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# Hardened state behaviour of self-compacting concrete pavement mixes containing alternative aggregates and secondary binders

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## HIGHLIGHTS

- Effect of RCAs on hardened state behaviour of two grades of SCC pavement mixes was investigated.
- Suitability of designed concrete mixes were evaluated for their effective utilization in SCC-CRCP.
- Application of 100% RCAs is suggested in high volume fly ash self-compacting concrete pavement mixes.

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## ABSTRACT

Hardened state behaviour of two grades (normal- and medium-strength) of Self-Compacting Concrete (SCC) pavement mixes containing varying proportions of Recycled Concrete Aggregates (RCAs) as an alternative aggregate is reported in this paper. These two SCC grades were designed by varying the proportions of fly ash, silica fume and metakaolin in binary and ternary blends of Portland cement. The suitability of these mixes were evaluated for Continuously Reinforced Concrete Pavements (CRCP) application considering various performance as well as the quality control parameters. The results (both experimental and analytical) depicted that inclusion of RCA in Saturated-Surface-Dry (SSD) moisture state would not have any negative effect on fresh and hardened state behaviour of the SCC-CRCP mixes. Although the cement content in some of the mixes were higher than the recommended limit, all the mixes could meet the minimum stipulated flexural strength criterion of 4.5 MPa at 28 days of curing for CRCP. However, to maximize the benefit (utilizing fewer natural resources and more recycled materials) without compromising with the engineering properties, high-volume fly ash based (50%) normal-grade SCC containing 100% RCAs is recommended.



## 1. Introduction

Self-Compacting Concrete (SCC) is a high-performance concrete that requires no compaction for paving owing to its high fluidity. These concrete mixtures are usually free from segregation and holds the ability to flow through even heavy reinforcement whilst attaining complete compaction characteristics under its self-weight [1]. SCC has shown excellent durability characteristics in comparison to Normal Vibrated Concrete and is usually designed for areas of congested reinforcements such as buildings, bridges, and tunnels [2]. However, its application in concrete pavement construction is still being explored. SCC could hold greater potential, especially for Continuously Reinforced Concrete Pavements (CRCP), which are reinforced with transverse and longitudinal reinforcement bars to arrest random cracks. On the other hand, the continuous exploitation of natural aggregates has shown an exponential decrease in the surplus supply of road construction aggregates needs some options to be explore for alternative aggregates. Owing to this, the utilization of recycled aggregates has become predominant as a reliable substitute for natural aggregates for pavement construction. One such recycled aggregates available predominantly is Recycled Concrete Aggregates (RCAs). RCAs are the aggregates generated from Construction and Demolition (C&D) waste which is a viable solution for utilization in new pavement applications but usually ends up in landfills. The utilization

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of RCAs in concrete pavement applications could positively be a moral solution in favour of the environment and economy of the construction [3,4]. The main difference between RCAs and Natural Concrete Aggregates (NCAs) is that the RCA particles have higher water demand and possess low specific density owing to the presence of porous adhered mortar layer [5,6]. Over the years, the application of RCAs is suggested in both the conventional as well as in SCC mixes [7,8]. It is well documented in literature [9–21] that difference in the fresh, hardened and durability properties of the self-compacting recycled aggregate concrete is mainly due to the high water absorption, irregular particle shape and size, low specific gravity and weak Interfacial Transition Zone (ITZ) of the recycled aggregate particles.

Gesoglu et al. [22] studied the effect of RCAs (both coarse and finer fraction) on hardened state wherein the authors reported a decrease in the mechanical strength of the SCCs with the incorporation of RCA. Meanwhile, Manzi et al. [23] demonstrated that 40% of RCA could be utilized for the production of SCC mixes without much compromising with the mechanical strength of the concrete. On the other hand, Omrane et al. [24] suggested the incorporation of RCA particles up to 50%, beyond which, it may degrade the overall quality of the SCC concrete. All these studies reported the weak ITZ between RCA and mortar paste as the main reason for failure in RCA incorporated SCC mixes. To overcome this issue, several researchers investigated the potential of different supplementary cementitious materials (SCMs) to improve the hardened state behaviour of different grades of SCC mixes containing RCAs [25,26]. The utilization of SCMs (as a replacement to Portland cement) in SCC pavements plays a pivotal role in the mix design due to its requirement of increased paste content. Several researchers reported the use of industrial by-products like fly ash, silica fume, rice husk ash, blast furnace slag and metakaolin for the production of SCC mixes [27–30]. According to Uysal et al. [31], the incorporation of SCMs in SCC mixes is prominent in improving its fresh, hardened and durability characteristics in terms of workability, strength and permeability. This improved performance of SCC made with SCMs is mainly attributed to: (a) Filling ability of SCMs between the cement particles and (b) Pozzolanic activity of the SCMs [32,33]. The filling ability of SCMs contributes to the pore refinement of the microstructure which decreases the permeable voids in concrete, whereas, the pozzolanic activity of the SCMs comprises the reaction of silica with the calcium hydroxide generated from the cement hydration [34–36]. Besides the SCC mixes showing enhanced performance with the incorporation of SCMs, Ulucan et al. [37] observed that the incorporation of fly ash could reduce the compressive strength of the SCC mixes, irrespective of the incorporation level. This decrease in the compressive strength was mainly attributed to the slow pozzolanic reaction and dilution effect of fly ash in the concrete mixes. However, the dilution effect of fly ash particles could be beneficial in terms of the workability of the SCC mixes. At the fresh state of the SCC mix, the improved flowability of concrete is mainly attributed to the ball bearing effect of the rounded fly ash particles [38,39]. Zhao et al. [40] also confirmed the increase in the workability of the SCC with the incorporation of fly ash particles. This increase in workability was attributed to the increase in paste content of the SCC due to incorporation of low specific gravity fly ash particles which in turn reduces the friction at the fine aggregate-paste interface and improves the plasticity and cohesiveness of the mix.

As far as the durability of RCA incorporated SCC mixes are concerned, Singh and Singh [41] reported a decrease in the carbonation and electrical resistance of the SCC mixes when the coarser fraction of RCAs was utilized. However, the aforesaid losses in the resistance were compensated with the incorporation of metakaolin. Metakaolin and Silica fume are the two most commonly used SCMs in the production of the high-strength SCCs. Both the metakaolin and silica fume have their unique characteristics in terms of their high pozzolanic reaction and specific surface area [42]. The BET surface area of both the materials is comparable and in the range of 12,000–20,000 $m^2$/kg [43]. It is reported in the literature that both the mineral admixtures improve the hardened as well as the durability properties of SCC to a great extent, however, mixes made with metakaolin are more durable relative to the mixes made with silica fume [44–46]. Kadri et al. [47] reported that both the silica fume and metakaolin contributes to the early age strength development in mortar. The maximum gain of strength for the SCCs containing metakaolin was observed during the first 14 days of curing [48]. According to Guneyisi and Gesoglu [49], the utilization of metakaolin in the SCC increases the cohesion in concrete which in turn prolonged the V-funnel time. Further, they reported that ternary blends of Portland cement, fly ash and metakaolin remarkably diminish this effect of the metakaolin. On the other hand, the incorporation of silica fume in the SCC is reported to have no effect on viscosity of the concrete [50].

### 1.1. Research objective and scope

The main objective of the present study is to investigate the potential of various waste materials, both aggregates and binders, for preparations of SCC mixes designated to be used for CRCP. Two grades of SCC viz. normal- and medium-strength, has been studied in the present investigation. In both the mixes, natural coarse aggregates were replaced by coarse recycled concrete aggregates in a proportion of 0%, 50% and 100% by volume. Both the grades of SCC pavement mixes were designed using fly ash, silica fume, and metakaolin in binary and in ternary cementitious blends to achieve the desired cube characteristic strength. A control series of SCC was designed with Portland cement as only binder at all replacement levels of recycled aggregates to compare the properties of the SCC due to incorporation of the various SCMs. The behaviour of concrete was investigated in terms of its fresh state properties, compressive strength, split-tensile strength, flexural strength, water absorption, and permeable voids. The change in behaviour of SCC across a grade of concrete is attributed to the presence of various SCMs whereas within a grade it is attributed to the presence of coarse recycled aggregates.

## 2. Research significance

Design of SCC pavement mixes produced using waste generated from industries and Construction and Demolition (C&D) is a viable solution keeping in view the demand of upgrowing construction practices and insight of sustainability. Pozzolans like fly ash, silica fume and metakaolin are invariably used as supplementary cementitious materials in the design of SCC and effect of their inclusion on mechanical and structural properties are reported by the various authors. However, a limited number of studies focus on their utilization along with alternative aggregates to produce strength-based SCC pavement mixes for their possible applications in continuously reinforced concrete pavements. The present study specifically aims to fill this gap in the literature and effort has been made to design a SCC mixture suitable to be used for Continuously Reinforced Concrete Pavement (CRCP) applications. It is expected that the study findings could be used for establishments of codal provisions for sustainable SCC mixes for CRCP application.

## 3. Experimental program

### 3.1. Materials

Portland cement of grade-43 conforming to IS 8112 [51] was used in this investigation. Industrial by-products such as class-F fly ash, metakaolin, and silica fume were added as part volumetric replacement of cement to achieve the desired grade of the SCC pavement mixes. Physical and chemical properties of Portland cement, fly ash, silica fume and metakaolin are summarized in Table 1. Locally available river sand passing through 4.75 mm and confirming to IS 383 [52] was used as the Fine Aggregates (FA). Crushed river stone of the maximum nominal size of 12.5 mm confirming to IS 383 [52] was used as the Natural Coarse Aggregates (NCAs). To simulate the actual field scenario, laboratory concrete of unknown provenance (different grades) was used to produce coarse recycled aggregates with the help of a jaw crusher. Further to mention, utilization of laboratory-produced Recycled Concrete Aggregates (RCAs) are considered advantageous because of their higher adhered mortar content and this choice is reported to correspond to a 'worst-case' scenario' in the literature [53]. To avoid the variability in the results due to different morphology characteristics, the considered recycled concrete aggregate particles were manually blended with the NCAs in such a way that the grading curve of both the aggregates coincide and confirms the requirement of IS 383 [52]. The measured physical and mechanical properties of the aggregates are reported in Table 2.

It may be noted that both the NCAs and the RCAs were used in the Saturated-Surface-Dry (SSD) moisture condition and the same was achieved by pre-soaking them in water for 24 h prior to casting. After completion of the soaking period, the aggregates were spread on a clean laboratory floor and any water attached to the surface of the aggregate particles was removed with a soft cloth following which the aggregates were batched in the concrete mixer. For illustration, a typical sample of the coarse NCAs and the coarse RCAs is shown in the Fig. 1. To increase the workability of the SCC pavement mixes, a polycarboxylic-ether based superplasticizer was used as the High Range Water Reducing Admixture (HRWRA). A water-soluble copolymer-based Viscosity Modifying Admixture (VMA) was used to induce the robustness and stability to the designed SCC mixes. The specific gravity values of the HRWRA and the VMA were 1.08 and 1.01, respectively. Potable tap water from a single source was used for the casting of the considered SCC pavement mixes throughout the investigation.

### 3.2. Mix proportions

A rational method is proposed for mix design of the SCC using the mix design considerations of Su et al. [54], Sensale et al. [55] and Hemalatha et al. [56]. In the proposed rational approach, the SCC is assumed as a two-phase system consisting of paste and aggregates. The mix design approach is illustrated with the help of a flow chart as shown in Fig. 2. Two-phase system of paste and aggregates adopted in this investigation is supported by the work carried out by several researchers [54,57–59]. A control SCC containing Portland cement was designed with the aforesaid rational approach without using any supplementary cementitious material. Once the control SCC pavement mix is designed, the amount of SCMs to be added to obtain the desired cube strength value was estimated based on the literature and of trial and error method. The self-compactibility of the various designed SCCs was ensured by adjusting the dosage of HRWRA and VMA.

Total paste content of all the designed SCC pavement mixes was nominally fixed at 43%. The air entrainment and aggregate content for all the considered mixes were fixed at 2% and 55%, respectively. A control SCC (CR0) made with the NCA particles was finalized without any target compressive strength at a sand to aggregate ratio of 0.55 and water-to-cement (w/c) ratio of 0.34. The normal- and the medium-strength SCCs were produced by adjusting the dosages of fly ash (F), silica fume (S) and metakaolin (K) as part volumetric replacement in CR0 using trial and error process. In normal-strength SCC pavement mix (FR0), fly ash was used as binary cementitious blend at 50% volumetric replacement for a target cube compressive strength of 35 MPa. The total paste content of FR0 and CR0 was intentionally kept constant for the comparison purpose. In the medium-strength SCC pavement mix (SR0), cement, fly ash and silica fume were used as ternary blend in the proportion of 70%, 25% and 5%, respectively. The grade of concrete was targeted for a cube compressive strength of 50 MPa and the paste content was kept constant as in CR0 and FR0. Another companion medium-strength SCC (MR0) was obtained by volumetrically replacing silica fume with metakaolin at the same proportions (5%) in the SR0 mixes. The changes in the behaviour of the SCCs across the grade of concrete was attributed to the presence of relative proportions of the various SCMs. In all the four designed mixes of SCC (CR0, FR0, SR0 and MR0), the NCAs were replaced with the RCAs at 50% and 100% by volume of the total coarse aggregates. This corresponds to the design of control SCCs (CR0, CR50, and CR100), normal-strength SCCs (FR0, FR50 and FR100), medium-strength SCCs containing silica fume (SR0, SR50, and SR100) and medium-strength SCCs containing metakaolin (MR0, MR50, MR100). The four SCC mixes made with natural coarse aggregates will be considered as control concrete for the SCCs made with the coarse recycled aggregates for the comparison purpose. The change in behaviour of SCC within a series or grade of concrete was attributed to the relative proportions of the recycled aggregates. The mix proportion of the designed SCCs is shown in Table 3.

### 3.3. Mixing and casting procedure

All the SCC pavement mixes were produced in a tilting-drum type mixer. The mixing sequence, mixing time, temperature and humidity were kept nominally unchanged during the casting pro-

**Table 1**
Measured properties of Portland cement, fly ash, metakaolin, and silica fume.

| Parameter | Cement | Fly ash | Metakaolin | Silica fume |
|---|---|---|---|---|
| CaO (%) | 65.31 | 3.71 | 0.88 | 1.86 |
| $SiO_2$ (%) | 15.03 | 59.12 | 57.31 | 92.13 |
| $Al_2O_3$ (%) | 5.15 | 27.12 | 33.28 | 0.80 |
| $Fe_2O_3$ (%) | 3.93 | 4.78 | 3.59 | 1.27 |
| MgO (%) | 4.05 | 0.58 | 0.19 | 0.21 |
| $SO_3$ (%) | 2.65 | 0.21 | 0.32 | 0.56 |
| $K_2O$ (%) | 0.71 | 2.28 | 0.45 | 0.86 |
| $Na_2O$ (%) | 0.59 | 0.10 | 0.37 | 0.35 |
| Specific gravity | 3.15 | 2.34 | 2.62 | 2.10 |
| Specific surface area ($m^2$/kg) | 305 | 328 | 14,112 | 20,050 |

**Table 2**
Measured physical and mechanical properties of the aggregates.

| Aggregate | Bulk density (kg/m$^3$) | Water absorption (%) | Specific gravity | Fineness modulus | ACV[a] (%) | AIV[b] (%) | Residual mortar (%) |
|---|---|---|---|---|---|---|---|
| NCA | 1725 | 0.65 | 2.70 | 6.42 | 18.23 | 18.12 | – |
| RCA | 1685 | 4.01 | 2.48 | 6.42 | 26.25 | 24.31 | 41.33 |
| FA | 1693 | 1.11 | 2.64 | 2.73 | – | – | – |

[a] Aggregate Crushing Value.
[b] Aggregate Impact Value.


**Fig. 1.** Typical sample of the coarse aggregates (a) NCAs; (b) RCAs.

cedure. The casting procedure followed in the present research was supported by the available literature [59,60]. The fine and the coarse aggregates were dry-mixed for 30 s followed by the addition of one-third of the total water for one minute after which all the ingredients were allowed to rest for one minute. Subsequently, cement and the SCM(s) were added and mixing was continued for another minute after which the next one-third of water was introduced in the mixer followed by another 2 min of mixing. Afterward, the remaining one-third of the total water mixed with the HRWRA and the VMA was poured into the mixer and the constituents were allowed to mix for 2 min. After completion of this round of mixing, the ingredients in the mixer were left to rest for 2 min and at the end, after another 2 min of mixing, the production of the SCC mix stood completed. The stepwise procedure of mixing the SCC is illustrated with the help of a flow chart as shown in Fig. 3.

### 3.4. Test program

#### 3.4.1. Fresh state properties

Fresh state properties of the considered SCC mixes were evaluated in compliance with the guidelines of the EFNARC 2002 and EFNARC 2005 [2,61]. The behaviour of fresh concrete to ensure its filling ability, passing ability and segregation resistance was measured in terms of Slump flow diameter, V-funnel time, L-box blocking ratio and U-box filling height. Slump flow test measures the ultimate spread diameter (Slump flow diameter) and time taken to reach first 500 mm spread ($T_{500mm}$) using Abram's cone to determine the filling ability of the SCCs. V-funnel test just after mixing measures the filling ability of concrete in terms of time ($V_f$) required to flow the concrete through the funnel apparatus. Segregation resistance of the SCC was measured using V-funnel test after 5 min of the rest period ($V_{f5min.}$). L-box blocking ratio and U-box height difference was measured to ensure the passing ability of the considered SCCs. The fresh density of all the designed mixes was evaluated as per ASTM C138 [62].

#### 3.4.2. Mechanical properties

Mechanical properties of both the grades of the SCC were evaluated in terms of its compressive strength, split-tensile strength and flexural strength. Typical test configuration and setup for the measurement of mechanical behaviour of the SCCs is presented in Figs. 4 and 5, respectively. Compressive strength of the cubical specimens of size 150 mm × 150 mm × 150 mm was measured after 1, 3, 7, and 28 days of moist curing according to IS 516 [63]. The tensile strength of the concrete was determined at 28 days in terms of split-tensile strength using cylindrical specimens of size 150 mm × 300 mm as per IS 5816 [64]. Concrete pavements are mainly designed based on the flexural strength determined at 28 days of water curing. Owing to this, the flexural strength of the considered SCC pavement mixes was determined after 28 days of moist curing using the four-point bending test on the prism specimens of size 100 mm × 100 mm × 500 mm, in accordance with IS 516 [63]. Three replicates were cast and tested in the present study for each mechanical characterization.

#### 3.4.3. Water absorption and permeable voids

Water absorption and permeable voids of both the grades of the hardened SCC were evaluated using the cores extracted from the cylindrical specimens after 28 days of moist curing. The cores were extracted with the help of a concrete core cutter and the tests were conducted after 28 days of water curing as per the procedure recommended in ASTM C642 [65].

#### 3.4.4. Quality control parameters

For CRCP pavements, quality control parameters are generally less owing to difficulty in the extraction of cores due to the presence of reinforcing bars. Keeping the same in mind, Rebound

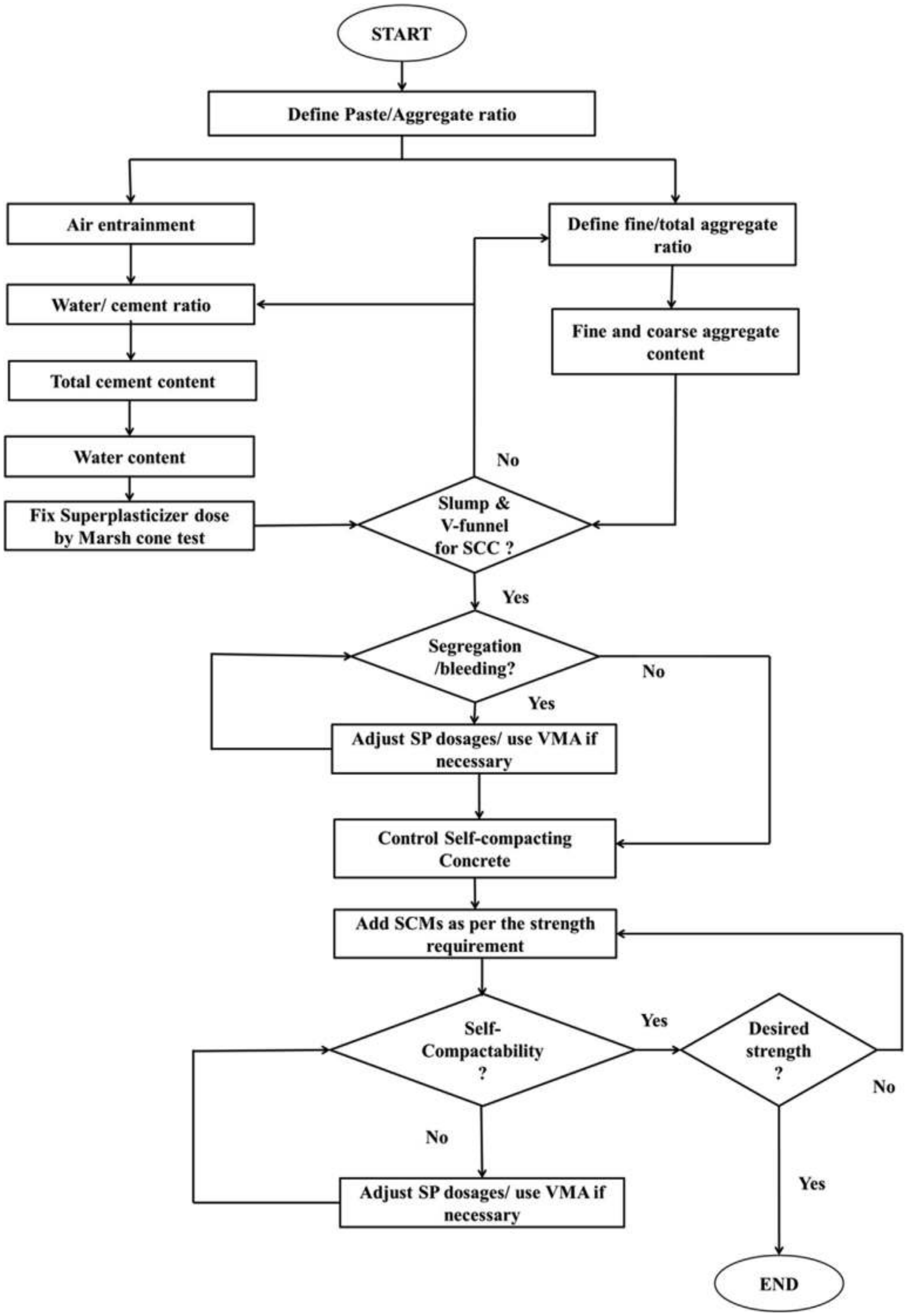


**Fig. 2.** Flow chart of the mix design approach.

Hammer test which is easy to perform in the field conditions to ascertain the quality of SCC-CRCP pavement was considered for the study. In addition, for determining the homogeneity and surface characteristics, another Non-Destructive Test (NDT) i.e. Ultrasonic Pulse Velocity (UPV) was adopted. The Rebound hammer test was performed on the concrete cubes of SCC using an N-type hammer as per the codal provisions of IS 13311(Part 2) [66]. The UPV test was performed on the opposite faces of the cubical specimens according to IS 13311(Part 1) [67]. Both the UPV and the Rebound hammer tests were performed after 28 days of water curing.

## 4. Results and discussion

### 4.1. Fresh properties

The measured fresh properties of the different grades of the SCC pavement mixes are summarized in Table 4. All the considered SCC pavement mixes were designed for a target slump flow of 735 ± 20 mm and the dosage of HRWRA was adjusted accordingly to achieve the desired workability. It was observed that the dosages of the HRWRA increased with an increase in the grade of the SCC which is attributed to the presence of ternary cementi-

**Table 3**
Mix proportions of different grades of the SCC containing RCAs.

| Series | Mix ID | Constituents | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Powder content ($kg/m^3$) | Cement ($kg/m^3$) | Fly ash ($kg/m^3$) | Metakaolin ($kg/m^3$) | Silica fume ($kg/m^3$) | FA ($kg/m^3$) | NCA ($kg/m^3$) | RCA ($kg/m^3$) | HRWRA[a] | w/p[b] |
| Control concrete | CR0 | 624 | 624 | – | – | – | 798.60 | 668.25 | 0 | 0.40 | 0.34 |
| | CR50 | 624 | 624 | – | – | – | 798.60 | 334.12 | 306.90 | | |
| | CR100 | 624 | 624 | – | – | – | 798.60 | – | 613.80 | | |
| Normal-strength concrete | FR0 | 576 | 288 | 288 | – | – | 798.60 | 668.25 | 0 | 0.27 | 0.34 |
| | FR50 | 576 | 288 | 288 | – | – | 798.60 | 334.12 | 306.90 | | |
| | FR100 | 576 | 288 | 288 | – | – | 798.60 | – | 613.80 | | |
| Medium-strength concrete | SR0 | 592 | 414 | 148 | – | 30 | 798.60 | 668.25 | 0 | 0.44 | 0.34 |
| | SR50 | 592 | 414 | 148 | – | 30 | 798.60 | 334.12 | 306.90 | | |
| | SR100 | 592 | 414 | 148 | – | 30 | 798.60 | – | 613.80 | | |
| | MR0 | 596 | 417 | 149 | 30 | – | 798.60 | 668.25 | 0 | 0.44 | 0.34 |
| | MR50 | 596 | 417 | 149 | 30 | – | 798.60 | 334.12 | 306.90 | | |
| | MR100 | 596 | 417 | 149 | 30 | – | 798.60 | – | 613.80 | | |

[a] Percentage by mass of total powder content.
[b] Water by powder (Portland Cement + SCMs) ratio.

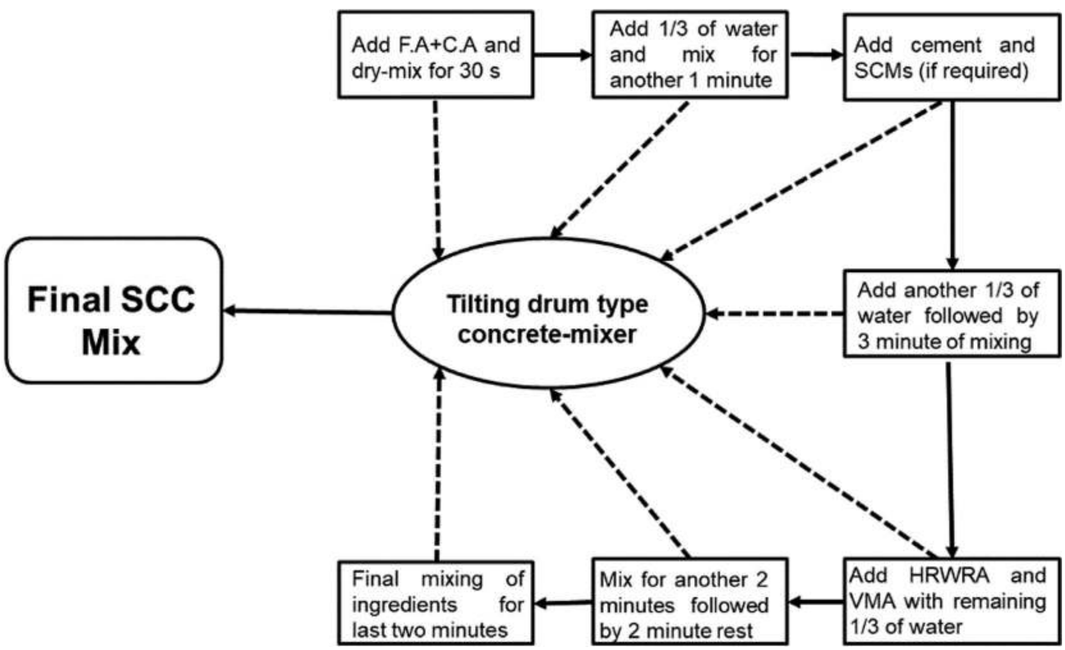


**Fig. 3.** Mixing procedure for the SCC pavement mixes.

tious blends in the higher concrete grades. However, the dosage of HRWRA remained the same when natural aggregates were replaced with the Recycled aggregates. The VMA was introduced in the SCCs to obtain a stable mix free from the segregation and the bleeding. The amount of VMA was fixed at 0.3% by trial and error for all the considered SCCs. It was observed that the measured values of the slump in all the four series of the SCCs (CR, FR, SR and MR series) increased with an increase in the RCA incorporation level. This increase in flow is mainly attributed to the higher water absorption of the RCA particles which squeezes out water to the mix when used in SSD moisture state and increases the effective water/powder ratio during the mixing procedure. According to Poon et al. [11], the initial free water-content and the moisture state of the aggregate particles in the concrete mixes significantly affect the initial slump of the concrete. The higher initial slump and quicker slump loss was observed in case of the aggregates used in oven dried moisture state whereas the particles used in the SSD moisture state shows the normal initial slumps and the slump losses. Mefteh et al. [68] suggested the use of RCA in the pre-wetting and the SSD moisture state to improve the workability of concrete. All the self-compactability parameters of the designed SCCs such as V-funnel time, $T_{500mm}$ time, L-box ratio and U-box height were in compliance with the recommendations of EFNARC 2002 and EFNARC 2005 [2,61] but no clear trend (except for the slump) was observed in their measured values.

The fresh density of the considered SCCs was in the range of 2200–2500 $kg/m^3$ and decreased with an increase in the RCA replacement level, Fig. 6. Within a grade (CR-series, FR-series, SR-series and MR-series), the maximum decrease in fresh density with complete replacement of the NCAs with the RCAs was not more than 5% in any case. According to Kou and Poon [69], the wet density of the SCCs decreases with incorporation of the fine recycled aggregates and this was attributed to the difference between the specific gravity of fine recycled aggregates and natural sand. Grdic et al. [18] confirmed a decrease of 3.40% when all the natural coarse aggregates of the SCC were replaced with the coarse recycled aggregates. This decrease in the fresh density was attributed to the porousness of recycled aggregates due to adhered mortar content.

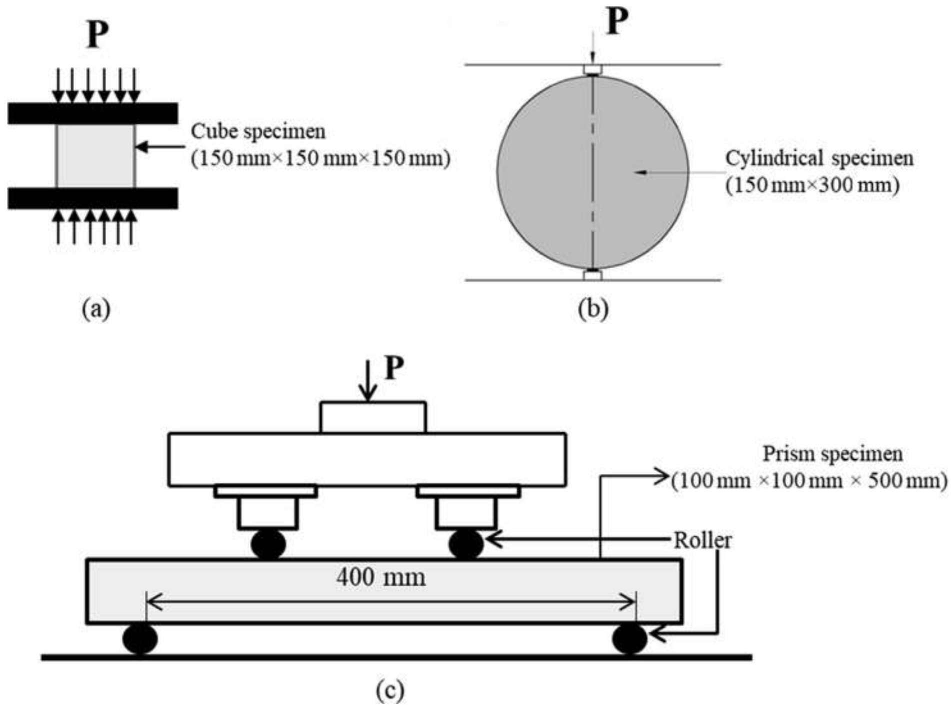


**Fig. 4.** Configuration of test setup for the (a) Compressive strength; (b) Split-tensile strength; (c) Flexural strength.

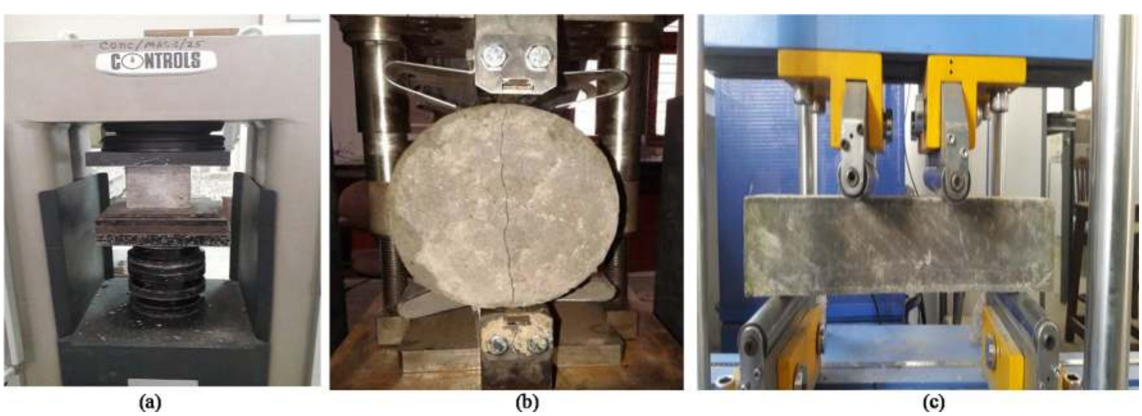


**Fig. 5.** Test setup for the (a) Compressive strength; (b) Split-tensile strength; (c) Flexural strength.

**Table 4**
Measured fresh properties of different grades of the SCC containing RCAs.

| Group | Mix ID | Slump (mm) | $T_{500mm}$ (s) | $V_f$(s) | $V_{f5min}$(s) | L-Box ratio | U-Box (mm) |
|---|---|---|---|---|---|---|---|
| | | Acceptable range as per EFNARC 2002 [61] & EFNARC 2005 [2] | | | | | |
| | | (550–850) | (2–5) | (<25 s) | (<25 s) | (0.8–1) | (0–30) |
| Control SCCs | CR0 | 725 | 2.1 | 6.1 | 7.5 | 0.86 | 9 |
| | CR50 | 733 | 2.7 | 6.8 | 9.8 | 0.85 | 14 |
| | CR100 | 745 | 2.5 | 7.9 | 9.9 | 0.83 | 17 |
| Normal-strength SCCs | FR0 | 735 | 2.3 | 7.0 | 9.5 | 0.93 | 15 |
| | FR50 | 745 | 2.6 | 8.5 | 10.8 | 0.85 | 11 |
| | FR100 | 755 | 2.8 | 8.6 | 11.2 | 0.88 | 17 |
| Medium- strength SCCs | SR0 | 725 | 3.0 | 6.1 | 8.0 | 0.87 | 19 |
| | SR50 | 732 | 3.2 | 6.5 | 8.1 | 0.84 | 23 |
| | SR100 | 740 | 3.0 | 6.0 | 8.8 | 0.88 | 24 |
| | MR0 | 718 | 2.2 | 7.3 | 9.5 | 0.89 | 20 |
| | MR50 | 733 | 2.2 | 7.5 | 9.8 | 0.90 | 10 |
| | MR100 | 748 | 2.0 | 7.0 | 9.1 | 0.91 | 7 |

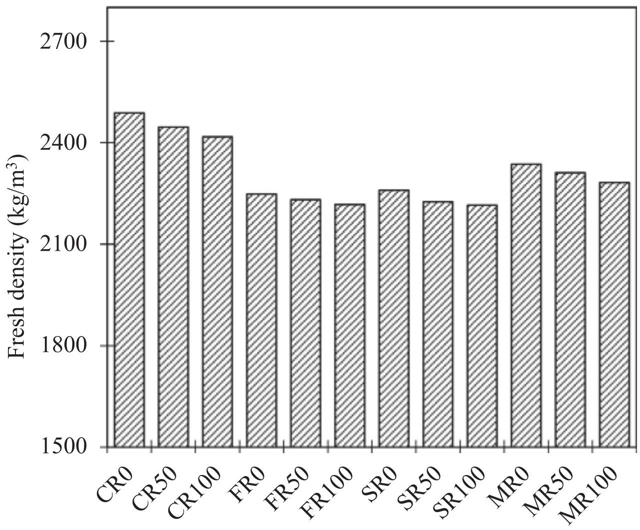


**Fig. 6.** Measured fresh density of different grades of the SCC.

### *4.2. Compressive strength*

Compressive strength of two grades of the SCC along with the control SCC mixes at 28-days of curing is presented in Fig. 7. The trends in compressive strength are decreasing with increase in the RCA replacement level. For example, the compressive strength of the medium-strength SCC (MR0) was 55 MPa which decreased to 52 MPa when all the NCAs in the MR0 were replaced with the RCAs. It may be noted that although a decreasing trend was observed in all the designed SCCs with incorporation of the recycled aggregates, this decrease was not significant in any case and was less than 7% for all the considered mixes. The decrease in compressive strength on the complete replacement of NCA with the RCA was approximately 7%, 3%, 5% and 4% for CR-series, FR-series, SR-series and MR-series of the SCCs, respectively. The results of the present study explore the possible use of the RCA in the SSD moisture state for the production of the normal- and the medium-strength SCCs. Further review of the results indicates that the compressive strength of the control concretes (CR-series) was more than that of the medium-strength SCCs made with both silica fume and metakaolin. The application of these control concretes in place of the medium-strength SCCs is restricted due to its high cement content (654 kg/m$^3$) which makes it unsuitable for use in paving practices as per the durability aspect of concrete pavements are concerned. It may also be noted from Fig. 7 that compressive strength of the companion medium-strength SCCs made with metakaolin shows somewhat higher compressive strength relative to the SCCs made with the silica fume. For the concretes made with natural aggregates, a similar behaviour with respect to these two mineral admixtures was reported by Guneyisi et al. [43] and Hassan et al. [50].

Mefteh et al. [68] investigated the effect of three different moisture state of the RCAs on the compressive strength of the concrete. They reported the dry moisture state of the RCA as the best choice to utilize in the production of the quality hardened concrete. Tuyan et al. [70] also suggested that the incorporation of coarse recycled aggregates up to 60% in the production of self-compacting concrete is feasible without any considerable loss in the mechanical strength of the concrete. They used coarse RCA particles in the saturated surface dry moisture state. Meanwhile, Wang [71] reported a decrease of more than 20% in the compressive strength of the SCC when all the NCAs were replaced with the air dried coarse recycled aggregates. A limited number of studies are carried out which suggests the complete utilization of recycled aggregates in the production of SCC without compromising their mechanical properties.

The minimum compressive strength requisition for a concrete pavement to accommodate high intensity traffic is 40 MPa at 28 days of curing age. Based on the findings from this study, the complete utilization of coarse recycled aggregates in the SSD moisture state may be suggested with the help of a rational mix design approach to develop the normal- and the medium-strength SCC pavement mixes.

### *4.3. Strength development*

The strength development of two grades of the SCCs with respect to the time of curing is presented in Fig. 8. It is clear from the figure that up to 3 days of curing, the rate of gain of strength for all the designed SCCs was similar. The highest rate of gain of strength was observed during the period of 3–7 days of curing which is irrespective of the grade of the SCC and the replacement levels of the RCA. The slope of the lines during this curing period (3–7 days) was significantly lower in case of the normal-strength SCCs relative to the medium-strength SCCs. This decrease in the rate of gain of strength is attributed to the presence of fly ash as a binary cementitious blend in the SCC. A similar trend was observed with respect to the rate of gain of strength of the SCCs

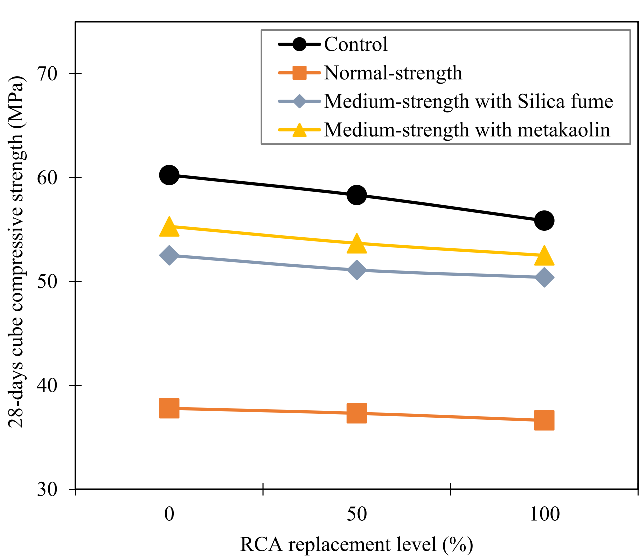


**Fig. 7.** Twenty-eight days cube-compressive strength of different grades of the SCC.

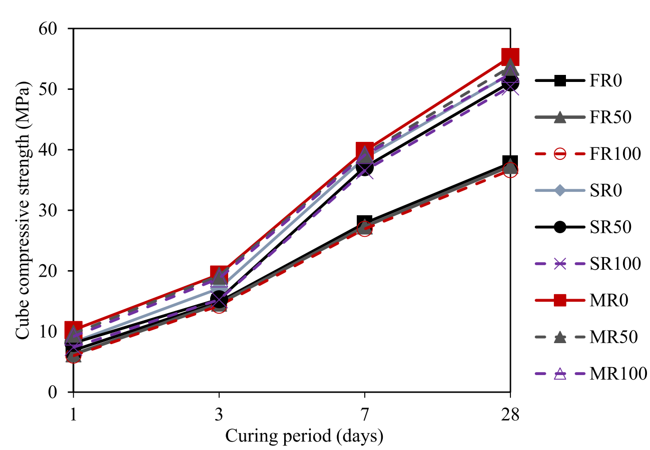


**Fig. 8.** Strength development of different grades of the SCC.

beyond 7-days of the curing. It may however be noted that for all the designed SCCs, the slope of the lines for the concrete made with and without RCA was more or less similar, which shows that rate of gain of strength remains same even when all the NCAs were replaced with the RCAs.

### *4.4. Split-tensile and flexural strength*

Measured values of the split-tensile and the flexural strength (at 28 days of curing age) of different grades of the SCC containing RCA are presented in Fig. 9. Amongst the control groups, the CR0 mix showed the highest strength which is attributed to the higher cement consumption by the mix in comparative to other mixes. Meanwhile, metakaolin was found to be the most superior amongst the studied SCMs. From Fig. 9a, it was observed that MR0 showed better strength followed by SR0 and FR0 mixes, respectively. The low performance of the FR0 mix is due to the slow strength development of fly ash particles at early ages. On the other hand, the incorporation of RCA was found to reduce the split tensile and flexural strength of the SCCs mixes (see Fig. 9b and c). For instance, the test results indicate a decrease in both the spilt-tensile and the flexural strength values with incorporation of the RCAs. The decrease in split-tensile strength on the complete replacement of NCAs with RCAs was about 11% and 7% corresponding to the normal- and the medium-strength SCCs, respectively. In case of the flexural strength of the SCCs, the decrease was not more than 4% in any case when all the NCAs were replaced with the RCAs. Results from the investigation are indicative of the utilization of RCA particles in the production of different grades of the SCC without compromising the mechanical behaviour of the concrete. Further review of the results indicates an increase in both the split-tensile and the flexural strength of the medium-strength SCCs relative to the normal-strength SCCs. This improved mechanical behaviour across the grade of concrete is attributed to the presence of silica fume and metakaolin when used as a ternary cementitious blend in the SCCs. Both silica fume and metakaolin has been reported to enhance to the mechanical and durability properties of concrete mixtures owing to rich reactive silica content. During the secondary pozzolanic reaction, this reactive silica reacts with the unreacted calcium hydroxide and produces additional calcium-hydrate-silicate phases which is responsible for contributing to the strength development. Moreover, the higher surface area characteristics of both silica fume and metakaolin may also have contributed to the pore refinement of the SCC mixes containing silica fume and metakaolin. Furthermore, the presence of alumina in Metakaolin was also detected by X-Ray Fluorescence Spectrometer and these alumina particles might have also reacted with the calcium hydroxide, resulting in more pore refinement, dense ITZ and microstructure of the SCC mixes containing metakaolin. Moreover, in the presence of calcite, the alumina particles might have reacted to form monocarboaluminate and hemicarboaluminate and contributed towards space filling and thus to concrete strength.

Concrete pavements are designed taking into consideration the flexural strength obtained after 28 days of curing age. For pavements that are to serve high intensity traffic, the minimum flexural strength requirement at the same curing age is 4.5 MPa [72]. With respect to this value, all the series of SCCs met this benchmark and hence could be suggested for the production of RCA incorporated SCC pavement mixes. However, flexural strength values of medium grade SCCs containing both silica fume and metakaolin were noted to be considerably higher than the requirement of an M40 grade

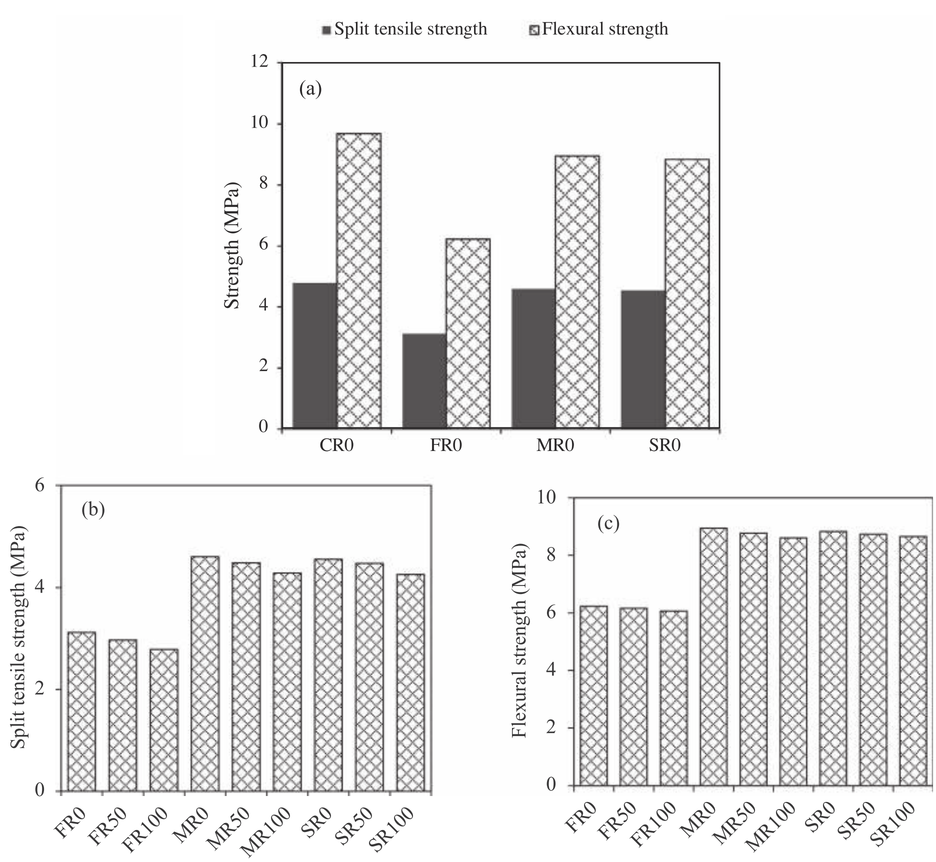


**Fig. 9.** (a) Split-tensile and flexural strength of control group (b) Split-tensile and (c) flexural strength of different grades of the SCC.

concrete. Silica fume being an expensive material may not seem the best option to be utilized along with a higher cement content, for the production of SCC pavement mixes. On the other hand, the normal grade SCC mixes that contain fly ash particles could prove to be the best option owing to its lower cement content (305 kg/$m^3$) in the combination of 100% recycled concrete aggregates would further result in a sustainable SCC pavement.

### 4.5. Relationship between compressive and flexural strength

It is well known that there exists a power equation between the compressive and flexural strength of concrete mixes. As per IS:456 [73], this equation is $f_r = 0.7\sqrt{f_{ck}}$, where $f_{ck}$ is the compressive strength at 28 days and $f_r$ is the target flexural strength at the same curing age. A linear relationship was established between the experimental compressive and flexural strength that was obtained at 28 days of age and is presented in Fig. 10. It can be seen that the established equation overestimates the flexural strength based on the experimental compressive strength which strongly indicates that the inclusion of the studied materials (Recycled concrete aggregates, fly ash, silica fume, and metakaolin) affects the hardened properties of the SCC pavement mixes.

### 4.6. Statistical analysis

Analysis of Variance (ANOVA) was carried out to recognize the effects of RCA, fly ash, and silica fume on the fresh density ($D$), compressive strength ($f_{ck}$), flexural strength ($f_r$), and split tensile strength ($f_{st}$) of the studied SCC pavement mixes which is presented in Table 5. Afterwards, a regression analysis was performed and relationships were established to realize the effects of incorporating these materials in the studied SCC pavement mixes and is being tabulated in Table 6. The most important parameters in the analysis of variance are the $f$-values and the $p$-values. These values represent whether the means of a given population within groups are significantly different from each other and how well the model fits the observed data. A typical flowchart of ANOVA is shown in Fig. 11. The ANOVA and regression analysis were performed using Minitab software, a statistical software tool designed for easy interactive use. From Table 5, it can be seen that the $f$-values are greater than the $f$-critical with $p$-values smaller than the alpha level (0.05). This indicates that the RCA content, cement content, fly ash, and silica fume affect density, compressive strength, flexural strength, and split tensile strength of the SCC pavement mixes. This behaviour may be due to the porous adhered mortar present in the surface of the RCA particles which may have resulted in a weaker ITZ and contributing in a negative effect on the concrete properties. A few higher $p$-values and lower $f$-values were also noted but this probably may be due to some random errors (sampling errors) or there may be some systematic effects that causes the mean in one group to differ from the mean in another. Although the incorporation of these waste materials has some effect on the strength of the SCC, this effect was observed to be less detrimental with not more than 11% variation between the strength properties of SCC made with conventional materials and SCC made with waste materials. However, more studies need to be taken up to come to a strong and universal conclusion pertaining to the effects of the considered waste materials in the production of SCC-CRCP mixes.

To further explore the effects of incorporating the studied materials, a statistical relationship was established by linear regression analysis using Minitab software tool and is shown in Table 6. It is to be noted that the software was not able to provide any realization on the effect of incorporating Metakaolin on the SCC pavement mixes. Hence, the only considered variants in the linear relationship were cement content, RCA content, fly ash, and silica fume content. Based on the established relationships (Eq. (1), Table 6), it can be realized that adding these materials have an inverse effect on the studied properties of the SCCs when compared to the control mixes. This is probably due to incorporation of RCA particles, the presence of porous adhered mortar on the RCA particles results in a weaker adhesion between the aggregate and the mortar paste, and is the main cause of strength reduction. However, the incorporation of silica fume was noted to show a much prominent effect on the strength of the SCCs mainly due to the densification of the microstructure by the additional C-S-H gels formed during the secondary pozzolanic reaction. On the other hand, the utilization of lower cement content and the slow hydration process of the fly ash particles may have contributed to the lowest strength in the normal grade SCCs.

Based on the established models, the predicted model values of $D$, $f_{ck}$, $f_r$, and $f_{st}$ were obtained and plotted against the experimental values as show in Fig. 12. As can be seen, the scatterplot between the experimental and modelled values follows a well fitted line with the goodness of fit being greater than 0.99. To check the reliability of the goodness of fit of the established models, the Kolmogorov-Smirnov Normality test was performed on the residuals of the predicted models. This test evaluates the null hypothesis

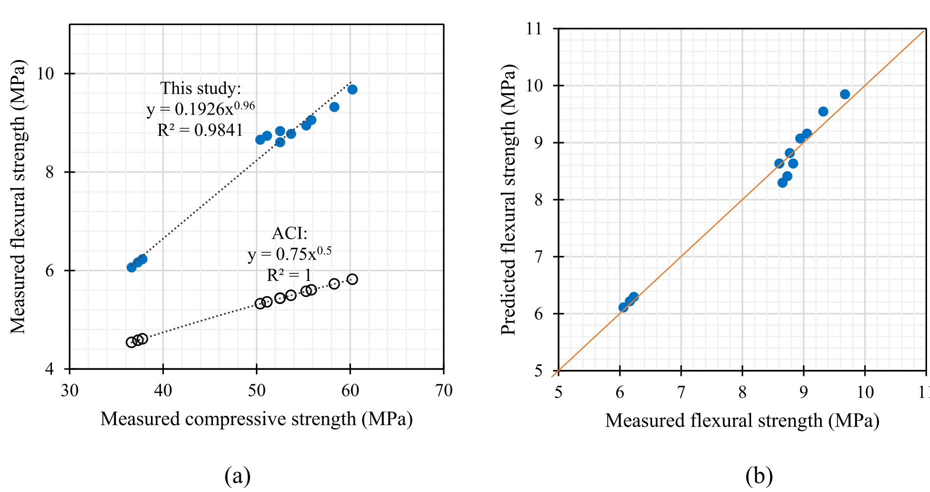


**Fig. 10.** (a) Fitted line plot for compressive and flexural strength, and (b) Scatterplot comparing the experimental and predicted values of flexural strength.

**Table 5**
ANOVA test results.

| | Source of variation | df | Adj. SS | Adj. MS | *f*-value | *p*-value | *f*-critical |
|---|---|---|---|---|---|---|---|
| Density | Cement content | 3 | 1660 | 1660.3 | 20.93 | 0.003 | 3.5874 |
| | RCA content | 2 | 5000 | 5000 | 63.03 | 0.000 | 3.9823 |
| | Fly ash | 2 | 54 | 53.6 | 0.68 | 0.000 | 3.9823 |
| | Silica Fume | 1 | 7143 | 7142.6 | 90.03 | 0.000 | 4.8443 |
| | Error | 7 | 555 | 79.3 | | | |
| | Total | 11 | 100,506 | | | | |
| Compressive strength | Cement content | 3 | 30.495 | 30.495 | 72.71 | 0.000 | 3.5874 |
| | RCA content | 2 | 13.676 | 13.676 | 32.61 | 0.001 | 3.9823 |
| | Fly ash | 1 | 74.509 | 74.509 | 177.65 | 0.000 | 3.9823 |
| | Silica Fume | 1 | 4.721 | 4.721 | 11.26 | 0.012 | 4.8443 |
| | Error | 7 | 2.936 | 0.419 | | | |
| | Total | 11 | 752.409 | | | | |
| Flexural strength | Cement content | 3 | 2.1152 | 2.11516 | 216.03 | 0.000 | 3.5874 |
| | RCA content | 2 | 0.2129 | 0.21288 | 21.74 | 0.002 | 3.9823 |
| | Fly ash | 2 | 3.7046 | 3.70458 | 378.36 | 0.000 | 3.9823 |
| | Silica Fume | 1 | 0.0166 | 0.01662 | 1.70 | 0.234 | 4.8443 |
| | Error | 7 | 0.0685 | 0.00979 | | | |
| | Total | 11 | 18.6674 | | | | |
| Split tensile strength | Cement content | 3 | 1.04266 | 1.04266 | 188.03 | 0.000 | 3.5874 |
| | RCA content | 2 | 0.31205 | 0.31205 | 56.27 | 0.000 | 3.9823 |
| | Fly ash | 2 | 1.54393 | 1.54393 | 278.42 | 0.000 | 3.9823 |
| | Silica Fume | 1 | 0.00655 | 0.00655 | 1.18 | 0.313 | 4.8443 |
| | Error | 7 | 0.03882 | 0.00555 | | | |
| | Total | 11 | 5.39629 | | | | |

**Table 6**
Regression results obtained from the study.

| | Source of variation | Coefficients | Standard error coefficient | t-value | p-value |
|---|---|---|---|---|---|
| Density | Constant | 1976 | 107 | 18.40 | 0.000 |
| | Cement content | 0.764 | 0.167 | 4.57 | 0.003 |
| | RCA content | −0.0984 | 0.0124 | −7.94 | 0.000 |
| | Fly ash | 0.159 | 0.193 | 0.82 | 0.438 |
| | Silica Fume | −2.380 | 0.251 | −9.49 | 0.000 |
| Compressive strength | Constant | 127.17 | 7.81 | 16.29 | 0.000 |
| | Cement content | −0.1036 | 0.0121 | −8.53 | 0.000 |
| | RCA content | −0.005145 | 0.000901 | −5.71 | 0.001 |
| | Fly ash | −0.1870 | 0.0140 | −13.33 | 0.000 |
| | Silica Fume | 0.0612 | 0.0182 | 3.35 | 0.012 |
| Flexural strength | Constant | 27.35 | 1.19 | 22.93 | 0.000 |
| | Cement content | −0.02727 | 0.00186 | −14.70 | 0.000 |
| | RCA content | −0.000642 | 0.000138 | −4.66 | 0.002 |
| | Fly ash | −0.04170 | 0.00214 | −19.45 | 0.000 |
| | Silica Fume | −0.00363 | 0.00279 | −1.30 | 0.234 |
| Split tensile strength | Constant | 17.205 | 0.897 | 19.17 | 0.000 |
| | Cement content | −0.01915 | 0.00140 | −13.71 | 0.000 |
| | RCA content | −0.000777 | 0.000104 | −7.50 | 0.000 |
| | Fly ash | −0.02692 | 0.00161 | −16.69 | 0.000 |
| | Silica Fume | −0.00228 | 0.00210 | −1.09 | 0.313 |
| Regression models | $D = 1976 + 0.764C - 0.0984\,RCA + 0.159F - 2.380\,S$; $R^2 = 0.994$ | | | | |
| | $f_{ck} = 127.17 - 0.1036C - 0.005145\,RCA - 0.1870F + 0.0612\,S$; $R^2 = 0.996$ Equation 1 | | | | |
| | $f_r = 27.35 - 0.02727C - 0.000642\,RCA - 0.04170F - 0.00363\,S$; $R^2 = 0.996$ | | | | |
| | $f_{st} = 17.205 - 0.01915C - 0.000777\,RCA - 0.02692F - 0.00228\,S$; $R^2 = 0.992$ | | | | |

Note: $D$ = Density (kg/m$^3$); $f_{ck}$ = Compressive strength in MPa; $C$ = Cement content (kg/m$^3$); $RCA$ = Recycled concrete aggregates (kg/m$^3$); $F$ = Fly ash content (kg/m$^3$); $S$ = Silica Fume content (kg/m$^3$).

($H_0$) that the residuals of the predicted models follows the normal distribution. The $H_0$ is usually rejected if the *p*-values of the test are less than the alpha level (0.05 in this case). This means that the residuals of the predicted models do not follow a normal distribution curve. The Kolmogorov-Smirnov normality test compares the empirical cumulative distribution function of sample points with the distribution desired in case the sample points are normal. If this observed difference is sufficiently large, the test will reject the null hypothesis of population normality. It can be realized from Fig. 13 that the p-values of all predicted models ($D$, $f_{ck}$, $f_r$, and $f_{st}$) are greater than the alpha level of 0.05 indicating that the residuals of the predicted models follows the normal distribution in an acceptable manner.

### 4.7. Bulk density

The measured values of the bulk density of the designed SCCs are presented in Fig. 14. Within a given grade of concrete, the bulk density decreased with increase in the amount of the RCAs. This decreasing trend of the bulk density is consistent for all the four series (CR, FR, SR and MR series) of the SCCs and attributed to the difference in specific gravity of the NCAs and the RCAs. The results illustrate that bulk density of all the considered SCCs lies in the range of 2130–2410 kg/m$^3$. It may be noted that trends in the bulk density were not clear across the grade of the SCCs, however, it decreased with incorporation of the SCMs in the FR, SR and MR series relative to the CR-series of the mixes. This decrease is

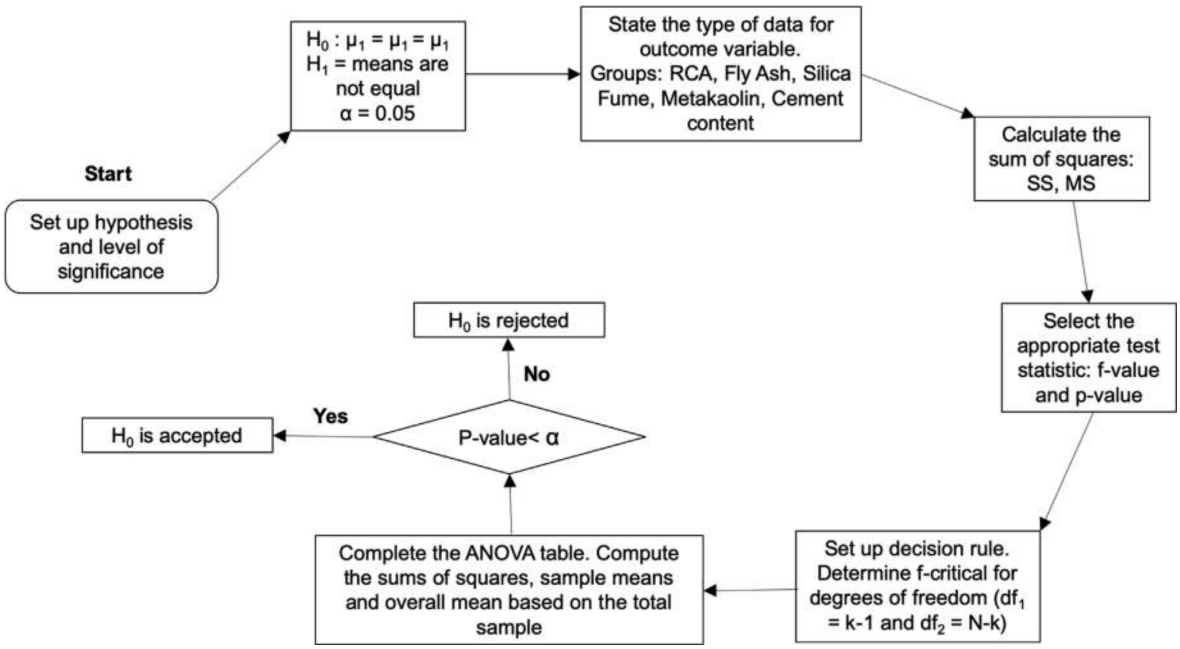


**Fig. 11.** Typical flowchart of ANOVA.

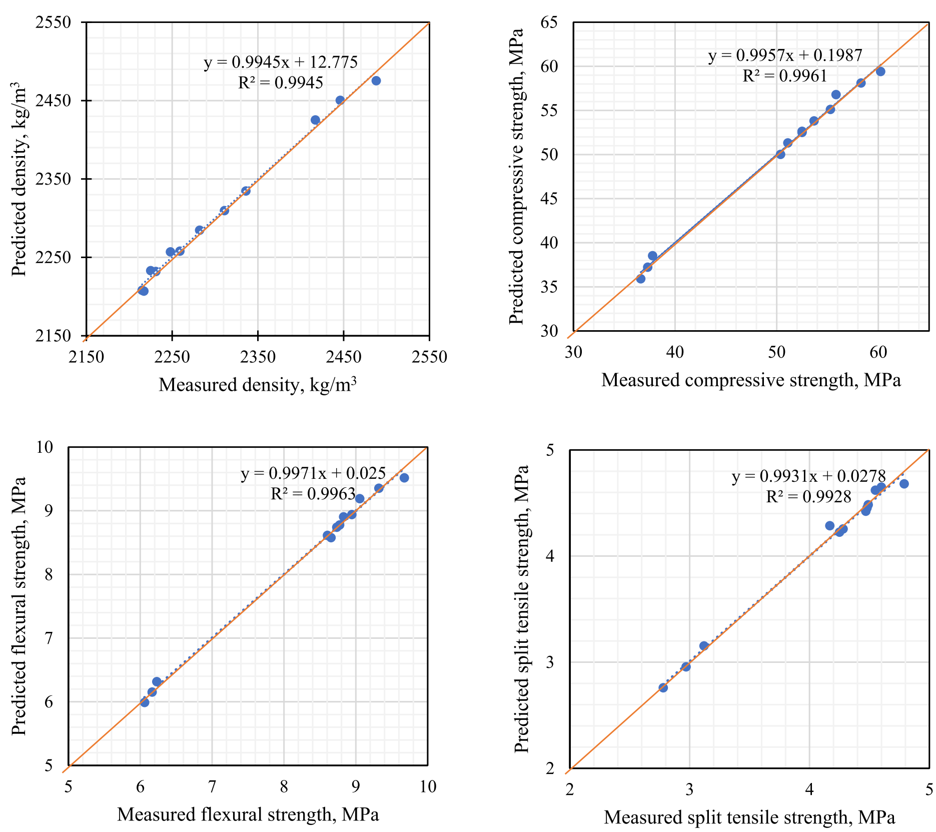


**Fig. 12.** Scatterplot comparing the experimental and predicted values obtained from regression models.

attributed to the lower specific gravity of the considered SCMs relative to that of the Portland cement.

### 4.8. Permeable voids

Permeable voids in different grades of the SCC increased with incorporation of the coarse recycled aggregates as depicted in Fig. 15. This increase is attributed to the porous microstructure of RCA particles due to the adhered mortar content [74]. The increase in permeable voids of the SCC on complete replacement of the NCAs with the RCAs were 41%, 5%, 13% corresponding to the FR, SR and MR series of the mixes, respectively. This percentage increase was minor in case of the medium-strength SCCs made with silica fume (SR-series) and metakaolin (MR-series) which is

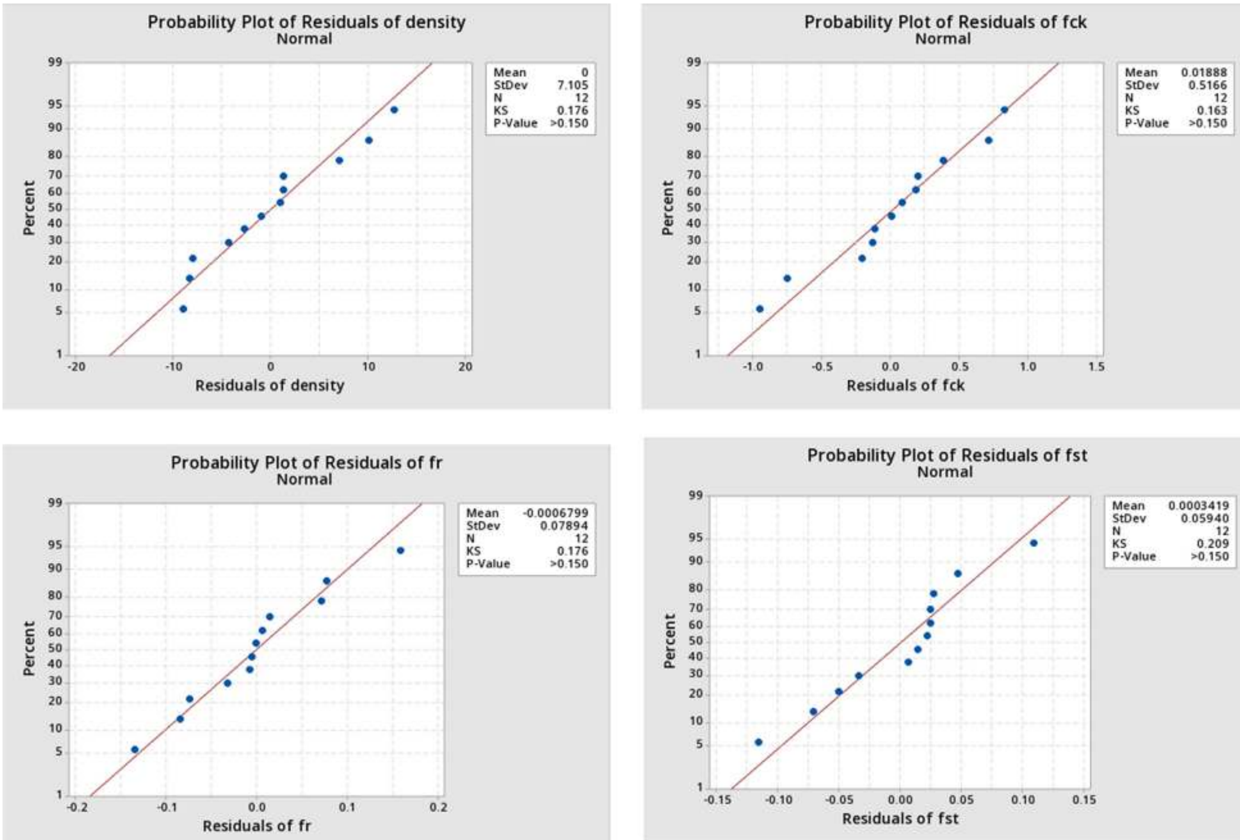


**Fig. 13.** Kolmogorov Smirnov normality test on residuals of predicted models.

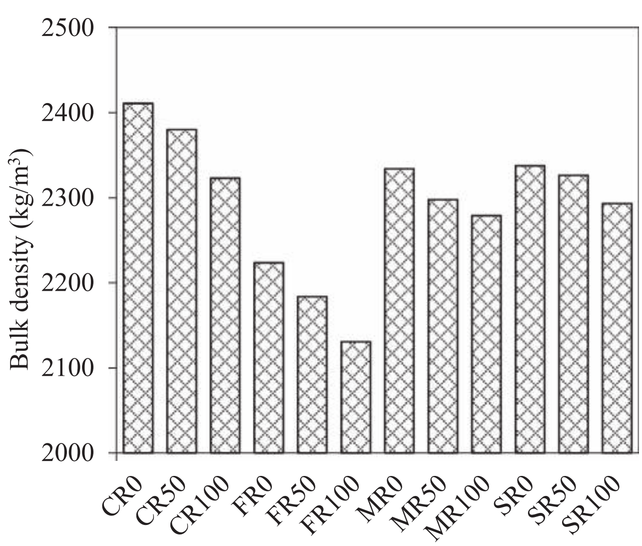


**Fig. 14.** Bulk density of different grades of the SCC.

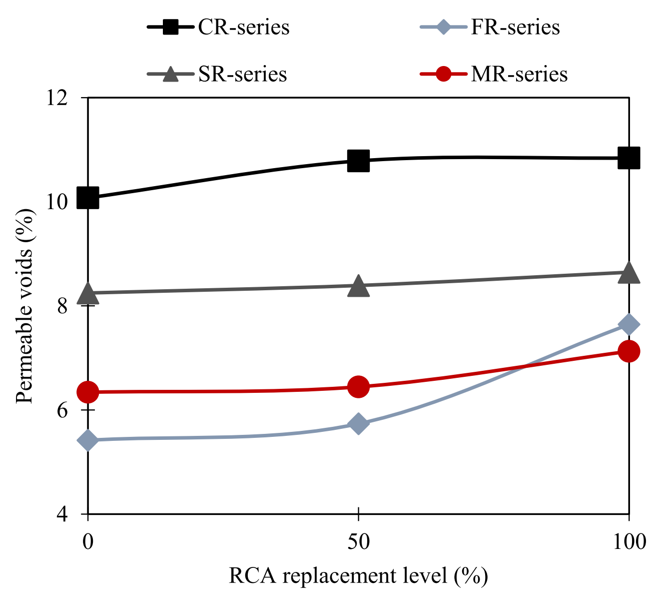


**Fig. 15.** Permeable voids in the different grades of the SCC.

attributed to the micro-filling effect of ultrafine silica fume and metakaolin which densified the porous microstructure of the recycled aggregates [75]. Across the grade of concrete, the permeable voids decreased in the FR, SR and MR series relative to the CR series of the SCCs which is attributed to the presence of different SCMs in these concretes. For example, the permeable voids were more than 10% in case of the mixes of CR-series which decreased to about 5–8% with incorporation of fly ash, silica fume and metakaolin in the normal- and the medium-strength SCCs. A similar trend is also reported in the literature for the SCC made with the natural aggregates [60].

### 4.9. Water absorption

Water absorption of the considered SCCs increased with incorporation of the coarse recycled aggregates as depicted in Fig. 16.

This increase is again attributed to the presence of porous microstructure of the RCA particles. The increase in water absorption of the SCC on complete replacement of the NCAs with the RCAs were 34%, 4%, 15% corresponding to the FR, SR and MR series of the concretes, respectively. This percentage increase was lower in case of the medium-strength SCCs made with silica fume (SR-series) and metakaolin (MR-series) which is similar to the trends observed in case of the permeable voids. Across the grade of concrete, the water absorption decreased in the FR, SR and MR series relative to the CR series of the SCCs which is attributed to the decreased continuous capillary pores due to the presence of different SCMs in these concretes. A similar trend was also observed in the permeable voids of the considered SCCs.

### 4.10. Non-destructive tests

The homogeneity and the surface characteristics of the designed SCCs were measured in terms of the Ultrasonic Pulse Velocity (UPV) and the Rebound Number (RN). The measured values are presented in Fig. 17 which indicates a decrease in the UPV and the RN values with inclusion of the recycled aggregates. Review of the results shows a decrease of less than 5% in the UPV values of the considered SCCs when all the NCAs were replaced with the RCAs. This decrease is attributed to the presence of porous coarse recycled aggregates in the mix which increased the time to travel the ultrasonic waves and thereby decrease the pulse velocities. The decrease in the rebound number of the considered SCCs was not more than 7% in any case when NCAs were replaced with the RCAs. Results of the investigations ensure the homogeneity and soundness of the hardened SCC made with the recycled aggregates.

Measured values of the UPV and the Rebound hammer test are plotted in Fig. 18 which showed a linear best fit between these two parameters with the $R^2$ value equals to 0.89. As illustrated in the figure, a strong linear correlation was also obtained for the compressive strength vs UPV and the compressive strength vs Rebound number. The linear relationships obtained among these parameters were applicable irrespective of the SCC grade and the RCA replacement level. Results of this investigation indicate that both the UPV and the Rebound hammer test corresponds to the quantification of compressive strength of the SCCs containing RCA. It is known that there exists variation within the laboratory concrete strength and the actual in-situ concrete strength due to several factors such as inadequate quality control, variation in the materials utilized in laboratory and on-site, and environmental conditions. Moreover, the presence of heavy reinforcements in CRCP makes it very difficult to obtain prismatic core specimens from the already constructed SCC-CRCP. Owing to this, the application of NDTs such as Ultrasonic Pulse Velocity and Rebound Hammer could prove to be very useful in determining the strength of the SCC-CRCP on-site. Moreover, the equations provided in Fig. 18 could also be adopted to obtain the compressive strength and other properties of concrete from the existing constructed SCC-CRCPs without having the need to test separate specimens cast simultaneously for compressive, flexural, and tensile strengths.

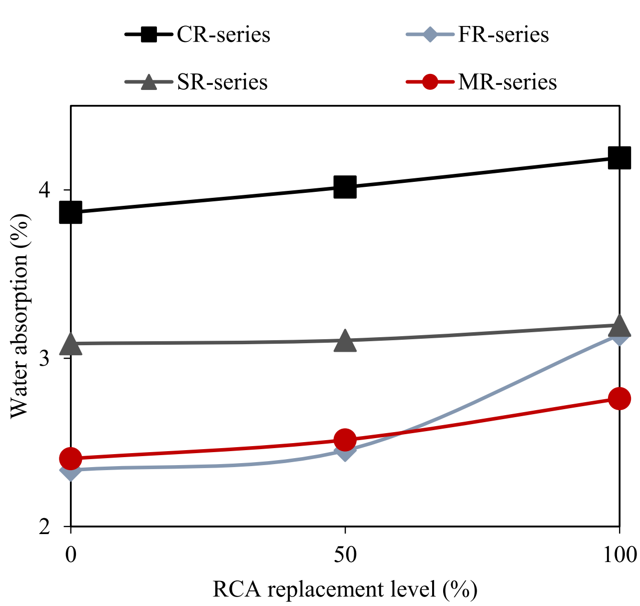


**Fig. 16.** Water absorption of different grades of the SCC.

### 4.11. Cost analysis

The effect of recycled concrete aggregates, fly ash, silica fume, and metakaolin on the material cost for the production of 1 $m^3$ of SCC pavement mix is presented in Table 7. Hence, only the material costs were considered. In addition, the cost of RCA was assumed as zero; however, 1% of the total cost of the mixture was considered as the processing charges of the RCAs. Since, the considered concrete ingredients were procured from the local market, the transportation costs are not included in the analysis. As can be seen, the CR-series, containing NCA aggregates only, incurred the highest cost of about Rs. 5054 per cubic meter of concrete. In the CR-series, most of the cost was incurred by the consumption of Portland cement alone. Replacing Portland cement by silica fume particles in proportion of 5% was able to cut down the total cost by about 12%, in comparison to the CR0 mix. The reduction in material cost was noted to much higher when RCA was incorporated in the SR-series SCCs. For instances, when 100% RCA was incorporated into the SR-series mix, the overall cost of materials was noted to be 9%, 12%, and 2% lower than the SR0, CR0, and CR100 mixes, respectively. Utilizing metakaolin was noted to further lower down the overall cost of the SCC pavement mixes as can be seen in Table 7.

The utilization of silica fume and metakaolin would not only lower down the cost of the project but would also improve the mechanical and durability properties of the SCC pavement mixes. Further incorporation of RCA into this system would certainly incur much lower cost as well as contribute towards eliminating the need of RCA disposal landfills, overall leading to a sustainable development. However, the observed flexural strength of the SR-series and MR-series SCCs was noted to be considerably higher than the minimum requirement flexural strength of 4.5 MPa for a high-grade paving mixture. In such cases, the utilization of fly ash along with RCA proves to be the best option amongst all owing to its low cost and fulfilment of the desired strength requirements for an M40 grade paving concrete. From Table 7, it can be seen that the fly ash incorporated SCC mixes showed the lowest overall cost of about Rs. 2845 to Rs. 3325 per cubic meter of concrete. Conclusively, it can be recommended that utilization of 100% recycled aggregates in combination with 50% fly ash would prove to be best possible solution for the production of self-compacting concrete pavement mixes.

## 5. Special discussion and recommendations

The present study focusses on the feasibility of recycled concrete aggregates, fly ash, silica fume, and metakaolin as a replacement material for the production of self-compacting concrete pavement mixes. Based on the flexural strength criterion, it was observed that all the series (CR-series, FR-series, SR-series, and MR-series) holds great potential to be recommended for concrete

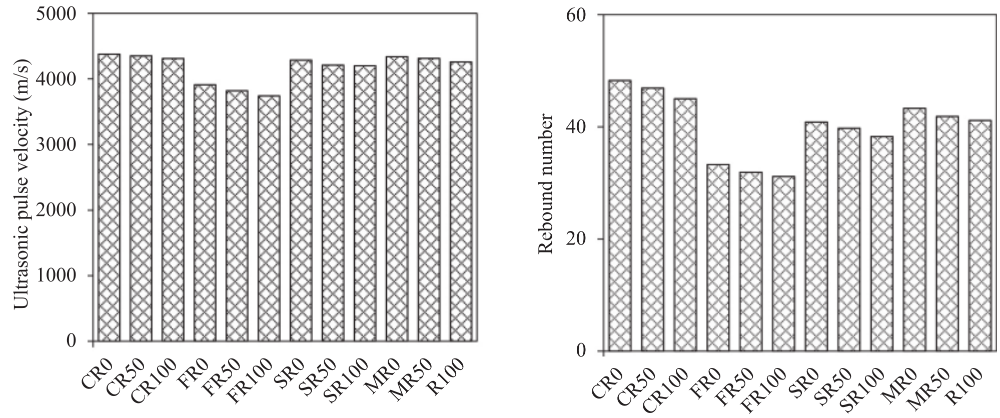


**Fig. 17.** Non-destructive test results of the considered SCCs.

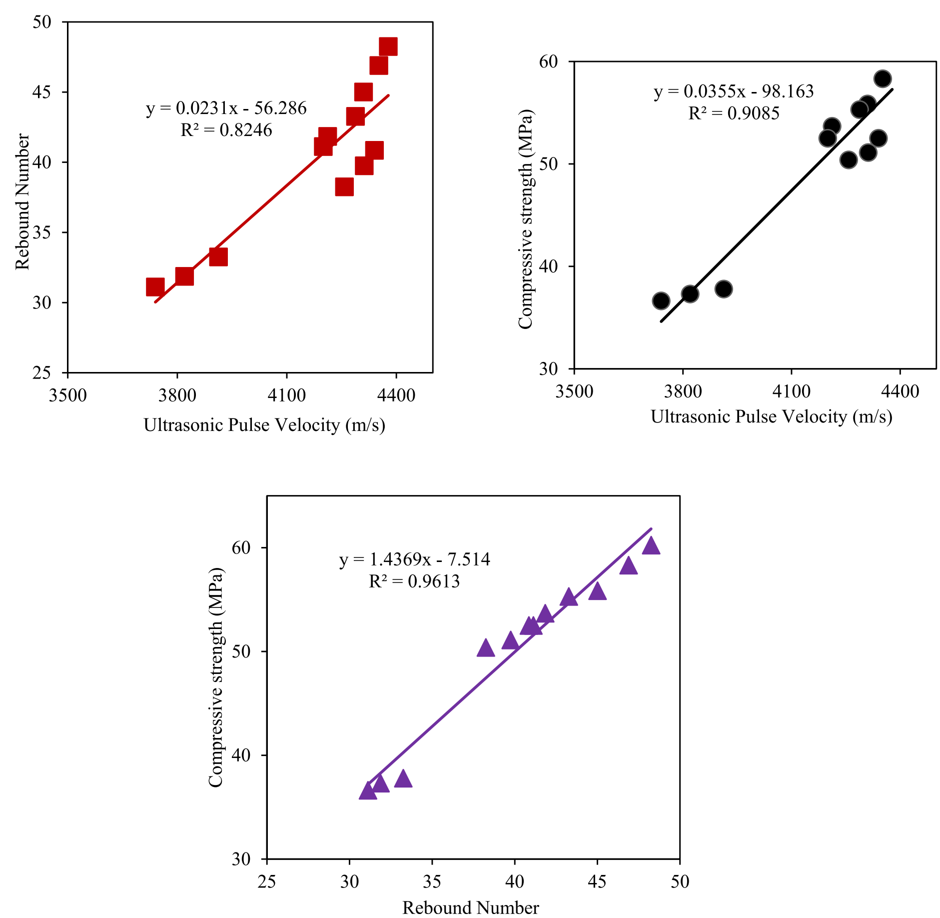


**Fig. 18.** Relationship between compressive strength, rebound number and UPV.

pavements. Although CR-series (containing only RCA and no SCM) showed the highest flexural strength amongst all other series, it may be prone to durability related issues owing to its high cement content. On the other, the SR and MR-series (containing RCAs, silica fume, and metakaolin) also showed high superiority but the flexural strength achieved is considerably higher than that required for an M-40 grade concrete. Generally, a minimum 28-day compressive and flexural strength of 40 MPa and 4.5 MPa, respectively, is required for a paving concrete to be used for highways [72]. Although the SR and MR-series SCCs shows great potential, its use in paving applications may not seem favourable despite its lower cost than the CR-series SCCs. IRC: 44 [76] and MoRTH [77] recommends the maximum cement content to be not more than 425 kg/m$^3$ for a paving grade concrete of highest quality. Taking into this threshold limit, the cement content in the SR and MR-series SCCs goes beyond this limit. If such condition prevails, the FR-series SCCs (containing RCAs and fly ash only) seems to be the best option amongst all. Although the FR-series SCCs has lower flexural strength than the SR and MR-series SCCs, its flexural strength was still above the permissible limit for an M-40 grade paving concrete. Moreover, the utilization of recycled concrete aggregates and fly ash would contribute in overall towards lower

**Table 7**
Cost analysis.

| | CPWD rates: Cement = Rs. 6/kg; Sand and Aggregate = Rs. 1/kg; Fly ash = Rs. 1.2/kg; Silica Fume = Rs. 32/kg; Metakaolin = Rs. 20/kg | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CR0 | CR50 | CR100 | FR0 | FR50 | FR100 | SR0 | SR50 | SR100 | MR0 | MR50 | MR100 |
| Cement | 3924 | 3924 | 3924 | 1830 | 1830 | 1830 | 2604 | 2604 | 2604 | 2625 | 2625 | 2625 |
| NCA | 508 | 254 | 0 | 508 | 254 | 0 | 508 | 254 | 0 | 508 | 254 | 0 |
| Sand | 621 | 621 | 621 | 621 | 621 | 621 | 621 | 621 | 621 | 621 | 621 | 621 |
| RCA | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fly ash | 0 | 0 | 0 | 366 | 366 | 366 | 186 | 186 | 186 | 187 | 187 | 187 |
| Silica Fume | 0 | 0 | 0 | 0 | 0 | 0 | 992 | 992 | 992 | 0 | 0 | 0 |
| Metakaolin | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 620 | 620 | 620 |
| Total cost | 5054 | 4799 | 4545 | 3325 | 3071 | 2817 | 4911 | 4657 | 4403 | 4562 | 4307 | 4053 |
| RCA processing cost | 0 | 47.9 | 45.45 | 0 | 30.71 | 28.17 | 0 | 46.57 | 44.03 | 0 | 43.07 | 40.53 |
| Overall cost | 5054 | 4847 | 4591 | 3325 | 3102 | 2845 | 4911 | 4516 | 4447 | 4562 | 4350 | 4094 |

Note: All units in Indian National Rupees. Rs. = Rupees; NCA = Natural coarse aggregates; RCA = Recycled Concrete Aggregates; CPWD = Central Public Works Department, Govt. of India.

natural aggregate consumption, lower cement consumption, reduction in cost of aggregates and cement, elimination of RCA and fly ash disposal landfills, and reduction in the carbon footprints as well.

This study mainly focusses on determining the best possible mix design proportion for SCC pavement mixes based on a comprehensive experimental work. One important aspect that is not part of the present study is the application of SCC pavement mixes that best suits its purpose. The main issue related to SCCs is that it is prone to cracking and several other structural defects owing to its high cement content. Since SCCs are self-consolidating concrete mixtures, its utilization in Continuously Reinforced Concrete Pavements (CRCP) or Pre-cast Prestressed Concrete Pavements (PPCP) best suits its purpose. Generally, CRCPs contains continuous, longitudinal steel reinforcement without transverse joints and is known to be an excellent long-life pavement solution for highly trafficked and heavily loaded roadways, such as interstate highways and expressways [78,79]. The drawback in CRCPs is its high initial construction cost as compared to the conventional Jointed Plain Cement Concrete Pavements (JPCP) owing to the presence of continuous reinforcements in CRCPs [79,80]. However, CRCPs can provide about 40 years of exceptional pavement performance with minimal maintenance if properly designed and constructed [79]. Thus, the utilization of SCCs in CRCP applications would be a novelistic approach wherein high traffic, heavy axle loadings, delays and smooth riding is increasingly important. Moreover, the utilization of waste materials like recycled concrete aggregates and fly ash would lead to a further sustainable development. Another possible application of SCCs is Pre-Cast Prestressed Concrete Pavement. PPCP is an innovative solution towards a sustainable concrete pavement which can be fabricated off-site, transported and installed at project site, and thus, offers rapid construction in small windows [81,82]. Not only this, PPCPs can be constructed in all weather and climatic conditions [81]. In lieu of this, the application of SCCs in PPCPs along with the utilization of waste materials like recycled concrete aggregates, fly ash, and SCMs like silica fume and metakaolin would add on to a sustainable PPCP.

## 6. Conclusions

The present study investigates the effects of Self-Compacting Concrete (SCC) pavement mixes made with Recycled Concrete Aggregates (RCA). Natural Concrete Aggregates were volumetrically replaced by RCA in proportions of 0, 50, and 100%, respectively. To improve the properties of the SCC pavement mixes made with RCAs; fly ash, silica fume, and metakaolin was incorporated and designated as normal and medium grade SCCs. Based on the test results and analyses, the following conclusions were drawn.

1. With increase in the grades of the SCC, the dosage of high-range water reducing admixture increases but remained the same in the case RCA incorporated mixes. On the other hand, the slump flow diameter increases with the incorporation of RCA owing to its higher water absorption capacities.
2. Although the bulk density and strength properties decreases with incorporation of RCA, the compressive strength loss was less than 5% only, whereas, in the case of flexural strength, it was lesser than 4%. The recommended flexural strength of 4.5 MPa for an M40 paving grade concrete was satisfied by both the normal and medium-grade SCC pavement mixes. However, in order to maximize the benefit (utilizing fewer natural resources and more recycled materials) with adequate engineering properties, the normal-grade concrete made with RCA and fly ash best serves this purpose.
3. ANOVA results confirmed that amount of RCA, Portland cement, fly ash, and silica fume added into the mixture affect density, compressive strength, split tensile and flexural strength of the SCC pavement mixes. Moreover, the regression equations showed a good correlation between the predicted and experimental values with the residuals following a normal distribution in an acceptable manner.
4. The presence of porous adhered mortar around the RCA certainly increased the total concentration of permeable voids and also the water absorption capacities of the designed SCC pavement mixes.
5. SCC pavement mixes having unique characteristics in terms of high flowability and compaction without external vibrations could be utilization in CRCP as a good alternative owing to the presence of heavy steel reinforcements. In such scenarios, the application of Non-Destructive Tests such as Ultrasonic Pulse Velocity and Rebound Hammer could prove to be helpful in determining the strength of SCC-CRCP on-site. Moreover, the NDTs could be useful to predict the compressive strength of the SCC-CRCP on-site.
6. The primary benefit of utilizing of RCA and the selected mineral admixtures is the reduction in the cost of materials. Conclusively, the utilization of 100% recycled aggregates in combination with 50% fly ash would prove to be best possible solution for the production of self-compacting concrete pavement mixes.

## CRediT authorship contribution statement

**Ran Bir Singh:** Conceptualization, Methodology, Data curation, Formal analysis, Supervision, Writing - original draft, Writing - review & editing. **Solomon Debbarma:** Data curation, Formal analysis, Writing - original draft. **Navanit Kumar:** Investigation. **Surender Singh:** Supervision, Writing - review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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