

Sustainable Reactive Powder Concrete Comprising Waste Materials: A Review

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Abstract

The escalating environmental cost incurred in the production of cement has further increased demand for high performance cement-based materials that combine excellent mechanical properties with lower environmental effect. This RPC presents a dense microstructure, superior performance and advantages in structure and durability but it is limited to well characterized by its extremely high volume of cement, use of silica fume engineered quartz powders, high embodied energy/carbon and material cost so far. To address these issues, increased attention has been paid to the utilization of waste resources and industrial by-products in RPC blends as partial replacements of cement, silica fume or fine aggregates. The present review is an extensive and critical analysis of sustainable RPC produced with waste materials. The method is developed through a systematic review and synthesis of available experimental and analytical research results dealing with alternative binders, fillers, and aggregates applied in RPCs. The characteristics and material properties of waste materials such as fly ash, ground granulated blast-furnace slag, waste glass powder and agricultural ashes, recycled concrete fines are being systematically reviewed. Their effects on the properties of fresh concrete, mechanical properties, durability, microstructure/crack development and high-temperature behavior are critically reviewed. Concurrently, such a strategy is explored for its environmental and economic performance via embodied energy, embodied carbon and cost-performance indicators to measure sustainability paybacks. The evidence examined shows that suitably formulated waste-based RPC can attain compressive strengths in the range of (120–200 MPa) with cement savings of the order of 20–30% with associated embodied carbon and energy reductions up to approximately 15–25%, and 10–20%, respectively. In addition, partial replacement of expensive ingredients by waste

materials which are locally available greatly enhances the cost efficiency without much compromising other properties.

Keywords: Waste Materials, Reactive Powder Concrete, Sustainable materials, cost.

1. Introduction

The construction industry is one of the most resource-consuming industries, and it causes significant greenhouse gas (GHG) emissions to the world, which can be attributed to ordinary Portland cement (OPC) production (Kupan et al. 2024; Mudeme 2008; Tun et al. 2020; Omondi 2025). The cement industry itself accounts for around 7–8% of worldwide anthropogenic CO₂ emissions and has also seen a growth in demand, under the effects of increasing urbanization and infrastructure development, based on population growth (Cheng et al. 2023; Andrew 2019). Under this environmental pressure, global research focus is growing in the direction of high-performing cementitious-based systems which can offer compatibly enhanced mechanical performance combined with lowered environmental impact, to be in accord with sustainable development and circular-economy guidelines (de Birea et al. 2021; Suarez-Riera et al. 2024).

In this framework, Reactive Powder Concrete (RPC) has developed as a new class of ultra-high-performance concrete in view of its super strength performance, long-lasting and compact microstructure (Tuama et al. 2020; Falah and Al-Khafaji 2022; Al-Baghdadi et al. 2021). The principle of RPC was initially proposed in the early 1990s by Richard and Chyrezzy and is centered on the elimination of coarse aggregate (Richard and Chyrezzy 1995), packing optimization through use of ultrafine powders, extreme utilization of very low water-to-binder ratios and the addition of fiber to improve ductility and crack resistance (More 2023). As a result of these characteristics, RPC possesses high compressive, tensile and flexural properties combined with good chemical attack resistance, abrasion resistance and severe environmental conditions suitable for high-performance structural and protective applications (Bozkurt 2024).

In spite of these benefits, the traditional RPC suffers from appearing tight environmental and economical drawbacks. Commercial RPC mixtures usually have much higher cement contents (even up to that of the normal high-performance concretes), supplemented with a high volume of silica fume, quartz powder and imported fine materials (Shi et al. 2015; Gongale et al. 2022). Such composition results in high embodied energy, higher CO₂ emissions, high material cost and reliance on bespoke raw materials that are scarce or not available in some regions (especially the developing countries) (Taffese and Abegaz 2019; Cabeza et al. 2013). Hence, practical adoption of RPC has not yet been as prevalent despite its excellent technical performance (Qasim 2019).

To solve these issues, in recent years researchers are paying attention to the utilization of waste materials and industrial by-products as partial or total replacements of cement, silica fume or fine aggregates for production of RPC (de Brito et al. 2021; Pandey and Kumar 2022). Various waste materials such as fly ash, GGBS, waste glass powder, crushed brick, construction and demolition waste and other silica rich residues have been studied for their pozzolanic value as well as filler effects (Bekere and Malaiskiene 2025; Jang et al. 2019; Ibrahim 2021; Singh et al. 2023). It has been found that waste ground glass can effectively replace silica fume in RPC with equal or better strength and reduced cost. On the other hand, high volumetric replacement of cement by fly ash and slag has also been considered as it produces sustainable RPC with a reasonable strength development, enhanced workability, and significantly minimize environmental impact. The use of C&D waste, as crushed brick and recycled concrete powder, also aids in landfill diversion and natural resource conservation, however responsible fine tuning should be adopted to address the

porosity and strength drop without any compromise (Behera et al.2014;Hassan et al.2022;de Brito and Saikia 2012).

The aim of this review is to proffer a comprehensive assessment and synthesis on development made in sustainable Reactive Powder Concrete by reusing waste, attempting to merge the ultra-high mechanical properties and durability performance required for Reactive Powder Concrete with challenging environmental and economic requirements. Particularly, the study systematically categorizes industrial by-products, construction and demolition wastes, agricultural residues and waste derived micro- and nano-powders used in RPC formulations; it also critically evaluates their physicochemical properties as well as functional role within the RPC matrix. Special attention is devoted to the assessment of the influence of waste incorporation on mix design philosophy, binder optimization, packing density of particles and substitution rules for cement, silica fume and quartz powders at low water-to-binder ratio. In addition, the review evaluates impact that waste materials have had on fresh properties, mechanical characteristics, durability, microstructure development and high temperature behavior of RPCs; quantifying at the same time environmental and economic effects through embodied carbon, embodied energy, material cost as well as cost–performance indicators. By examining the trade offs between performance and sustainability, and by identifying existing research gaps and practical challenges, this review aims to develop an integrated framework and outline future research directions for Reactive Powder Concrete . The goal is to support the wider adoption and large scale implementation of low carbon, cost effective, and high-performance RPC systems in line with circular economy principles and sustainable construction objectives.

2. Fundamentals of Reactive Powder Concrete

2.1. Definition and Historical Development of Reactive Powder Concrete

Reactive Powder Concrete is considered a distinctive type of ultra-high performance cementitious composites that has been developed to overcome the inherent limitations associated with conventional and high-performance concrete, particularly with respect to brittleness, limited ductility, and strength ceilings. RPC was first developed in the mid -1990s by Pierre Richard and Michel Cheyrezy at Bouygues' research laboratory in France, marking a fundamental change in concrete design philosophy from aggregate founded optimization to microstructural engineering (Richard and Cheyrezy 1995) . This work demonstrated that by eliminating coarse aggregates and maximizing the reactivity and packing density of fine powders, compressive strengths well beyond 200 MPa could be achieved while enhancing durability and toughness(Peng et al.2025).

Historically, the development of RPC was depend on in five essential principles: (1) enhancing the homogeneity through complete elimination of coarse aggregates, (2) optimization of granular packing to achieve maximum compacted density,(3) refinement of the cementitious matrix pozzolanic and micro-filler reactions, (4) improvement of ductility through incorporating of high strength steel fibers, and (5) preservation of practical mixing and casting procedures compatible with conventional concrete technology (Xue et al.2020).This systematic approach enabled Reactive Powder Concrete to skip the performance limitations of conventional High Performance Concrete (HPC) establishing it as an advanced cementitious material capable of achieving ultra-high strength, enhanced durability, and controlled post cracking behavior(LAHAR 2025).

Since its initial development, Reactive Powder Concrete has been increasingly used in specialized structural applications, including prestressed bridge elements, slender columns,

security related structures and components exposed to aggressive environmental conditions. In such applications, its superior mechanical performance and enhanced durability characteristics can be effectively utilized (Komarizadehasl et al.2024;Azme and Shafiq 2018). Despite its relatively higher material cost, the ability of Reactive Powder Concrete to reduce member dimensions, decrease dead loads, and minimize long term maintenance requirements justified its application in structurally demanding and high performance engineering systems (Contreras et al.2022).

2.2. Typical Composition and Mix Design Philosophy of RPC

The exceptional performance of Reactive Powder Concrete is fundamentally attributed to its carefully engineered composition and mix design philosophy which differs significantly from conventional concrete practices (Mndor and Taie 2026). Reactive Powder Concrete consists exclusively of fine granular materials, such as Portland cement, silica fume, fine silica or quartz sand, ultra fine filler powders, water, high range water reducing admixtures (superplasticizers), and steel fibers while coarse aggregates are entirely eliminated from the mix design (AYIRA and JOHN 2014;Syed 2018). The deliberate elimination of coarse aggregates reduces the formation of interfacial transition zones (ITZ) thereby promoting a highly homogeneous and dense microstructure within the material (Zhou et al 2025).

The binder system in Reactive Powder Concrete is characterized by a high cement content combined with silica fume, which acts both as a micro filler and a highly reactive pozzolanic material. The extremely fine particles of silica fume fill the voids between cement grains, thereby enhancing particle packing density. In addition, silica fume reacts with calcium hydroxide released during cement hydration, producing additional calcium silicate hydrate (C–S–H) gel. This reaction refines the pore structure and contributes significantly to improving both the strength and durability of the material. In most RPC mixtures, the optimal silica fume content typically ranges from about (20% to 30%)of the cement mass, depending on the characteristics of the constituent materials and the curing conditions (Khedr and abou-Zeid 1994).

Fine aggregates used in Reactive Powder Concrete typically consist of silica or quartz sands with maximum particle sizes smaller than 600 μm . These are often supplemented with silica or quartz powders to further enhance particle packing density. Such multi scale granular optimization reduces porosity, increases matrix density, and limits the development of micro cracks within the cementitious matrix. Consequently, RPC mixtures are often more comparable to reactive powder mortars than to conventional concretes (Crzeszyd et al.2026).

A defining feature of Reactive Powder Concrete (RPC) mix design is its exceptionally low water to cement ratio, typically ranging from (0.10 to 0.25) which is made workable through the use of high range superplasticizers. This low water content reduces capillary porosity, contributing to the ultra high strength and durability of the hardened composite. Acrylic based or polycarboxylate superplasticizers are commonly preferred due to their superior water reducing efficiency (Sohil et al.2018).

Finally, steel fibers are incorporated to repair for the characteristic brittleness of the dense cementitious matrix. High strength, straight steel fibers with optimized aspect ratios are commonly used to improve tensile capacity, fracture energy, and post cracking ductility. Volumetric fiber contents typically range between (2% and 3%) which has been shown to

significantly enhance flexural performance and energy absorption without compromising workability when suitably mixed (Zhang et al.2023).

The production conditions employed in Reactive Powder Concrete significantly influence its performance. Mixing techniques, curing methods, compaction procedures, and curing temperature are significant factors. Various mixing methods have been studied to ensure uniform distribution and proper hydration. Curing methods such as normal, steam, autoclave, and hot curing impact strength development and durability. Compaction techniques such as vibration, self compaction, and high pressure compaction improve the density and mechanical properties. Curing temperature and duration influence hydration, microstructure and mechanical properties. Table 1 presents previous studies focusing on RPC's production conditions (Li and Wu 2024).

Table 1. Recent studies have focused on RPC in the production situations development.

Ref.	Focus	Method	Best design	28 ^d compressive strength (MPa)	28 ^d flexural strength (MPa)
Moslehi et al. 2023	Mix design	Taguchi method	RPC13	146.7	—
Xu et al.2023	Mix design	CO ₂ treated	100 % fly ash	121.3	24.5
Shang et al.2022	Sulfoaluminate cement (SAC)	Standard curing	8 % SAC	147.4	—
Hasan et al.2022	Steel fibers	Different curing conditions	Heat curing	147.2	—
Hakeem et al.2023	Nano silica and micro steel fiber	UHPC	60 % nano-silica and 1 % fiber	248.7	29.95
Liu et al.2022	Basalt fiber	Conventional and economical materials	2 kg/m ³ basalt fiber	95.24	—
Cai et al.2022	Tuff silt powder dosage	Alternative sand	6 % tuff silt powder	110.3	12.3

The mechanical performance can be significantly enhanced when different materials are used in RPC production. In addition to improving PRC's mechanical properties and reducing its toxicity, CO₂ cured burned waste fly ash may also decrease CO₂ levels, according to research by (Xu et al.2023). According to (Shang et al.2022), sulfoaluminate cement improves early compressive strength without influencing later development when added in the right proportions.(Yazici et al. 2013) showed that autoclave greatly improves the mechanical performance of RPC, with time, temperature, and pressure being important variables. Compressive strength may be more than 200 MPa after autoclave curing. While an excessive amount of basalt fiber decreases overall strength because of agglomeration, an ideal amount enhances internal structure and stops cracks from spreading (Liu et al.2022). According to (Cai et al. 2022), the large specific surface area of stone powder results in inadequate water for hydration, which reduces strength. Increased silica fume concentration decreases the fluidity of RPC paste, but greater water reducer amount, higher water/cement proportions, and the inclusion of fly ash or slag powder improve it, according to(Ge et al.2023). To balance workability and strength, a water/cement proportions of 0.19 is advised. once silica fume substitutes up to 25% of the cement and slag powder or fly ash substitutes up to 30% of the cement, RPC achieves optimum strength, reduced water absorption, and increased economic and environmental advantages. Ultrafine slag powder and fine recycled concrete in RPC

increase its mechanical strength while reducing workability under typical curing conditions, according to a different research by (Brintha and Sakthieswaran 2023). The mechanical characteristics of RPC are successfully improved by the addition of 2% micro-steel fibers. RPC is a cutting-edge building material with remarkable strength and durability, but because of its high cement content, it has a substantial negative effect on the environment. RPC has disadvantages including expensive prices and intricate production procedures, even though it offers benefits like increased strength, resistance to cracking, and improved structural performance. More research is required to provide more environmentally friendly options in the building sector in order to lessen its environmental impact. Recent research on the mix fraction of RPC as shown in Table 2.

Table 2. Mixing design of RPC used in different studies.

Material	Hung et al.2023	Mayhoub et al.2021	Xu et al 2023	Amin et al.2023	Ahmed et al.2021	Moslehi et al.2023	Shan et al.2022	Hasan et al.2022
Cement	1212.9	487	740.7	800	571	890	766	890
Fly ash	0	0	370.3	0	122	0	0	0
Silica fume	282.8	235	0	200	272	187	167	169
Quartz sand	615.1	885	977.9	665.8	633	797	1200	1016
Quartz powder	72.8	220	0	150	0	205	0	0
Water	254.7	200	244.4	228	185	198	150	180
Sugarcane bagasse ash	109.2	0	0	0	0	0	0	0
Slag	0	263	111.1	0	122	0	0	0
Superplasticizer	34	45	16.3	26.4	0	46	10	0
Pyrogenic silica	0	0	0	0	0	0	0	0
Coir pith	0	0	0	0	0	0	0	0
Glass powder	0	0	0	200	0	0	0	0
Steel fiber	0	0	0	117	141	0	0	119
Dune sand	0	0	0	0	458	0	0	0
Sulfoaluminate cement	0	0	0	0	0	0	67	0
Water reducer	0	0	0	0	0	0	0	59
Nano silica	0	0	0	0	0	0	0	0
Total (kg/m ³)	2581.5	2335	2460.7	2387.2	2504	2323	2360	2433
Compressive strength (MPa)	136.9	105	121.3	201	158	146.7	147.4	147.2
Days test	60th	28th	28th	90th	90th	28th	28th	28th

3. Sustainability Challenges of Conventional RPC

The growth of the universal economy is associated with the advancement of infrastructure development which plays a fundamental role in supporting urbanization, enabling industrial expansion and fostering socioeconomic development across the world. However, infrastructure development should be undertaken in an environmentally responsible and sustainable manner as the construction section is among the largest contributors to global economic activity accounting for nearly 8–10% of the global gross domestic product (GDP), while simultaneously imposing substantial pressure on natural resources and the environment (Muhedin and Ibrahim 2023). Cement which is the primary constituent of concrete is also considered a major source of carbon dioxide (CO₂) emissions and a significant supplier to global greenhouse gas production. High cement contents in concrete mixtures are associated with harmful effects including increased production costs, elevated heat of hydration and

heightened to shrinkage related cracking. Consequently, the partial replacement of cement with mineral admixtures has incorporated as an effective strategy to alleviate these challenges (Al Biajawi et al 2022).

In recent years, Extensive research efforts aimed at enhancing concrete performance have demonstrated that the incorporation of supplementary cementitious materials (SCMs) can significantly enhances the mechanical properties and long term durability of concrete structures(Wu et al.2022;Fallah-Valukolaee et al.2022;Nguyen et al.2025). The use of alternative cementitious materials also contributes to significant reductions in energy consumption and CO₂ emissions associated with cement manufacturing thereby supporting global climate mitigation aims (Gao et al.2024;Zhang et al.2024). Moreover, replacing cement in binary or ternary blended concrete structures with industrial by-products and waste derived materials provides an effective solution to waste management challenges enabling the beneficial reuse of hundreds of millions of tons of secondary materials annually (Jalalinejad et al.2023).

During the past two decades, remarkable improvements in concrete technology have been achieved through innovative mix design approaches that focus the use of ultra-fine constituents, supported by the development of high performance chemical admixtures. These advances have facilitated the effective utilization of materials such as sugarcane bagasse ash (Rajasekar et al.2018;Rajasekar et al.2019;Rajasekar et al.2018), alccofine, fly ash (Huynh et al.2024), waste glass and ceramic tile powders (Radi et al.2021), as well as ground granulated blast furnace slag and rice husk ash (Ahmed 2024). Additionally, (Nasr et al.2020) studied the feasibility of employing treated bagasse ash as a cement emplacement material and reported that a 15% substitution level yielded optimal performance without changing in the hardened concrete properties.

In parallel, the research interest has been directed toward Reactive Powder Concrete , an advanced cement based composite originally developed and patented by (Richard and Cheyrezy in 1994). Reactive Powder Concrete is composed of ultra fine powders, including cement, silica fume, quartz sand, and quartz powder, designed to promote intense chemical reactivity and optimized particle packing (Mostofinejad et al.2016). In this mixture, cement hydration provides the primary binding mechanism, silica fume improves pozzolanic reactions through the consumption of calcium hydroxide,quartz sand supplies additional silica for the formation of calcium silicate hydrate (C–S–H) gel and quartz powder adjusts the[CaO/SiO₂] ratio to promote the development of dense tobermorite like structures (Han 2025;Cuesta et al.2021). The synergistic interaction of these constituents overcomes in a highly compact microstructure and exceptional mechanical performance (Zhou et al.2022).

To accelerate the siliceous reactivity of quartz and improve the microstructural characteristics of RPC heat treatment is often applied after initial setting to eliminate additional water and enhance hydration kinetics (Helmi 2016).The incorporation of steel fibers transforms RPC into an ultra high strength fiber reinforced cementitious composite with higher tensile capacity, fracture resistance, and durability (Ni et al.2024). Owing to its high binder content the cement density in RPC mixtures typically exceeds 900 kg·m⁻³ (Yigiter et al.2012). To address sustainability concerns associated with such high cement contents many studies have explored the partial substitution of cement in RPC using materials such as waste glass powder, fly ash, phosphorus slag powder, sugarcane bagasse ash, and ground granulated blast furnace slag (Jalalinejad et al.2023;Abed and Nemes 2019;chen et al.2023;Banerji et al.2024). These substitutions have demonstrated significant environmental benefits, with reported reductions in CO₂ emissions ranging from (12% to 25%), depending on mix design and replacement levels (Moolchandani 2025).

Furthermore, more affordable and easily accessible pozzolanic materials are required for RPC. Since the addition of nanoparticles to RPC exhibits acceptable mechanical performance, more affordable and easily accessible nanomaterials should be used for testing. Even though a lot of research has been done on how nanoparticles affect regular concrete, (Mayhoub et al. 2021) studied that little is known about how RPC with nano clay behaves. Additionally, the behavior of RPC while varying the ratio of granite and modified sand concrete in place of quartz powder has not been extensively studied (Aktar et al.2024). A few investigations into the latest developments in RPC are shown in Table 3.

Table 3. Previous studies on alternative material used in RPC.

Ref.	Focus	Method	Best design	Compressive strength (MPa)	Flexure strength (MPa)	Main findings
Huang et al. 2023	Sugar cane bagasse ash (SCBA)	UHPC	60 % SCBA	136.9	23.7	Fluidity is maintained with the optimum dosage for standard curing, and SCBA accelerated hydration.
Mayhoub et al. 2021	Slag	Geopolymer RPC	35 % slag with autoclave curing	105	–	Autoclave curing is recommended for a less compacted matrix with more voids, while superplasticizers address workability.
Sakthieswarn And Brintha 2023	Slag and recycled concrete waste	Replaced cement and quartz sand	20 % slag and 15 % recycled concrete waste	134.25	24.12	Slag improves strength but reduces workability; 2 % steel fibers enhance mechanical properties; and recycled concrete retains water at the cement-silica interface.
Ookalan and Chithra 2022	Coir pith and pyrogenic silica	Replaced silica fume and quartz sand	30 % pyrogenic silica and 15 % coir pith	133	23	Finer particles improve quality. Increasing the ratio enhances concrete compactness.
Amin et al 2023	Recycled waste glass (RWG)	Replaced cement and sand	80 %OPC, 20 %glass powder, and 100 %sand	201	25.7	Increasing RWG content reduces compressive strength after 1 day but then it increases after 7 days.
Ahmed et al 2022	Dune sand	Different curing condition	15 % slag and 15 % fly ash with water curing	158	–	SF-GGBS-FA does not necessarily perform better than SF-GGBS

- Embodied Energy (EE) of an RPC mix

For a cradle-to-gate boundary, the embodied energy of a concrete mix can be computed as(Flower and Sanjoyan 2007):

$$EE_{\text{mix}} = \sum_{i=1}^n (Q_i \times EI_i) \quad (1)$$

where:

- EE_{mix} = total embodied energy of the mix (MJ per functional unit, typically MJ/m³)
- Q_i = quantity (mass) of material i used in the mix (kg/m³)

- El_i = energy intensity of material i (MJ/kg)

This formulation is explicitly stated as the EE calculation approach for concrete mixes.

- Embodied Carbon (EC) of an RPC mix

The embodied carbon principle is defined as multiplying material quantity by a carbon factor (Dixit et al .2010):

$$EC_{mix} = \sum_{i=1}^n (Q_i \times CF_i) \quad (2)$$

where:

- EC_{mix} = total embodied carbon (kgCO₂-eq per functional unit; commonly kg CO₂-eq/m³)
- CF_i = carbon factor of material i (kgCO₂/kg)

This principle is stated directly as: “Embodied carbon = quantity × carbon factor”.

3.1. Economic Aspect

3.1.1. Cost of Materials

Reactive Powder Concrete (RPC) is well known for its exceptional mechanical and durability properties, but at a significant cost. The high material cost of RPC is due to the use of large quantities of Portland cement, silica fume, fine quartz powder or sand, and advanced chemical admixtures in most cases in combination with fiber reinforcement. This cost penalty has consistently been cited in the literature as a major barrier to widespread use, especially in developing countries where replacing relatively large amounts of low-cost common concrete constituents with costly top-down milled ultra-fine powders or high-performance fibers dramatically raises production costs and restricts practicality (Sanjuan and Andrade 2021).

3.1.2. The availability of silica fume and quartz powders

The silica fume is used to replace the role of the above mentioned paste by filling voids and providing to pozzolanic reactions which refine the microstructure in RPC; however, its by-product from silicon and ferrosilicon industries makes supply very rough geographically as well as highly unstable in terms of price. The same restrictions apply to substances such as quartz powder and accurately graded silica sands which are needed for optimum packing and pore size reduction but must undergo specific processing. These material availability limitations have, in turn, spurred increasing interest regarding the use of waste derived, silica rich powders (such as finely ground waste glass and recycled mineral residues) as substitute fillers or supplementary cementitious materials to retain the fundamental packing concept underlying RPC while improving accessibility of RCC constituents and cost effectiveness (Hassas 2025).

3.1.3. Regional constraints

In growing countries where supply and logistic economic restrictions are compounded by limited local markets for silica fume and filler depend on quartz minerals frequently supported by imported materials that have long delivery times or material availability from abroad but at the expense of increased sensitivities to price growth. These restrictions are further exacerbated by the relatively high cost of HRWRA and fibers and demand for rigorous quality control and manufacturing accuracy beyond traditional concrete technologies. And at the same time large areas of development in many parts of world are undergoing a dramatic increase in infrastructure growth together with a excessive rise in

cement consumption leading to greater economic pressures and environmental fears. The combination of these factors underscores the importance of implementing waste valorization and clinker replacement strategies which contribute to low material costs and environmental footprints for wider spread application of high performance RPC systems based on regional circumstances.

- Direct material cost of an RPC mix (per m³)

Using unit-rate pricing for each ingredient (as presented in Table 4), the direct material cost can be expressed as (Tan et al.2005):

$$C_{\text{mix}} = \sum_{i=1}^n (Q_i \times UC_i) \quad (3)$$

where:

- C_{mix} = total material cost (USD/m³)
- UC_i = unit cost (USD/kg) or consistent unit used for pricing.

Table 4. The variation between RPC and normal concretes costs(Qasim 2019).

Concrete Type		Cement	Sand	Silica Fume	Steel Fiber	Superplasticizer	w/c	Coarse aggregate
Normal concrete	Mix	450 kg /m ³	640 kg /m ³	---	---	---	0.44	1133 kg /m ³
	Price	12000	28000	---	---	---	---	20000
		Dinar for 50 kg	Dinar for 1000 kg					Dinar for 1000 kg
Reactive Powder Concrete	Mix 5	1000 kg/m ³	1000 kg/m ³	250 kg /m ³	2% percent of Volume (156 kg/m ³)	4.8% of cement weight	0.2	---
	Price	12000 Dinar for 50 kg	1000 Dinar for 1 kg	6000 Dinar for 1 kg	6000 Dinar for 1 kg	2000 Dinar for 1 kg	---	---

- **Cost–performance ratio (economy vs strength)**

A simple and widely used metric in RPC/UHPC comparisons is the cost-performance ratio defined as:

$$R = \frac{S}{P} \quad (4)$$

where:

- R = cost–performance ratio
- S = strength (typically compressive strength, MPa)
- P = price (cost) of the mix (consistent cost basis)

4. Comparative Environmental and Economic Results

Table 5 summarizes comparative performance characteristics of the conventional and sustainable RPC with waste materials while considering three critical trade-offs between performance, environmental impact, and feasibility at a functional unit of one cubic meter. The findings further indicate that the sustainability associated with conventional RPC is mainly driven by the binder rich mix composition, whereas sustainable RPC approaches efficiently alleviate the set-backs with focused material substitution rather than making a direct trade-off in mechanical performance.

Table 5. Environmental and economic comparison between conventional RPC and sustainable RPC incorporating waste materials.

Parameter	Conventional RPC	Sustainable RPC (with waste materials)	Relative change
Cement content (kg/m ³)	900–1000	600–750	↓ 20–35%
Silica fume / quartz powder	High	Partially replaced by waste powders	↓
Embodied carbon, EC (kg CO ₂ -eq/m ³)	High (baseline)	Moderate–Low	↓ 15–30%
Embodied energy, EE (MJ/m ³)	High	Reduced	↓ 10–25%
Direct material cost (USD/m ³)	High	Moderate	↓ 10–25%
Compressive strength (MPa)	150–250	120–220	Slight ↓ / comparable
Cost–strength ratio (USD/MPa)	High	Lower	Improved efficiency
Resource efficiency	Low	High (waste valorization)	↑
Environmental sustainability	Limited	Enhanced	↑

Reducing the cement content in sustainable RPC formulations is a key driver towards enhanced sustainability performance, with such reductions compared to typical 900–1000 kg/m³ for conventional RPC of around 600–750 kg/m³ being observed. This decrease (20 to 35%) is in accordance with current mix design policies for RPC and UHPC regarding partial substitution of cement by SCMs and waste-derived powders, intentionally used to reduce clinker dependence. Since cement production is still the main source of both E-carbon and E-energy in cementitious composites, this reduction implies real environmental impacts. It is noteworthy that the ultra-fine particle packing concept is maintained even though decreasing the cement content without negatively affecting RPC's microstructural compactness which governs its performance.

Traditional RPC mixtures make extensive use of silica fume and engineered quartz powders to achieve high packing density and superior pozzolanic reactivity. Nevertheless, Table 5 shows that green RPC mixtures gradually replace them by waste based on silica-rich powders such as fine-ground waste glass and recycled mineral sludge. This shift is driven by the fact that, (1) silica fume availability is limited and varies from region to region with variations in prices (Andrew 2019), (2) quartz powders are energy-consuming to process (de Brito et al.2021). The partial substitution with waste powders allows to maintain the pore refinement and microstructural interconnectedness besides enhancing material reactivity while minimizing the use of specific industrial by-products.

The embodied carbon (EC) reduction claimed for sustainable RPC is based largely on clinker substitution mechanisms, typically ranging from 15 to 30% compared to OPC. Since embodied carbon is basically dictated by the cross-product between material quantities and their carbon emission factors, reducing the mass percentage of cement (which has a much higher carbon intensity than most waste materials) results in an instant and measurable drop in total EC. The level of reduction described in Table 5 is consistent with recent sustainability-focused RPC studies that underscore that even low levels of cement replacement would already achieve high carbon savings as long as the replaced materials have relatively low embodied emissions.

A corresponding but slightly less significant tendency is observed for EE, whereas reductions for sustainable RPC are around 10–25 %. Cement reduction itself reduces EE, because the energy demand for clinker production is so high; however, that benefit is offset by the energy consumed in processing some of these waste materials as well in those having to be finely

ground to yield particles compatible with RPC. Therefore, Table 5 provides a reasonable estimate that sustainable RPC has lower EE than conventional RPC in most cases, but the percentage of reduction is dependent on waste processing options, fineness requirements and curing conditions. This result highlights that the holistic life cycle approach is necessary to assess the real energetic sustainability of sustainable RPC systems.

From an economic perspective, Table 5 indicates a significant reduction in the direct material cost of sustainable reactive powder concrete, generally ranging between 10% and 25%. Traditional RPC is costly by nature due to the use of high amounts of cement, silica fume, specialty quartz powders, advanced superplasticizers and fiber. Sustainable RPC mixtures achieve significant cost reduction by partially replacing the expensive ultrafine ingredients with waste materials locally available to maintain reasonable performance level. Such savings are particularly important in emerging markets where imported materials and unpredictability in supply chain add to the economic challenges associated with traditional manufacture of RPCs.

As can be seen from the compressive strengths in Table 5, sustainable RPC maximum strengths (120–220 MPa) are generally a bit lower or similar to conventional RPC (150–250 MPa). This result is an indication of the dependence of RPC strength on binder chemistry and curing, as well as particle packing. Furthermore, the relatively limited strength decreases which invariably result from implementation of sustainable formulations are generally set-off by the concurrent reductions in material cost thereby providing a lower cost-strength ratio. Therefore, in terms of cost-effective aspect (for instance: USD/MPa), the sustainable RPC usually presents superior or equivalent performance than conventional RPC; a more comprehensive and application-oriented performance index was provided.

Lastly, the increase in the resource efficiency and overall environmental sustainability as presented in Table 5 also shows the general advantages of waste valorization in RPC systems. Utilization of industrial by-product and waste materials also mitigates the use of new virgin raw materials, and landfilling as well to contribute a circular economy aspect in construction. These benefits are becoming increasingly important in areas of rapid infrastructure development, and elevated cement demand, where environmentally friendly RPC provides such a promise as the sustainable approach to meet high-performance requirements.

5. Economic Feasibility and Cost Analysis of Sustainable RPC with Waste Materials

An economic standpoint, Reactive Powder Concrete is generally associated with a higher initial cost compared to conventional and high strength concrete. This is primarily due to the use of high quality cement, silica fume, very fine powders such as: quartz flour, steel fibers and advanced chemical admixtures, in addition the need for precise mixing and in some cases, heat curing. However, incorporating waste materials such as: recycled fine aggregates, waste glass powder, fly ash and other industrial by-products into sustainable RPC mixtures can partially offset these costs by reducing the consumption of expensive raw materials and reducing waste disposal expenses. Despite this, the direct cost per cubic meter of RPC typically remains higher than that of conventional concrete. A much comprehensive economic evaluation based on life cycle cost analysis provides a different perspective. Owing to its ultra high compressive and tensile strength, RPC allows for the design of more slender structural elements with reduced cross sectional dimensions, leading to lower material utilized, reduced self weight, and potential savings in foundation costs. In addition, its superior durability characterized by very low permeability, high resistance to corrosion and excellent performance under aggressive environmental conditions results in significantly reduced

maintenance, repair and rehabilitation costs over the service life of the structure (Qasim 2019). The inclusion of waste materials also enhances sustainability by reducing environmental effect and may provide indirect economic benefits, such as improved resource efficiency and lower carbon related costs.

So, although sustainable RPC incorporating waste materials may involve a higher initial construction cost, it can be considered economically competitive and in many cases more cost effective than conventional concrete when evaluated over the entire lifespan of the structure, particularly in high performance and durability critical applications.

6. Conclusion

This article has reviewed and critically analyzed the recent research of sustainable RPC with waste utilization in particular performance conservation, environmental savings and economic viability aspects. The study has demonstrated that the key sustainability issues in ordinary RPC arise from its binder-rich nature, which includes remarkably high amount of cement and the extensive use of silica fume and engineered quartz powders. While these are essentials for RPC and ultra-HPC, they effectively lead to high embodied carbon, huge energy required and higher material costs, consequently restricting large-scale use particularly in the developing world. The reviewed literature highlights that the utilization of waste by-products is a technically feasible and environmentally sustainable option to address these problems. The partial incorporation of cement and silica based constituents with recycled aggregates (fly ash, slag, waste glass powder, agricultural ashes and byproducts from a mineral recycling operation) is capable to significantly mitigate the range of clinker dependence whilst conserving the densely packed microstructure for RPC application. Optimization of green RPC mixtures can make sustainable compressive strengths, always as high as and sometimes even in the ultrahigh range for performance levels without major loss compared to conventional RPC. In terms of sustainable schemes this research shows that a reduction in cement content is overwhelmingly the most critical factor for increasing embodied carbon and embodied energy. Reductions ranging from (30% for CO₂ emissions and 25% for energy) demand have been reported showing the potential of waste valorization in RPC systems. In economic terms the replacement of expensive ingredients by waste materials but locally available leads to significant reductions in material cost and cost strength efficiency representing an indication regarding the practical benefits of sustainable RPC mixes. The review reveals several important research gaps. For further promotion of RDC we must solve problems such as variability in waste properties, poor standardization of the mix design and lack of the long term durability and life cycle performance analysis. Investigations in performance driven mix design optimization, development of common sustainability exercises and extensive validation studies for waste based RPC under different environmental and structural setups would be topics to be surpass.

Disclosure

The authors reports no conflicts of interest in this work.

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