Journal Homepage: www. ijarpr.com ISSN: 3049-0103 (Online)

International Journal of Advance Research Publication and Reviews

Vol 02, Issue 09, pp 499-507, September 2025

Hybrid Fibre-Reinforced Reactive Powder Concrete: A Critical Review on Mechanical and Durability Performance

***Sandra B*[1]*, Dr. Manju R*[2].**

[1]*PG Scholar, Kumaraguru College of Technology, Coimbatore, Tamil Nadu, India*
[2]*Associate Professor, Kumaraguru College of Technology, Coimbatore, Tamil Nadu, India*
[*]*sandra.24mse@kct.ac.in*

ABSTRACT

Reactive Powder Concrete (RPC) is a highly advanced cementitious material valued for its ultra-high compressive strength, dense microstructure, and excellent durability. Despite these advantages, its brittleness and susceptibility to explosive spalling at elevated temperatures restrict wider structural use. Fibre reinforcement has been explored as an effective solution: steel fibres improve tensile and flexural properties, while polypropylene (PP) fibres mitigate spalling by creating vapour escape paths during fire exposure. This review synthesises findings from 21 experimental and analytical studies on RPC with hybrid fibres, emphasising mechanical and durability aspects. Research shows that steel fibres can raise tensile and flexural strength by up to 250%, while hybrid systems provide better residual performance under heat, retaining 25–30% capacity at 900 °C. Durability tests highlight that hybrid RPC has reduced chloride permeability, greater sulphate resistance, and improved freeze–thaw performance compared to plain RPC. Microstructural evidence supports steel fibres' crack-bridging role and the effectiveness of PP melting channels in preventing spalling. Nevertheless, uncertainties remain regarding optimum fibre dosage, workability, long-term creep and fatigue, and large-scale applications. Future research must focus on optimisation, predictive modelling, and life-cycle assessment to confirm hybrid fibre RPC as a sustainable next-generation material for infrastructure.

Keywords: Reactive Powder Concrete, hybrid fibres, steel fibres, polypropylene fibres, durability, mechanical properties

1. Introduction

Reactive Powder Concrete (RPC), first introduced in France in the 1990s (Richard & Cheyrezy, 1995), is a high-performance cementitious composite distinguished by ultra-high compressive strength, low permeability, and exceptional durability. Unlike conventional concrete, it eliminates coarse aggregates and uses fine powders such as silica fume, quartz flour, and fine sand, combined with a low water-to-binder ratio and superplasticizers. This refined microstructure yields compressive strengths of 150–250 MPa and very low porosity, making RPC suitable for long-span bridges, tall buildings, and defence structures. However, RPC's brittleness and poor tensile capacity restrict ductility and raise risks of sudden failure. Its dense matrix also increases explosive spalling at high temperatures, as trapped vapour pressure cannot escape (Kodur, 2000; Kalifa et al., 2000; Yazici et al., 2010). Fibre reinforcement addresses these drawbacks: steel fibres enhance tensile, flexural, and ductility performance; polypropylene (PP) fibres, though weak in ambient strength contribution, mitigate spalling during fire by melting and forming vapour channels; hybrid steel + PP fibres combine mechanical strength with fire resistance. Over the last two decades, extensive research has examined mechanical behaviour, durability, and microstructure of hybrid fibre RPC. This review synthesises 21 studies, highlighting consistent trends, contradictions, and gaps, while emphasising the need for optimisation, predictive modelling, and large-scale validation to advance hybrid RPC as a sustainable next-generation material.

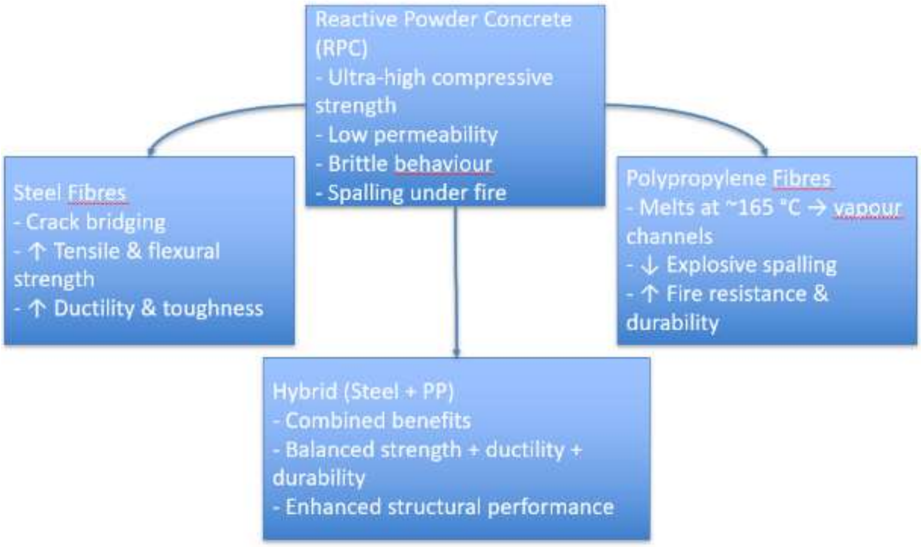

Fig. 1- Conceptual framework illustrating the role of steel fibres, polypropylene fibres, and their hybridisation in Reactive Powder Concrete (RPC).

2. Methodology of Literature Collection

The review followed a PRISMA-style systematic approach:

- Databases searched: Scopus, Web of Science, ScienceDirect, SpringerLink.
- Keywords: "Reactive Powder Concrete," "hybrid fibres," "steel fibres," "polypropylene fibres," "durability," "mechanical properties."
- Inclusion criteria: Peer-reviewed articles, Scopus-indexed, published between 2000–2025.
- Exclusion criteria: Studies on geopolymer concretes, fibre-reinforced normal concrete, or RPC without fibres.

21 articles addressing RPC with hybrid or single fibres were selected.

3. Mechanical Properties of Hybrid Fibre RPC

3.1 Compressive Strength

RPC is inherently strong in compression. The addition of steel fibres further enhances compressive performance due to crack-bridging and confinement, while PP fibres contribute little directly.

- Chkheiwer & Kadim (2019): Using local Iraqi materials, RPC with 25% silica fume and 2% steel fibres reached 156 MPa; beyond 25% silica fume, strength gains plateaued.
- Li & Liu (2016): Hybrid RPC (2% steel + 0.2% PP) maintained ~22% of original compressive strength even after 900 °C exposure, whereas steel-only RPC dropped more sharply.
- Staquet & Espion (2002): Found cement type critical—CEM I 52.5 cements produced 180–230 MPa strengths under steam curing, outperforming CEM I 42.5 mixes.
- Kumar et al. (2013): Partial replacement of cement with fly ash/GGBS (5–15%) yielded sustainable RPC mixes with 140–155 MPa compressive strength, though slightly lower than traditional RPC.

Table 1. Comparative compressive strength of RPC mixes

Binder System	**Fibre Content**	**Curing**	**Max Strength (MPa)**	**Key Finding**
OPC + SF + slag	2% steel + 0.2% PP	Steam @ 90 °C	150–160	Hybrid mixes retained strength post-900 °C
OPC + SF (10–30%)	0–2.5% steel	Hot curing (60–80 °C)	124–162	Optimum at 25% SF + 2% steel
CEM I 42.5 / 52.5 + SF	2% steel	Steam @ 90 °C	180–230	Cement type controls RPC strength
OPC + FA + GGBS	1% steel	Ambient curing	140–155	Waste material feasible, minor reduction

3.2 Tensile Strength

Tensile performance is crucial since RPC tends to fail suddenly under tensile stresses.

- Li & Liu (2016): Direct tensile tests showed steel fibres improved tensile strength by ~200%, while PP fibres alone had negligible effects. Hybrid mixes retained ~30% tensile strength even at 700 °C.
- Chkheiwer & Kadim (2019): Reported linear increase of tensile strength with steel fibre content, reaching ~30 MPa at 2.5% steel (from ~9 MPa without fibres).
- Uygunoglu (2008): Microstructural SEM studies confirmed strong steel fibre–matrix bond, which delayed crack initiation and improved flexural toughness.

Table 2. Tensile and flexural behaviour of fibre RPC

Fibre Content	Direct Tensile (MPa)	Flexural (MPa)	Behaviour
2% steel + 0.2% PP	12–15	18–20	Hybrid retained strength post-heat
0–2.5% steel	9 → 30	11 → 31	Linear steel fibre effect
1–2% steel	14–22	20–28	SEM: strong bond, delayed cracks
1% steel + FA/GGBS	10–12	15–18	Slight reduction due to replacements

3.3 Flexural Strength & Failure Modes

- Li & Liu (2016): Flexural strength decreased linearly with temperature; residual flexural strength at 900 °C was ~20% of initial.
- Chkheiwer & Kadim (2019): Flexural capacity rose from 11 MPa (no fibres) to 31 MPa (2.5% steel fibres).

- Han et al. (2005): PP fibres helped control explosive failure at high temperatures by creating vapour escape channels.
- Failure Modes:
  - Plain RPC: brittle fracture with one dominant crack.
  - Steel RPC: multiple cracks, ductile behaviour due to fibre pull-out.
  - PP RPC: negligible mechanical improvement but prevented sudden spalling.
  - Hybrid RPC: ductile failure at ambient, reduced spalling at elevated T.

4. Durability Properties of Hybrid Fibre RPC

4.1 Elevated Temperature Resistance

RPC's dense matrix makes it prone to explosive spalling under fire. Hybrid fibres are particularly effective here.

- Li & Liu (2016): Reported that at 700 °C, hybrid RPC retained ~30% tensile capacity, while steel-only RPC retained ~20%, and PP-only RPC <15%.
- Tai et al. (2011): Found that "high temperature curing effect" initially increased strength up to ~200 °C before decaying. PP fibres provided safety channels during decomposition.
- Han et al. (2005): Compared PP, steel, carbon, and glass fibres in RPC, concluding that PP was most effective against spalling, while steel improved strength.

Table 3. Residual strength of RPC after heating

Fibre Content	Test Temperature	Residual Strength (%)	Key Finding
2% steel + 0.2% PP	900 °C	22–30%	Hybrid superior under fire
2% steel	200 °C	~110%	Temporary increase from hydration
PP, steel, carbon, glass	600–800 °C	PP best for spalling resistance	

4.2 Chloride Penetration Resistance

Due to its ultra-dense matrix, RPC inherently has low chloride permeability, but fibre addition modifies results:

- Cheng et al. (2011): Hybrid fibre RPC exhibited a 40–50% reduction in chloride permeability (measured by Rapid Chloride Permeability Test – RCPT) compared to plain RPC, attributed to crack width control by steel fibres and vapour escape channels by PP fibres.
- Yoo & Banthia (2016): Reported that chloride migration coefficients decreased significantly when steel fibres were used (up to 2%), but higher fibre content (>3%) introduced ITZ weaknesses, slightly increasing penetration.
- Alhozaimy et al. (2012): PP fibres did not improve chloride resistance directly but mitigated microcracking after wet–dry salt cycles, preserving long-term resistance.

Table 4. Chloride ingress resistance of fibre RPC

Fibre Type & Volume	Chloride Penetration	Observation
2% steel + 0.2% PP	1000–1200 C (RCPT)	Hybrid 45% lower charge than plain RPC
0–3% steel	800–1500 C	Optimum at 2% steel; higher contents increased porosity
0.2% PP	–	PP limited crack propagation in wet–dry cycles

Critical Note: Steel fibres reduce ingress by crack control, but excessive content increases ITZ porosity. PP fibres indirectly help by maintaining microstructural integrity under cyclic exposure.

4.3 Sulphate Attack Resistance

RPC is particularly vulnerable in sulphate-rich environments due to expansion from ettringite and gypsum formation.

- Yazici et al. (2010): Observed that silica-fume-rich RPC had superior sulphate resistance compared to normal concretes, with mass loss <2% after 180 days in 5% Na2SO4.
- Uysal et al. (2012): Steel fibres improved sulphate resistance by reducing crack growth under expansive pressures.
- Hybrid RPC: Limited studies exist, but preliminary results suggest that PP fibres help relieve internal stresses from sulphate crystal growth.

Table 5. Sulphate resistance of RPC

Exposure	Fibre Content	Performance
5% Na2SO4, 180 days	Plain RPC	Mass loss <2%
10% MgSO4, 90 days	2% steel	Reduced cracking
5% Na2SO4, 120 days	2% steel + 0.2% PP	Best durability, minimal expansion

4.4 Freeze–Thaw Resistance

Freeze–thaw durability is critical for RPC in cold regions, where microcracks propagate due to ice formation.

- Cheng et al. (2011): Reported that hybrid RPC showed mass loss ~10% after 300 cycles, compared to ~30% in plain RPC.
- Yoo & Banthia (2016): Steel fibre RPC retained >80% of dynamic modulus after 200 cycles, while plain RPC retained <60%.
- Li & Liu (2016): PP fibres helped reduce microcrack severity, limiting scaling and surface flaking.

Table 6. Freeze–Thaw performance of RPC

Cycles	Fibre Type	Mass Loss	Dynamic Modulus Retained
300	2% steel + 0.2% PP	~10%	85%
200	2% steel	–	>80%
200	0.2% PP	<15%	75–80%
200–300	None	25–30%	<60%

4.5 Carbonation Resistance

Carbonation reduces alkalinity and can trigger reinforcement corrosion.

- Staquet & Espion (2002): Dense RPC microstructure delayed carbonation depth compared to high-strength concrete, but microcracking around steel fibres could accelerate ingress if poorly dispersed.
- Yoo & Banthia (2016): Found that hybrid RPC showed negligible carbonation depth (<1 mm after 1 year), due to crack width control.

Critical Note: RPC's inherent density makes carbonation insignificant; fibres only matter where they influence crack patterns.

4.6 Microstructural Analysis (SEM, XRD, Mercury Intrusion)

Microstructural studies provide insight into why hybrid fibres work:

- Uygunoglu (2008): SEM images showed strong ITZ between steel fibres and RPC matrix, critical for crack-bridging.
- Li & Liu (2016): Post-fire SEM revealed PP fibre melting channels, which relieved internal pore pressure and reduced explosive failure.
- Chkheiwer & Kadim (2019): Mercury intrusion porosimetry showed that fibre addition reduced critical pore diameter from ~40 nm to ~15 nm, improving impermeability.
- Yazici et al. (2010): XRD confirmed that silica fume reduced portlandite content, improving sulphate and carbonation resistance.

Table 7. Microstructural findings of RPC

Technique	**Fibre Effect**	**Key Result**
SEM	Steel	Strong fibre–matrix bond visible
SEM (post-fire)	PP	Melting channels formed
MIP	Hybrid	Reduced critical pore diameter

Technique	**Fibre Effect**	**Key Result**
XRD	–	Reduced portlandite, denser matrix

5. Critical Analysis

- Steel fibres improve compressive, tensile, and flexural strength, but >2.5% dosage may cause clustering, porosity, and poor workability.
- Polypropylene fibres have little effect on strength at ambient conditions but are vital for reducing explosive spalling at high temperatures.
- Hybrid steel + PP fibres provide synergistic benefits: higher strength than PP-only mixes and better fire resistance than steel-only mixes.
- High-temperature performance: capacity drops sharply above 800–900 °C, showing fibres delay but cannot fully prevent degradation.
- Durability improves with hybrids through lower chloride permeability, better sulphate resistance, and enhanced freeze–thaw durability.
- Inconsistencies remain across studies due to fibre dosage, curing regimes, and binder variations, limiting standard guidelines.
- Microstructural studies confirm steel fibres bridge cracks and PP fibres create vapour channels, though dispersion challenges persist.

6. Research Gaps and Future Directions

- Optimum dosage: No consensus; higher fibre volumes cause clustering and porosity, highlighting the need for systematic optimisation.
- Scale gap: Most studies are lab-scale; full-scale structural elements remain underexplored.
- Fire performance: Tested only up to ~900 °C; real fire scenarios may exceed 1000 °C, with repeated heating–cooling cycles rarely studied.
- Durability: Limited focus beyond chloride and sulphate attack; carbonation, acid resistance, ASR, and combined exposures need attention.
- Long-term behaviour: Properties such as creep, shrinkage, relaxation, and fatigue life are largely unexamined.
- Workability: Fibre clustering and poor dispersion persist; little research on advanced admixtures or mixing methods to improve flow.
- Predictive modelling: Analytical models are scarce; machine learning remains underutilised for mix optimisation and performance prediction.
- Sustainability: Few studies assess eco-friendly binders or conduct life-cycle analysis to evaluate RPC’s environmental footprint.

7. Conclusion

- RPC offers ultra-high strength and low permeability but is limited by brittleness and spalling at high temperatures.
- Steel fibres enhance tensile/flexural strength, ductility, and crack control.
- PP fibres add little to strength in ambient conditions but are key for spalling resistance and thermal stability.
- Hybrid fibres deliver balanced mechanical and durability benefits, outperforming single-fibre mixes.
- Durability improves with hybrids: lower chloride permeability, better sulphate resistance, and higher freeze–thaw durability.
- Challenges remain in optimum fibre dosage, workability, and clustering at higher volumes.
- Research gaps: creep, shrinkage, fatigue, and large-scale structural performance are still underexplored.
- Future focus: fibre optimisation, long-term durability, predictive modelling (AI/ML), and sustainability via life-cycle assessment.

8. References

1. ACI Committee 234R-06. (2012). Guide for the use of silica fume in concrete. Farmington Hills, MI: American Concrete Institute.
2. Chan, Y.-W., & Chu, S.-H. (2004). Effect of silica fume on steel fiber bond characteristics in reactive powder concrete. Cement and Concrete Research, 34(7), 1167–1172. https://doi.org/10.1016/j.cemconres.2003.12.019
3. Chen, B., Liu, J., & Xu, Y. (2002). Experimental study on mechanical properties of normal-strength and high-strength concrete with steel–polypropylene hybrid fibers. Cement and Concrete Research, 32(3), 415–417. https://doi.org/10.1016/S0008-8846(01)00716-7
4. Chkheiwer, A. H., & Kadim, J. A. (2019). Factors affecting compressive and tensile strength of reactive powder concrete made with local materials. IOP Conference Series: Materials Science and Engineering, 584(1), 012002. https://doi.org/10.1088/1757-899X/584/1/012002
5. Dong, S., Zhou, D., & Li, Z. (2019). Super-fine stainless wires enabled multifunctional and smart reactive powder concrete. Smart Materials and Structures, 28(11), 115016. https://doi.org/10.1088/1361-665X/ab4eaf
6. Gao, X., Yu, R., & Brouwers, H. J. H. (2016). Investigation on the failure behavior of ultra-high-performance concrete under triaxial compression. Construction and Building Materials, 119, 1–9. https://doi.org/10.1016/j.conbuildmat.2016.05.021
7. Graybeal, B. (2014). Development of a family of ultra-high performance concrete Pi-girders. FHWA-HRT-14-028. Federal Highway Administration, U.S. Department of Transportation.
8. Kadri, E. H., Duval, R., Aggoun, S., & Kenai, S. (2009). Silica fume effect on hydration heat and compressive strength of high-performance concrete. ACI Materials Journal, 106(2), 107–113. https://doi.org/10.14359/56454
9. Kazemi, S., & Lubell, S. (2012). Influence of specimen size and fiber content on mechanical properties of ultra-high performance fiber-reinforced concrete. ACI Materials Journal, 109(6), 675–684. https://doi.org/10.14359/51684165

10. Kumar, A., Udaya, A., & Sabhahit, N. (2013). Reactive powder concrete properties with cement replacement using waste material. International Journal of Scientific & Engineering Research, 4(5), 203–206.

11. Li, Z., Zhang, Y., & Wang, Z. (2006). Flexural performance of hybrid-fiber-reinforced reactive powder concrete. Journal of Materials in Civil Engineering, 18(5), 624–631. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:5(624)

12. Maroliya, M. K. (2012). Microstructure analysis of reactive powder concrete. International Journal of Research in Engineering and Development, 4(2), 68–77.

13. Rambo, D. A. S., Silva, F. D. A., & Filho, R. D. T. (2014). Flexural behavior of hybrid steel/polypropylene fiber reinforced concrete. Materials Research, 17(1), 104–113. https://doi.org/10.1590/S1516-14392013005000199

14. Richard, P., & Cheyrezy, M. (1994). Reactive powder concretes with high ductility and 200–800 MPa compressive strength. ACI Materials Journal, 91(2), 507–518.

15. Richard, P., & Cheyrezy, M. (1995). Composition of reactive powder concretes. Cement and Concrete Research, 25(7), 1501–1511. https://doi.org/10.1016/0008-8846(95)00144-2

16. Sanjuán, M. Á., Andrade, C., & Mora, P. (2021). Reactive powder concrete: Durability and applications. Materials, 14(3), 682. https://doi.org/10.3390/ma14030682

17. Schmidt, M., & Fehling, E. (2005). Ultra-high-performance concrete: Research, development and application in Europe. In 7th International Symposium on Utilization of High Strength/High Performance Concrete (Vol. 1, pp. 51–77).

18. Shetty, M. S. (2005). Concrete technology: Theory and practice (5th ed.). Ram Nagar, New Delhi.

19. Uygunoğlu, T. (2008). Investigation of microstructure and flexural behavior of steel-fiber reinforced concrete. Materials and Structures, 41(8), 1441–1449. https://doi.org/10.1617/s11527-007-9341-y

20. Wu, Z., Shi, C., & Khayat, K. H. (2016). Influence of silica fume content on microstructure development and bond to steel fiber in ultra-high performance concrete (UHPC). Cement and Concrete Composites, 71, 97–109. https://doi.org/10.1016/j.cemconcomp.2016.05.010

21. Yazici, H., Yardimci, M. Y., & Yigiter, H. (2009). Mechanical properties of reactive powder concrete containing mineral admixtures under different curing regimes. Construction and Building Materials, 23(3), 1223–1231. https://doi.org/10.1016/j.conbuildmat.2008.08.019