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Successive recycled coarse aggregate effect on mechanical behavior and microstructural characteristics of concrete

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Abstract. With the increase in industrialization and urbanization, growing demand has enhanced rate of new constructions and old demolitions. To avoid serious environmental impacts and hazards recycled concrete aggregates (RCA) is being adopted in all over the world. This paper investigates successive recycled coarse aggregates (SRCA) in which old concrete made with RCA in form of concrete cubes was used. The cubes were crushed to prepare new concrete using aggregates from crushing of old concrete, used as SRCA. The mechanical behavior of concrete was determined containing SRCA; the properties of SRCA were evaluated and then compared with natural aggregates (NA). Replacement of NA with SRCA in ratio upto 100% by weight was studied for workability, mechanical properties and microstructural analysis. It was observed that with the increase in replacement ratio workability and compressive strength decreased but in acceptable limits so SRCA can be used in low strength concretes rather than high strength concrete structures.

Keywords: successive recycled coarse aggregate; waste; fly ash strength; scanning electron microscope; X-ray diffraction

1. Introduction

The concrete plays an important role in construction industry, either in the improvement of structures or in construction of new buildings and infrastructures. The total annual concrete consumption estimated all over the world is 10 billion tons (Meyer 2009). Beside, natural aggregates are continuously depriving from atmosphere due to over exploitation of resources (Metha 2001). Tons of wastes are discarded on demolition of buildings and roads, these wastes often disposed considering them worthless (McNeil and Kang 2013). Due to massive load, in the year 1992 sustainable development was introduced in Rio summit by Agenda 21 (1992). Mehta (2001) reported that concrete industry consumes 12.6 billion tonnes of natural resources produced in the world. The demand for construction aggregates rises 5.2 percent annually to 51.7 billion metric tons in 2019 (Freedonia 2016). The main consumption of natural resources is in construction sector which results in major quantity of construction and demolition waste (C&D waste). It mainly has solid wastes in large volume (Arslan *et al.* 2012).

For instance, the U.S. construction industry generates over 100 million tons of C&D waste per year (Mills *et al.* 1999). According to studies, U.S creates 29% of solid waste in construction sector (Rogoff and Williams 1994), each year 70 million tons of wastes gets discarded (Sealey *et al.* 2001). Construction waste generated in European union was 860 million tons out of total waste generated 2.5 billion tons in year 2010 (Freedonia 2012), C&D waste generated in India annually is 23.75 million tonnes (Arora and Singh 2016). It is predicted that demand of coarse aggregates will double in next 2 to 3 decades (Oikonomou 2005). The coarse aggregate consumption is most in developing countries like China, India and Brazil. India stands second in cement production with 7% total production (Agenda 21 1992).

The demolished waste needs a lot of space for dumping so it is needed to recycle these wastes into coarse aggregates instead of dumping them (Yaragal *et al*. 2016). The production of one ton of NA emits 4600 tons of carbon however RCA produces 2400 tons of carbon (Sonawane and Pimplikar 2013). The use of recycled concrete from demolition wastes either partially or fully in place of natural aggregates can improve sustainability of structures (McGinnis *et al.* 2017). The quality of recycled aggregates somehow depends upon demolition technique applied i.e., traditional or selective, selective demolition technique improves the properties of aggregates which results in better quality of concrete product (Colangelo and Cioffi 2016). Fresh and hardened concrete from sites were studied for its properties and tests showed RCA made with old concrete gives better opportunities for reuse (Shah *et al.* 2013, Yaragal and Roshan 2017).

McNeil and Kang (2013) investigated properties of RCA by replacing NA in concrete and observed that RCA is more porous, less dense and has high water absorption in comparison with NA. Pedro *et al*. (2017), Verma and Ashish

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et al. (2017) determined that properties of NA are distinct from that of RCA in physical terms i.e., the mortar that adheres to its surface which is responsible for quality loss. Due to this density is reduced which increases the water absorption of RCA. Amnon (2003), Elhakam *et al.* (2012), Tabsh and Abdelfatah (2009) indicated reduction in compressive strength by 25% as compared to NA. Moreover, RCA showed more porosity and water absorption, low density and strength in comparison to NA. RAC with silica fume (Abdollahzadeh *et al.* 2016), micro-silica (Shaikh *et al.* 2015), nano-silica (Prusty *et al.* 2015) and Portland pozzzolana cement (Saha and Rajasekaran 2016) were investigated for compressive strength and Wang *et al.* (2012) also investigated the Taiwan made recycled mineral admixture based on fly ash, slag, glass sand and rubber powder. Brito and Saikia (2012) determined reduction in strength on replacement of NA with same amount of RCA. Tahar *et al.* (2017) determined that workability of RCA depends upon the combination of cement admixture and the nature of admixture and amount of C_3A. Tavakoli and Soroushian (1996), Kang *et al.* (2012) observed that splitting tensile strength of concrete made with RCA is less affected by RCA content. It showed better or comparable results of splitting tensile strength as compared to NA. Vijayaraghaven *et al.* (2017) indicated that concrete made with copper slag, iron slag and RAC own more strength in comparison with traditional concrete mix. Arora and Singh (2016) determined flexural fatigue performance of concrete beams made with NA in comparison with concrete beams made with complete replacement of NA with RCA through Weibull distribution. Pham *et al.* (2015) used OpenSees platform to model pre cast RAC finite element models and studied dynamic response for pre cast RAC. Wang *et al.* (2017) improved the strength of RCA by treating RCA with solution that weakens the attached mortar, the treated RCA has decreased water absorption and increased compressive strength. In some investigations it was analyzed that RCA is 10-25% lower than NA in its mechanical properties. RCA was observed inferior in its properties as compared to NA but it was under acceptable limits and can be used in structures with lower loads (Tabsh and Abdelfatah 2009, Serres *et al.* 2016). (Mukharjee and Barai 2015, Ashish *et al.* 2016a, Ashish *et al.* 2016b, Ashish *et al.* 2016, Verma *et al.* 2016, Raj and Bhoopesh 2017) investigated different waste materials for sustainable growth in of construction development.

2. Research significance

From the present literature it was noticed that a lot of data is available on recycled aggregate concrete but a very little information is available of successive recycle concrete aggregate and this area of concrete needs to be explored. It is very important to analyze the probable use of SRCA in construction and development of economy. Therefore the present study determines the mechanical behavior of concrete containing SRCA; the properties of SRCA were evaluated and then compared with NA. Replacement of NA with successive recycled coarse aggregate in ratio upto 100% by weight was studied for workability, mechanical properties and microstructural analysis

Table 1 Physical properties of SRCA and NA

Aggregates used	SRCA	NA
Fineness modulus	6.65	6.84
Specific gravity	2.46	2.49
Aggregate impact value (%)	29.78	17.15
Aggregate crushing value (%)	24.80	16.50
Water absorption (%)	5.25	0.75

Table 2 Chemical properties of cement and fly ash

Oxides	OPC	fly ash
Calcium oxide (CaO)	64.38	18.42
Silica Oxide (SiO_2)	21.58	36.47
Aluminium oxide (Al_2O_3)	4.39	16.95
Iron oxide (Fe_2O_3)	4.25	20.05
Magnesium oxide (MgO)	1.02	2.54
Potassium oxide (K_2O)	0.74	0.89
Sodium oxide (Na_2O)	0.31	0.80
Sulphur trioxide (SO_3)	2.74	3.54

3. Experimental program

In this study the NA were replaced with SRCA at varying replacement levels. The mix containing SRCA was cast in several batches and each batch consisted of cube specimens of size 150 mm×150 mm×150 mm. The samples were tested for determining compressive strength, a cylindrical specimen of size 150 mm×300 mm was tested for determining the splitting tensile strength. All samples were casted with and without SRCA. The variables include cement, fly ash, coarse aggregate, sand, SRCA and water.

4. Materials

In this study ordinary Portland cement (OPC) 43 grade confirming to BIS: 8112 (2013) was used. Table 1 depicts the physical properties of SRCA and NA, SRCA of specific gravity as 2.46, well graded SRCA size upto 12.5 mm, and aggregate crushing value around 30% were used, after processing in the laboratory. Natural coarse aggregate and successive recycled coarse aggregate as per BIS: 2386-1 (1983); BIS: 2386-2 (1963) and BIS: 2386-4 (1983) were determined with fineness modulus 6.84 and 6.65 respectively shown in Table 2 and used in this research, 20 mm down size of natural coarse aggregate is used. Aggregates were partially saturated before mixing. The concrete mix was prepared with normal river sand with specific gravity 2.62 confirming to Zone-II as per BIS: 383 (1970). Cleaning of sand and coarse aggregates is done by washing and drying to remove dirt, powder before testing. Normal water was used for performing all experiments. The SRCA percentage replacement (R%) is the ratio of successive recycled to total aggregate (by weight). The concrete mixture made with RCA and NA attains optimum

Table 3 Nomenclature

Nomenclature	Designation
NA	NA
RCA	Recycled concrete aggregate
SRCA	SRCA
OPC	Ordinary Portland Cement
R-00	Control cement concrete mixture
R-10	10% SRCA as NA replacement
R-20	20% SRCA as NA replacement
R-30	30% SRCA as NA replacement
R-40	40% SRCA as NA replacement
R-50	50% SRCA as NA replacement
R-60	60% SRCA as NA replacement
R-70	70% SRCA as NA replacement
R-80	80% SRCA as NA replacement
R-90	90% SRCA as NA replacement
R-100	100% SRCA as NA replacement

Table 4 Mix proportion with workability properties of concrete

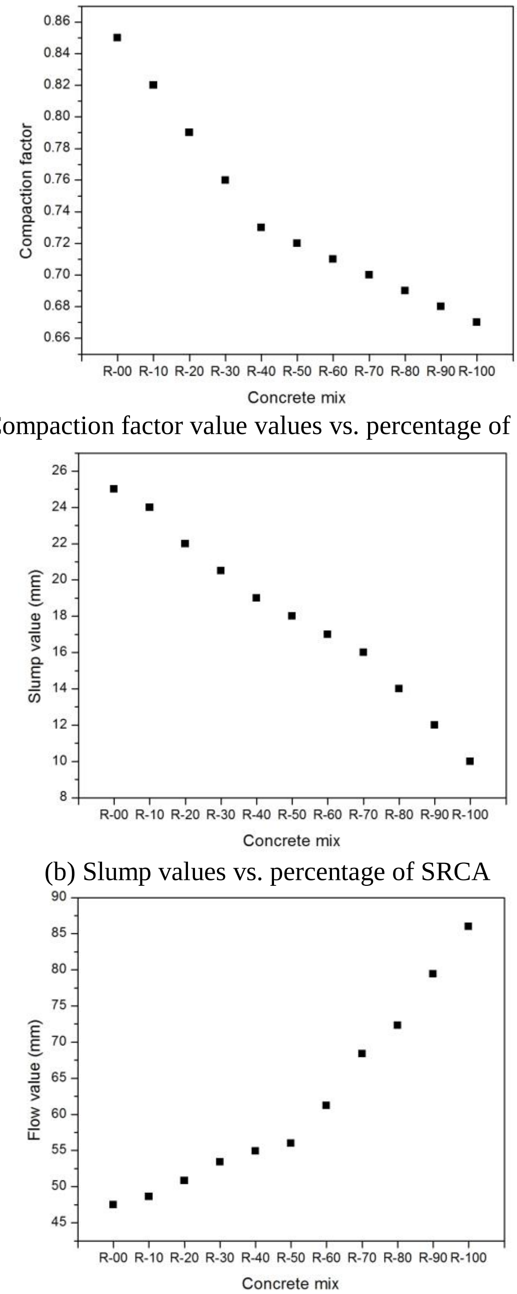
Sr. No.	Nomenclature	R%	Cement (Kg/m^3)	Fly ash (Kg/m^3)	Fine aggregate (Kg/m^3)	Coarse aggregate (Kg/m^3)	SRCA (Kg/m^3)	Water (liters/m^3)
1	R-00	0	420	150	635	1171.0	0	131.5
2	R-10	10	420	150	635	1054.0	117.0	131.5
3	R-20	20	420	150	635	937.0	234.0	131.5
4	R-30	30	420	150	635	820.0	351.0	131.5
5	R-40	40	420	150	635	703.0	468.0	131.5
6	R-50	50	420	150	635	585.5	585.5	131.5
7	R-60	60	420	150	635	468.0	703.0	131.5
8	R-70	70	420	150	635	351.0	820.0	131.5
9	R-80	80	420	150	635	234.0	937.0	131.5
10	R-90	90	420	150	635	117.0	1054.0	131.5
11	R-100	100	420	150	635	0	1171.0	131.5

workability with the use of polycarboxylic ether based superplasticizer in suitable dosages. Uniform strength can be achieved by controlling the workability using uniform quality of concrete. Table 3 and Table 4 represents the terminology for all concrete mixtures and properties of concrete mixtures respectively.

5. Experimental

The old concrete was in the form of concrete cubes, it was tested for compressive strength at curing ages of 28, 56 and 90 days using standard procedure. These concrete cubes were made with RCA which was collected from the demolished building in Ambala (India). The building was demolished using selective technique. Old concrete were tested for compressive strength after which the cubes were crushed by a mini jaw crusher and dried in an oven. The new concrete was prepared using aggregates from crushing the old concrete used as SRCA. The concrete mix without SRCA is identified as R-00. Replacement of NA with successive recycled coarse aggregate in ratio 0%, 10%, 20%, 30% 40%, 50%, 60%, 70%, 80%, 90% and 100% by weight was studied for workability, mechanical properties and microstructural analysis. In control mixture, cement content is 420 kg/m^3; fine aggregate content is 635 kg/m^3 as shown in Table 4.

In above concrete mixes workability was measured by flow table test as per BS EN 12350-5 (2009), slump test as per BIS: 7320 (1974) and compaction test as per BIS: 5515 (1983). The test specimens for compressive and splitting tensile strength were cast according to BIS: 516 (1959). After the specified period of curing the specimens were taken out of the curing tank and their surfaces were wiped off. The various tests were performed for testing of cubes at 7 & 28 days.



(a) Compaction factor value values vs. percentage of SRCA

(b) Slump values vs. percentage of SRCA

(c) Flow value vs. percentage of SRCA

Fig. 1 Fresh properties of concrete

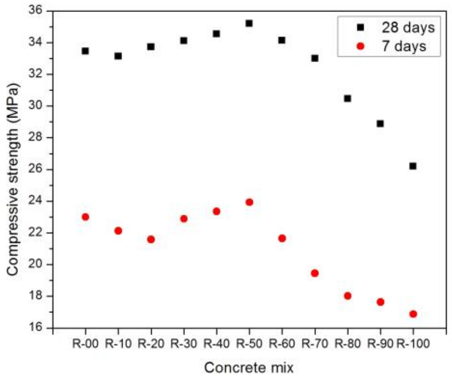


Fig. 2 Compressive strength vs. percentage of SRCA for 7 and 28 days

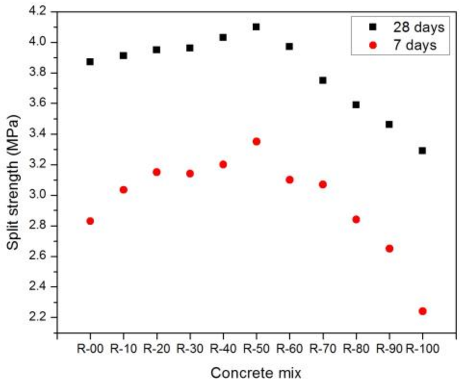


Fig. 3 Splitting tensile strength vs. percentage of SRCA for 7 and 28 days

6. Result and discussion

6.1 Workability of concrete

Workability of control concrete mixture and blended concrete mixture incorporating SRCA with NA was measured upto 100% proportions. The properties of workability depend upon factors like moisture in aggregate, texture and size of aggregate, water absorption. As per BIS: 7320 (1974) for slump value, slump cone test was evaluated for cement concrete, as per BIS: 5515 (1983) for compaction value, compaction factor test was evaluated for cement concrete and as per BS EN 12350-5 (2009) for flow value, flow table test was evaluated of the cement concrete. Fig. 1 depict that slump value and compaction factor value decreases whereas increase in flow value was observed. With the increase in SRCA replacement ratio, workability reduces. No major effect was observed upto 20% replacement ratio of RAC but with increase of replacement ratio there can be observed fall in workability. This is because SRAC is high in porosity as compared to NA. So workability of SRAC is lower than NA. Similar results were analysed by Debied *et al*. (2009), Debied *et al*. (2010), Malešev *et al*. (2010).

6.2 Variation of compressive strength

The results of compressive strength for 7 and 28 days of curing ages were tested according to BIS: 516 (1959). Fig. 2 clearly depicts reduction in compressive strength at different replacement percentages of NCA with SRCA. Concrete mix with 100% NA has compressive strength 23.0 MPa for 7 days of curing ages and 33.5 MPa for 28 days of curing ages whereas compressive strength of concrete mix with 100% SRCA shows considerable decrease in compressive strength. The concrete mix containing 100% SRCA has compressive strength 16.9 MPa and 26.2 MPa for 7 and 28 days of curing ages respectively. The maximum value of compressive strength was achieved at 50% replacement of NCA with SRCA. For concrete mix R50, compressive strength obtained was 23.9 MPa and 35.2 MPa for 7 and 28 days of curing ages. It can be observed that with the further increase in replacement ratio of SRCA, compressive strength decreased. Similar observations were investigated by Etxeberria *et al*. (2007). The decrease in compressive strength is due to low water availability in RCA which formed weak interfacial transition zone (ITZ). Low water availability between old mortar and aggregate is the reason for weaker interfacial transition zone due to which concrete fails. The compressive strength of RAC depends upon the quality of recycled aggregate (RA); high compressive strength can be attained with a better quality of RA. However, SRCA can be used in low strength concrete rather than high strength concrete Tam *et al*. (2007).

6.3 Variation of splitting tensile strength

The results of splitting tensile strength for 7 and 28 days of curing ages were tested according to BIS: 516 (1959). Fig. 3 clearly depicts reduction in splitting tensile strength at different replacement percentages of NCA with SRCA. Concrete mix with 100% NA has splitting tensile strength 2.8 MPa for 7 days of curing ages and 3.9 MPa for 28 days of curing ages, whereas, splitting tensile strength of concrete mix with 100% SRCA shows considerable decrease in splitting tensile strength. The concrete mix containing 100% SRCA has splitting tensile strength 2.4 MPa and 3.3 MPa for 7 and 28 days of curing ages respectively. The maximum value of splitting tensile was achieved at 50% replacement of NCA with SRCA. For concrete mix R50, splitting tensile strength obtained was 3.3 MPa and 4.1 MPa for 7 and 28 days of curing ages. It can be observed that with the further increase in replacement ratio of SRCA, splitting tensile strength decreased. Similar observations were analyzed by Fonseca *et al*. (2011), Kou and Poon (2013). The splitting tensile strength was higher for SRCA as compared to NA because of absorption capacity of adhered concrete and effectiveness of interfacial transition zone present in recycled aggregate. The good bond characteristics between aggregate and mortar matrix is somehow due to absence of any harmful effect on recycled concrete tensile strength Sagoe-Crentsil *et al*. (2001).

6.4 Concrete strength standard deviation

The standard deviation of SRCA is shown in Table 5. Concrete mix containing 100% NA have standard deviation

Table 5 Compressive strength standard deviation of concrete with or without SRCA

Nomenclature	R-00	R-10	R-20	R-30	R-40	R-50	R-60	R-70	R-80	R-90	R-100
Standard deviation σ (MPa)	2.10	1.90	2.26	2.49	2.76	3.16	2.51	1.82	0.28	-0.69	-2.32

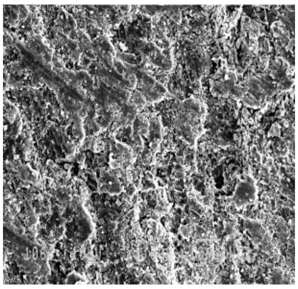
2.10 MPa for 28 days curing period whereas Concrete mix containing 100% SRCA have standard deviation negative 2.32 MPa for 28 days curing period. The standard deviation is 3.16 MPa for samples with 50% replacement of NA by SRCA for 28 days of curing ages. The results showed standard deviations are somewhat improved with the replacement percentage of RCA except 100% RCA replacement, But results are not much different than natural concrete.

6.5 Scanning electron microscope

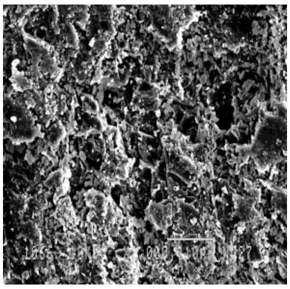
Compressive strength test was generated from fractured pieces of concrete specimen which were used for observing micrographs at ages of 28 days. Thin layer of gold is coated on concrete specimens to make them electrically conductive before placing on the SEM. SEM images of control concrete (R-00), SRCA concrete mixtures R-50 and R-100 at 28 days are shown in Fig. 4. The intrinsic parameters, ITZ and the weak microstructure of RCA are the main reasons for lower compressive strength moreover other reason for lower compressive strength can be weak bond between old ITZ and new ITZ as this mutual bonding influences the mechanical properties and due to micro and macro pores present in SRCA along with NA, poor behavior was observed The satisfactory performance was achieved for R-50 mix, and it was observed that lower replacement of NA with SRCA shows not much effect on strength properties. However, more than 50% replacement (R-60 to R-100) of SRCA shows unsatisfactory results at 28 days curing period.

6.6 X-Ray diffraction phase identification

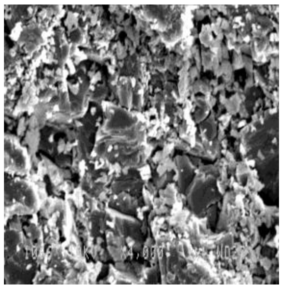
Identification of phases was performed in X-ray diffraction technique for the concrete samples made with



(a) R-20 at X1000

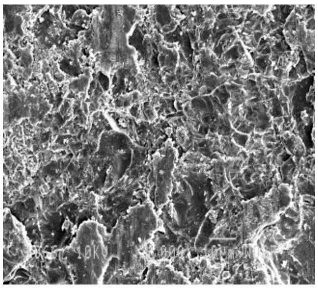


(b) R-20 at X2000

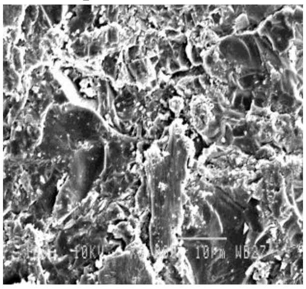


(c) R-20 at X4000

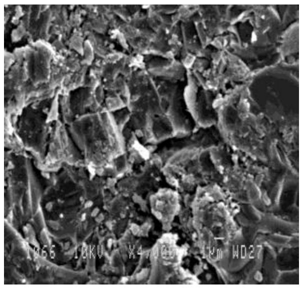
20% Replacement of RCA



(d) R-50 at X1000

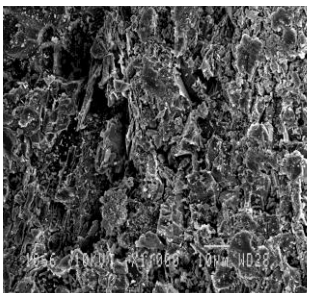


(e) R-50 at X2000

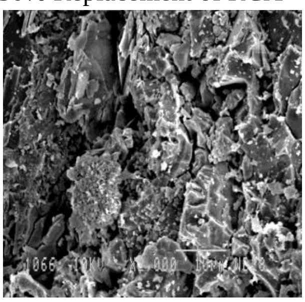


(f) R-50 at X4000

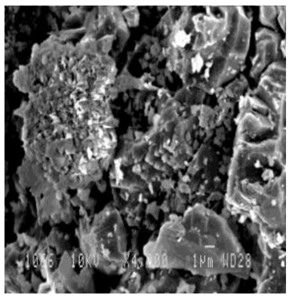
50% Replacement of RCA



(g) R-100 at X1000



(h) R-100 at X2000



(i) R-100 at X4000

100% Replacement of RCA

Fig. 4 Scanning electron microscope of concrete containing RCA as replacement of NA

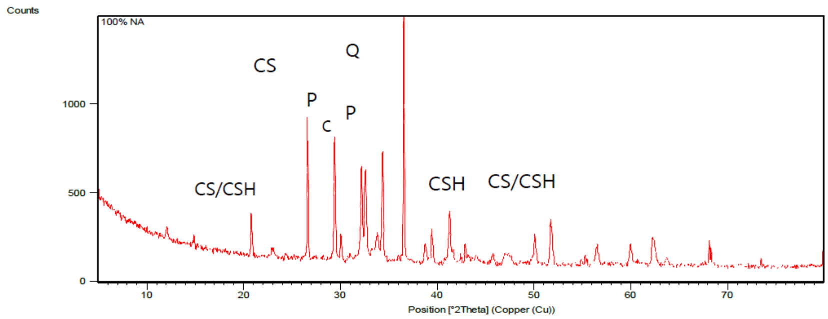


Fig. 5 X-ray-diffraction pattern of cement concrete without SRCA at 28 days

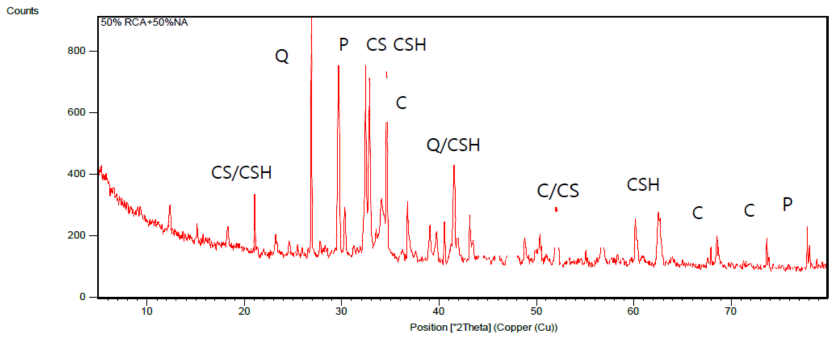


Fig. 6 X-ray-diffraction pattern of cement concrete containing 50% SRCA as NA replacement at 28 days

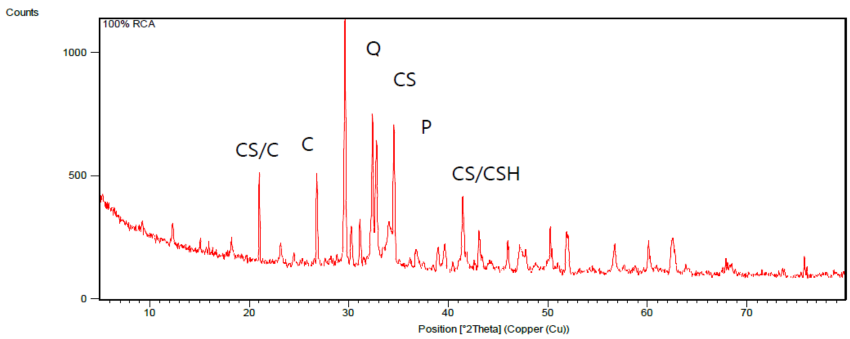


Fig. 7 X-ray-diffraction pattern of cement concrete containing 100% SRCA as NA replacement at 28 days

SRCA as replacement of NA and control concrete at 28 days curing ages. The observations were performed for diffraction angle 2θ ranged between 10° to 80° in steps of 2θ=0.017°. In XRD spectrum Calcium silicate hydrate (CSH), calcium silicate (CS), calcium hydroxide (P) and calcite (C) were the phases observed in cement paste as depicted in Figs. 5-7. The fragments of aggregate in the form of quartz (Q) and silica (Q) were observed in XRD spectrums. It was investigated that on replacement of SRCA with NA there is a change in proportions of phases, there is not much effect on result on addition of SRCA. In XRD investigations Fig. 6 shows higher calcium silicate hydrate (CSH) and calcium silicate (CS) in comparison of control concrete. There was no change observed in the phase composition on replacement of NA with 100% SRCA in concrete mixture in Fig. 7.

5. Conclusions

On the basis of results obtained in present study, the following conclusions can be drawn.

- The results of compressive strength of SRCA showed reduced performance in comparison to NA. The compressive strength decreased by 26.7% for 7 days of curing and 21.7% for 28 days of curing ages.
- The results of compressive strength for 50% replacement of NA with SRCA marginal increased compressive strength by 4.0% and 5.2% for 7 and 28 days of curing ages respectively.
- SRCA possess relatively lower bulk density, specific gravity and high water absorption as compared to NA. This is mainly due to the porous mortar adhering to SRCA.
- The results of splitting tensile strength of SRCA decreased by 20.7% for 7 days of curing ages and 14.7% for 28 days of curing ages.

It is advisable to carry out trial castings with SRCA proposed to be used in order to arrive at the water content and its proportion to suit the workability levels and strength requirements respectively.

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