Recycling RAP in Geopolymer Concrete for Sustainable Pavement Solutions

A. Ghosh
Research Associate, Indian Institute of Technology Roorkee, Roorkee, India, a_ghosh@ce.iitr.ac.in

A. Sachdeva
PhD Scholar, Indian Institute of Technology Roorkee, Roorkee, India

S.I. Sk
Contractual Faculty, National Institute of Technology Hamirpur, Hamirpur, India

G.D.R.N Ransinchung & P. Kumar
Professor, Indian Institute of Technology Roorkee, Roorkee, India

ABSTRACT: This study investigates the potential of using coarse and fine Recycled Asphalt Pavement (RAP) fractions as substitutes for natural aggregates in paving-grade geopolymer concrete (GPC). Findings highlight that higher RAP content significantly impacts strength and durability, necessitating limitations on the proportion of RAP used. An optimal mix with 50% coarse RAP achieved a flexural strength of 4.72 MPa after 7 days of ambient curing while reducing carbon emissions by 56.16% compared to traditional concrete. Furthermore, fine RAP mixes exhibited a higher surface abrasion loss, with a maximum of 0.288 mm, indicating that coarser RAP fractions are more suitable for designing Pavement Quality Concrete (PQC). Furthermore, fine RAP mixes exhibited higher loss in surface abrasion depicting a maximum of 0.288mm suggesting the potential recycling of coarser RAP fractions for rigid pavement applications.

1 INTRODUCTION

1.1 *General*

Geopolymer Concrete (GPC) is emerging as a sustainable alternative to traditional Portland Cement Concrete (PCC), leveraging industrial by-products like Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) as binders to reduce greenhouse gas emissions (Davidovits, 1988). Unlike PCC, GPC eliminates the need for cement clinkers, significantly lowering its carbon footprint. Despite extensive research on GPC for in building constructions, its potential in pavement construction, particularly for heavy traffic roads, remains underexplored. Reclaimed Asphalt Pavement (RAP) offers an additional opportunity to incorporate recycled materials, reducing the demand for natural aggregates. However, challenges such as reduced strength and workability due to adhered bitumen persist. By eliminating cement, GPC with RAP offers significant environmental advantages, including lower greenhouse gas emissions compared to PCC. This study focuses on integrating RAP into GPC for pavement applications, providing a sustainable solution that meets performance demands for heavy traffic infrastructure while enhancing environmental sustainability.

2 MATERIALS USED AND METHODOLOGY

2.1 *Materials*

This study investigated the use of Class F and GGBS as precursors for geopolymer concrete. The mechanical properties revealed a specific gravity of 2.21 for FA and 2.82 for GGBS, with respective specific surface areas of 395 m^2/kg and 424.01 m^2/kg. The XRF analysis in Table 1 indicates a Si/Al ratio of 2 for FA, confirming its suitability as a precursor, while the high Ca content in GGBS supports effective ambient curing.

For activation, 14M sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were used in a ratio of 0.5. Aggregates for the study were sourced from a local quarry, while RAP was obtained from a deteriorating section of the National Highway. The 20-year-old RAP was stockpiled for a year, leading to oxidation and stiffening of the asphalt. The RAP was then sieved into coarse (>4.75mm) and fine (<4.75mm) fractions, with bitumen content of 3.5% for fine RAP and 2.2% for coarse RAP. Natural aggregates included Zone II sand and coarse aggregates of 19mm and 10mm nominal sizes.

Table 1. Chemical composition of the studied wastes

Wastes	Chemical components (% by mass)									
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	K_2O	P_2O_5	MgO	LOI (%)
GGBS	27.32	1.57	12.09	1.95	54.27	1.21	1.12	-	0.22	3
FA	56.70	3.51	26.31	7.17	1.54	0.11	2.82	1.10	-	1

*LOI- Loss on Ignition

2.2 *Methodology*

The water/geopolymer solid ratio was determined similarly to the water/binder ratio used in conventional concrete, while the alkaline activator-to-binder ratio was maintained below 0.45. To assess various substitution scenarios, natural aggregates were replaced with RAP aggregates—coarser fraction (RAP-C) and finer fraction (RAP-F)—at replacement levels of 25%, 50%, 75%, and 100%. All the considered design parameters have been based on the author’s previous studies where the choice has been explicitly explained (Ghosh et. al, 2024)

The preparation of the geopolymer samples followed the process used for cement concrete mixes, starting with a dry blend of the materials, followed by a wet mixing phase. The activator solution was prepared 24 hours before casting to allow the heat generated from the sodium hydroxide and water reaction to dissipate. The samples were cured at ambient temperature to replicate real-world conditions, reflecting typical on-site curing practices.

3 RESULTS AND DISCUSSION

3.1 *Compressive strength*

The compressive strength of GPC mixtures, including those with and without RAP, was tested at 7, 28, and 90 days under ambient curing conditions (Fig. 1). Previous studies on traditional cement and geopolymer concrete (Debbarma et al., 2020) have shown that the mix using only natural aggregates consistently produced the highest strength at all measured time points. Incorporating RAP reduced compressive strength, with the RAP-F mix (fine RAP) showing less decline compared to the RAP-C mix (coarse RAP). The primary factor in this reduction was asphalt cohesion failure. Interestingly, RAP-F performed better in compression than RAP-C, despite having a higher asphalt content. At a 50% replacement rate, RAP-F reached a 7-day compressive strength of 46 MPa, outperforming RAP-C by 3.3%. In contrast, when for 100% RAP mixes, RAP-F experienced a strength reduction of 48%, whereas RAP-C saw a more significant decline of 57%. The 50% RAP-F mix met the required 40 MPa strength for PQC applications after 7 days (MoRTH, 2013), with the potential for up to 75% RAP replacement after 28 days.

The strength development of GPC follows a pattern similar to that of cement concrete, showing gradual improvement over time as Calcium-Silicate-Hydate and Calcium-Aluminate-Hydrate continue to form. The most substantial increase in strength happens within the first 28 days, after which the rate of growth significantly decreases. In conventional cement mixes, RAP's impact is more evident at 28 days, with failures attributed to asphalt cohesion. In contrast, GPC shows substantial strength development by 7 days, where failures are more related to poor bonding between RAP aggregates and the geopolymer matrix. This highlights the importance of optimizing RAP content and ensuring adequate interfacial bonding to achieve desired performance levels in GPC.

3.2 *Flexural strength*

The integration of RAP also led to a significant reduction in flexural strength, an observation similar to compressive strength decrement, regardless of the RAP type or replacement proportion (Fig 2). At all tested replacement levels and curing ages, the 25% RAP-C mix exhibited maximum flexural strength, followed by the RAP-F mixes. In contrast to the compression strength trend, RAP-C mixes performed better in flexural strength overall. At a 50% replacement level, RAP-C met the required minimum flexural strength of 4.5 MPa for PQC (MoRTH, 2013) at 7 days, while RAP-F mixes did not reach this threshold even at 28 days (4.43 MPa and 4.1 MPa, respectively). However, both RAP-F and RAP-C mixes showed satisfactory flexural strength at a 25% replacement level at both 7 and 28 days.

The 75% RAP-F mix met the required compressive strength but failed to satisfy the flexural strength requirements. This highlights the importance of flexural strength in pavement design, suggesting that coarse RAP offers superior performance compared to fine RAP when used in geopolymer concrete. The results emphasize the need for careful selection of RAP type to ensure optimal material properties for specific engineering applications.

3.3 *Resistance to surface abrasion*

Figure 3 presents the surface abrasion resistance, measured as wear depth (d) after 90 days of ambient curing. The control mix, which did not contain any RAP, exhibited the least wear depth at 0.05 mm. In contrast, incorporating RAP led to an increase in wear depth, suggesting a reduction in abrasion resistance. The finer RAP fraction (RAP-F) resulted in more pronounced abrasion, with the 100% RAP-F mix showing the highest wear depth of 0.288 mm. At lower replacement rates (up to 50%), the abrasion resistance across all mixes was comparable, with a mean wear depth of 0.081 mm. Although no specific standards for geopolymer mixes containing RAP exist, the results were benchmarked against conventional paver block standards, which allow a maximum wear depth of 1 mm for heavy traffic areas. This investigation underscores the feasibility of incorporating RAP into geopolymer concrete while also revealing that coarse RAP provides superior abrasion resistance.

3.4 *Carbon emissions*

The carbon emissions (kgCO_2 eq/kg) and embodied energy (MJ/kg) for materials used in both GPC and PCC were analyzed, as shown in Table 2. Due to limited regional data, insights from international studies were used, assuming they are applicable. The transportation phase was not considered, as it is assumed to be similar for both PCC and GPC. The analysis of carbon emissions and embodied energy during the production phase (Fig 4) revealed that the control GPC mix had the highest CO_2 emissions at 181.51 kg CO_2 eq./m^3. Incorporating RAP significantly reduced emissions, with the 100% coarse RAP (100RAP-C) mix having the lowest emissions at 165.53 kg CO_2 eq./m^3. The optimal 50% coarse RAP mix (50RAP-C) reduced emissions by 5% compared to the control mix and by 56.16% compared to PCC. Fine RAP mixes showed a less significant reduction in CO_2 emissions, likely due to the higher volume of coarse aggregates in the mix.

Energy consumption followed a similar pattern, with the control mix consuming 2282.43 MJ. The 100% fine RAP mix reduced carbon emissions and energy consumption by 8.8% and 2.71%, respectively, while 100% coarse RAP reduced emissions by 12.09% but energy use by only 2.23%. These results suggest that fine RAP is more effective in reducing energy consumption, while coarse RAP has a greater impact on reducing carbon emissions.

Table 2. Carbon and emission coefficients of studied materials

Material	Carbon Emission (kgCO_2 eq/kg)	Embodied Energy (MJ/kg)	Source
FA	0.01	0.1	Hammond & Jones (2008)
GGBS	0.066	0.64	Indian database, IFC (2017)
NaOH	0.625	10.8	Turner & Collins (2013)
Na_2SiO_3	0.445	5.3	Heath et al., 2014; Fawar et al., 1999
CA	0.017	0.3	Hammond & Jones (2008)
NA	0.009	0.11	Hammond & Jones (2008)
RAP	0.00209	0.0308	Lu et al. (2018)
Water	-	0.2	Hammond & Jones (2008)
Admixture	0.72	11.4	Nepune (2022); Flower & Sanjayan (2007)
Cement	0.91	6.4	Indian database, IFC (2017)

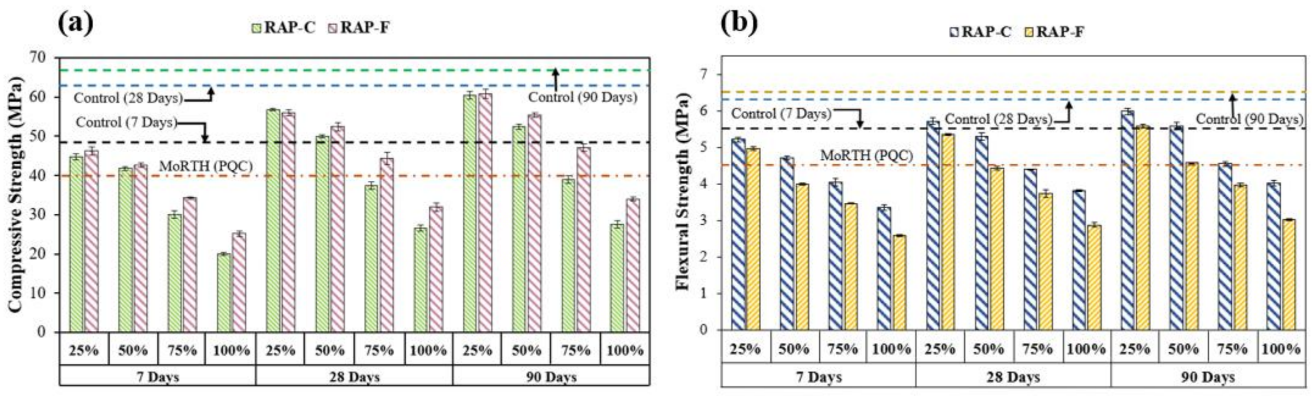

Figure 1. (a) Compressive strength and (b) flexural strength of the studied mixes at different curing periods

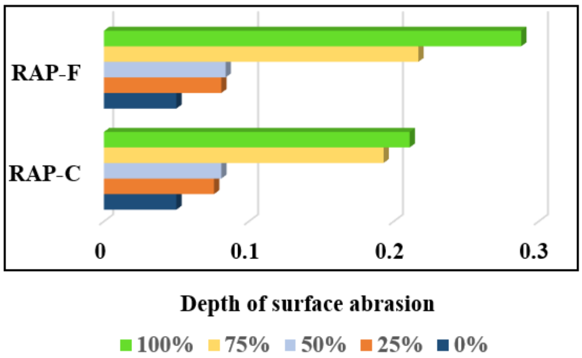

Figure 3. Resistance to surface abrasion of the different geopolymer concrete mixes

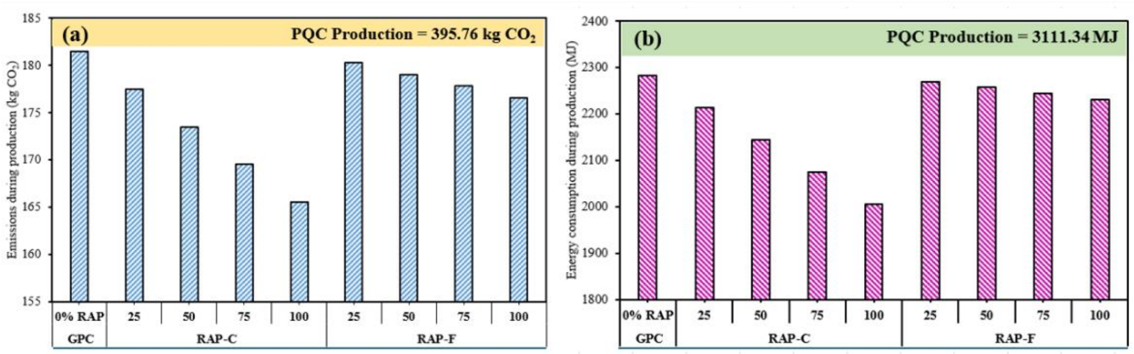

Figure 4. Carbon dioxide emissions and energy consumption during the production phase of concrete

4 CONCLUSION

This study demonstrated that coarse RAP aggregates outperformed fine RAP in flexural strength, while fine RAP provided superior compressive strength in geopolymer concrete. Replacing 50% of natural coarse aggregates with RAP in Pavement Quality Concrete (PQC) satisfied strength requirements after 7 days, achieving compressive and flexural strengths of 41.80 MPa and 4.72 MPa, respectively. Fine RAP replaced up to 25% of natural sand and up to 75% for compressive strength-focused applications. Geopolymer concrete with natural aggregates reduced carbon emissions by 50% compared to Portland cement, with a 54% reduction when 50% coarse RAP was used. Additionally, RAP-inclusive mixes exhibited strong resistance to surface abrasion.

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