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ROLE OF RECYCLED CERAMICS TOWARDS SUSTAINABLE HIGH STRENGTH SELF-COMPACTING CONCRETE

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ABSTRACT

Applications of Self consolidating concrete (SCC) are on the rise day by day throughout the world in various fields like precast members production, construction of tall buildings, earth retaining structures, deep foundations, bridge decks, pavements, repair and retrofitting works etc. This might be due to its improved constructability in terms of faster placement of concrete, less involvement of skilled labour, penetration into congested reinforced areas and so on. Construction industries are facing challenges in acquiring raw materials throughout the year. To maintain continuous supply, sustainability of the resources and identification of alternative resources is highly desirable. The present paper addresses one such alternative of employing recycled ceramics as a partial replacement to cement as well as fine and coarse aggregates. Cement and aggregates in SCC mix of strength about 60 MPa, are partially replaced with Recycled ceramic powder and recycled ceramic aggregates up to 50% in increments of 12.5%. Desired fresh properties are obtained by varying the dosage of the superplasticizer. From the results, it was observed that recycled ceramic powder and fine aggregates can replace the cement and fine aggregates up to 40% by weight without loss in compressive and split tensile strengths. Recycled ceramic coarse aggregates can be used up to 20% by weight of normal coarse aggregates with the desired flow and hardened properties, but beyond this SCC mixes are found to be subjected to bleeding and segregation and considerable loss in mechanical properties.

Keywords: ceramic powder, ceramic fine aggregate, ceramic coarse aggregate, self-consolidating concrete.

INTRODUCTION

Interest of modern concrete construction industry rests in the construction of durable concrete structures and implementation faster construction processes with less skilled workers. In this context use of self-compacting concrete is on high demand as it readily satisfies both fresh and hardened state requirements of concrete. SCC is also gaining popularity all over the world from the viewpoint of quality concrete products after the finishing [H. Okamura and M. Ouchi 2003; Mohamed, O.A. *et al.* 2018]. Several mineral additives, industrial wastes and by-products are employed as supplementary materials to binder as well aggregates and produced quality SCC mixes as reported in the previous investigations. Efforts were made towards the production of sustainable and durable SCC by partially replacing cement. Cement in SCC was replaced by alternative binders and their combinations like slag, limestone powder, class -F fly ash, calcareous fly ash, and silica fume [García-Taengua E *et al.* 2016, Mohammed, K. M. *et al.* 2015, Anastasiou, E., *et al.* 2012, Ahmad, S. *et al.* 2019]. Using suitable superplasticizers and viscosity modifying admixtures up to 60% cement replacement by either fly ash or slag are found to be exhibiting similar fresh and hardened properties as that of conventional SCC mixes [Lachemi, M *et al.* 2003, Hannesson, G *et al.* 2012 and Kuder, K *et al.* 2012].

Rice huck substitution as partial replacement of cement in SCC in the range of 15 to 20% by weight resulted in enhanced flow and hardened concrete with refined microstructures [Safiuddin, M. *et al.* 2010; Makul, N., & Sua-iam, G. 2018]. Combined use of rice husk and bagasse ash also found to be effective in developing required slump and mechanical properties of SCC and can save cement up to 40% by weight [Lertwattanaruk, P., & Makul, N. 2021]. It was reported that use of pumice and natural zeolite could possibly replace the cement in SCC up to 10 to 15% by weight while satisfying the flow and strength properties. It was understood that although early strength are on lower side later strengths are quite comparable to conventional mixes (Ghasemi, M., *et al.* 2019). From the efforts of using volcanic ash as partial replacement of cement up to 50% by mass it was observed that there is an improvement in fresh hardened and durable properties of SCC. Results indicated that possible replacement of cement by volcanic ash up to 40% by mass leads to economical mixes while simultaneously address environmental pollution and assists in sustainability of the resources[Hossain, K. M. A., & Lachemi, M. 2010].

Along with partial replacement of cement, natural fine aggregates are also substituted with recycled and industrial by products. Fly ash along with aluminium waste is employed as partial replacement of cement and fine aggregate up to 20% and 75% by weight and the results indicated that better flow and compressive strength compared to conventional SCC at the same time reduced the cost of concrete per cubic meter (Sua-iam, G., & Makul, N 2015). A waste generated in the production of kaolin was employed in SCC as partial replacement to coarse aggregates for achieving economy and environmental benefits [Azeredo, G., & Diniz, M. 2013]. Steel slag aggregates were used as coarse aggregates replacement in producing SCC with comparable fresh and hardened properties (Qasrawi, H. (2018). Investigations proved that use of scattering- filling aggregates lead to higher compressive strengths of SCC (Shen, W *et al*. 2010). Recycled aggregates are used as an alternative to natural coarse aggregates and reported that the compressive strength enhanced up to 40% replacement and also increases the water absorption and chloride ion penetration (Tuyan, M. *et al*. 2014). When recycled powder and recycled coarse aggregate combined replaced cement and natural coarse aggregates, it results in enhanced fresh properties and slight reduction in compressive, split tensile strength and resistance to chloride penetration (Duan, Z, 2020).

In recent times ceramic waste powder whose particle size is less than 125 µm was used substitution to cement in SCC mixes and found that up to 15% replacement the flowability and strength properties are comparable to that conventional SCC (Subasi, S., 2017). Very fine particles of waste ceramic sizes of the order 5-10 µm was effectively employed as alternative replacement to cement up to 60% by weight, the produced SCC exhibited better flow properties and strength properties (Aly, S. T. 2019). The present investigation aims at utilization of recycled ceramics as partial replacement of binder as well as aggregates in high strength SCC mixes and there by contributing sustainability of resources while reducing cost of SCC per cubic meter of concrete.

EXPERIMENTAL RESEARCH

Trial tests were performed to arrive at a mix of targeted strength 50 MPa. Conventional approach of concrete mix design was adopted while satisfying the requirement of SCC as recommended by EFNARC. Adjustments in aggregate, binder and super plasticizer are made to get the desired slump and compressive strength values. Total binder content in all the mixes was kept at 500 kg/m^3. Mix without fly ash content was designated as F-0. Fly ash content was varied in percentages of 10, 20, 30 and 40and the corresponding mixes are designated as F-10, F-20, F-30 and F-40. Mix proportions of these mixes is provided in Table-1.

Table-1. Mix design details.

Mixture Ingredients	F-0	F-10	F-20	F-30	F-40	F-50
Cement (kg/m^3)	500	500	400	350	300	250
Fly ash (kg/m^3)	0	50	100	150	200	250
Sand (kg/m^3)	890	890	890	890	890	890
Coarse Aggregates (kg/m^3)	845	845	845	845	845	845
Water, liters	180	180	180	180	180	180
Super plasticizer	5	5.5	5.5	5.5	5.5	5.5
w/c	0.36	0.36	0.36	0.36	0.36	0.36

Mixes where in cement was replaced with ceramic powder in percentages of 12.5, 25, 37.5 and 50 are denoted by RCP-12.5, RCP-25, RCP-37.5 and RCP-50respectively. Similarly, when fine and coarse aggregates in SCC mix are replaced by ceramic fine and coarse aggregates the mixes are designated as RCF-12.5, RCF-25 etc. and RCC-12.5, RCC-25 etc.

Materials Characterization

Cement: Major binder used in this experimental work is Portland cement (PC) 53 grade which confirms to IS: 12269. Total surface area per unit mass and specific gravity are 333 m^2/kg and 3.15 respectively as provided by manufacturer. Chemical configuration of cement was presented in Table-2.

Fly ash: Supplementary binder namely fly ash was acquired from National Thermal Power plant, Ibrahimpatnam, India. Specific gravity and surface area of fly ash sample was found to be 2.16 and 380 m^2/kg. Chemical characterization of fly ash was detailed in Table-1.

Table-2. Chemical configuration of PC and FA.

Oxide	Cement	Fly ash
SiO_2	21.89	58.13
Al_2O_3	6.73	32.54
CaO	60.31	1.41
Fe_2O_3	3.8	4.04
MgO	3.45	0.71
Na_2O	0.27	0.17
K_2O	0.25	0.96
SO_3	0.53	0.12

Aggregates: Crushed granite was used as coarse aggregate having a specific gravity of 2.89 and maximum particle size of 20 mm. Locally available river sand confirming to Zone III was used as fine aggregate having a specific gravity of 2.64, with a fineness modulus of 2.93.

Superplasticizer: Naphthalene Formaldehyde based Chemical admixture Master Rheobuild 920SH, with a specific gravity of 1.2 was used to maintain the required

ARPN Journal of Engineering and Applied Sciences

workability. The recommended dosage as per manufacturer ranges from 0.45% to 1.8% of cementitious content and has the specific gravity of 1.20 at 27 °C temperature.

Recycled Ceramic aggregates and powder: Damaged ceramic products dumped at the manufacturing plant were collected as shown in Figure-1. Collected pieces were broken with help of hammer into small size aggregates of approximately 20 to 25 mm as shown in Figure-2. Later these ceramic aggregates are further reduced in in size by crushing the min Los angles machine after rotating the drum for required number of revolutions. The maximum size of recycled ceramic coarse aggregates used in this investigation is 20 mm.

Figure-1. Damaged ceramic products.

Figure-2. Manually crushed ceramic products.

These aggregates are passing through 20 mm and retained on 12.5 mm. Ceramic fine aggregates are taken after passing through 600 microns sieve size as 80% particle size of the natural aggregates lies in that range. Particle size of recycled ceramic powder used as partial replacement of cement was taken after sieving through 75-micron sieve. The chemical composition of the ceramic powder is provided in Table-3.

Table-3. Chemical composition of recycled ceramics.

Oxide (%)	Ceramic powder
SiO_2	60.38
Al_2O_3	18.25
Fe_2O_3	1.95
CaO	2.34
Na_2O	5.69
K_2O	8.25
ZrO_2	2.38
SO_2	0.76

RESULTS AND DISCUSSIONS

Fresh Properties of SCC Mixes with Fly Ash

From Figure-3 it is evident that slump values of SCC mix reduced when fly ash is used as a replacement of cement. The range of slump values of mix is about 670 to 686 mm belongs to the slump flow class SF2. Low Slump values due to the presence of fly ash particles and their increased specific surface area and hence more requirement of water to wet the surface of the particles. Similar findings were reported in previous studies in relation to slump values when cement was replaced by rice husk ash and ceramic powders. (Chopra and Siddique 2015, Pande and Makarande 2013, Aly, S. T. *et al*., 2018). Resistance to flow of the mix after the flow initiated is measured through T_{50}time flow test. T_{50} values of the SCC mixes are in the range 5-7 sec as shown in Figure-4. According EFNARC guidelines increasing T_{50} values represents mix with higher viscosity. Along with viscosity filling ability is assessed through V-funnel test. From Figure-5 it is evident that V-funnel time values of the mixes are in the range of 11-13 sec. The passing ability is assessed through L- box test and the values obtained are represented in Figure-6. The values obtained are less than the maximum limit specified by EFNARC.

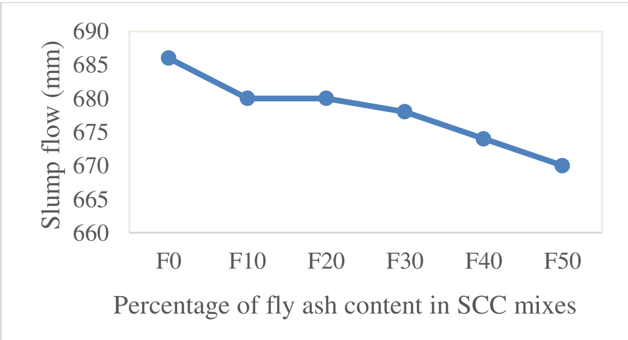

Figure-3. Slump flow with fly ash content.

VOL. 17, NO. 21, NOVEMBER 2022 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

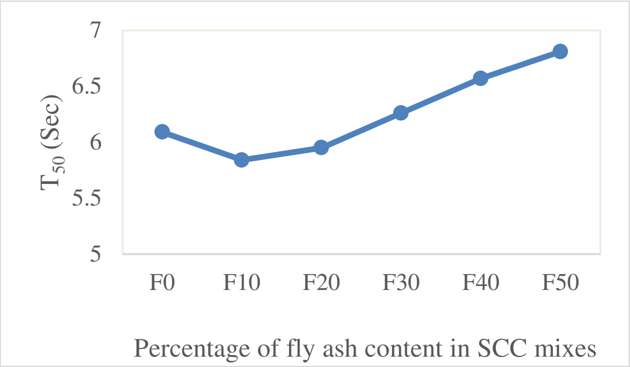

Figure-4. T50 values with flyash content.

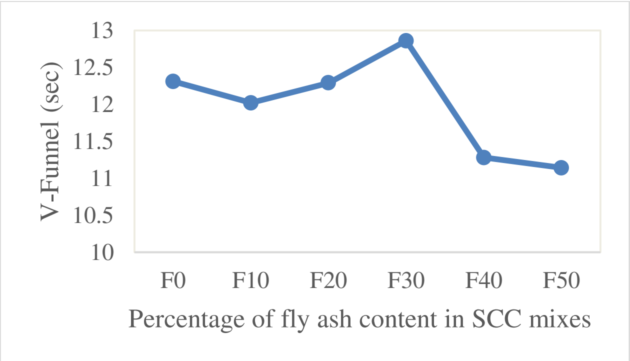

Figure-5. V-Funnel values with fly ash content.

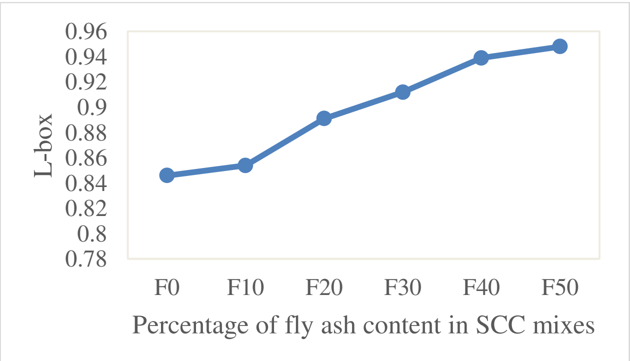

Figure-6. L-box values with fly ash content

Fresh Properties of SCC Mixes with Recycled Ceramic Content

The dosage of the superplasticizer in case of recycled ceramic powder (RCP) as partial replacement of cement is varied from 1.1 to 1.2% of binder content and the slump flow values obtained are similar range (672 to 685 mm) as that fly ash mixes. As recycled fine aggregates (RCF) replaces natural fine aggregates in varying percentages the slump values are found to be in the range of 668 to 682 mm, while the superplasticizer is varied in the range of 1.2 to 1.3% of binder content. For both RCP and RCF mixes, T50 and V-funnel values are less than 7 and 13 seconds respectively. The slump values are very low for those mixes in which natural aggregates are replaced with recycled ceramics are used coarse aggregates and are found to be in the range of 610-622 mm when the dosage of super plasticizer was varied between 1.1to 1.2% of binder content. It appears that the ceramic coarse aggregates are not freely mixing with the other ingredients of concrete. This may be due to the irregular sharp shape and less water absorption of ceramic aggregates. It is also noticed, further increase in dosage of superplasticizer resulted in segregation and bleeding.

Compressive Strength

Figure-7 represents contrast among the compressive strength evolvements of SCC mixes with out and with inclusion of fly ash. As the percentage replacement of cement by fly ash increases early age compressive strength are increasing up to 20% and further increase in fly ash content leads to slight decline in the compressive strength. At early ages the compressive strength of SCC mixes with fly ash is considerably lower than SCC mix with OPC alone. But at later ages the compressive strength of SCC mixes with and without fly ash are comparable [Hannesson, G *et al*., 2012]. This might be due to the gradual development of cementing action from the activation of pozzolanic reaction of fly ash particles with the age of concrete. Enhancement in compressive strength from 28 to 56 days is also quite significant in case of fly ash SCC mixes.

VOL. 17, NO. 21, NOVEMBER 2022 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

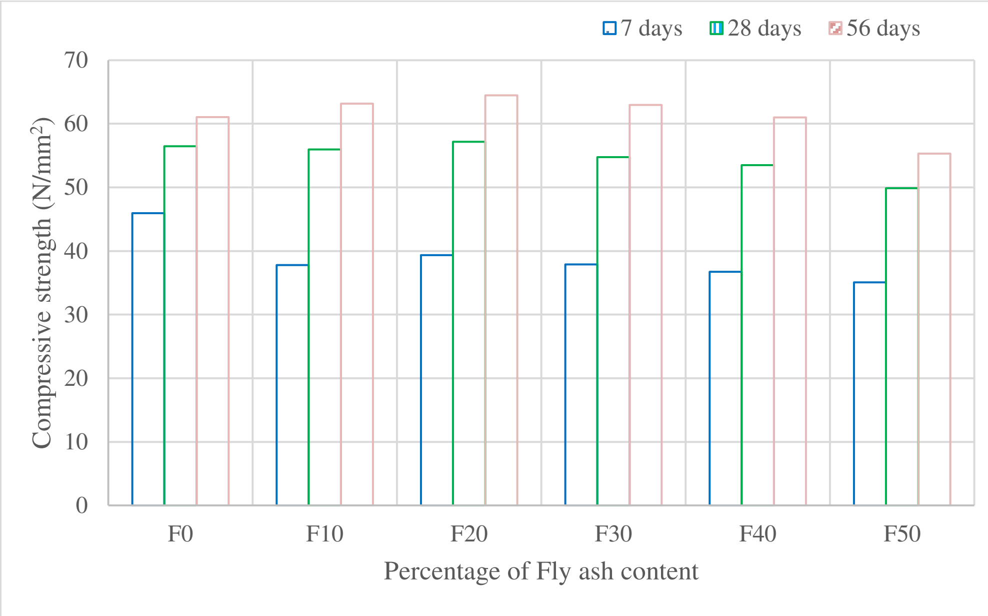

Figure-7. Compressive strength development of with fly ash content.

Among all the mixes compressive strengths of F40 mix, in which 40 % of the cement is replaced with fly ash found to have similar strength as that of SCC mix with OPC alone (F0). F0 mix was denoted as the control mix in order to compare the compressive strength of mixes where recycled ceramic aggregates and powder are utilized as alternative aggregates and binder in SCC mixes.

Figure-8 illustrates 7, 28 and 56 days compressive strength of SCC mixes where cement is replaced by recycled ceramic powder (RCP) in percentages of 12.5, 25, 37.5 and 50. At early ages the compressive strength of control mix is on higher side than RCP mixes. However, a significant progression in the strength of RCP mixes at 28 and 56 days curing period and strength values considerably greater than the conventional SCC mixes. It is also noticed that compressive strength in RCP mixes are on higher side than the SCC mixes with 40 % fly ash replacement at early ages but at later ages the strengths are marginally on higher side.

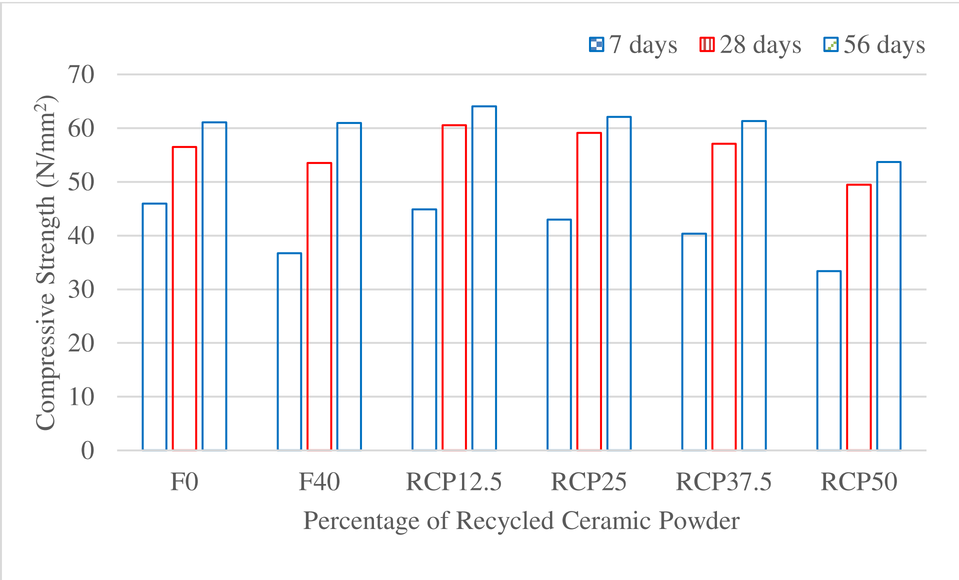

Figure-8. Compressive strength development of with Recycled ceramic powder.

It is evident from the figure that about 35% of cement can be effectively replaced with recycled ceramic waste without compromising the flow as well as strength properties in comparison to control mix. This statement is almost in agreement with the Aly, S. T. *et al*. 2018, where in it was reported that ceramic waste powder can replaces 40% cement in SCC mixes.

VOL. 17, NO. 21, NOVEMBER 2022 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Figure-9 indicates the comparison between the compressive strength development of SCC mixes without and with partial replacement of river sand with recycled ceramic fine aggregates (RCF). Upto 40 % replacement with RCF there is an increase in the compressive strength values. Beyond this limit a decline in the strength was noted. However, at 50% substitution of river sand the compressive strengths are comparable to control mix.

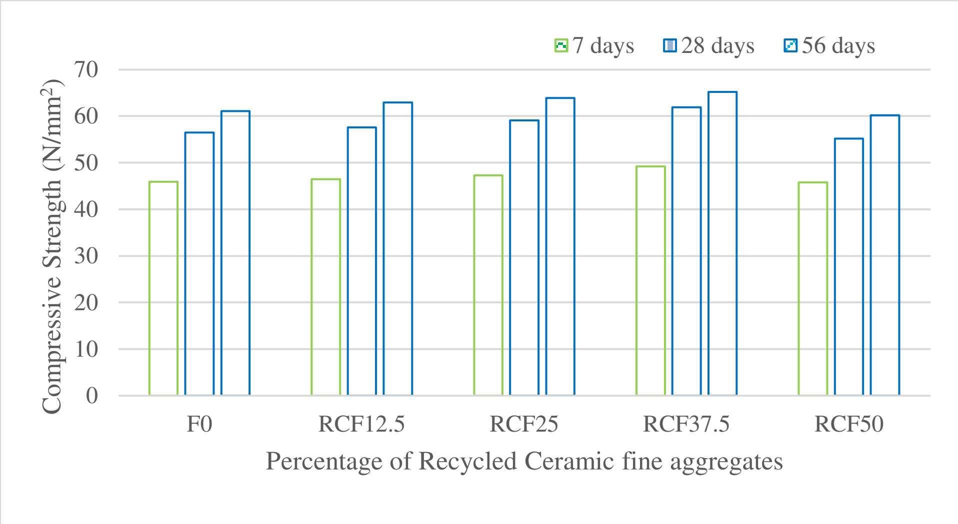

Figure-9. Compressive strength development of with Recycled ceramic fine aggregate.

This improved strength might be due to better interlocking arrangement arising from the rough texture and shapes of crushed ceramic fine aggregates cement matrix and reduction in the porosity of concrete (H. Donza, *et al*. 2002). Beyond 50% replacement of river sand a slight decline in compressive strength was noticed. Hence it can be understood that partial replacement of river sand with RCF will leads better mechanical properties.

Figure-10 depicts the compressive strength development of SCC mixes when natural coarse aggregates are replaced with recycled ceramic coarse (RCC) aggregates. It was found that use of RCC aggregates not only reduced the slump values of SCC mixes but also comparatively the compressive strengths are on lower side than the control mix.

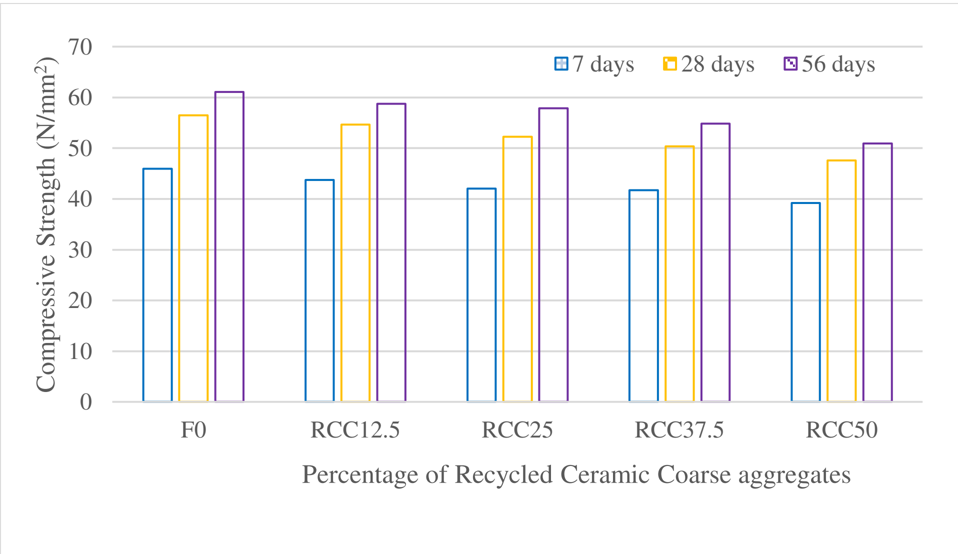

Figure-10. Compressive strength development of with recycled ceramic coarse aggregate.

It was observed that aggregates of this size are not freely moving in flow of concrete and hence segregation of concrete is also noticed at higher replacements. Beyond 25 % substitution with RCC aggregates considerable decrease in the compressive strength are noticed. Figure-11 represents tensile strengths of SCC mixes when recycled ceramic powder (RCP) is used as substitution to cement in various percentages. It

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ARPN Journal of Engineering and Applied Sciences

can be observed that the split tensile strength of RCP mixes at early ages is on lower side when compared to control mix.

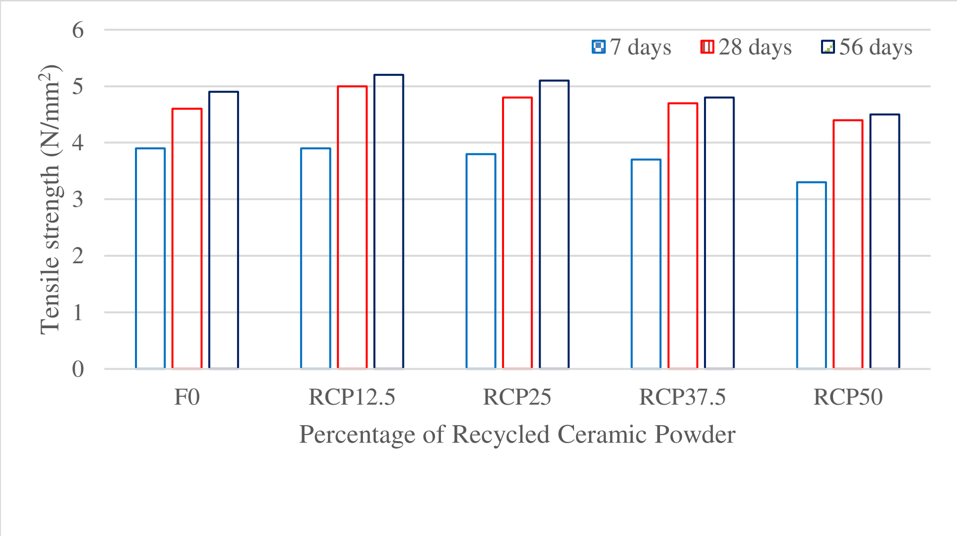

Figure-11. Split tensile strength development of with recycled ceramic powder.

But beyond 28 days the strength values are comparable to control mix up to 38 % replacement with RCP. Further increase in content of RCP resulted in slight reduction in split tensile strength and trends are similar to that of compressive strength. Figure-12 shows 7, 28 ad 56 days split tensile strengths values of SCC mixes when river sand is replaced with recycled ceramic fine aggregates. Similar to the compressive strength values of RCF mixes; compared to control mixes a significant improvement in tensile strength values is noticed.

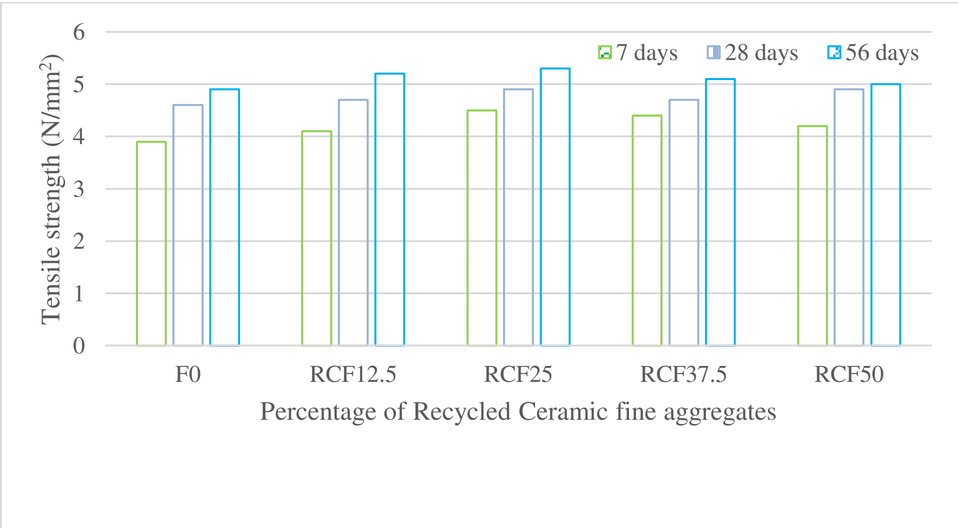

Figure-12. Split tensile strength development of with recycled ceramic fine aggregate.

From the obtained results it can be inferred that upto 50% replacement of river sand with RCF aggregates SCC mixes are performing better in relation to split tensile strength. Beyond this a slight decrease in the tensile strengths was noticed in comparison to control mix.

Figure-13 depicts the split tensile strengths of SCC mixes when natural coarse aggregates are substituted with recycled ceramic coarse (RCC) aggregates. It was found as the percentage replacement of RCC aggregates increases split tensile strengths are decreasing gradually. Beyond 25% replacement the reduction strength was more pronounced.

ARPN Journal of Engineering and Applied Sciences

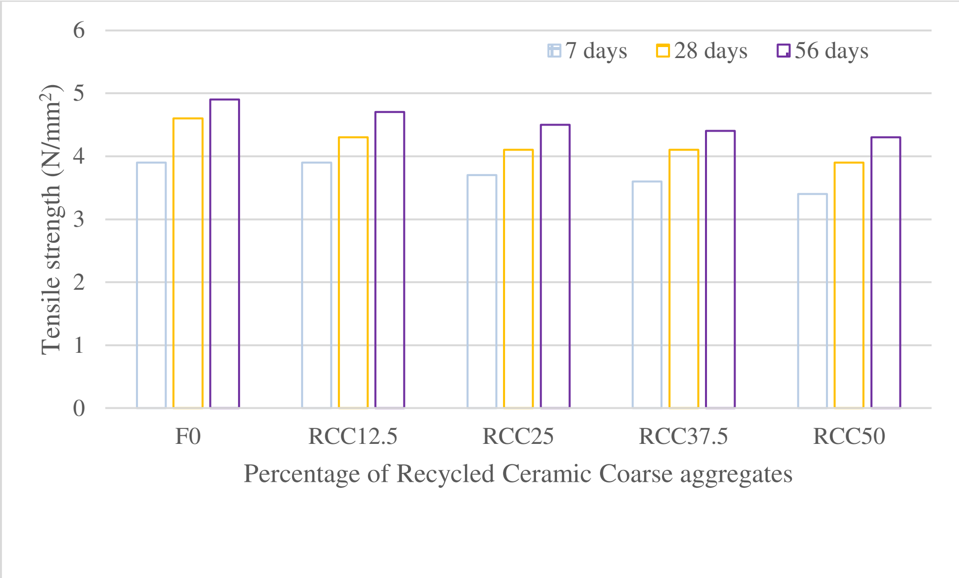

Figure-13. Split tensile strength development of with recycled ceramic coarse aggregate.

CONCLUSIONS

From the experimental investigation executed it is understood that usage of recycled ceramics as partial replacement to cement and aggregates in self consolidated concrete is quite appropriate. The following are the conclusions drawn from the results of the investigation.

a) Slump values of SCC mixes with partial replacement of cement with recycled ceramic powder is satisfactory and finds suitable application for normal applications.
b) Recycled ceramic powder (RCP) can be effectively employed as partial replacement to cement in SCC up to 38% and possible to achieve similar compressive and tensile strengths as that of conventional SCC.
c) The mechanical properties of SCC mixes with RCP replacement are comparable to that of cement replacement by fly ash of same percentage.
d) Recycled ceramic fine aggregates can be used as partial replacement to river sand and possible to attain similar flow properties by adjusting the dosage of the super plasticizer.
e) It is observed that natural fine aggregates in conventional SCC mixes can be replaced with recycled ceramic fine aggregates up to 40 % without compromising for the split tensile and compressive strengths.
f) The flow properties of SCC mixes in which natural coarse aggregates are partial replaced with recycled ceramic coarse aggregates up to 20%are satisfactory, beyond this excess dosage of superplasticizer results in segregation and bleeding.
g) Use of recycled ceramic coarse aggregates in SCC mixes as partial replacement to natural coarse aggregates is not yielding any improvement in the mechanical properties.
h) The percentage reduction in the cost of SCC per cubic meter with the use of recycled ceramic powder is found to be 25%.
i) The percentage reduction in the cost of SCC per cubic meter with the use of recycled ceramics fine and coarse aggregates is found to be 8 and 2 % respectively.

Declarations

Conflict of interest: On behalf of all the authors, the corresponding author declares that there is no conflict of interest.

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VOL. 17, NO. 21, NOVEMBER 2022 ISSN 1819-6608
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