Chapter 12
Alternative Fine Aggregates to Produce Sustainable Self Compacting Concrete: A Review

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Abstract Self-compacting concrete (SCC), because of its magnificent fresh and hardened properties, is widely used around the world. Continuous increase in construction activities lead to enormous depletion of exhaustible resources and now the industry is on the verge of recognising the worth of such limited exhaustible resources. The disposal of some waste products into the land, on the other hand, leads to environmental imbalance. As a result of these factors, the approach to sustainable construction is becoming more prominent. As a result, researchers have performed experimental investigations into the feasibility of alternative fine aggregates (AFA) as a replacement for river sand in order to promote sustainable development and safeguard the environment. This paper provides a comprehensive overview of alternate sand's physical characteristics, as well as their impact on SCC's fresh and hardened properties. The use of AFA contributes significantly to the reduction of environmental pollution by lowering carbon dioxide emissions. SCC production costs are also reduced by using alternative fines. As a result, this paper seeks to give useful and important information on the subject, as well as a platform for new scholars to conduct future SCC research.

Keywords Alternative fines · Self-compacting concrete · Filling ability · Sustainable development · Manufactured sand

12.1 Introduction

Self-compacting concrete (SCC) has been termed "the most important development in concrete construction." Although, it was designed to address a growing shortage of skilled labour and deal with inefficient compaction, it has turned out to be profitable due to a variety of factors, including excellent segregation resistance and fluidity, increased durability, greater design freedom, faster construction, easier

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placement, less manpower, superior surface finish, and no need for specialised equipment. SCC was developed in Japan in 1986 for the first time, and its ability to self-consolidate and flow was partly attributable to the early development of superplasticizers (Okamura 1997; Okamura and Ouchi 2003).

Aggregates account for around 60–70% of the total volume in SCC. Self-compacting concrete's fresh and hardened qualities are mostly determined by the aggregates, therefore choosing right aggregates is crucial. The effects of fine aggregate texture and shapes are more significant as compared to that of coarse aggregate (Nanthagopalan and Santhanam 2011). One of the factors that can affect the flowability of SCC is poor aggregate gradation. This difficulty could be overcome by using inert and reactive fillers (Aijaz et al. 2014).

Over the last few decades, the rapid rise of construction has resulted in a massive spending on naturally occurring resources for concrete manufacturing (Bounedjema et al. 2017). As a result, the availability of these natural elements is becoming increasingly limited. The withdrawal of river sand, which accounts for around 35% of concrete volume, has major environmental repercussions, thus it is urgent to reduce its use and explore other possibilities (Mundra et al. 2016). Crushed Rock Sand (CRS), Recycled Fine Aggregates (RFA), and Industrial by-products are examples of alternative fine aggregates. These alternative fines can be employed as a full or partial substitute for river sand, resulting in two benefits: conservation of natural resources and mitigating environmental issues (Singh et al. 2018; Su et al. (2001).

12.2 Alternative Fine Aggregates

Crushed rock sand (CRS) is a feasible substitute to river sand and it also reduce waste disposal problem (Nanthagopalan and Santhanam 2011). Crushed rock sand is manufactured by crushing the quarried stone to a particle size less than 4.75 mm. Sridharan et al. (2006) observed that 20–25% of the entire production is left out as waste-quarry dust in each crusher unit in India. This waste problem may be overcome as it can be effectively used in concrete fabrication. The distinct roots from which CRS is manufactured are granite, limestone, sandstone, diorite, metamorphic siltstone, etc. Crushed rock sand is obtained by the sieving of crushed rock aggregates having different mineralogical configuration (Bonavetti and Irassar 1994). CRS is refined by crushing, screening, and shaping along with washing into ultimate products. The properties rely on parent rock fracture mode, composition, manufacturing process, location and nearby climatic condition. It also depends upon type of the crushing process like vertical shaft impact, impact crusher, etc. (Srivastava and Singh 2020).

Recycled fine aggregates, obtained from recycling of mineral scrap material, are produced mainly from C&D waste (Kou and Poon 2009a, b, c). Massive volume of construction and demolition (C&D) waste is generated every season and its disposition has turned into a serious environmental and social complication (Ji et al. 2013; Zhao et al. 2015). Reclaiming of this waste construction material is tempting as

Table 12.1 Physical properties of CRS

Author	Specific gravity	Fineness modulus	Water absorption (%)
Jadhav and Kulkarni (2013)	2.84	2.84	5.6
Nanthagopalan and Santhanam (2011)	2.65	–	1.0
Bouziani (2013)	2.7	2.14	5.71
Ding et al. (2016)	2.72	3.34	0.7
Bounedjema et al. (2017)	2.62	2.97	–
Wang et al. (2020)	2.61	3.33	–

Table 12.2 Physical properties of RFA

Author	Bulk density (kg/m^3)	Water absorption (%)	Fineness modulus	Specific gravity
Kirthika et al. (2020)	2690	10.61	2.83	2.51
Behera et al. (2019)	1260	11.5	2.56	2.1
Exteberria et al. (2013)	2010	13.1	–	–
Kou and Poon (2009a, b, c)	2300	11.86	–	–
Pan et al. (2017)	2640	4.35	2.8	–
Seung-Tae Lee (2009)	–	6.59	2.89	2.39
Stefanidou et al. (2014)	2450	8.0	4.97	–

compared to the use of exhaustible assets. The leading sources of RFA are bricks, concrete, bitumen, glass, etc. Recycled concrete fine aggregates are of poor calibre because of which they require some treatment to enhance their quality and escalate employment of the same (Kumar et al. 2019). As per the articles of researchers, RFA requires higher percentage of SP than river sand because of dust and old adhered mortar present in it (Singh et al. 2018).

Physical properties of several alternative fine aggregates play a key role in defining their behaviour and should be studied. Tables 12.1 and 12.2 show the physical parameters of crushed rock sand (CRS) and recycled fine aggregates (RFA).

12.3 Properties in Fresh State

12.3.1 Filling Ability

Filling ability which determines self-compacting ability of a concrete, depends mostly on particle shape and micro-roughness, but proportion of fines and clay lumps also makes significant effect. Crushed rock sand would possibly increase the water demand (Mahalakshmi and Khed 2020; Shen et al. 2018). A graphical representation showing the slump flow variation by different researchers is given in Fig. 12.1.

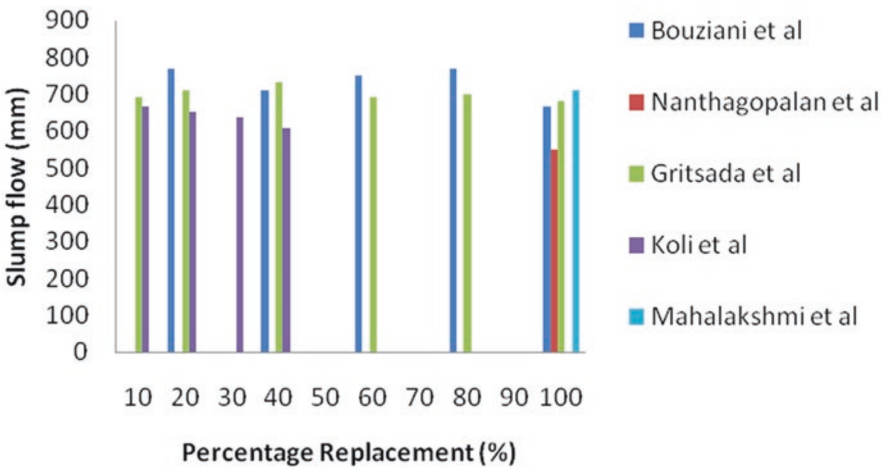

Fig. 12.1 Slump Flow variation of CRS

Tayeb Bouziani (2013) observed higher value of slump flow up to 80% CRS substitution possibly because of improved workability due to proper blending of particles with river sand. However, at complete replacement of natural sand, 11% reduction was reported which could be ascribed to the irregular shape of CRS particles and the excessive fines present in it. There was 13% increase in the slump flow at 60% substitution of crushed limestone sand while at 100% replacement of river sand, only 2.9% reduction was reported. The improvement in the slump value is attributable to the smooth texture and spherical shape of limestone particles (Sua-iam and Makul 2013). Utilisation of crushed rock sand up to 65% resulted in much higher slump flow of 845 mm which was counteracted by addition of certain percentage of limestone fines. This gives an idea that the incorporation of limestone fines has a positive effect on SCC which is mainly due to the increase in water demand of limestone fines (Benyamina et al. 2019). Similarly, Koli and Gundakalle (2016) developed SCC with different percentages of crushed rock sand and found that slump flow value declined as the replacement percentage of CRS is raised. This is so because of rough and angular shape of CRS and also due to the presence of more fines in the concrete that reduces flowability. Nanthagopalan and Santhanam (2011) reported that excess paste volume is required to achieve higher slump flow. Complete replacement of RS by CRS was beneficial for SCC as it contains higher proportion of fines, but it may result in increased water demand. Similar experimental investigations were reported where complete replacement of river sand by M-sand resulted in the slump flow of 708 mm (Mahalakshmi and Khed 2020). Also, incorporation of crushed rock sand by 25% along-with 30% fly ash as SCM lead to an increase in the slump flow by 20 mm (Güneyisi et al. 2012).

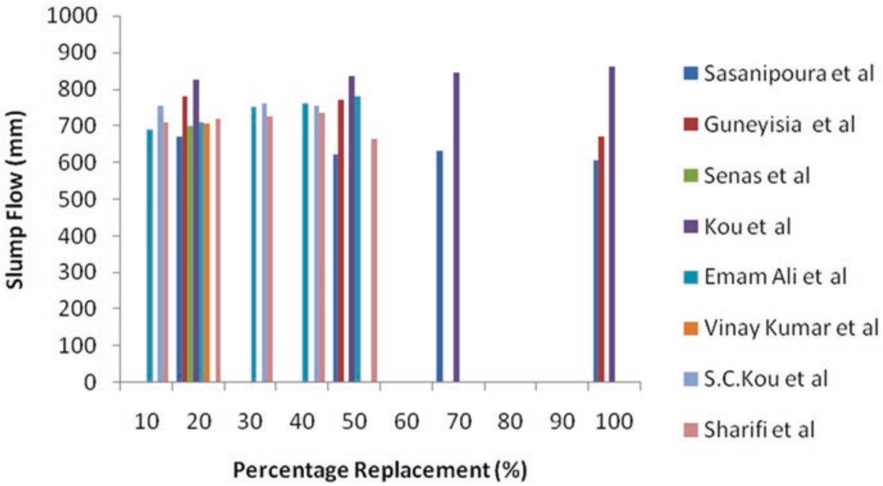

Fig. 12.2 Slump flow variation for RFA

Different types of recycled fines have different impact on the filling ability of SCC as shown in Fig. 12.2. It was observed that addition of recycled glass enhanced the filling ability while recycled concrete aggregates showed opposite effect. SCC made with recycled glass showed high flowability even at low dosage of super plasticizer. The continuous increase in the slump flow is due to finer particles of glass which contribute in filling most of the voids and also due to low water absorption of recycled glass particles (Emam and Al-tersawy 2012; Mahalakshmi and Khed 2020). Smooth surface of recycled glass aggregate was the factor found to be responsible for positive results (Güneyisi et al. 2016). Kou and Poon (2009a, b, c) developed SCC with 0%, 25%, 50%, 75% and 100% recycled aggregates and found the slump value increasing continuously up to 100% replacement. The higher water requirement of recycled aggregates increased the flow as some portion of water is available for increasing the flowability. Similar results were reported by Guneyisi et al. (2016) while varying proportions of RFA were utilised and the slump value increased continuously. With the increase in % of RFA, the slump flow remained more or less the same with reference to the control mix (Señas et al. 2016; Kou and Poon 2009a, b, c).

The slump flow of concrete decreased with the addition of recycled fine aggregate on account of uneven surface texture because of the old mortar adhered to the surface. There was 10% reduction in passing ability when natural sand was replaced from 25% to 100% (Sasanipour and Aslani 2020). The addition of recycled fine aggregates up to 20% in SCC showed slump value similar to reference SCC beyond which further increase in replacement of fine aggregates caused significant drop in slump value. It was noticed that SCC with 100% replacement failed to maintain the flowability characteristic after 45 min (Gesoglu et al. 2015). Slump flow time was also observed to reduce on account of addition of recycled fine aggregates

(Carro-lópez et al. 2015). Lopez et al. 2017 developed SCC with 0%, 20%, 50% and 100% recycled sand and found that the complete replacement of natural sand leads to segregation. Further, he reported that sample with 100% replacement by RFA loses it flowability after 90 min. Kumar et al. (2017) designed concrete with 20% recycled fine aggregates and reported that the inclusion of RFA decreases the filling ability slightly when compared to reference concrete.

12.3.2 Passing Ability

The major factors governing the passing ability of SCC are particle shape, powder content and water absorption of aggregate. The fine content in CRS leads to an increase in paste volume due to which the aggregates scatter systematically and thus concrete passes through the bars without clogging of the aggregates (Nanthagopalan and Santhanam 2011). Mahalakshmi and Khed 2020 reported an enhancement in the passing ability with the L-box ratio being 0.86. Similarly, Benyamina et al. (2019) found that the replacement of natural sand by crushed sand till 65% showed high L-Box values. The clayey particles present in fine aggregate increases the water demand and thus reduces the passing ability as indicated by the lower L Box value (Bouziani 2013; Sua-iam and Makul 2013; Shen et al. 2016; Shen et al. 2018). The incorporation of crushed sand up to 30% in the concrete mixture yielded satisfactory results beyond which passing ability decreases (Koli and Gundakalle 2016). Bouziani (2013) reported that the L Box ratio declined after 80% substitution of crushed rock sand due to the excess clay particles present in it. The angular shape and rough texture of crushed rock sand was found to be responsible for increasing the frictional resistance in paste volume and thus restrict the passing ability of concrete.

Incorporating recycled fine aggregates up to 100% in concrete keeps on enhancing the passing ability of SCC (Kumar et al. 2017; Koli and Gundakalle 2016). Kou and Poon (2009a, b, c) used recycled glass in SCC and found that the blocking ratios varied from 0.84 to 0.87 which means that the samples achieved adequate passing ability. Similar results were also reported by Sharifi et al. (2013) where the L-Box ratio was reported to decrease with the increase in proportion of recycled glass. The ratio went from 0.94 to 0.82 showing a decrease in passing ability despite satisfying EFNARC guidelines. The reason for low value is due to sharp particles of glass which makes it problematic to pass through the reinforcement bars (Mahalakshmi and Khed 2020). The L-Box ratio (H2/H1) decreased with the rise in the % amount of recycled fine aggregates. At 0% addition of RFA, the H2/H1 ratio was around 0.91 and at 20%, 50% and 100%, the ratio dropped down to 0.85, 0.90 and 0.78 respectively. Blockage at neck was observed when recycled fine aggregate percentage exceeded 50% (Kou and Poon 2009a, b, c).

12.4 Properties in Hardened State

12.4.1 Compressive Strength

Compressive strength is markedly affiliated to surface morphology of crushed rock sand particles (Shen et al. 2018). Powerful paste-fine aggregate interface and the inherent strength of CRS particles result in increased compressive strength (Donza et al. 2002). It was reported that an increase of around 12% occurred when the natural river sand was entirely replaced by crushed rock sand with the possible reason being the presence of greater quantity of fines and angular shape of CRS particles (Bouziani 2013). At complete replacement of RS by CRS, when SCC was designed for M-20 grade, the strength was found to be 23.56 MPa. Similarly, for M-40 grade and M-30 grade, compressive strength was reported as 46.25 MPa and 37.25 MPa respectively (Hameed et al. 2012). A rise in the value of compressive strength was seen with the addition of 65% crushed rock sand. The developed SCC had a compressive strength of 72 MPa at 28 days. However, addition of limestone fines as filler may lead to an increase in the early day's strength (Benyamina et al. 2019).

Compressive strength of SCC is affected by water cement ratio. At 100 percent substitution by CRS, the results determine that at lower water cement ratio, the strength was reported to be higher. At 0.7 w/c (without VMA), the compressive strength reported was 60 MPa and at 1.2 w/c (with VMA), the compressive strength was 25 MPa (Nanthagopalan and Santhanam 2011).

With 25% replacement of crushed rock sand, strength of around 58 MPa was reported. However, with the addition of 5% limestone filler and 30% fly ash in place of cement, the compressive strength was reported to increase up to 64 MPa (Güneyisi et al. 2012).

Compressive strength enhanced with 10% addition of limestone fine as natural sand replacement. The strength at 100% natural sand came out to be 65 MPa while at 10% LS, it came out to be 67.5 MPa showing an increase of 3.85%. However, the strength was observed to be decreasing with further addition of LS. The increase in strength is due to fine particles of limestone which act as fillers and helps in enhancing the microstructure while as further increase of limestone particles do not contribute to the filler effect and hence strength value decreases (Sua-iam and Makul 2013).

A continuous improvement in strength was reported with the addition of CRS up to 40%. Strength gain of around 6.51% was recorded at 30% CRS substitution after which a slight decrease in strength occurred at 40% CRS. The strength gain may be due to better interlocking of CRS particles within concrete matrix (Koli and Gundakalle 2016). SCC designed for 40 MPa gave a compressive strength of 44.50 MPa when river sand is completely replaced by M-sand. Figure 12.3 shows a graph which compares strength ratio for different CRS.

The elements that influence the strength of self-consolidating concrete are the type of aggregate employed, water cement ratio and dosage of silica fume (Gesoglu et al. 2015). The replacement of the natural fine aggregates with recycled fine

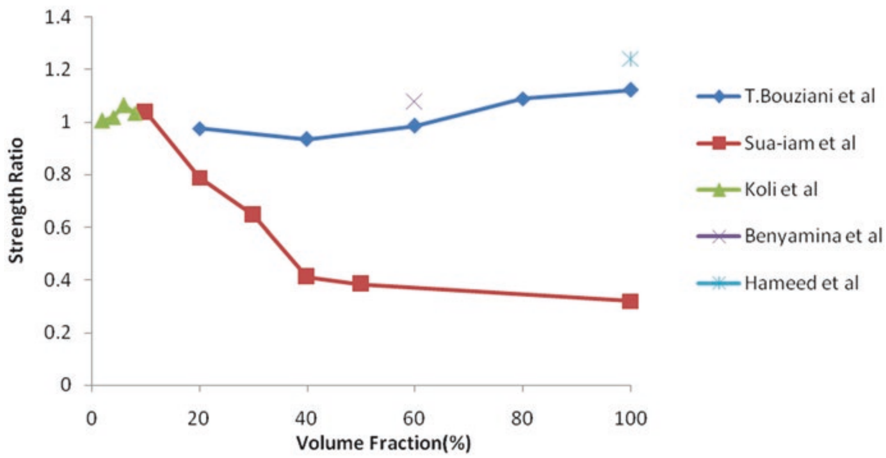

Fig. 12.3 Graphical representation of variation in compressive strength of CRS

aggregates shows a decline in compressive strength (Gesoglu et al. 2015; Sasanipour and Aslani 2020). It was observed by Sasanipour and Aslani (2020) that as the percentage of recycled fine aggregate increases, the strength drops significantly. Around 52% reduction in strength occurred due to substitution of 75% of recycled fine aggregates. The possible reason for inferior results is the old mortar adhered to the surface which reduces quality of ITZ. When the self-compacting concrete is formed with full substitution of fine aggregate by recycled aggregates, the strength was found to decrease by 15.8–26.9%. The lower strength demonstrated by recycled aggregates is because of low quality of ITZ between the recycled aggregates and cement matrix. Further, it was observed that low water binder ratio and silica fume compensates the drop in strength upto certain percentage (Gesoglu et al. 2015). The compressive strength decreased by 5% on account of additional use of 20% recycled fine aggregates (Señas et al. 2016). Kou and Poon (2009a, b, c) formed SCC with different portion of recycled fine aggregate and found that upto 50% addition of RFA, the strength does not seem to be affected. For 75 and 100% replacement ratio, strength was observed to decrease by 10%. Addition of fly ash proves to be beneficial as the reduction in strength is further decreased because of the pozzolanic reactivity. Compressive strength was found to be 5% higher for SCC with 20% recycled fine aggregate when compared with control mixture (Kumar et al. 2017). With the addition of recycled glass of varying percentage, the compressive strength was found to decrease by 6%, 10.4%, 12.7%, 17.5% and 23.5% at 10%, 20%, 30%, 40% and 50% substitution respectively (Emam and Al-tersawy 2012). Kou and Poon (2009a, b, c) added glass waste in SCC in the proportion 15%, 30% and 45%

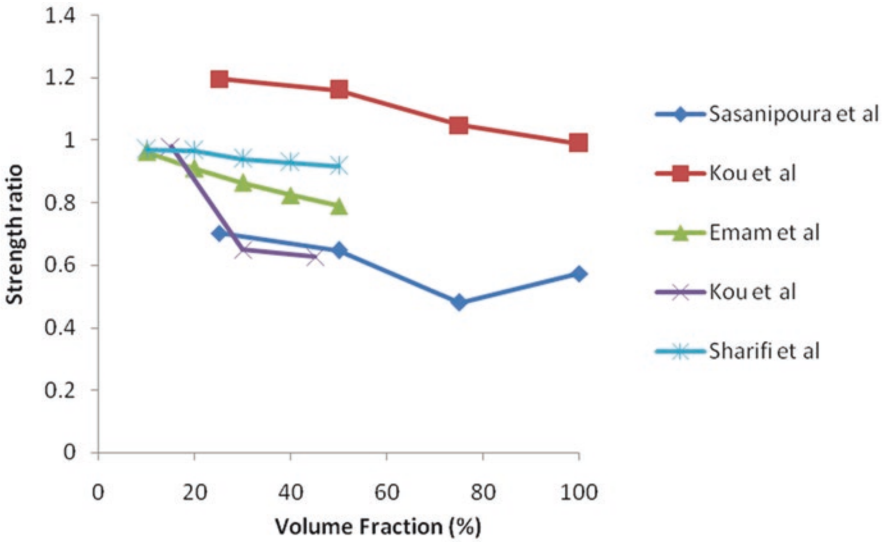

Fig. 12.4 Variation of Compressive strength with increasing percentage of RFA

and observed reduction of 1.5%, 4.2% and 8.5% respectively. The possible mechanism could be weak bonding between recycled glass waste and cement matrix (Emam and Al-tersawy 2012; Kou and Poon 2009a, b, c). On increasing the percentage of recycled waste glass, compressive strength declined due to weak adhesion (Mahalakshmi and Khed 2020). The variation of compressive strength with varying percentage of RFA is shown in Fig. 12.4.

12.4.2 Splitting Tensile Strength

Slight decrease in tensile strength was observed at 100% replacement of river sand. For M20 grade, the splitting tensile strength was found to be 2.85 MPa and for M30 and M40 grade, it was 3.15 MPa and 3.85 MPa respectively. Thesubstitution of river sand with 85% crushed rock sand and 15% MSP yielded better results (Hameed et al. 2012). 90 days splitting tensile strength of the SCC developed by 25% incorporation of crushed rock sand was reported to be approximately 4.0 MPa. Further, with the incorporation of 30% fly ash and 5% limestone filler, the strength increased by around 17.5%, i.e., 4.7 MPa (Güneyisi et al. 2012).

It was observed that the replacement of natural aggregates with recycled fines reduces the splitting tensile strength, but with lesser magnitude than compressive strength (Sasanipour and Aslani 2020). Concrete mixture with 100% recycled fine aggregates showed minimum strength when compared to other replacement ratios. The strength was found to decrease by 19.5% in comparison to normal concrete (Gesoglu et al. 2015). The tensile strength was found to decrease by 11% when recycled fine aggregates are added in SCC (Kou and Poon 2009a, b, c). Further, the samples with fly ash showed much higher strength than control mixture. Kumar et al. (2017) designed SCC with 20% FRA and reported 18% increase in tensile strength when compared to natural aggregate SCC. A decrease in the pattern of strength was noticed with the inclusion of recycled fine glass in SCC. The values decreased by 10.6%, 10.6%, 12.7%, 17% and 23.4% at 10%, 20%, 30%, 40% and 50% RFA substitution respectively. The splitting tensile strength was found to decrease by 11.5% due to the replacement of naturally available fine aggregates with glass waste. The reason could be increase of fineness modulus of fine aggregates that decreases the density and poor bonding among recycled glass fine and cement matrix (Emam and Al-tersawy 2012; Kou and Poon 2009a, b, c). With increasing percentage of recycled waste glass, the strength increased initially up to 20% replacement and then decreased. The possible decrease is due to reduction in density of SCC (Mahalakshmi and Khed 2020). The variation of splitting tensile strength with varying percentage of RFA is shown in Fig. 12.5.

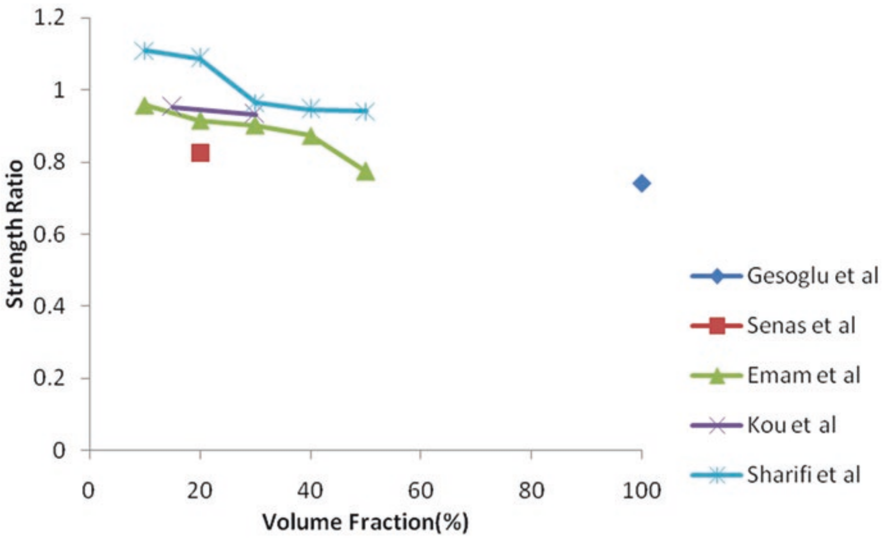

Fig. 12.5 Variation in splitting tensile strength with increasing percentage of RFA

12.4.3 Flexural Strength

With the substitution of crushed rock sand to 65%, 28 days flexural strength was found to be around 2.4 MPa. The addition of limestone filler decreased the flexural strength, but their incorporation led to an increase in the initial day's strength (Benyamina et al. 2019). Up to 30% substitution of CRS in SCC, the flexural strength was found to enhance by 8.60% after which a marginal decrease was noticed. The reason for increase in flexural strength may be because of the collaborative effect of improved interlocking and gradation of CRS particles (Koli and Gundakalle 2016).

Reduction in flexural strength was recorded by the inclusion of recycled aggregates. It was observed that strength decreases up to 20.3 to 27% with complete substitution of natural fine aggregates in SCC. The possible explanation for poor performance is the use of low quality of aggregates. It was further concluded that strength can be enhanced provided that recycled aggregates are taken from high strength concrete compared to reference mixture (Gesoglu et al. 2015). Addition of silica fume in self-compacting concrete improves the flexural strength of concrete (Emam and Al-tersawy 2012). Addition of recycled glass waste up to 10% resulted in marginal increase of flexural strength due to the fact that small volume of glass makes a better adhesion with glass and cement paste after which decrease in strength was reported. The decrease is because of high smoothness of glass which lowers the bond strength (Mahalakshmi and Khed 2020).

12.5 Discussion

Different alternative fines can be utilised as an alternative for river sand in sustainable and environmentally friendly construction. Waste materials from construction and demolition projects can be recovered and used as fine aggregate. This study assesses prior findings on the replacement of natural river sand with AFA, demonstrating that using these helps to maintain environmental balance while also increasing the qualities of SCC up to a certain substitution ratio.

12.5.1 Current Challenges

Although there are a variety of alternative fines that can be used effectively in SCC, there are a number of obstacles that prevent its widespread use. Studies reflect that at same replacement ratio, variation in engineering properties occur due to lack of command on composition and quality of alternative fines. Improper gradation and presence of impurities (particularly in CRS) leads to negative impacts at higher replacement levels of alternative fines. Removal of old adhered mortar from recycled fine aggregates is still a challenge as it needs to be cost effective. Because of a lack of government support and public awareness, there has been insufficient research in this sector.

12.5.2 Research Gaps

Following research gaps have been identified for further research based on the literature review:

- A thorough investigation into the use of alternate fines in SCC.
- Establishment of a common proportioning procedure for various fines.
- Cost-effective treatment process for recycled fine aggregates to lower the percentage of water absorption and remove old-adhered mortar.
- A study related to processes that control gradation and shape of CRS particles.
- Additional research into the durability qualities of alternate fines and their impact on SCC is required.

12.6 Conclusion

While there has been a lot of research into the use of AFA in conventional concrete, there are just a few examples of it being used in SCC. The following conclusions are reached as a result of the review work:

1. The physical characteristics of crushed rock sand are similar with natural river sand. Basalt and dolomite have high specific gravity which gives demonstrates the presence of coarser particles. Further, dolomite and limestone crushed sand contain excessive fines and result in higher water demand.
2. Specific gravity of recycled fine aggregate is less than that of normal fine aggregate on account of the presence of old-adhered mortar. RFA is porous and thus has high water absorbing potential. However, pre-treatment of RFA can decrease water absorption due to micro-packing effect.
3. CRS substitution in SCC shows an improvement in compressive strength due to angular shape and the presence of greater amount of fines. However, 100% inclusion of crushed rocks sand may not give overall better results.
4. RFA at lower percentage substitution is well-suited in SCC. Recycled glass waste, on the other hand, can be substituted up to 30% as it improves the fresh properties.
5. If the problem pertaining to excessive fines in CRS is dealt with properly, the overall performance may be boosted. Pre-treatment/processing of alternative fines also end up giving better results.

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