



Hybrid Steel–Polypropylene Fibre Reinforcement for Structural Recycled Aggregate Concrete: A Critical Review with Reference to Indian Practice

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ABSTRACT :

Recycled coarse aggregate (RCA) produced from demolished concrete can ease two problems at once: the shortage of natural aggregate and the growing volume of construction and demolition (C&D) waste. Its use in structural concrete remains limited, mainly because the old mortar attached to each recycled particle lowers the stiffness, tensile strength and toughness of the concrete. In India, IS 383:2016 therefore permits RCA only up to 20% of the coarse aggregate in reinforced concrete of grade M25 and below. This review examines whether fibre reinforcement, and in particular hybrids of stiff steel macro fibres and fine polypropylene (PP) micro fibres, can offset these weaknesses. The literature is reviewed under five heads: the properties of RCA and the role of the double interfacial transition zone; the mechanical and durability behaviour of recycled aggregate concrete (RAC); aggregate treatment as an alternative remedy; mono-fibre and hybrid-fibre reinforcement, including the quantification of fibre synergy; and the flexural and shear behaviour of reinforced RAC members. The evidence shows that fibres act directly on the cracking-related weaknesses of RAC, while aggregate treatment mainly improves strength and absorption. Hybrid fibres outperform single fibres at the same total dosage in many natural aggregate studies, but evidence within recycled aggregate matrices, and especially at member scale, is still thin. Indian codes contain no provisions for fibre-reinforced concrete or for high RCA contents. The review closes with a set of research needs, including member-scale tests at high replacement, deflection and crack-width models for fibre-reinforced RAC, and standard methods for reporting fibre synergy.

Keywords: recycled aggregate concrete, hybrid fibre reinforcement, steel fibre, polypropylene fibre, fibre synergy, flexural behaviour, IS 383:2016, sustainable construction

Introduction

Sand and gravel are the most extracted solid materials on the planet. Global use is estimated at 40–50 billion tonnes a year, and extraction at this rate is causing river-bed erosion, falling groundwater levels and damage to coastal systems (UNEP, 2019; UNEP, 2022). Concrete is the largest single consumer of these aggregates. At the same time, the construction sector produces large quantities of C&D waste. India alone is estimated to generate about 150 million tonnes of such waste every year, yet only a small fraction, of the order of 1%, passes through formal recycling plants (CSE, 2020). Most of the rest is dumped on open land, along roads or near water bodies.

National policy has begun to respond. The Construction and Demolition Waste Management Rules, 2016 require segregation and processing of C&D waste (MoEFCC, 2016), and the Central Pollution Control Board has issued guidelines for its environmental management (CPCB, 2017). The revised aggregate standard, IS 383:2016, recognises recycled concrete aggregate as a coarse aggregate for concrete for the first time (BIS, 2016). Its permission is cautious, however. RCA may form up to 25% of the coarse aggregate in plain concrete and up to 20% in reinforced concrete of grade M25 and below (BIS, 2016). These limits rest on the known behaviour of recycled aggregate concrete without any compensating measure.

The reason for caution is well documented. Recycled particles carry a layer of old cement mortar, which makes them porous and weak, and creates two interfacial zones in the new concrete instead of one (Hansen, 1986; Etxeberria et al., 2007; Tam et al., 2005). The result is a concrete that is less stiff, weaker in tension and more brittle than natural aggregate concrete (NAC) (Xiao et al., 2005; Silva et al., 2016). In structural members, these weaknesses show up mainly as larger deflections and wider cracks rather than lower strength (Ignjatović et al., 2013; Knaack & Kurama, 2015).

Two broad routes exist for improving RAC. The first is to treat the aggregate so that the old mortar is removed or strengthened (Tam et al., 2007b; Wang et al., 2020). The second is to leave the aggregate as it is and add fibres that bridge cracks in the hardened concrete (Gao & Zhang, 2018; Kachouh et al., 2019). Fibres are of particular interest because they act on exactly the properties that RAC lacks: tensile capacity, toughness and crack control. A hybrid of two fibre types, one acting on fine cracks and the other on wide cracks, may achieve this more efficiently than a single fibre (Banthia & Gupta, 2004; Qian & Stroeve, 2000).

Several reviews have covered RAC (Behera et al., 2014; Tam et al., 2018; Xiao et al., 2012) or hybrid fibre-reinforced concrete in natural aggregate matrices (Banthia & Gupta, 2004; Banthia et al., 2014). Fewer have examined the two together, and fewer still have looked at the question from the standpoint of structural members and Indian codes. This paper reviews the relevant literature with three aims:

1. To explain, from the mechanics of the material, why RAC is deficient and which deficiencies fibres can and cannot address.
2. To assess the evidence for hybrid steel–PP fibre systems, and the methods used to quantify their synergy.
3. To identify the gaps that must be closed before high RCA contents can be used in reinforced concrete members in India.

Recycled coarse aggregate

1.1. Adhered mortar

Almost every difference between recycled and natural coarse aggregate traces back to one feature: the hardened mortar that stays attached to the original stone after crushing. Hansen's early state-of-the-art report showed that this mortar controls the density, absorption and strength of the aggregate, and that its amount depends on the parent concrete, the crusher and the number of crushing stages (Hansen, 1986). Finer fractions tend to carry more mortar than coarser ones (de Juan & Gutiérrez, 2009; de Brito & Saikia, 2013). De Juan and Gutiérrez measured the mortar content directly and found that it correlates closely with water absorption and density, so a single indicator can describe aggregate quality reasonably well (de Juan & Gutiérrez, 2009).

The practical lesson is that RCA cannot be specified by type alone. Material from two demolition sites, or even two crushing runs at the same site, can produce noticeably different concrete. Each source has to be tested.

1.2. Physical and mechanical properties

The direction of change between natural aggregate and RCA is consistent across studies, even though the magnitudes vary. Table 1 summarises these changes and their effect on concrete. Water absorption shows the largest relative increase. Good natural aggregate usually absorbs less than 1–2% of water, while RCA commonly absorbs several times more because the attached mortar is porous and micro-cracked (Poon et al., 2004; Etxeberria et al., 2007). Specific gravity falls, and the Los Angeles abrasion, crushing and impact values rise (Behera et al., 2014; Thomas et al., 2018). RCA from weak parent concrete may fail the limits set for structural aggregate (Behera et al., 2014).

Table 1 - Effect of adhered mortar on recycled coarse aggregate and its consequences for concrete

Property of RCA	Change relative to natural aggregate	Main consequence in concrete
Water absorption	Large increase	Loss of workability; uncertain free water unless aggregate is pre-saturated
Specific gravity and bulk density	Decrease	Lighter concrete; mix must be proportioned by volume
Abrasion, crushing and impact values	Increase	Weaker aggregate phase; cracks pass through particles
Interfacial zones	Two zones (old and new) instead of one	Lower tensile strength, stiffness and toughness
Variability	Higher, depends on parent concrete	Source-by-source testing needed

1.3. The double interfacial transition zone

In NAC, a single interfacial transition zone (ITZ) forms between the stone and the cement paste. This zone is more porous and weaker than the bulk paste. RAC contains two such zones (Fig. 1). The old ITZ lies between the original stone and the attached mortar; it comes from the parent concrete and is often already micro-cracked by crushing. The new ITZ forms between the attached mortar and the fresh paste (Etxeberria et al., 2007; Tam et al., 2005). A crack therefore has two weak paths to follow. This explains why fracture in RAC often runs through the recycled particle instead of around it, which is rarely seen in normal-strength NAC (Xiao et al., 2005).

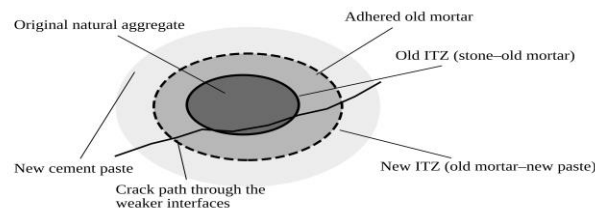


Fig. 1 - Schematic of a recycled coarse aggregate particle in new concrete, showing the old and new interfacial transition zones and a typical crack path.

The new ITZ can be improved. Pre-soaking RCA in acid removes part of the mortar and reduces absorption (Tam et al., 2007b), and pozzolanic additions densify the new zone by consuming calcium hydroxide (Ann et al., 2008). The fact that such treatments help confirms that the interfaces control the behaviour.

1.4. Classification and code limits

RILEM TC 121-DRG proposed one of the first classifications of recycled aggregates, based on density and composition, and reserved the highest class for aggregate made from concrete alone (RILEM TC 121-DRG, 1994). IS 383:2016 makes a similar distinction. It separates recycled concrete aggregate, made only from concrete waste, from recycled aggregate that may also contain brick, tile or stone, and allows only the former in structural concrete (BIS, 2016). Kwan et al. (2012) showed that the amount of RCA, rather than its mere presence, decides whether design and durability properties remain acceptable. This supports the graded limits found in most codes.

Behaviour of recycled aggregate concrete

1.5. Strength and stiffness

The mechanical effect of RCA has been studied widely, and the direction of the effect is not in doubt. Xiao et al. (2005) tested replacement ratios from 0 to 100% and found that compressive strength, peak strain and elastic modulus all changed with replacement, and that fracture increasingly passed through the aggregate. Etxeberria et al. (2007) found that 25% replacement gave concrete similar to the control, while full replacement needed a lower water–cement ratio and more cement to reach the same strength. Limbachiya et al. (2000) reported no significant effect on high-strength concrete up to 30% replacement. Malešev et al. (2010) concluded that RAC can be used structurally when the mix is adjusted for the aggregate.

Three trends recur across these studies. First, below about 25–30% replacement, the change in strength is small and often within normal batch variation. Second, the elastic modulus falls more steeply than compressive strength, because the attached mortar is much less stiff than the original stone. Silva et al. (2016) analysed a large database and showed that the usual strength–modulus relationships overestimate the modulus of RAC. Third, the loss in tensile strength matters more than its relative size suggests, because tension already limits the cracking behaviour of concrete.

1.6. Shrinkage, creep and durability

Long-term and durability properties change in the same direction. Drying shrinkage and creep increase because the total volume of paste in the concrete rises when old mortar is added with the aggregate (Silva et al., 2015). Higher connected porosity raises water absorption, carbonation depth and chloride penetration (Thomas et al., 2013). Kou and Poon (2013) showed that much of this penalty can be offset by adding fly ash, so that the long-term performance of such mixes approaches that of conventional concrete. Butler et al. (2011) examined the bond between RAC and reinforcing steel and found that bond strength depends mainly on aggregate quality rather than on replacement ratio.

1.7. Workability and batching

The high absorption of RCA makes batching a real concern. Poon et al. (2004) showed that the moisture state of the aggregate controls both slump loss and strength. Two approaches are common. In the first, dry aggregate is batched with extra water to cover absorption. In the second, aggregate is pre-soaked and batched in the saturated surface-dry condition. The second keeps the effective water–cement ratio known and constant, and is generally easier to justify when mixes are compared. Because RCA is lighter, replacement on an equal-volume basis also keeps the paste-to-aggregate ratio unchanged, whereas equal-mass replacement silently adds aggregate volume.

Aggregate treatment versus fibre reinforcement

Since the weaknesses of RAC come from the attached mortar, many studies have tried to remove or strengthen it. The main methods are compared in Table 2.

Table 2 - Treatment methods for recycled concrete aggregate

Method	Principle	Reported benefit	Main drawback
Mechanical grinding or repeated crushing	Rubs off attached mortar	Lower absorption, higher density	Energy use; fines generated; loss of yield
Acid pre-soaking (Tam et al., 2007b)	Dissolves part of the mortar	Clear drop in absorption	Chemical handling; effluent; residual acid risk to steel
Thermal treatment	Weakens mortar by heating	Effective mortar removal	High energy demand reduces carbon benefit
Pozzolanic slurry coating (Ann et al., 2008; Ismail & Ramli, 2013)	Densifies the new ITZ	Better strength and durability	Extra processing and curing time

Method	Principle	Reported benefit	Main drawback
Two-stage mixing (Tam et al., 2005; Tam et al., 2007a)	Coats aggregate with part of the cement and water first	Higher strength at the same mix proportions	Changed batching sequence
Microbial carbonate precipitation (Wang et al., 2017)	Bio-deposited calcite seals surface pores	Lower absorption	Long treatment; not yet practical at scale

Wang et al. (2020) compared several of these methods on a common basis and concluded that their technical gains are broadly similar, so the choice depends mostly on processing cost. Two points follow. Treatment adds a processing stage whose energy and chemical burden partly cancels the environmental gain of recycling. And treatment improves strength without making the concrete less brittle, because a denser interface does not by itself raise fracture energy. Fibre reinforcement takes a different approach. It leaves the aggregate untreated and compensates for its weaknesses after cracking, which is where RAC falls shortest. The two routes are not exclusive, and combined use has been reported (Katkuda & Shatarat, 2017).

Fibre reinforcement in recycled aggregate concrete

1.8. Role of individual fibre types

Fibres differ in stiffness, size and cost, and so in what they contribute (ACI Committee 544, 2009; Bentur & Mindess, 2007). Table 3 compares the four types most often used with RAC. Naaman and Reinhardt (2006) classify fibre composites by their tensile response and make the point that fibre content and fibre–matrix bond together decide whether a composite softens or hardens after cracking. Banthia and Trottier (1994) showed that the deformed ends of steel fibres control their pull-out resistance, and hence their effect after cracking.

Table 3 - Fibre types used with recycled aggregate concrete and their main action

Fibre	Stiffness and size	Main action	Limitation
Hooked-end steel	High modulus; macro scale	Bridges wide cracks; raises toughness and residual strength	Workability loss; corrosion at the surface; cost
Polypropylene	Low modulus; micro scale	Restrains plastic shrinkage and fine cracks	Little gain in strength or post-peak load
Alkali-resistant glass	Medium–high modulus; fine	Acts on micro-cracking	Long-term alkali attack unless AR grade
Basalt	Medium–high modulus; fine	Improves tensile and flexural strength	Limited structural data

Steel fibres act mainly after the concrete has cracked. Mohammadi et al. (2008) reported large gains in flexural strength and toughness with steel fibres, together with a marked loss of workability at higher doses. In RAC, Cameiro et al. (2014) found that steel fibres changed the compressive stress–strain curve considerably, raising post-peak energy while changing peak strength only modestly. Gao and Zhang (2018) reported similar gains in flexural performance and proposed an evaluation method for steel fibre-reinforced RAC. Kachouh et al. (2019) showed that steel fibres recover a substantial part of the strength lost when natural aggregate is fully replaced.

Polypropylene fibres are flexible, fine and of low modulus. Their value lies in controlling plastic and drying shrinkage cracks and in improving impact resistance, not in raising strength (Alhozaimy et al., 1996; Song et al., 2005). Das et al. (2018) found PP fibres effective in reducing the shrinkage cracking to which RAC is prone. Ali and Qureshi (2019) reported better mechanical and durability performance of RAC with glass fibres, and Katkhuda and Shatarat (2017) found basalt fibres useful in RAC, especially together with acid treatment of the aggregate.

The common thread is that no single fibre improves every property. Stiff, coarse fibres add toughness but reduce workability. Fine fibres improve crack control but add little strength.

1.9. Why fibres suit recycled aggregate concrete

The weaknesses of RAC fall into two groups. Properties governed by cracking and post-cracking behaviour, such as tensile strength, toughness, crack width and ductility, are reduced because cracks start more easily and run through weak interfaces. Properties governed by the uncracked material, mainly the elastic modulus and hence the stiffness before cracking, are reduced because the attached mortar is soft. Fibres are inactive until the matrix cracks (Bentur & Mindess, 2007). They can therefore be expected to restore the first group of properties well, and the second group only slightly. This distinction is important for design, because deflection checks depend heavily on stiffness. A fibre-reinforced RAC member may have ample strength and crack control and still deflect more than an equivalent NAC member.

Hybrid fibre systems

1.10. Basis of hybridisation

Banthia and Gupta (2004) set out the main bases on which fibres can be combined. In a size-based hybrid, a fine fibre controls micro-cracks while a coarse fibre bridges macro-cracks. In a modulus-based hybrid, a stiff fibre provides strength and a flexible fibre provides strain capacity. In a function-based hybrid, one fibre improves fresh or early-age behaviour while the other improves hardened performance. A steel–PP hybrid combines all three: the steel is coarse, stiff and acts in the hardened state, while the PP is fine, flexible and acts from the plastic stage onwards.

1.11. Multi-scale crack arrest

Cracking in concrete develops in stages. Micro-cracks form first at weak points such as the ITZ, then join up into a macro-crack that opens and finally splits the member. Each stage calls for a different reinforcement scale (Fig. 2). Fine fibres are numerous and closely spaced, so they intercept micro-cracks early and delay their joining. Coarse fibres are fewer and further apart, so they do little at that stage but carry the load once a macro-crack has formed and opened (Qian & Stroeven, 2000; Lawler et al., 2005).

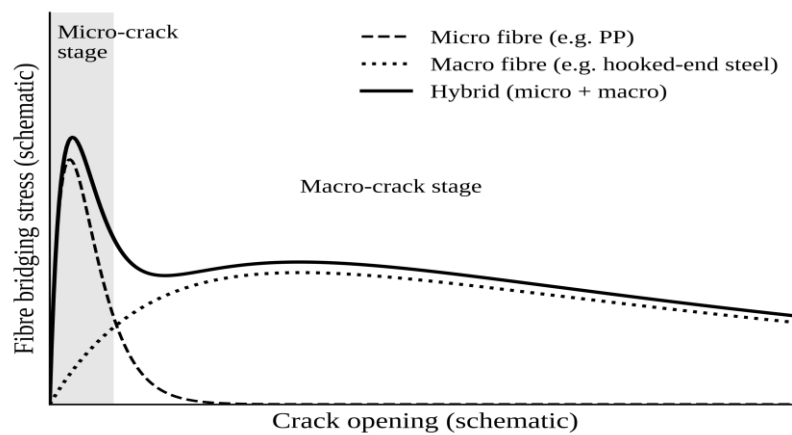


Fig. 2 - Schematic of fibre bridging stress against crack opening for micro, macro and hybrid fibre systems.

When both fibres are present, the micro fibres delay the formation of the macro-crack. The crack therefore forms later and in a matrix that is already more highly stressed, so the macro fibres are engaged under more favourable conditions than in a mono-fibre mix (Banthia & Gupta, 2004; Sivakumar & Santhanam, 2007). The combined effect can then exceed the sum of the separate effects. This is the basis of the claim of positive synergy.

This mechanism has special relevance to RAC. The double ITZ multiplies the sites where micro-cracks can start, so fine fibres have more work to do in RAC than in NAC. At the same time, the reduced tensile capacity of RAC means that macro fibres are called on earlier. In principle, a hybrid system should therefore gain more over a mono-fibre system in RAC than in NAC. This expectation is plausible but has not yet been widely tested.

1.12. Quantifying synergy

A claim of synergy needs a baseline. The usual approach compares the measured property of the hybrid mix with the value predicted by adding the separate contributions of each fibre (Banthia & Gupta, 2004; Banthia et al., 2014). Because a hybrid contains each fibre at only part of its mono-fibre dose, the separate contributions should be scaled by dose. A general form of the prediction is:

$$P_{pred} = P_0 + \frac{V_A}{V_{A,m}}(P_A - P_0) + \frac{V_B}{V_{B,m}}(P_B - P_0) \quad (1)$$

and the synergy index is:

$$S = \frac{P_H}{P_{pred}} \quad (2)$$

where P_0 is the property of the plain mix, P_A and P_B are the properties of the mono-fibre mixes at fibre contents $V_{A,m}$ and $V_{B,m}$, V_A and V_B are the fibre contents in the hybrid, and P_H is the measured property of the hybrid. A value of S above 1 indicates positive synergy. Fig. 3 shows the logic of this assessment.

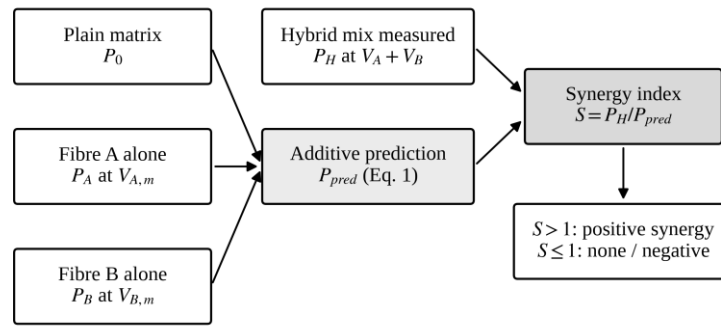


Fig. 3 - Framework for assessing synergy in a hybrid fibre system.

Two cautions apply. Equation (1) assumes that each fibre's effect scales linearly with its dose, which is only an approximation. And the index depends on the property measured, the doses used and the matrix. A study reporting synergy should therefore state the plain and mono-fibre reference mixes and the exact form of the baseline. Studies that compare a hybrid only with a plain mix cannot show synergy at all.

1.13. Experimental evidence

Table 4 summarises key studies on hybrid fibre systems. Banthia and Gupta (2004) showed in a high-strength matrix that micro–macro hybrids outperformed single fibres at the same total volume. Banthia and Soleimani (2005) extended the work to flexural response, and Banthia et al. (2014) later confirmed synergy in direct shear as well as flexure. Qian and Stroeven (2000) found that PP raised first-crack strength while steel controlled the post-peak branch. Lawler et al. (2005) observed finer crack spacing and lower permeability under load in hybrid mixes. Yao et al. (2003) reported synergy at low total fibre content, and Sivakumar and Santhanam (2007) found that metallic–non-metallic hybrids exceeded steel alone in flexural toughness.

Table 4 - Selected studies on hybrid fibre-reinforced concrete

Study	Fibre combination	Matrix	Main finding
Banthia and Gupta (2004)	Steel macro fibre with micro fibres	High-strength NAC	Positive synergy in flexural toughness; bases of hybridisation proposed
Qian and Stroeven (2000)	Steel + PP	NAC	PP raises first-crack strength; steel governs post-peak response
Lawler et al. (2005)	Micro + macro fibres	NAC	Finer cracking; lower permeability under load
Yao et al. (2003)	Carbon, steel and PP combinations	NAC	Synergy at low total fibre content
Sivakumar and Santhanam (2007)	Steel + non-metallic	High-strength NAC	Hybrid exceeds steel alone in flexural toughness
Afroughsabet and Ozbakkaloglu (2015)	Steel + PP	High-strength NAC	Better mechanical and durability performance
Mohseni et al. (2017)	Fibre combinations	Self-compacting RAC	Improvement confirmed in a recycled aggregate matrix

Two limits recur in this evidence. Synergy depends on the property: several authors report clear synergy in flexural toughness and little or none in compressive strength (Banthia & Gupta, 2004; Sivakumar & Santhanam, 2007). Synergy also depends on dose, and it can disappear or reverse when both fibres are added at high contents, because dispersion worsens and more air is trapped (Afroughsabet & Ozbakkaloglu, 2015). The hybrid ratio is therefore a variable to be tested, not a value to be assumed. Most important for this review, nearly all of this evidence comes from natural aggregate matrices. Studies of hybrid fibres in RAC remain few (Mohseni et al., 2017), and they are mostly limited to cubes, cylinders and prisms.

Structural behaviour of reinforced RAC members

1.14. Flexure

Member-level studies are far fewer than material studies, but their findings agree (Table 5). Ajdukiewicz and Kliszczewicz (2007) tested beams and columns of RAC and NAC and found broadly similar structural behaviour, with differences traced mainly to the lower modulus of RAC. Ignjatović et al. (2013) found that full replacement left the ultimate flexural capacity of reinforced beams almost unchanged, while service deflections were larger and cracking more extensive. Choi and Yun (2013) found similar short-term behaviour and showed that the difference grows over time as the higher creep and shrinkage of RAC take effect. Knaack and Kurama (2015) reached similar conclusions in tests on beams with recycled coarse aggregate.

Table 5 - Selected studies on the flexural behaviour of reinforced RAC beams

Study	Scope	Main finding
Ajdukiewicz and Kliszczewicz (2007)	Beams and columns, up to full replacement	Comparable behaviour; differences due to lower modulus
Ignjatović et al. (2013)	Beams, partial and full replacement	Ultimate capacity retained; larger deflection and cracking
Choi and Yun (2013)	Beams, short and long term	Similar short-term capacity; much larger long-term deflection
Knaack and Kurama (2015)	Beams with recycled coarse aggregate	Capacity retained; stiffness and serviceability reduced
Tošić et al. (2016)	Database of beam tests	Code flexural predictions safe; deflection less reliable

The reason is simple mechanics. In an under-reinforced section, the moment capacity is controlled by the yield force of the tension steel and the lever arm, and both depend only weakly on concrete strength. The depth of the compression block adjusts to make up the difference. Serviceability, on the other hand, depends on the cracked flexural stiffness and the cracking moment, which depend directly on the modulus and tensile strength of the concrete. These are the properties RAC degrades most. Tošić et al. (2016) compiled a database of RAC beam tests and found that Eurocode 2 flexural predictions remained safe while deflection predictions were less reliable.

Fibres change the post-cracking part of this picture. In steel fibre-reinforced RAC, flexural toughness and residual strength rise markedly (Gao & Zhang, 2018), and the fibres crossing a crack carry tension that the code models for conventional concrete do not count. Design to IS 456:2000 (BIS, 2000) can therefore be expected to underestimate the capacity of fibre-reinforced RAC beams. That is safe but wasteful. Reliable test data on crack width, crack spacing and ductility of hybrid fibre-reinforced RAC beams are still scarce.

1.15. Shear

Shear is the more sensitive case, because the concrete contribution to shear resistance depends on tensile strength and aggregate interlock, and RAC weakens both. Arezoumandi et al. tested beams with 100% RCA and no stirrups, and found lower shear capacity than in comparable NAC beams. They linked the loss to weaker aggregate interlock along cracks that pass through the aggregate (Arezoumandi et al., 2014). Ignjatović et al. (2017) tested beams with and without shear reinforcement and found that adequate stirrups largely hide the difference, while beams without stirrups show it clearly.

Fibres crossing a diagonal crack add a further component of shear resistance, acting much like distributed web reinforcement. Sahoo and Sharma (2014) showed that steel fibres can partly replace stirrups and, at sufficient dose, change brittle diagonal-tension failure into ductile flexural failure. Ding et al. and Amin and Foster developed models for the fibre contribution to shear in beams with and without stirrups (Ding et al., 2012; Amin & Foster, 2016). This mechanism is particularly useful in RAC, because the fibres make up for the aggregate interlock that recycled aggregate weakens.

Codes and design provisions

Table 6 lists the provisions most relevant to the use of fibre-reinforced RAC in India. The gap is clear. IS 456:2000 has no provisions for recycled aggregate or for fibres (BIS, 2000). IS 383:2016 allows limited RCA but makes no allowance for measures that offset its weaknesses (BIS, 2016). Design guidance for fibre-reinforced concrete exists in ACI 544.4R (ACI Committee 544, 2018) and in the fib Model Code 2010 (fib, 2013), and test methods for flexural toughness are given by RILEM TC 162-TDF (RILEM TC 162-TDF, 2002) and ASTM C1609 (ASTM, 2019). None of these addresses fibres and recycled aggregate together.

Table 6 - Code provisions relevant to fibre-reinforced recycled aggregate concrete

Document	Relevant provision	Implication
IS 383:2016 (BIS, 2016)	RCA up to 25% in plain and 20% in reinforced concrete (M25 and below); brick-bearing aggregate excluded from structural use	Sets the present limit for structural RAC
IS 456:2000 (BIS, 2000)	Limit state design; deflection and crack-width limits; no terms for RCA or fibres	Basis for checking members; ignores fibre bridging
IS 10262:2019 (BIS, 2019)	Mix proportioning; water correction for aggregate absorption	Absorption correction is critical for RCA
ACI 544.1R and 544.4R (ACI Committee 544, 2009; ACI Committee 544, 2018)	Reporting and design guidance for fibre-reinforced concrete	Fibre design framework absent from Indian codes
fib Model Code 2010 (fib, 2013)	Residual-strength-based design of fibre-reinforced concrete	Possible model for an Indian provision
RILEM TC 162-TDF; ASTM C1609 (RILEM TC 162-TDF, 2002; ASTM, 2019)	Flexural toughness and residual strength tests	Standard basis for characterising fibre performance

Research gaps and future directions

The literature points to the following needs.

1. **Member-scale tests at high replacement.** Most hybrid fibre studies in RAC stop at the material scale. Beam and slab tests at 50–100% replacement are needed, with enough specimens per variable to separate real effects from scatter.
2. **Optimum hybrid ratio in recycled matrices.** Steel-to-PP ratios found best in NAC may not carry over to RAC, whose double ITZ changes how micro-cracks start. The ratio should be tested within the recycled matrix itself.
3. **Standard reporting of synergy.** Studies should report the plain and mono-fibre reference mixes and use a stated, dose-scaled baseline such as Eqs. (1) and (2), so that synergy values can be compared across studies.
4. **Serviceability models.** Deflection and crack-width prediction for fibre-reinforced RAC needs attention, because fibres restore cracking-related properties much better than stiffness. Modulus relationships specific to RAC (Silva et al., 2016) should be combined with models for fibre bridging.
5. **Long-term behaviour.** Creep, shrinkage and long-term deflection of fibre-reinforced RAC members are largely unstudied, though they are known to be critical for plain RAC (Choi & Yun, 2013).
6. **Shear without stirrups.** Tests on beams without stirrups would show whether fibres can restore the shear capacity that RAC loses through weaker aggregate interlock.
7. **Durability and life-cycle assessment.** The durability of fibre-reinforced RAC, including corrosion of steel fibres near the surface, and its life-cycle impact compared with treated-aggregate alternatives (Marinković et al., 2010), need study.
8. **Code development.** Indian provisions for fibre-reinforced concrete, and for RCA contents above the present limits when compensating measures are used, would allow the research to reach practice.

Conclusions

This review has examined the use of hybrid steel–polypropylene fibres to offset the weaknesses of recycled aggregate concrete in structural members. The main conclusions are:

1. The weaknesses of RAC come mainly from the old mortar attached to recycled particles, which creates two weak interfacial zones. RAC is therefore less stiff, weaker in tension and more brittle than natural aggregate concrete, and its properties vary with the source.
2. Aggregate treatment improves strength and absorption but adds processing cost and energy and does not reduce brittleness. Fibre reinforcement acts directly on the cracking-related weaknesses without changing the aggregate.
3. Fibres can be expected to restore properties governed by cracking, such as tensile strength, toughness, crack control and ductility, much better than properties governed by uncracked stiffness. Deflection should therefore be checked explicitly in fibre-reinforced RAC members.
4. Hybrid steel–PP systems work at two crack scales and often outperform single fibres at the same total content in natural aggregate concrete. Their synergy depends on the property, the doses and the matrix, and should be assessed against a dose-scaled baseline.
5. In reinforced RAC beams, flexural strength is largely retained while serviceability suffers. Steel fibres raise toughness and can add to shear resistance, but member-scale data for hybrid fibre-reinforced RAC are still scarce.
6. Indian codes contain no provisions for fibre-reinforced concrete or for higher RCA contents with compensating measures. Member-scale research and design models are needed before such use can be recommended.

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