



# Sustainable mortar mix using recycled fines obtained from construction and demolition waste

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Rivers are over exploited for natural sand extraction and production of cement has triggered global warming. For sustainable development a study has been conducted to use construction and demolition waste (CD-W) in cement-sand mortar. In the present study, crushed CD-W in the form of recycled concrete fine aggregate (RCFA) and recycled concrete powder (RCP) has been planned to be used in cement-sand mortar as replacement of natural standard sand (NSS) and cement, respectively. The effects of partial replacement of NSS and cement with RCFA and RCP on compressive strength and split tensile strength after 7<sup>th</sup> and 28<sup>th</sup> day of curing have been evaluated. Outcomes of elevating replacements of cement and sand in mortar have been found to be decreasing gradually, but falls above the minimum limit of 7.5 N/mm<sup>2</sup> as established by IS: 2250 (1981) for use of mortar in structural applications. Therefore, the study concludes the valid potential of RCFA to be utilized up to 100% percent and RCP up to 20% as partial replacement of natural sand and cement, respectively in mortar production.

**Keywords:** Cement-sand mortar, Construction and demolition waste (CD-W), Recycled concrete powder (RCP), Recycled concrete fine aggregate (RCFA).

## 1 Introduction

Contribution of construction industry in gross domestic product (GDP) and employment of most economies is very prominent. But carbon emission, waste generation and pollution (noise, air, and water quality) are few negative impacts of construction activities that cannot be overlooked<sup>1</sup>. In the modern times, using natural resources sustainably in the construction works without compromising the performance is the key requirement. Environmental degradation caused by construction waste in last few decades, encouraged the inevitability to come up with substitute waste management models and effective environmental friendly solutions for sustainable construction. Involving construction & demolition waste (CD-W) in the production of major building components (concrete and mortar) can be proved as a significant combination that will improve waste handling capacities of landfill sites and fulfill requirements of construction industries simultaneously. Approximately 35% of the total global waste accounts for CD-W<sup>2</sup>. Central pollution control board (CPCB) of India predicted that 25% of 62 MT of municipal solid waste generated per year

accounts for CD-W and total measure of waste from construction industry is 12-14.7MT/annum<sup>3</sup>. Vilas *et al.*<sup>4</sup> in 2007, stated production of CD-W to be 14.7 MT/annum. Sandeep *et al.*<sup>5</sup> estimated that India may reach production of 24 MT of CD-W per annum. Development alternatives<sup>6</sup> extrapolated the data for CD-W generation based on expected urban population growth of 2041 to be 2.7 BT/annum.

India is a country with numerous rivers flowing from almost all the states. Therefore, availability of natural sand seems to be eternal, but excavation of riverbed for sand extraction creates erosion and environmental tribulations. Globally, sand is the second most excavated natural material<sup>7</sup>. Also not all type of sand is suitable in construction. Unlike sand from river, desert sand is very fine and too smooth to provide required mechanical properties to concrete.

On the other hand, Portland cement production is an energy-intensive industry and is generating 5% of global anthropogenic CO<sub>2</sub> worldwide<sup>8</sup>. Annual global cement production had reached 2.8 billion tons in 2011 and is expected to raise 0.8 – 1.2% per year and project somewhere between 3700 and 4400 megatons by 2050<sup>9</sup>.

The properties of RCFA highly depend on the origin, composition, corresponding quality and the

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process of crushing of demolished concrete. CD-W has soaring possibilities to be re-used in mortars and form a novel alternative to original compositional components. Recycled concrete fine aggregate (RCFA) may have some un-hydrated cement preserved in it, but neglecting the binding properties of un-hydrated cement and considering its filler assets, it is proposed in the current study to be used as partial replacement of natural sand and cement. RCFA consists of  $\text{SiO}_2$  and  $\text{CaO}$ , therefore possesses properties of sand and cement both<sup>10</sup>. It is assumed that the un-hydrated cement (if any) of RCFA will contribute in increasing strength by producing water-cement reactions or by filling the voids of mortar.

Mariana Braga *et al.*<sup>11</sup> conducted a study to observe the effects of recycled concrete fine aggregate on the cement content of mortar and reported good results in water absorption and retentivity. Also, mechanical performance of the prepared mortar mix of cement-sand ratio 1:5 with 15% recycled concrete fines was found 30% more in compressive strength and 6% more in adhesive strength, when compared with a reference mortar (cement-sand ratio 1:4 and no recycled concrete fines). Charles Feys *et al.*<sup>12</sup> used Recycled Concrete Fine Aggregate with size ranging between 0 – 0.32 mm in 1:3 cement sand mortar as replacement of sand and cement and observed that due to the filling effect of RCFA, water absorption in immersion reduced but both flexural and compressive strength increased. However, mechanical properties were decreased when cement was replaced. E. F. Ledesma *et al.*<sup>13</sup> assessed short term and long term properties of masonry mortar produced by replacing 0, 5, 10, 20 and 40% of natural sand with recycled concrete fine aggregate. Original grain size distribution of recycled sand was used. Their research studies have proved the worth of replacing natural sand up to 40% with recycled sand and therefore suggested an environmental friendly masonry mortar.

G.A. Ferro *et al.*<sup>14</sup> and Luciana Restuccia *et al.*<sup>9</sup> used recycled sand against standard sand in mortar making and kept the water cement ratio constant at 0.5. In their study, four sand packets with 0, 25, 50 and 75% replacement of standard sand with recycled sand were prepared to analyze their mechanical behavior. They observed that the workability, flexural and compressive strength of mortar decreased with increased recycled sand. As the replacement increased the induced high water demand made the mechanical properties worst and to maintain the same characteristic strength, the mortar mix was assisted

with super-plasticizer. Comparable results were obtained at 50% replacement with super-plasticizer addition. Properties of RCFA from CD-W and its application in mortar have been premeditated by Catarina Neno *et al.*<sup>16</sup>, Cheng-Chih Fan *et al.*<sup>17</sup> and E. Fernandez *et al.*<sup>18</sup>. The results of the above studies showed that a fraction of natural sand can be successfully replaced with RCFA. Also, the reduced performance or the variation in the performance is reported due to the extremely porous structure recycled fine aggregates.

Girts Bumanis *et al.*<sup>19, 20</sup> suggested use of various wastes, such as environment threatening concrete saw sludge and combusted coal products as micro-filler in production of self compaction concrete. Their research has provided significant solutions to sludge disposal challenges and hence to environmental deterioration. The importance of collision disintegration technique in reduction of materials used as micro-fillers in self compacting concrete and its advantages in resulting improved mechanical properties up to 20% is also achieved<sup>21</sup>.

Somayeh Lotfi *et al.*<sup>22</sup> designed a lab scale heating air classification system, which is capable of separating the cementitious powder from sandy part of crushed concrete fines. They found that the separation of contaminants is efficiently at 500°C and the amount of recovered  $\text{CaO}$  from recycling process is equivalent to a low worth limestone's  $\text{CaO}$  content.

Above literature clearly introduced the use of recycled fine particles from CD-W into mortar for replacement of cement and sand or both, but to a restricted extend. The crushed CD-W particles ranging from 4.75 mm to 90  $\mu\text{m}$  in size is named as recycled concrete fine aggregate (RCFA) and finer particles with grain size less than 90  $\mu\text{m}$  as recycled concrete powder (RCP). Although the effectiveness of combination of recycled concrete powder and recycled concrete fine aggregate in mortar is the main aim of the research. Therefore, present investigation intended to examine the mortar mixes that contains RCFA up to 100% replacement of sand and RCP up to 20% replacement of cement.

## 2 Material Used

All the mortar mix samples were prepared as per IS-4031: Part 6 (1998)<sup>23</sup>, using following building materials and tested under controlled laboratory conditions, i.e., temperature 28°C (recommended 27±2°C) and relative humidity 62% (recommended 67±5%).

### 2.1 Cement

Portland pozzolana cement (PPC) is used for the research. The properties of cement used are in accordance with the specifications given in IS codes and are tabulated in Table 1.

### 2.2 Natural Standard Sand (NSS)

Natural Standard Sand (NSS) conforming to IS-650 (1991)<sup>30</sup> is used in mortar mixes. It's naturally occurring siliceous sand having round particles and silica content up to 98%. The processed natural standard sand is supplied in pre-packed bags for their use in cement factories and research laboratories. Standard sand is available in three grades, namely grade I (particle size 2mm – 1 mm), grade II (particle size 1mm – 500  $\mu$ m) and grade III (particle size 500  $\mu$ m – 90  $\mu$ m). All the three grades of NSS are used in equal proportional to prepare a well graded mortar mix.

The superiority and uniformity in physical and chemical properties of NSS that also provides proper grain size distribution, has made use of NSS worth

above any other natural sand utilization. Distribution of particle size throughout the study has to remain constant as it can influence the fresh and hardened characteristics of mortar<sup>31</sup> and current objective of research is to determine effect of RCFA and RCP.

### 2.3 Recycled Concrete Fine Aggregate (RCFA)

Aggregates of demolished concrete from composite CD-W is crushed in the ball mill and is sieved through sequenced set of sieves into three granular fractions (2mm-1mm, 1mm-500 $\mu$ m and 500 $\mu$ m-90 $\mu$ m) and again merged together in specific quantities to satisfy the grain size distribution of NSS.

Pictorial representation of grains of different grades of natural standard sand (NSS) and recycled concrete fine aggregate (RCFA) are shown in Fig.1 (a-c) and Fig. 2 (a-c).

Table 2 shows the physical properties of natural standard sand and recycled concrete fine aggregate. It can be clearly observed that the water absorption

Table 1 — Properties of portland pozzolana cement.

Properties	Observed	Recommended
Fineness	370 m <sup>2</sup> /kg	Not less than 300 m <sup>2</sup> /kg [24]
Specific gravity	2.90	Between 2.90 to 3.15 [25]
Normal consistency	31.75%	Between 26 to 33 % [26]
Soundness	1 mm	Not more than 5 mm [27]
Initial setting time	80 minutes	Minimum 60 minutes [28]
Final setting time	135 minutes	Maximum 600 minutes [28]
7 <sup>th</sup> day compressive strength	26.22 N/mm <sup>2</sup>	Minimum 22 N/mm <sup>2</sup> [29]
28 <sup>th</sup> day compressive strength	42.73 N/mm <sup>2</sup>	Minimum 33 N/mm <sup>2</sup> [29]



Fig. 1 — Different grades of natural standard sand (a) NSS-I, (b) NSS-II and (c) NSS-III.



Fig. 2 — Different grades of recycled concrete fine aggregate (a) RCFA-I, (b) RCFA -II and (c) RCFA -III.

Table 2 — Physical properties of NSS and RCFA.

Properties	Natural Standard Sand	Recycled Concrete Fine Aggregate
Colour	Grayish or Whitish	Grayish
Specific Gravity	2.64	2.70
Water Absorption	0.80%	2.6%
Shape of grain	Sub angular	Angular

percentages of RCFA are very high and silica content is comparable.

**2.4 Recycled Concrete Powder (RCP)**

The fraction of crushed CD-W passing through the 90µm sieve and retaining on the pan is considered as RCP, which has got its specific gravity in range of cement as 2.80, therefore is used for replacement of cement in the mortar mix.

The X-ray diffraction of RCFA and RCP is shown in Fig. 3. It clearly indicates the presence of Quartz, which is a reflection of silica content into it and hence proves its suitability as a supplement material for natural standard sand and also the fines in RCP are even smaller than the cement, hence they can work as a good filler material in the mortar mix and due to its siliceous properties may impart strength to the mix.

The particle size distribution curve for NSS and RCFA is plotted in Fig. 4.

Particle sizes of RCFA are found to be comparable with NSS due to the ease of sieving particles falling in this range. On a contrary, the particles grading of RCP are different as the particles smaller than 90µm are difficult to segregate in dry state. CD-W was given 1000 rotations in ball mill with equivalent charge for getting the optimum crushed fine aggregate following the required particle size gradation. Figure 5 shows the gradation of crushed recycled concrete obtained at different set of rotations.

**2.5 Other Materials**

Laboratory tap water is utilized for mixing dry mortar compositions. Physical characterization of recycled concrete fine aggregate is evidence for its lower density and higher water absorption as compared to natural sand, which makes the use of water requirement reducing agent obvious. Volume of paste required to bind RCFA based mortar is more than that of mortar made with natural round shaped fine aggregate of same particle size distribution<sup>32</sup>.

Superplasticizing admixture (SP)<sup>33</sup> confirming to IS-9103 (1999), ASTM C494 based on modified naphthalene formaldehyde sulphonate is used for limiting the increased water requirements in the mortar

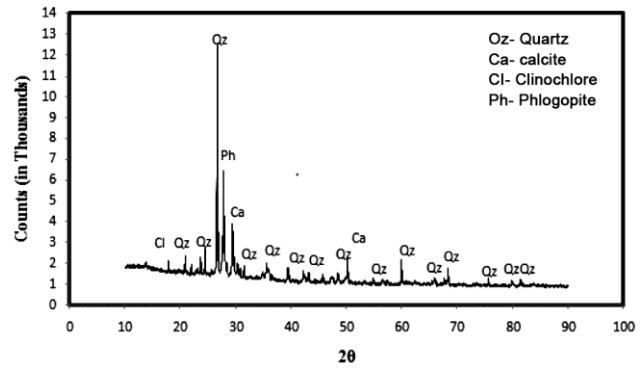


Fig. 3 — Results of X-Ray diffraction of RCFA (I, II and III) and RCP.

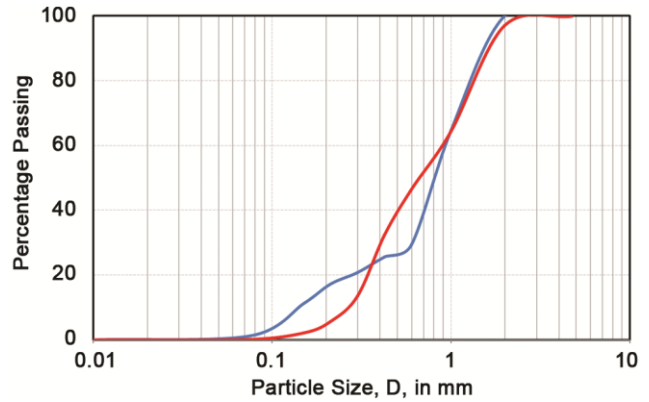


Fig. 4 — Particle size distribution curve of NSS and RCFA.

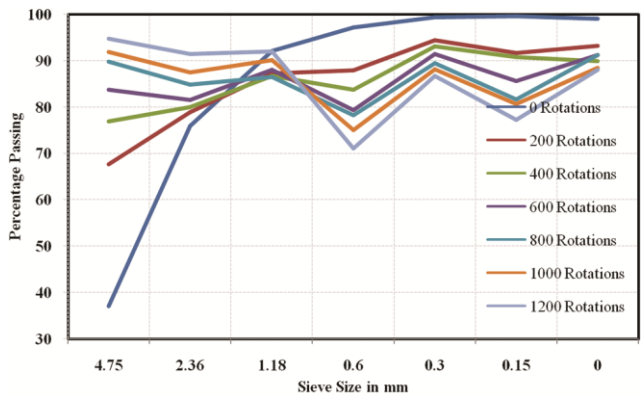


Fig. 5 — Gradation curve of crushed CD-W.

mixes. SP controlled the increased water requirements of mortar mix to attain desired workability and to facilitate easy casting. Also, it offers improved mechanical strength to hardened mortar.

**3 Methodology**

Mortar specimens were prepared as per the Indian standards by taking proportions by mass equals to one part of binder (cement), three parts of sand (NSS of each type into equal quantity) and water, calculated as



a function of normal consistency of the mix. Quantity of water (in ml) required for mixing 1:3 cement sand mortar for 1 cubical specimen of compressive strength testing and briquette specimens for split tensile strength testing is given by Eq. (1) and Eq. (2), respectively.

$$\left(\frac{P}{4} + 3\right) \times W \quad \dots (1)^{23}$$

$$\left[\frac{2}{3} \left(\frac{P}{(n+1)}\right) + K\right] \times W \quad \dots (2)^{34}$$

where,

*P* = Percentage of water required to produce normal consistency

*n* = No. of parts of sand to one part of cement by weight, which is 3 in this case

*K* = 6.5, constant for standard sand

*W* = Combined weight of cement and sand.

Dose of super-plasticizer (SP) is limited to 1.5% of binder, by Marsh cone test and the amount of SP added in each mortar mix varies to suit the flow diameter of mortar of 105mm at 25 drops of flow table in 15 seconds.

In particular, preparation of mortar mix satisfying one cubical mortar mould with internal dimensions, 70.6 mm x 70.6 mm x 70.6 mm as shown in Fig. 6, 200 gm of cement, 600 gm of NSS (200 gm of grade I, grade II and grade III each) and for preparation of six briquettes specimens in briquette mould as shown in Fig. 7 with dimensions, 300 gm of cement, 900 gm of NSS (300 gm each of grade I, grade II and grade III) are dry mixed and gauged with water as per calculations and SP as per requirement is used.

Series of mortar samples were prepared by replacing 0%, 5%, 10%, 15% and 20% of cement and named as

C<sub>0</sub>, C<sub>5</sub>, C<sub>10</sub>, C<sub>15</sub> and C<sub>20</sub> with RCP. Sand content of each series is then altered by replacing 0, 25, 50, 75 and 100% granular fraction of natural standard sand with corresponding fraction of RCFA and named as S<sub>0</sub>, S<sub>25</sub>, S<sub>50</sub>, S<sub>75</sub> and S<sub>100</sub>. The set of series is then primed to analyze the mechanical properties of the mortar supplemented with RCFA and RCP.

The study conducted in two phases, where physical characterization tests on cement replaced mixes were performed in former phase and compressive and split tensile strength of different sets of mortar having RCP and RCFA are compared with the traditional mortar cubes with no alteration in compositional materials. Table 3 shows the properties obtained at various cement alterations.

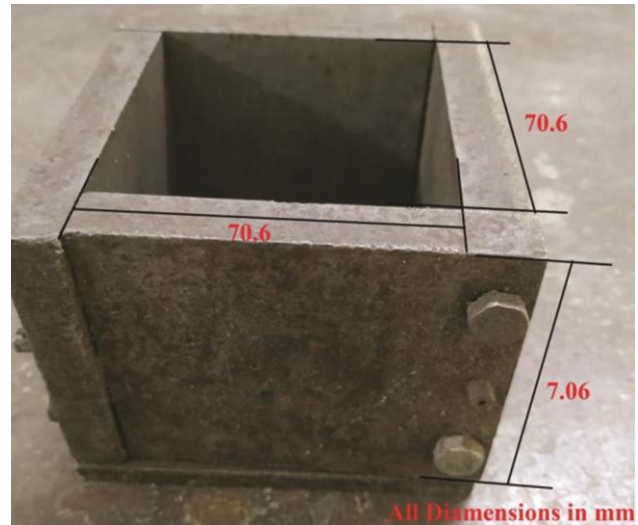


Fig. 6 — Cubical mould for specimens of compressive strength test.



Fig. 7 — Briquette mould for specimens of split tensile strength test.

Table 3 — Properties of cement replaced with RCP.

Properties	C <sub>0</sub> S <sub>0</sub>	C <sub>5</sub> S <sub>0</sub>	C <sub>10</sub> S <sub>0</sub>	C <sub>15</sub> S <sub>0</sub>	C <sub>20</sub> S <sub>0</sub>
Normal Consistency	31.75 %	32.25%	32.75%	33.25%	33.75%
Soundness	1 mm	0.5 mm	0 mm	0 mm	0 mm
Initial Setting Time (in minutes)	80	125	140	165	200
Final Setting Time (in minutes)	135	180	200	230	270

It can be observed with reference to the above given table that with the ascending percentage of cement replacement with RCP, the water requirement for normal consistency of binder mix increased; soundness, which is the indicator of presence of excess lime reduced and the setting times extended.

Table 4 represents the compositional details of mortars used for the various series of replacement of cement with RCP and sand with RCFA for compressive strength and split tensile strength determination.

#### 4 Results and Discussion

The mortar mixes with the composition as discussed in the Table 4 were prepared under controlled laboratory conditions and with special care of water requirements. The flow of all the fresh

mortar mixes is preserved constant to eliminate effects of mortar flow variations in mechanical strengths of mortar. Specimens made for the study were cured at normal room temperature by kept them immersed in potable water. The cubical specimens were tested for compressive strength under Universal Testing Machine (UTM) and split tensile strength with briquette testing machine on briquette specimens at 7<sup>th</sup> and 28<sup>th</sup> day of curing. The load (in Newton, N) at failure of compressive strength specimen is divided by area of cube subjected to loading, i.e., 4984.36 mm<sup>2</sup> for calculation of compressive strength. Whereas, for evaluation of split tensile strength, the failure load (in Newton, N) of split tensile strength specimens is divided by the area of neck of briquette subjected to extreme tension, which is 645 mm<sup>2</sup>.

Table 4 — Composition of mortar mixes.

Mortar Sample	Cement (%)	RCP (%)	NSS (%)	RCFA (%)	Water (ml)		SP (% of Binder)
					For Each Cubical Specimen [20]	For Each Briquette Sample [30]	
C <sub>0</sub> S <sub>0</sub>	0	0	100	0	87.5	21.875	-
C <sub>0</sub> S <sub>25</sub>			75	25			-
C <sub>0</sub> S <sub>50</sub>			50	50			-
C <sub>0</sub> S <sub>75</sub>			25	75			-
C <sub>0</sub> S <sub>100</sub>			0	100			-
C <sub>5</sub> S <sub>0</sub>	95	5	100	0	88.5	22.125	-
C <sub>5</sub> S <sub>25</sub>			75	25			-
C <sub>5</sub> S <sub>50</sub>			50	50			-
C <sub>5</sub> S <sub>75</sub>			25	75			-
C <sub>5</sub> S <sub>100</sub>			0	100			-
C <sub>10</sub> S <sub>0</sub>	90	10	100	0	89.5	22.375	-
C <sub>10</sub> S <sub>25</sub>			75	25			-
C <sub>10</sub> S <sub>50</sub>			50	50			-
C <sub>10</sub> S <sub>75</sub>			25	75			-
C <sub>10</sub> S <sub>100</sub>			0	100			-
C <sub>15</sub> S <sub>0</sub>	85	15	100	0	90.5	22.625	-
C <sub>15</sub> S <sub>25</sub>			75	25			0.5
C <sub>15</sub> S <sub>50</sub>			50	50			0.5
C <sub>15</sub> S <sub>75</sub>			25	75			1
C <sub>15</sub> S <sub>100</sub>			0	100			1.25
C <sub>20</sub> S <sub>0</sub>	80	20	100	0	91.5	22.875	-
C <sub>20</sub> S <sub>25</sub>			75	25			0.5
C <sub>20</sub> S <sub>50</sub>			50	50			0.5
C <sub>20</sub> S <sub>75</sub>			25	75			1
C <sub>20</sub> S <sub>100</sub>			0	100			1.5

Compressive strength of mortar is significant when the mortar is used in between the joints of brick or stone masonry as binder, because the types of loading is compressive in nature and the whole strength of masonry structure lies in the stability of its joints. Whereas, tensile strength of the cement mortar plays a vital role when the mortar is used for plastering the surface, because it ensures resistance to cracks caused under tensile stresses followed by thermal movements and drying shrinkage.

Figure 8 (a & b), and Fig. 9 (a & b) graphically demonstrates results of compressive strength and split tensile strength, respectively for mortar mixes with variable cement and NSS replacements with RCP and RCFA, respectively on 7<sup>th</sup> and 28<sup>th</sup> day of curing. C<sub>0</sub>S<sub>0</sub> serves as the reference mix for all the altered mortar mixes. Compressive strength of the reference sample, C<sub>0</sub>S<sub>0</sub>, is obtained to be 29.25 N/mm<sup>2</sup> and 42.73 N/mm<sup>2</sup> on 7<sup>th</sup> and 28<sup>th</sup> day of curing, respectively.

Compressive strength with ascending replacements with RCFA at 0% replacement of cement is found to be increasing and reached maximum of 30.92 N/mm<sup>2</sup> on 7<sup>th</sup> day and 44.51 N/mm<sup>2</sup> on 28<sup>th</sup> day, both at 50% RCFA. Angular particles provides more surface for

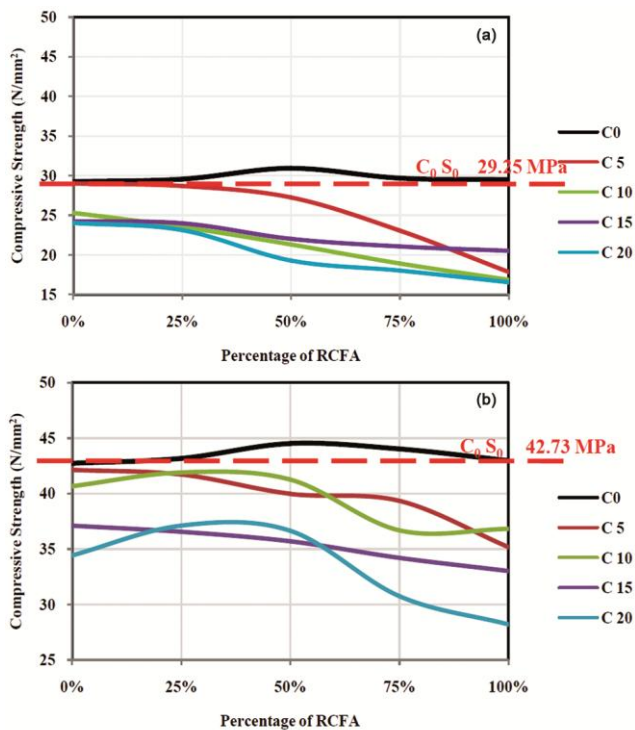


Fig. 8 — Compressive strength of various cement replacement series on different RCFA % (a) 7<sup>th</sup> day and (b) 28<sup>th</sup> day.

interlocking and rough surfaces offers better binding and improved mechanical characteristics<sup>35</sup>.

As the decreasing trend of compressive strength with increased cement replacement with RCP is evident from Fig. 8 at any age of test. RCP which was introduced in the mortar mix failed to serve as a micro-filler with binding properties. Steep degradation of compressive strength for all the mortar series with increasing percentage of RCFA in 7<sup>th</sup> day results exemplify that RCFA does not acquire early strength but can gain significant strength in 28 days of curing.

From Fig. 8 (b), it can be noticed that 28<sup>th</sup> day compressive strength of C<sub>5</sub> and C<sub>10</sub> series up to 50% replacement of sand is comparable to compressive strength of reference mortar mix (C<sub>0</sub>S<sub>0</sub>) with a slightly limiting variation of  $\pm 2$  N/mm<sup>2</sup>, which is within acceptable limits and can be considered equivalent to the reference mix.

Mortars with 28<sup>th</sup> day compressive strength higher than 10 N/mm<sup>2</sup> are usually suggested for structures demanding higher durability<sup>37</sup>.

According to Fig. 9 (b), split tensile strength of mortar mix with up to 50% RCFA at 20% RCP on 28<sup>th</sup> day is higher than that of reference mix. Thus, form most appropriate combination of tensile strength and material saving altogether.

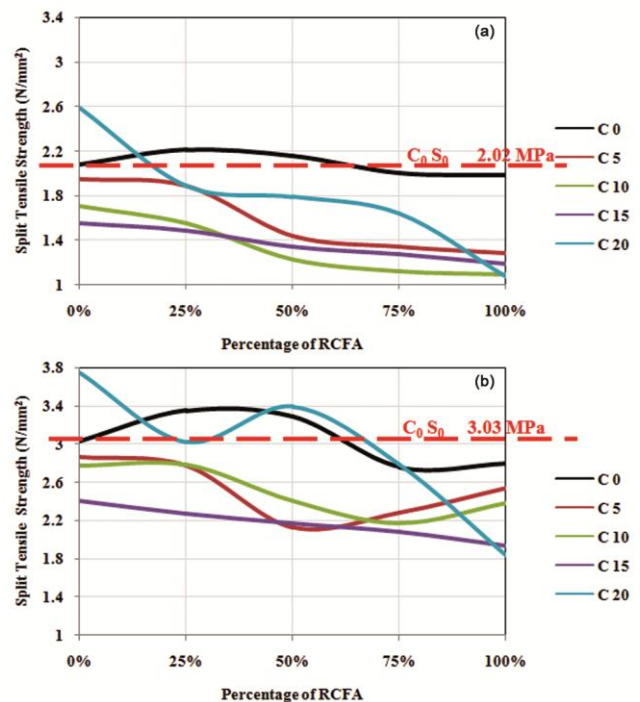


Fig. 9 — Split tensile strength of various cement replacement series on different RCFA % (a) 7<sup>th</sup> day and (b) 28<sup>th</sup> day.

The cement used is PPC, which is also low heat cement, thus can be classed as CEM.IV in ASTM specifications. Minimum tensile strength of CEM.IV on 28<sup>th</sup> day is given<sup>34</sup> as 300 psi or 2.06 N/mm<sup>2</sup>.

Therefore, minimum defined limits for compressive and split tensile strength of cement sand mortar for structural<sup>36</sup> use are 7.5 N/mm<sup>2</sup> and 2.06 N/mm<sup>2</sup>, respectively. Figures 10 and 11, graphically represents the compressive strengths and split tensile strengths of various mortar mixes as percentage increase/ decrease in minimum required strengths. As evident from Fig. 10, compressive strength of all the mortar mixes prepared are more than 250% of 7.5 N/mm<sup>2</sup>, being maximum of 389% at C<sub>20</sub> with S<sub>50</sub> composition. From Fig. 11, it is found that few mortar mixes can give negative results when

compared with minimum given standard. Maximum of 65% increase in split tensile strength at C<sub>20</sub>S<sub>50</sub> is obtained. Thus C<sub>20</sub>S<sub>50</sub> mix of mortar is best combination for compressive as well as split tensile strength and also safe increase in strengths above minimum requirement is achieved. 100% sand replacement can be made possible up to 10% RCP content. Whereas, at 15% and 20% RCP with 100% RCFA, compressive strength is considerably high but split tensile strength is found to be reduced even less than the minimum prescribed strength.

The pattern followed by the mechanical strengths of mounting cement replacements were varying greatly by declining constantly. Thus, test cubes limiting to 20% cement replacement with RCP in mortar were prepared. The flow of fresh mortar

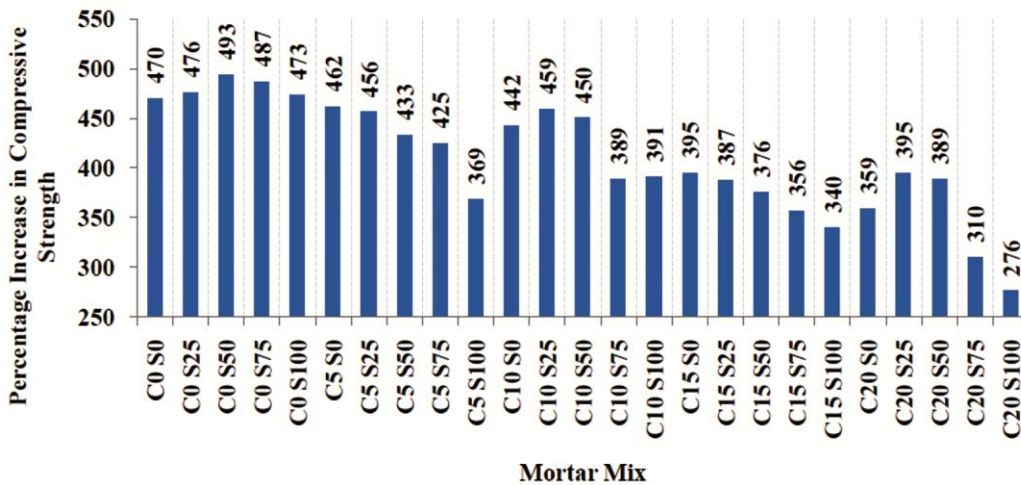


Fig. 10 — Percentage increase in compressive strength (28<sup>th</sup> day) of various mortar mixes as per IS-2250 (1981)<sup>36</sup>, greater than 7.5 N/mm<sup>2</sup>.

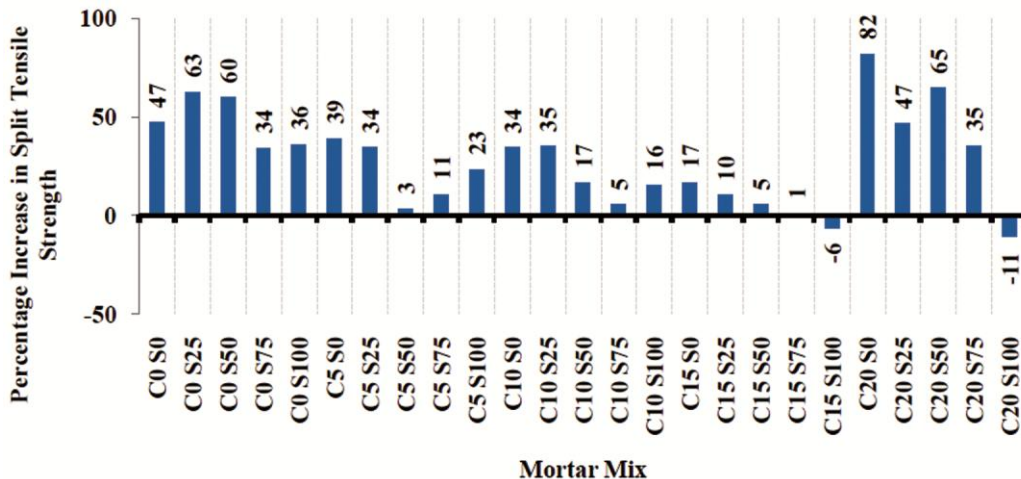


Fig. 11 — Percentage increase in split tensile strength (28<sup>th</sup> days) of various mortar mixes as given in C-150 58<sup>34</sup>, greater than 2.06N/mm<sup>2</sup>.



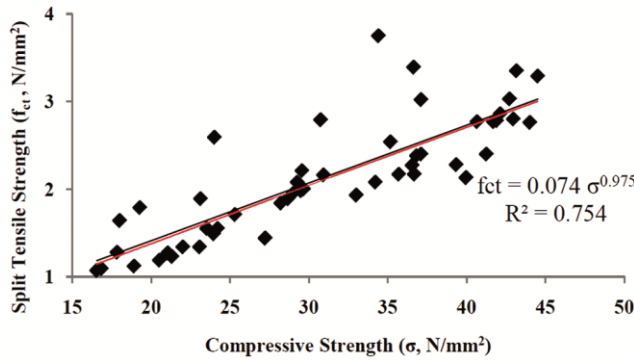


Fig.12 — Relationship between compressive strength and split tensile strength of mortar.

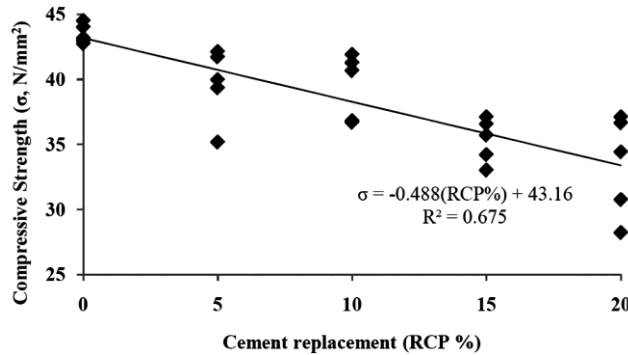


Fig.13 — Relationship between cement replacement and 28<sup>th</sup> day compressive strength.

decreases with incorporation of RCP and RCFA, replacement ratios plays vital role in controlling mechanical strengths of mortar<sup>17</sup>.

When split tensile strength of mortar is plotted against compressive strength, as in Fig. 12, a mathematical relationship between them is established and is shown in Eq. (3) and has degree of variance,  $R^2$  equals 0.754. Lower value of  $R^2$  is due to the continuous variation in composition of mortar with materials having diverse properties and combinations.

$$f_{ct} = 0.074 \sigma^{0.975} \quad \dots (3)$$

where,

$$f_{ct} = \text{split tensile strength in } N/mm^2$$

$$\sigma = \text{compressive strength in } N/mm^2$$

The relation between variations in compressive strength on different RCP percentages is shown in Fig. 13 and the equation that best satisfies the relation is given as Eq. (4).

$$\sigma = -0.488 (RCP\%) + 43.16 \quad \dots (4)$$

where,

$$\sigma = \text{compressive strength in } N/mm^2$$

*RCP % = percentage of RCP in mortar*

Compressive strength of mortar is a negative function of RCP %, therefore a declination in strength proofs the incompatibility of RCP in mortar that also effects the suitability of RCFA when used in combination of RCP. Use of similar product in concrete by Girts Bumanis *et al.*<sup>19</sup> has also showed the same trends.

### 5 Conclusions

In the current investigation, chemical composition of Recycled Concrete Fine Aggregate with XRD and exploration of mechanical behavior of mortar mixes with RCP and RCFA were analyzed and following conclusions were drawn:

- (i) Replacement of cement and sand with RCP and RCFA respectively caused a general reduction in compressive and split tensile strength of mortar mix. Basically, the hydrated cement content of RCFA and RCP influenced the mechanical properties adversely by raising water demand and due to its own low mechanical properties.
- (ii)  $C_{10}S_{50}$  gives comparable results with reference ( $C_0S_0$ ) mortar mix that means, maximum 10% cement and 50% sand can be replaced with the proposed alternative materials for acquiring similar compressive strength as that of reference mortar mix, hence it can be recommended to be used as binder in the joints of brick and stone masonry.
- (iii) 20% replacement of cement with Recycled Concrete Powder incorporated with 50% alteration in natural standard sand content for cement sand mortar gives superior outcomes in tensile loading. Thus this mortar mix can be used for plastering the surfaces, as it can withstand tensile stresses caused due to shrinkage and thermal movements on the outer surfaces of masonry structures.
- (iv)  $C_{20}S_{50}$  is the mortar mix with maximum replacement of cement and sand that has provided satisfactory results in compressive as well as tensile loading and thus can be recommended for structural applications.
- (v) As all the mixes are performing better than the minimum strength requirements demanded in IS-2250 (1981)<sup>36</sup> and minimum tensile strength requirements as per C-150 58 of ASTM specification<sup>34</sup> for structural application. Further

study on increasing percentage of replacements against cement with some strength supplementing micro-fillers can be conducted.

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