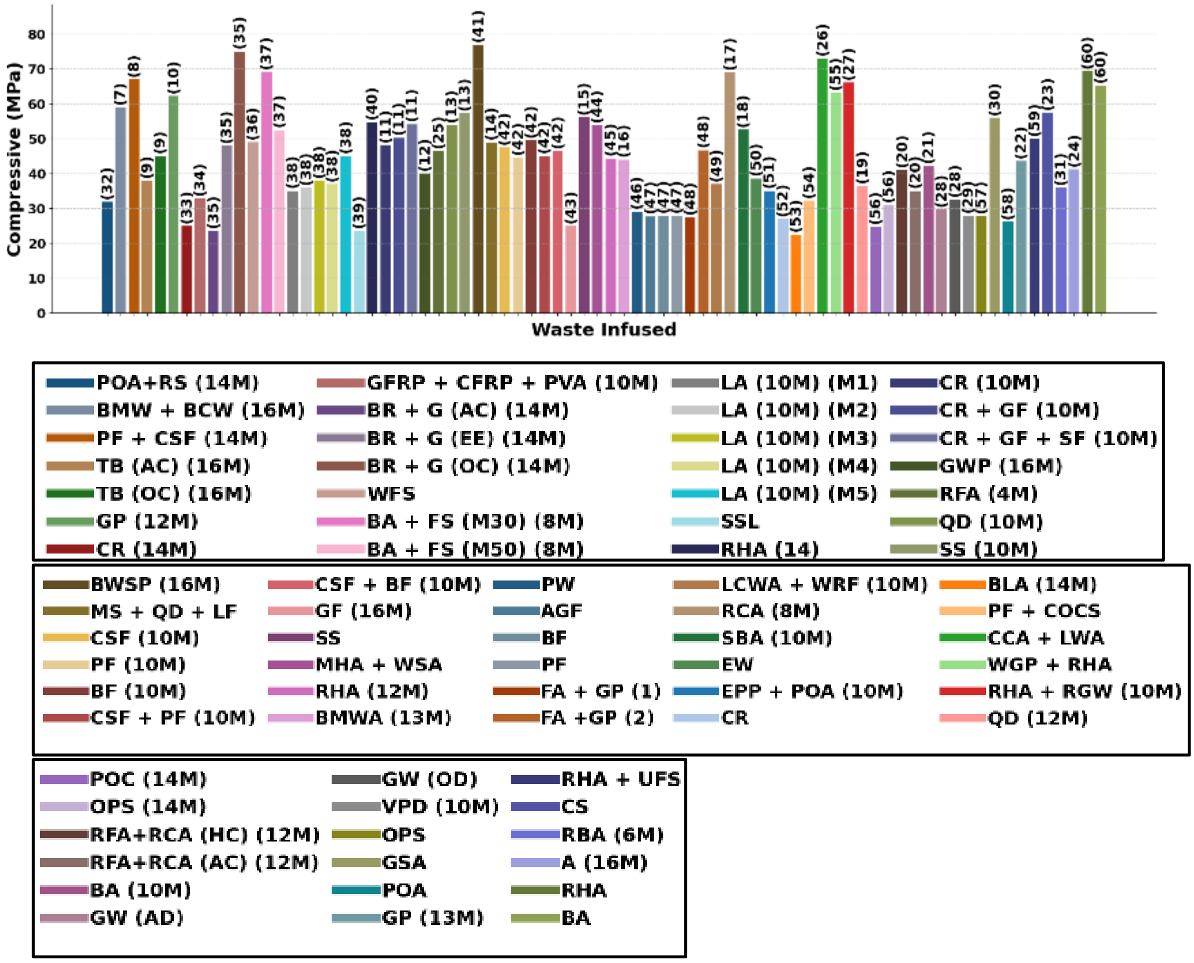


Fig. 5. Compressive strength of wasted infused concrete.

Fig.8(b) represents the Modulus of elasticity refers to the stiffness of the concrete, the deformation of concrete at a certain amount of strain. Density in Fig.8(c) refers to the physical property of the concrete, which shows the concentration of the material in Kg/m³. Fig.8c indicates how the density of the GPC varies with different chemical & waste compositions in the geopolymer concrete mixture. It also reflects the packing efficiency of the concrete. The higher the density and the lower the water absorption percentage, the more durable the concrete. Denser concrete helps the concrete resist damage from moisture and environmental exposure. Fig. 8(a) through the comparison, it has been seen that the mix design with Granite waste composite with air & oven dry showed the least water absorption percentage, about 3.3% & 3.4%. At the same time, the density of the mix composite is high.

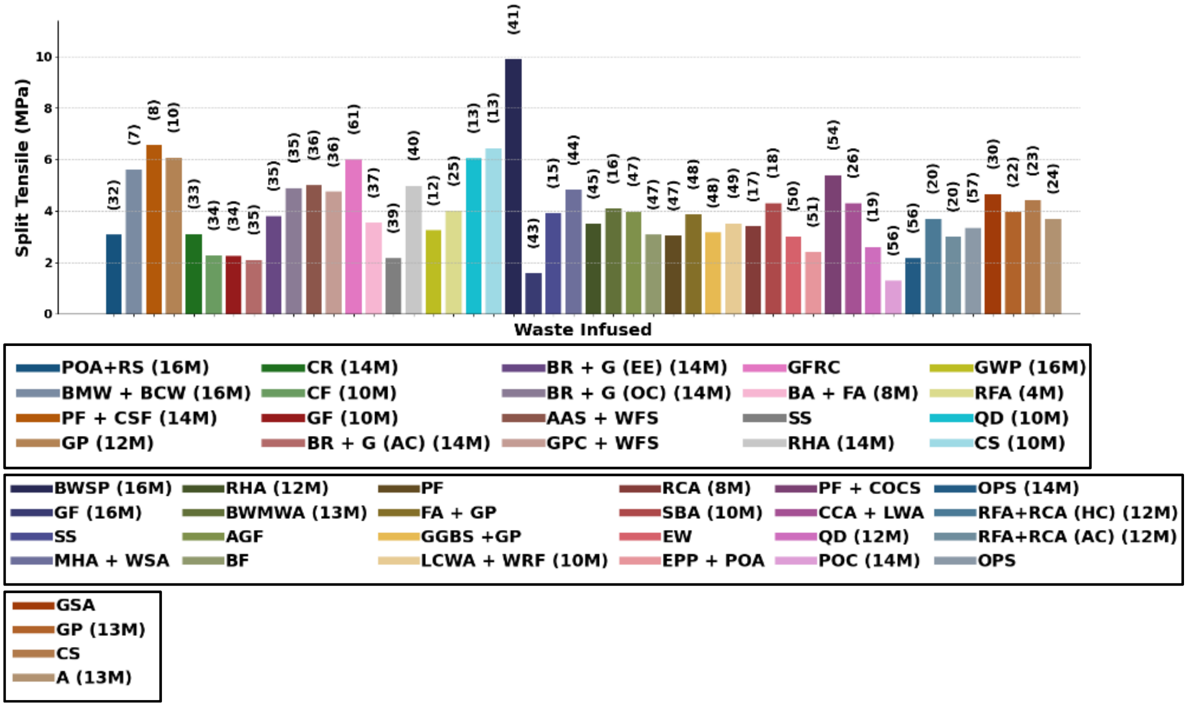


Fig. 6. Split tensile strength of wasted infused concrete.

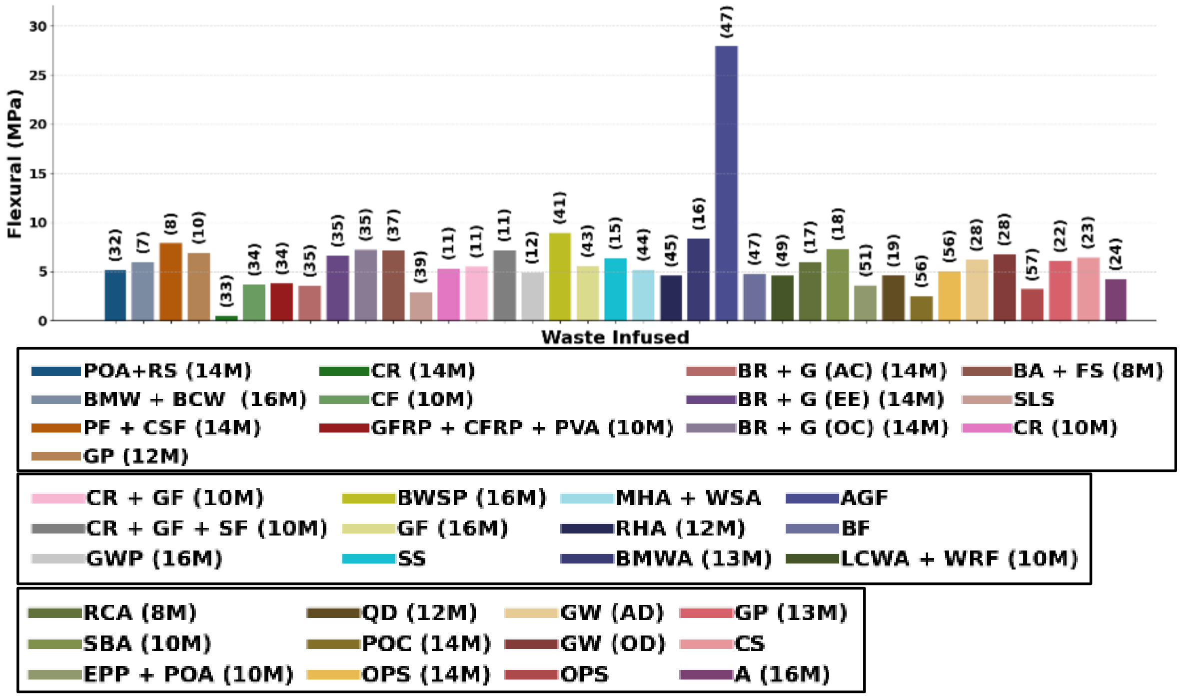
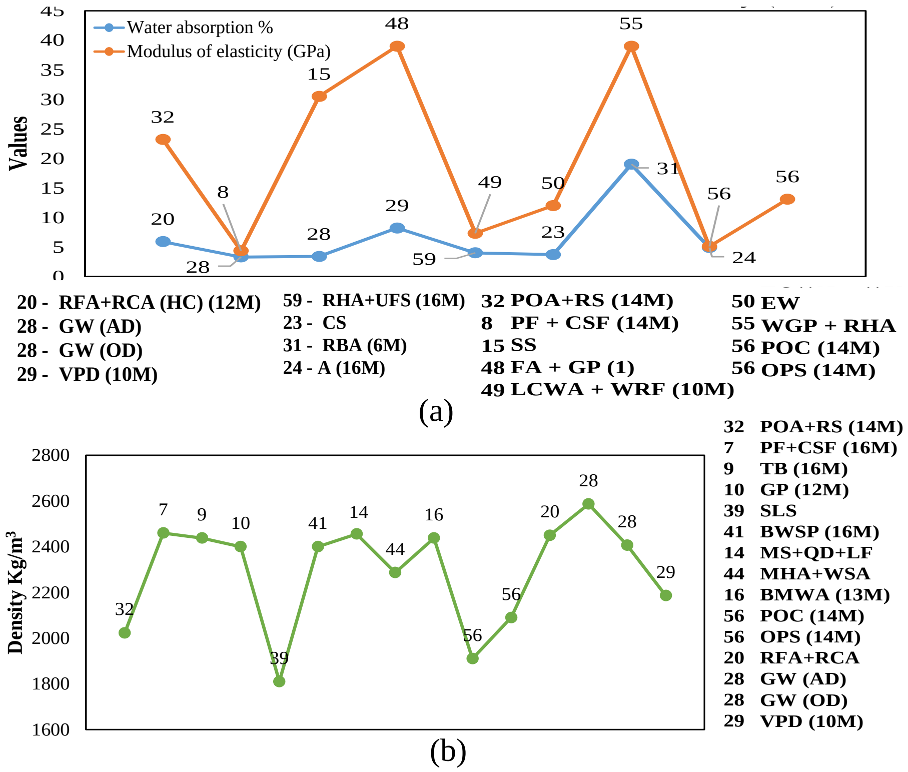


Fig. 7. Flexural strength of wasted infused concrete.



(a)

(b)

Fig. 8. Durability of concrete: (a) Modulus of elasticity and water absorption percentage (b) Density.

4. Conclusion

Expensive fibres only boost performance when they are integrated thoughtfully — cost alone doesn't equate to better results. Complexity doesn't automatically mean superiority, and combining wastes can cancel out benefits if their chemistries clash. While certain residues (for example, BWSP, PP fibre, and CS) appear promising, in-corporating waste must be guided by engineering design rather than sustainability slogans. It's not about piling in more waste; it's about creating the right synergy be-tween the cement matrix and the additives. Concrete containing CR often shows reduced strength, mainly because rubber particles are flexible and do not bond strongly with the cement matrix. When stiff, well-bonding fibres are added, however, this drawback is largely compensated. This suggests that using rubber by itself in structural concrete is not ideal, but it still holds value in hybrid mixes where upcycling potential can be realized. Flexural strength in concrete mainly comes from fibres bridging cracks under tension. Therefore, any future mixture designed for higher flex-ural resistance should give priority to fibre reinforcement, even in modest proportions. Several industrial by-products may be more appropriate in non-structural applications like paving units or barriers, or in carefully balanced blends, rather than in pri-mary load-bearing concrete. The key takeaway is that context, material composition, and mutual compatibility matter more than just recycling waste. It may be better if future studies shift their focus from "What waste can we incorporate?" toward "How can we design waste-based concretes that perform on par with conventional materials?

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