ISSN 2063-5346

Mechanical Properties of Self Compacting Concrete with Recycled Coarse Aggregate

Dr. Sumit Gandhi[1], Dr. Anjan Kumar Dutta[2], Dr. J. Prakash Arul Jose[3], Dr.S.Thenmozhi[4], S.P.Senthil kumar[5], Swapnil Balkrishna Gorade[6]

[1]Associate Professor and Head, Department of Civil Engineering, Jaypee University of Engineering and Technology, Guna, Madhya Pradesh, India.

[2]A.K. Dutta and Associates, HA-333, Flat no.1, Sector III, Salt Lake City, Kolkata, West Bengal-700097, India.

[3]Principal and Professor, Department of Civil Engineering, Annai College of Engineering &Technology, Kumbakonam, Tamilnadu, India.

[4]Associate Professor, Department of Civil Engineering, St.Joseph's College of Engineering, OMR, Chennai-600119, India.

[5]Associate Professor, Department of Civil Engineering, St.Joseph's College of Engineering, OMR, Chennai-600119, India.

[6]Assistant Professor, Department of Civil Engineering, Pimpri Chinchwad College of Engineering, Sector no-26, Nigdi Pradhikaran, Pune-411044, Maharashtra, India.

Abstract: The trash generated during construction and destruction that is present in older concrete structures is a critical issue since natural aggregates and raw materials for modern construction are becoming increasingly scarce. Reducing the use of natural aggregates and recycling demolition and construction debris in the concrete sector are answers to this issue. In order to create self-compacting concrete (SCC), this study looked into substituting recycled concrete aggregates (RCA) in various ratios (0%, 50%, 75%, and 100%). The SCC combinations included PVA fibres as well as several supplementary cementitious materials (SCMs) ingredients, including nano-silica (NS), fly ash (FA), and metakaolin (MK). For all SCC mixes, the flexural behaviour of SCC beams (load-carrying capacity, crack pattern, mid-span deflection, and flexural stiffness) as well as the fresh properties (slump flow, V-funnel, and L-box test) and hardened properties (compressive strength, splitting tensile strength, and flexural strength) were investigated. The findings of freshly-poured and hardened concrete shown that it is feasible to manufacture SCC with a complete replacement of RCA while very slightly altering the characteristics of the concrete. The optimal combination that met EFNARC requirements and had good fresh qualities was SCC with 100% RCA replacement, 20% MK, and 22% FA. Compressive strength decreased by 8.20% after 100% RCA substitution, whereas maximum load and flexural stiffness rose by 3.20 and 16.25%, respectively.

Keywords: recycled concrete aggregates; self-compacting concrete; supplementary cementitious materials; mechanical properties.

1. Introduction

Concrete is the most widely used building material in civil engineering, and its use is growing globally along with the expansion of construction activity. China produced 5.51 billion tonnes of concrete in 2017, using 5.0 billion tonnes of non-renewable natural aggregates, and generating 0.83 billion tonnes of carbon dioxide (CO2) [1]. Concrete manufacturing and transportation contribute

ISSN 2063-5346

around 10% of the CO2 in nature, which causes pollution issues [2]. However, as cities around the world become more populous, development has resulted in a daily rise in the amount of construction and demolition waste (CDW), which has led to a number of environmental issues like increased energy use, CO2 emissions, noise pollution, traffic congestion, loss of agricultural land, and consumption of resources. As a result, recycling CDW to create recycled concrete aggregates (RCA) requires the concrete industry to completely or partially replace natural coarse aggregate (NCA), which has become urgently necessary to save the environment furthermore to cut back on the use of non-renewable resources [4]. Numerous studies on the characteristics of fresh and hardened concrete with RCA as well as the structural performance of concrete components with RCA have been conducted over the past 20 years [5–9]. Also frequently used in concrete products is the use of supplemental cementitious materials (SCMs), such as nanosilica (NS), fly ash (FA), and metakaolin (MK). These components can greatly enhance the characteristics of freshly laid concrete when utilised at recommended quantities [10–13]. Additionally, the addition of polyvinyl alcohol (PVA) fibres to concrete improves its ductility, lowers the stress concentration caused by early flaws in recycled concrete components, and boosts the concrete's compressive strength [14]. To prevent bleeding and segregation, the SCC must remain homogeneous during transit, placement, and after placement [15].

Therefore, further research is required into the use of RCA and SCMs with SCC. Recent studies on the feasibility of producing SCC via RCA were conducted by several researchers. Grdic et al. [16] looked at the effects of using RCA at different ratios (0%, 50%, and 100%) in place of NCA. The findings demonstrated that the compressive strength, tensile strength, and density of the RCA mixes were inferior to those of the reference mixture. However, compared to the reference combination, these mixes absorbed more water. Guo et al. [1] demonstrated that the inclusion of RCA damaged the toughened qualities of SCC by proving that the mechanical properties of the generated SCC with RCA declined as the replacement ratio of RCA increased. Additionally, the mechanical qualities of SCC mixes were enhanced by the addition of fly ash and slag. In order to substitute natural aggregate, Kou and Poon [17] studied SCC with 25% to 50% recycled fine aggregate (RFA) and RCA. The outcomes demonstrated that the mechanical characteristics declined as the percentage of RFA rose. In order to manufacture SCC with RCA, Sadeghi-Nik et al. [18] investigated the effects of utilising MK and NS as additives. The results revealed that adding up to 20% of MK to cement with 2% NS increased the mechanical qualities. The addition of NS at 3% of the cement weight and PVA fibres at 3.6 kg/m3 to SCC mixtures was researched by Wang and Baolong Zhu [14]. The outcomes showed that SCC's mechanical characteristics have improved. SL, FA, and RCA were varied in twenty SCC mixes that Khodair and Bommareddy [19] investigated. The compressive and tensile strengths of concrete mixes were discovered to decrease as the RCA replacement amount was raised. Additionally, utilising SCMs to partially replace the cement reduced the compressive strength. By using RCA, Mohammed and Najim [20] investigated the flexural behaviour of SCC beams. The flexural capabilities of the tested beams were somewhat decreased by the RCA. In addition, the deflection corresponding to the cracking and ultimate loads rose, whereas the first-crack load and maximum load capacity reduced as the percentage of the RCA increased. In high-volume, fly-ash, self-consolidating concrete, Meena et al. [21] investigated the use of coal bottom ash and RCA as partial substitutes for natural fine and coarse aggregates.

The compressive, splitting tensile, flexural, and direct shear strengths all exhibited appreciable gains as a consequence. Four-point bending loads experiments were carried out by Yu et al. [22] on SCC beams with RCA and NCA while taking reinforcement ratio into consideration. The findings demonstrated that the tested beams' failure form, moment-deflection curves, and flexural strength were comparable to those containing NCA. On the other hand, compared to NCA-treated beams, the tested beams' cracking moment and fracture breadth were much reduced. When the flexural characteristics of beams with a 100% replacement rate of RCA were compared to those with NCA,

ISSN 2063-5346

Ignjatovic et al.'s research [23] showed that the ultimate bearing capacities were comparable. However, the deflection was enhanced by around 13% by the RCA beams. Less than 20 MPa was the compressive strength after 28 days. Using 450 kg/m3 of cement and SF added to the SCC mixtures, Mohammed and Najim [20] studied recycled aggregate SCC using RFA and RCA as substitutes for natural aggregates. For concrete structural components, the compressive strength varied from 40 to 52 MPa, which was sufficient With a cement content of 475 kg/m3 and 20% RCA, SCC was created by Mohseni et al. [24]. FA was also added to the cement. Greater than 50 MPa was the compressive strength after 28 days. Mo et al.'s [25] investigation looked at substituting the NCA with RCA and SF while maintaining a 635 kg/m3 cement concentration. After 28 days, the compressive strength of all recycled aggregate SCC mixtures varied from 60 to 70 MPa. Sadeghi-Nik et al. [18] created SCC with RCA contents of 20%, 40%, 60%, 80%, and 100%, as well as NS and MK, and a cement concentration of 427.3 kg/m3. The structural components might use the 40–55 MPa range of compressive strength.

Cement mortar and aggregates, which make approximately 65-75% of the volume of concrete, are its main components. As previously mentioned, a group of academics was interested in exploring cement substitutes to minimise CO2 emissions from the cement industry and offset its negative environmental effects since they wanted to produce ecologically friendly concrete [11]. Instead of employing fine or coarse aggregates or recycled aggregate from destroyed concrete, the opposing side was interested in using rubber. This study adopted the strategy of the second group, which was interested in RCA as opposed to NCA by examining the effects of SCM addition to cement on the characteristics of SCC and the bending behaviour of SCC beams. Therefore, the impacts of utilising binary SCMs (C with MK) or ternary SCMs (C with MK and FA, MK and NS, or C with NS and FA) to create SCC and replace NCA with RCA were examined. The impact of quaternary SCMs (C with MK, FA, and NS) on SCC with high RCA replacement levels has not been examined in any recent studies. This work investigated the structural behaviour of SCC beams with RCA under flexural four-point stress to fill this gap in the literature. This paper's main contribution was to increase the SCC is created by replacing the RCA in binary, ternary, and quaternary combinations up to 100% in order to obtain a better fresh status and similar toughened qualities.

2. Experimental Program

2.1. Materials

2.1.1. Cement and Supplementary Cementitious Materials (SCMs)

Ordinary Portland Cement (OPC) type II (grade 42.5) was utilised in the concrete mix design. The specific gravities of the SCMs employed in the concrete mixes in this investigation were MK, FA, and NS, with 2.6, 2.2, and 1.40, respectively. The MK was created by calcining kaolin for three hours at 850 C [26]. This study used FA classes F and NS with a PH of 9 and 90% SiO2 content. Table 1 lists the physical characteristics and chemical compositions of cement and SCMs.

2.1.2. Natural Aggregates and Recycled Coarse Aggregate (RCA)

Sand from the harsh desert, with a specific gravity of 2.65 and a fineness modulus of 2.6, was employed as a fine aggregate. The NCA was made of crushed limestone with a maximum nominal size of 14 mm and a specific gravity of 2.68. Both NCA and sand met Egyptian criteria ECP 203 [27] and were devoid of organic elements, clay, and silt.

The RCA was derived from concrete cubes that had previously been produced and had compressive strengths between 25 MPa and 30 MPa. These concrete cubes were first manually smashed with a hammer and then electrically crushed. The RCA that was created contained particles that ranged in size from 5 mm to 20 mm, respectively.

Table 1. Chemical compositions and physical properties of the used cement and SCMs.

Compound	Cement	Fly Ash	Metakaolin	Nano-Silica
SiO_2	21.20	55.20	52.25	90
Fe2O3	3.80	8.4	1.50	0.18
Al2O3	4.50	21.9	41.25	0.44
CaO	62.3	5.23	1.20	0.30
K_2O	0.65	1.20	.65	0.05
MgO	2.4	1.53	0.15	0.07
Na_2O	0.36	1.60	0.28	0.08
LIO	1.93	1.95	1.02	3.29
Loss on ignition	0.13	2.39	2.70	0.29
Specific gravity (g/m^3)	3.15	2.20	2.60	1.40

Table 2. Physical properties of the NCA, RCA, and sand.

Item in Mix	Specific Gravity	Fineness Modulus	Maximum Nominal Size (mm)
NCA	2.68	6.48	14
RCA	2.62	6.98	20
Sand	2.65	2.6	-

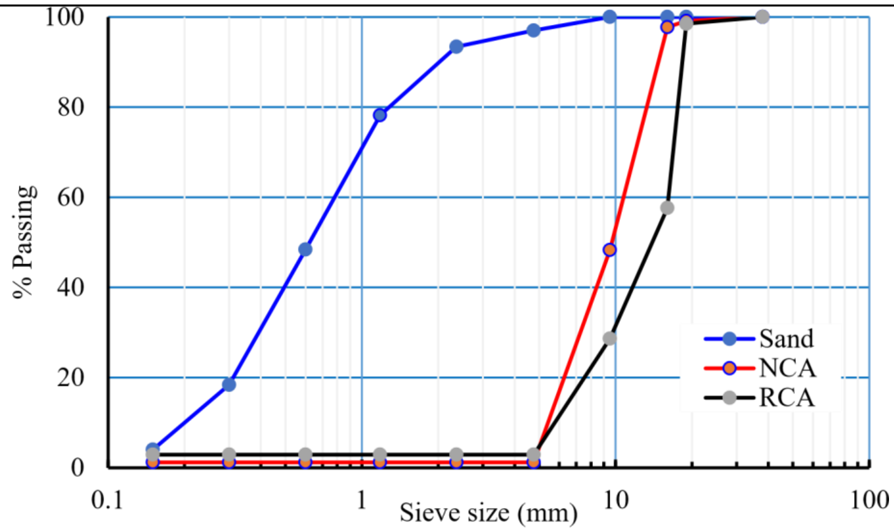

Figure 1. Grain size distribution of the NCA, RCA, and sand.

2.1.3. Water

Concrete samples were mixed and dried using potable water. The utilised water is devoid of salt, dirt, and silt. The pH was not less than 7, in accordance with ECP 203 [27].

2.1.4. Polyvinyl Alcohol (PVA) Fibres

The fibre had a diameter of 10 m, a length of 15 mm, and an elongation of 7%. The fiber's density, Young's modulus, and tensile strength are each 1200 MPa, 39 GPa, and 1.3 g/cm3, respectively.

2.1.5 Superplasticizer (SP)

ISSN 2063-5346

Sikaviscocrete 3425, a superplasticizer with a density of 1.05 kg/liter and a PH value of 4.0 that conformed with ECP 203 [27], was utilised. It was purchased from a local provider, Sika Egypt [28].

2.2. Mixing Proportions

The mixing procedure was carried out in accordance with Egyptian law [27]. In weight percentages of 50%, 75%, and 100%, the NCA was swapped out for the RCA. In order to create the SCC, MK, FA, and NS mixtures with and without PVA fibres were also added to the cement. The comparisons used 18 SCC mixes, including the control mixture, with a constant w/c ratio of 0.49. Binary (C and MK), ternary (C and MK, NS, and FA), and quaternary (C and MK, NS, and FA) mixes were all included in the mixtures. The NCA for the control mix (Q1) is 100%. To achieve equivalent mechanical qualities for RA-SCC mixes, the cement weight was 450 kg/m3, and the PVA fibre content was 3.6 kg/m3 for all combinations.

2.3. Casting and Curing of the Specimens

The compressive strength of the concrete was tested at 7, 28, and 56 days for each combination using nine 150 mm 150 mm 150 mm concrete cubes. For the splitting tensile strength tests, three concrete cylinders with dimensions of 300 mm in height and 150 mm in diameter were poured for each combination (see Figure 2b). To investigate the flexural strength of concrete, three conventional concrete prisms with a square cross-section of 100 mm 100 mm and a length of 400 mm were created. To study the flexure behaviour of the reinforced SCC beams with RCA, ten reinforced concrete beams with a rectangular cross-section of 120 mm 200 mm and a total length of 1800 mm were produced. Two 8 mm mild steel rebars (St280/450) were utilised as the top reinforcement for each beam, and two 12 mm steel rebars (St400/600) were used as the bottom reinforcement [29].

According to Figure 3, the transverse reinforcement consisted of 8 mm stirrups spaced uniformly at 10 mm intervals. The mechanical characteristics of the steel reinforcement employed are listed in Table 3.

Table 3. The mechanical properties of the used steel reinforcement.

Steel Type	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elastic Modulus (MPa)	% Elongation
400/600	400	600	210,000	15
280/450	280	450	210,000	30

2.4. Testing Procedures

The experimental programme was run in three stages. Studying the SCC mixtures' initial qualities was the first step. The hardened SCC mixes' mechanical characteristics, such as their compressive strength, tensile splitting strength, and flexural strength, were examined in the second phase. The third step examined the flexural behaviour of the SCC beams with RCA under four-point loading.

3. Test Results and Discussion

3.1. Fresh Properties of SCC

The fresh concrete properties for the SCC mixes with different combinations of RCA and SCMs in terms of slump flow, SI, L-box, and V-funnel test results are listed in Table 4.

ISSN 2063-5346

Table 4. The fresh concrete properties for the SCC mixes.

Mix Description	Slump Flow (mm)	SI	L-Box (H2/H1)	V-Funnel (s)
R0-MK	790	0	0.95	6.0
R0-MK-FA-PVA	740	0	0.93	6.0
R0-MK-NS-PVA	700	0	0.92	7
R0-NS-FA-PVA	730	0	0.92	6
R50-MK-FA-PVA	705	0	0.91	7
R50-MK-NS-PVA	650	0	0.90	8
R50-NS-FA-PVA	665	0	0.83	7
R75-MK-FA-PVA	680	1	0.90	8
R75-MK-NS-PVA	620	1	0.88	9
R75-NS-FA-PVA	630	0	0.81	9
R100-MK	690	1	0.92	8.0
R100-MK-FA	660	1	0.92	9.0
R100-MK-NS	640	0	0.92	9.5
R100-MK-PVA	620	1	0.85	10
R100-MK-FA-PVA	590	1	0.85	10
R100-MK-NS-PVA	585	2	0.85	11
R100-NS-FA-PVA	570	1	0.80	10
R100-MK-NS-FA-PVA	560	2	0.80	11

3.1.1. Slump Flow Results

According to EFNARC [30], the slump flow values for the SCC mixes varied from 560 to 790 mm, as shown in Table 5. Two perpendicular slump flow diameters were averaged to provide each value in this table. In contrast to the control mix R0-MK, the slump flow for mixes MK-FA-PVA reduced by 6.3%, 10.8%, 13.9%, and 25.3% for respective percentages of RCA replacements of 0%, 50%, 75%, and 100%. The results for mixes NS-FA-PVA and MK-NS-PVA are depicted in Figure 2 and were the same. As the RCA replacement ratio rose, there was a rise in water absorption [34,35]. Additionally, the interlocking behaviour was impacted by increasing the RCA content, which also increased friction and surface area and decreased flowability [36].

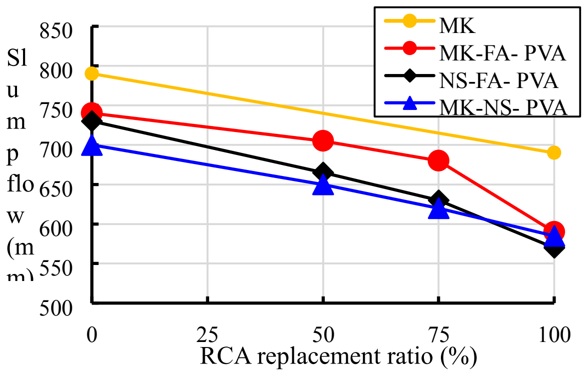

Figure 2. Effect of the RCA content on slump flow results.

ISSN 2063-5346

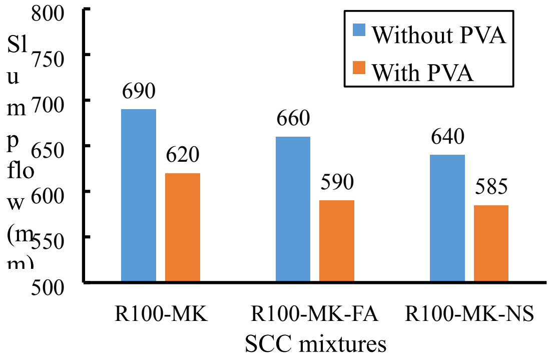

Figure 3. Effect of the PVA fibers on slump flow results for 100% RCA content.

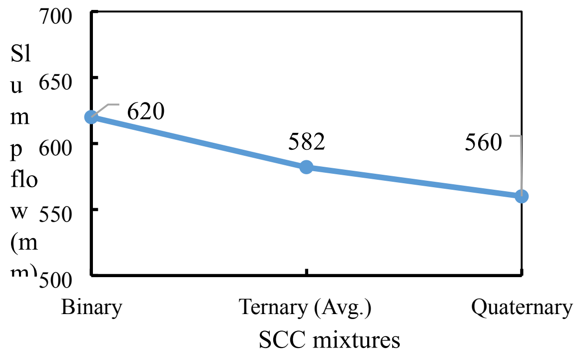

Figure 4. Effect of the SCMs on slump flow diameter for 100% RCA replacement.

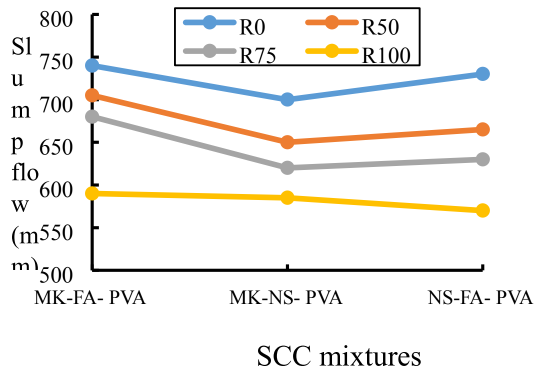

Figure 5. Hybrid effect of the ternary SCMs on the slump flow diameter.

3.1.2. The SCC Mixtures' Segregation Resistance

Table 5 contains the SI values for the SCC combinations with RCA and SCMs. Except for two combinations with 100% RCA substitution, all SCC mixtures had SI values of 0 or 1. These SI values showed a sufficient level of segregation resistance. The quaternary (R100-MK-NS-FA-PVA) and ternary (R100-MK-NS-PVA) mixtures, however, were insufficient and showed significant segregation. This behaviour was brought on by the RCA and SCMs' superior capacity to absorb water [35].

3.1.3. L-Box Results

Figure 10 displays the L-box test results for the SCC combinations, which are described in Table 5. The blocking ratio, also known as the H2/H1 ratio, assesses the concrete flow and the segregation resistance of the SCC brought on by the steel rebars. It has been demonstrated that the blocking ratio findings above 0.80 and were in accordance with the EFNARC [30]. As the RCA ratio grew, it was

ISSN 2063-5346

seen that the H2/H1 value dropped. Similar to the slump flow scenario, the fundamental cause was that when the amount of RCA replacement was raised, concrete got harsher owing to the irregularity and roughness of the RCA, which in turn enhanced the friction and blocking ability of the SCC mixes. Figure 11 illustrates how PVA fibres affected the L-box outcomes of the SCC mixes with 100% RCA concentration. Without and with PVA fibres, respectively, the H2/H1 value for the binary mixture (R100-MK) was decreased by 3.20% and 10.52% in comparison to the reference mixture. The ternary mixes (R100-MK-FA and R100-MK-NS) showed a comparable decrease. The blockage ratio was lowered by adding PVA fibres to the SCC mixes with RCA for the same reason as in the slump flow. The PVA fibres made the cement mix and aggregate particles more abrasive.

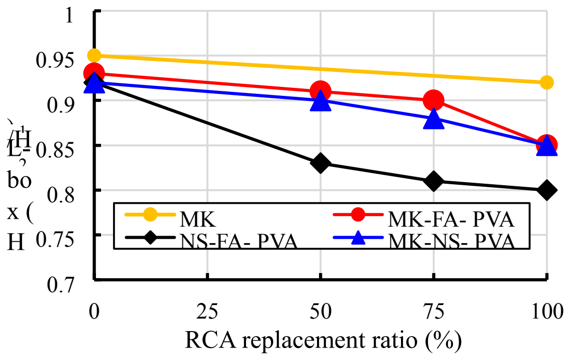

Figure 6. Effect of the RCA on the blocking ratio.

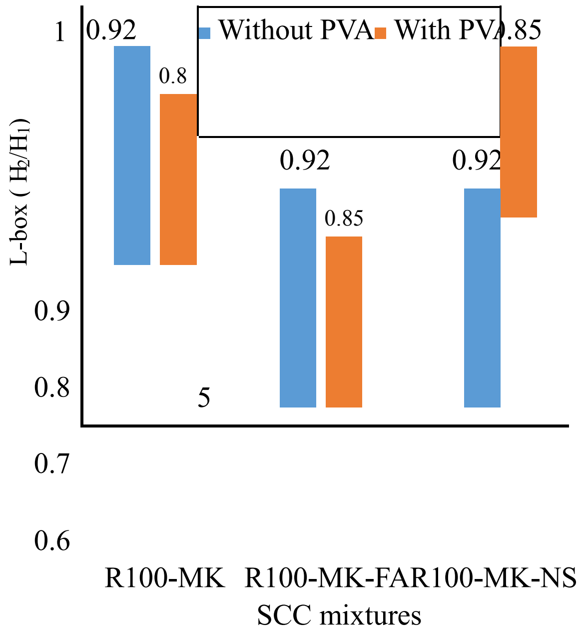

Figure 7. Effect of the PVA fibers on the blocking ratio for 100% RCA.

Figure 12 shows how the findings of the slump flow were impacted by the introduction of SCMs.

In comparison to the control mix (R0-MK), the average blocking ratio of binary, ternary, and quaternary mixes decreased by 10.5%, 12.6%, and 15.8%, respectively. The quaternary mixture had the lowest H2/H1 ratio, followed by the ternary mixture and the binary mixture. The SCMs' greater surface area improved how well new concrete adhered to them. Figure 13 depicts the hybrid effect of

ISSN 2063-5346

ternary SCMs on the blocking ratio for SCC mixes. The mixes containing MK and FA had the highest blocking ratio for 0% RCA. The lowest levels, however, were seen in the mixtures with FA and NS. The combinations with the similar pattern were also noted.

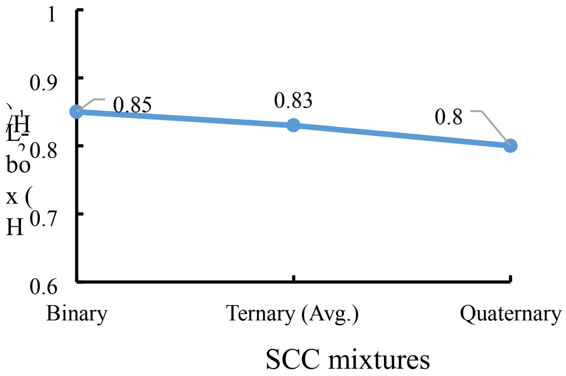

Figure 8. Effect of the SCMs on the blocking ratio for 100% RCA.

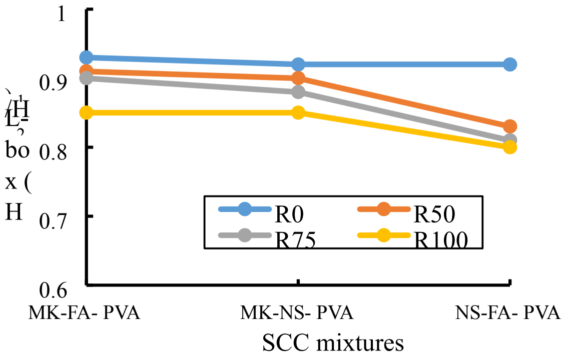

Figure 9. The hybrid effect of the ternary SCMs on the blocking ratio.

3.1.4. V-Funnel Test Results

Table 5 and Figure 14 include a list of the outcomes of the V-funnel test. The V-funnel flow time was within the EFNARC [30] tolerance range of 6 to 11 s. It has been shown that as the RCA replacement ratio was raised, the V-funnel flow time of the SCC mixes also rose. The RCA's angularity, surface roughness, and surface porosity, which absorbed more water and increased the friction between the aggregate and cement paste, may be primarily blamed for this behaviour. Figures shows that as compared to the reference mix R0-MK, the V-funnel flow durations of mixes R100-Mk without and with PVA fibres increased by 33.3% and 66.6%, respectively. The mixes R100-MK-FA and R100-MK-NS had the similar behaviour.

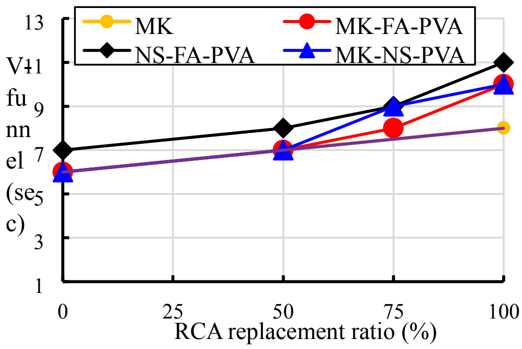

Figure 10. Effect of the RCA content on the V-funnel flow time.

ISSN 2063-5346

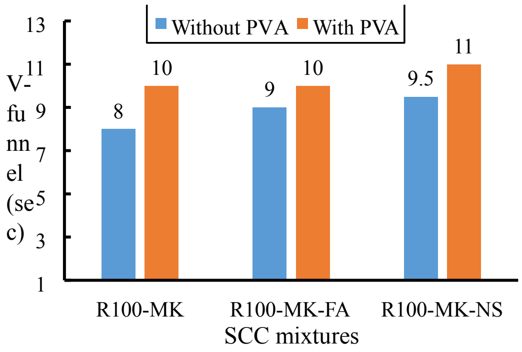

Figure 11. Effect of the PVA fibers on the V-funnel flow time for 100% RCA.

3.2 Mechanical Qualities of SCC Mixtures, Section

Table 5 lists the splitting tensile strength and flexural strength at 28 days, as well as the cube compressive strength at 7, 28, and 56 days. A three-measurement average is shown for each value.

Table 5. Mechanical properties of SCC with RCA.

Mix Description	Compressive Strength (MPa)			Splitting Strength (MPa)	Flexural Strength (MPa)
	7 Days	28 Days	56 Days		
R0-MK (Control)	37.33	43.11	56.50	4.30	4.80
R0-MK-FA-PVA	35.55	42.22	53.80	4.10	4.40
R0-MK-NS-PVA	32.80	42.60	48.60	3.70	4.52
R0-NS-FA-PVA	26.10	32.50	53.80	2.70	4.68
R50-MK-FA-PVA	31.67	40.00	50.20	3.55	4.00
R50-MK-NS-PVA	31.64	40.41	44.10	3.00	4.20
R50-NS-FA-PVA	22.50	30.00	42.10	2.50	4.30
R75-MK-FA-PVA	30.10	39.85	48.50	3.50	3.80
R75-MK-NS-PVA	30.62	38.89	39.80	2.90	3.90
R75-NS-FA-PVA	22.10	29.30	38.80	2.45	3.80
R100-MK	31.11	40.44	49.60	3.50	4.00
R100-MK-FA	37.33	39.56	47.60	2.60	3.70
R100-MK-NS	36.90	42.55	54.80	2.30	3.93
R100-MK-PVA	26.70	32.90	40.20	3.54	3.80
R100-MK-FA-PVA	28.70	35.30	45.60	3.40	3.30
R100-MK-NS-PVA	27.33	36.44	35.00	2.80	3.70
R100-NS-FA-PVA	21.35	28.44	35.70	2.30	4.62
R100-MK-NS-FAPVA	29.33	39.11	45.50	2.70	3.30

3.2.1. Compressive Strength of SCC Mixes

The impact of the RCA concentration on the 28-day cube compressive strength of the SCC mixes is shown in Figure 18. In the situations of 0%, 50%, 75%, and 100% RCA, respectively, the compressive strength of the mixes containing MK-FAPVA dropped by 2.1%, 7.2%, 7.6%, and 18.1% in comparison to the R0-MK mix. Similar decreases were seen in the groups with MK-NS-PVA and NS-FA-PVA, proving that the compressive strength's magnitude reduced as the RCA concentration rose. The same was seen at days 7 and 56 as well. These decreases in compressive strength might be

ISSN 2063-5346

due to the poorer binding between the RCA and cement paste, the microcracks created by the crushing process in the adhering mortars on the RCA, high porosity, and water content.

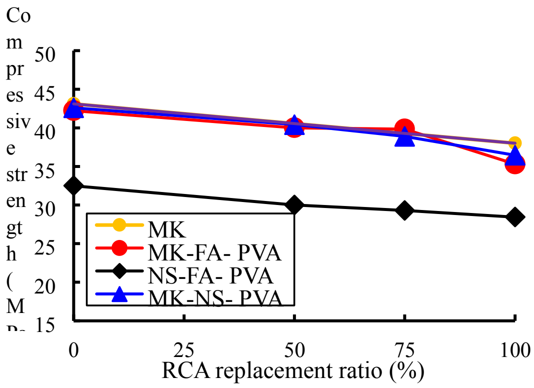

Figure 12. Effect of the RCA content on the 28-day cube compressive strength.

3.2.2. Splitting Tensile Strength

Figure 22 and Table 6 both show how the replacement ratio of the RCA affects the splitting tensile strength of SCC mixtures. It is clear that the splitting tensile strength fell for the mixtures including MK, FA, and PVA by 4.6%, 17.4%, 18.6%, and 20.9% in the situations of 0%, 50%, 75%, and 100% RCA, respectively, in comparison to the control mixture. The strength of the tensile splitting reduced when more NCA was replaced with RCA. The poor link between the RCA and cement paste and the alteration in the microstructure of the concrete for combinations including RCA were the primary causes of these decreases [19]. Figure 23 illustrates how the PVA fibres affected the SCC with 100% RCA content's splitting tensile strength. In comparison to the reference mix R0-MK, the tensile splitting strength of the mixtures R100-MK with and without PVA fibres fell by 18.60% and 17.60%, respectively. PVA fibres were added, and this improved the splitting tensile strength because the fibres could prevent microcracks in the concrete [37,41].

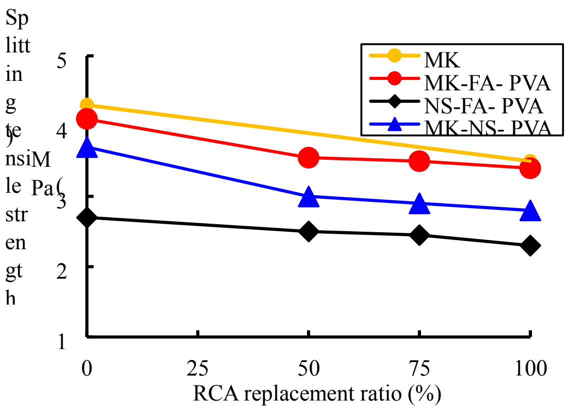

Figure 13. Effect of the RCA on the splitting tensile strength.

ISSN 2063-5346

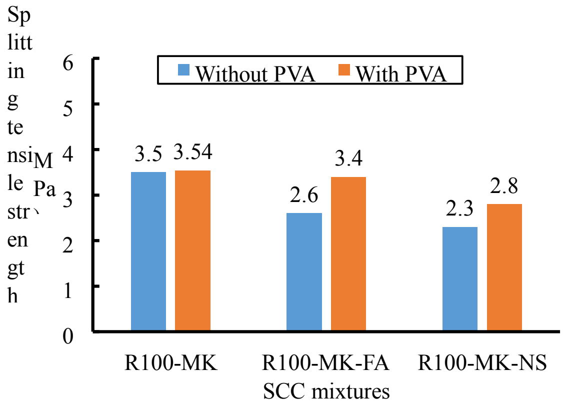

Figure 14. Effect of the PVA fibers on the splitting tensile strength for 100% RCA replacement.

Figure 24 shows how the kind of SCM integration affects the tensile splitting strength of SCC blends. The strongest tensile splitting is in binary compositions. However, the smallest value of tensile splitting strength is seen in ternary and quaternary combinations. Figure 25 shows the hybrid impact of ternary SCMs on the 28-day split tensile strength with 100% RCA. The splitting tensile strength of ternary SCC mixes was greatest for MK and FA (4.7 MPa), followed by ternary mixes MK and NS (3.7 MPa). With a value of 2.7 MPa, ternary mixtures including NS and FA exhibited the lowest split tensile strength. The 50, 75, and 100% RCA cases exhibit the same tendency. This is due to metakaolin's increased FA reactivity, which enhances the hydration and micro-filling capabilities of the voids in the concrete. The 28-day splitting tensile strength of RA-SCC mix values spans from 2.30 to 4.30 MPa, as indicated in Table 6, which is consistent with the findings from

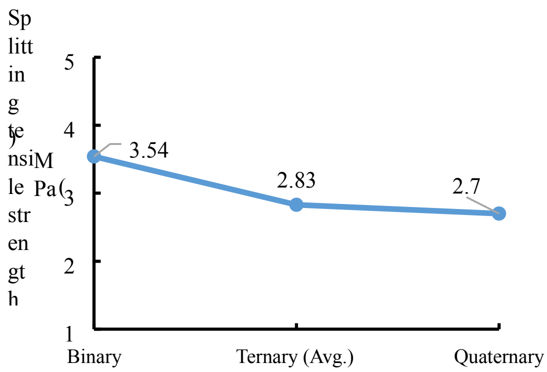

Figure 15. Effect of the SCMs incorporation type on the splitting tensile strength for 100% RCA replacement.

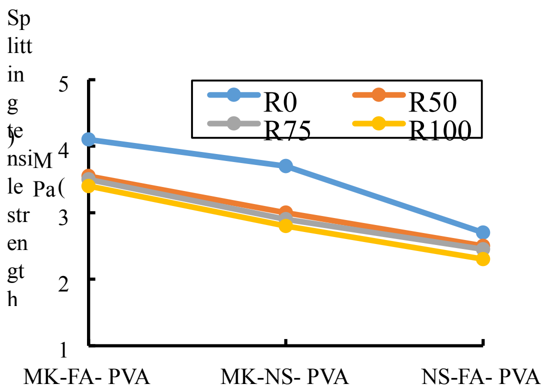

Figure 16. Hybrid effect of the ternary SCMs on the splitting tensile strength.

ISSN 2063-5346

3.2.3. Flexural Strength Results

3.3. Reinforced SCC Beam Results

The findings of the reinforced SCC beams after 56 days are shown in Table 6. The cracking loads, ultimate loads, maximum mid-span deflections, and flexural stiffness are among these outcomes. As the RCA replacement ratio rose, the first fracture developed earlier. This behaviour was caused by a decrease in RCA strength and a stronger connection between mortar and RCA surface compared to NCA. The ternary beams with 50% RCA (R50-MK-FA-PVA and R50-MK-NS-PVA) had an increase in their average ultimate loads of 1.2%. However, for the ternary beams with 100% RCA (R100MK-FA-PVA and R100-MK-NS-PVA), the average ultimate load reduced by 1.00%. The ultimate load of the ternary beams (R100-MK-FA and R100-MK-NS) increased whereas the ultimate load of the binary beam (R100-MK) dropped.

Table 6. Reinforced SCC beam results.

Beam Description	Cracking Load (kN)	Cracking Moment (kN·m)	Ultimate Load (kN)	Moment Capacity (kN·m)	Flexural Stiffness (kN/mm)	Maximum Deflection (mm)
R0-MK (Control beam)	55.00	13.75	69.80	17.45	8.00	14.80
R50-MK-FA-PVA	50.00	12.50	69.60	17.40	8.80	15.60
R50-MK-NS-PVA	50.00	12.50	71.70	17.93	8.90	16.60
R100-MK	45.00	11.25	67.90	16.98	7.40	16.40
R100-MK-FA	50.00	12.50	72.00	18.00	9.30	18.55
R100-MK-NS	48.00	12.00	72.40	18.10	8.80	20.00
R100-MK-PVA	53.00	13.25	76.40	19.10	7.50	19.14
R100-MK-FA-PVA	45.00	11.25	71.60	17.90	8.31	15.80
R100-MK-NS-PVA	45.00	11.25	66.60	16.65	6.40	16.75
R100-MK-NS-FA-PVA	51.00	13.00	70.20	17.55	8.15	14.70

Therefore, the ultimate load for the SCC beams was enhanced by switching out the NCA for 100% RCA and adding MK, FA, or NS to cement. The failure load for the beam (R100-MK-PVA) increased by a maximum of 9.5% above the reference mix. In addition, the binary mixture with PVA (R100-MK-PVA) had a 12.5% higher ultimate load than the binary mixture without PVA (R100-MK). Final load values were 72.00 and 71.60 KN for the ternary mixture (R100-MK-FA) with and without PVA fibres, respectively. This demonstrates that adding PVA fibres to ternary mixes has a detrimental impact on the ternary mixes' final load. The combination (R100-MK-NS) had a comparable decline. The greatest mid-span deflection of beams with various amounts of RCA is often larger than the control beam (R0-MK), as shown in Table 7. For instance, the mid-span deflection of the R50-MK-FA-PVA and R100-MK-FA-PVA beams was 5.40% and 6.80% higher than that of the control beam. Due to RCA's weaker interfacial zone than NCA [20], the performance is commensurate with that expected theoretically. The midspan deflection for all beams ranges from 14.80 to 20 mm, similar with RA-SCC beams manufactured with the same mix proportions [20]. The ultimate loads for all beams range between 66.60 MPa and 76.40 MPa.

ISSN 2063-5346

4. Conclusions

In order to create self-compacting concrete (SCC), this study looked into substituting recycled concrete aggregates (RCA) in various ratios (0%, 50%, 75%, and 100%). The SCC combinations included PVA fibres as well as several supplementary cementitious materials (SCMs) ingredients, including nano-silica (NS), fly ash (FA), and metakaolin (MK). For all SCC mixes, the flexural behaviour of SCC beams (load-carrying capacity, crack pattern, mid-span deflection, and flexural stiffness) as well as the fresh properties (slump flow, V-funnel, and L-box test) and hardened properties (compressive strength, splitting tensile strength, and flexural strength) were investigated. The following conclusions may be taken from the experimental programme that was carried out and the data that were examined:

1. PVA fibres have a negative impact on fresh characteristics, as shown by the fact that mixes with PVA fibres exhibit worse fresh properties at 100% RCA than mixes without PVA fibres.

2. When compared to all other formulations, including ternary mixtures with MK and FA or NS, binary mixtures with MK solely exhibited the greatest fresh characteristics. In addition, the least fresh RA-SCC characteristics are seen in quaternary SCC mixes, such as MK, FA, and NS.

3. The mechanical parameters of the SCC mixtures—compressive strength, tensile splitting strength, and flexural strength—declined as the RCA replacement ratio rose, illuminating the detrimental effects of raising the degree of RCA replacement.

4. The splitting tensile strength of the SCC mixes was improved by the addition of PVA fibres, while the compressive and flexural strength at a replacement level was lowered.

5. When FA and NS were added to cement in ternary SCC mixes, the compressive strength dropped. Nevertheless, ternary combinations with MK and FA or MK and NS outperformed the reference mixture in terms of asymptotic strength, showing that the mixes, which contain a mixture of MK and FA or MK and NS, enhance the mechanical characteristics of RA-SCC mixes.

6. The initial cracking load, average ultimate load capacity, and average flexural stiffness were all lowered for the ternary SCC beams with PVA fibres when the RCA replacement level was increased to 100% RCA. In contrast, the density and breadth of fractures at the failure loads are rising.

7. For the 100% RCA ternary mixes without PVA, the ultimate load and flexural stiffness for the reinforced SCC beams were dramatically enhanced.

References

1. Guo, Z.; Jiang, T.; Zhang, J.; Kong, X.; Chen, C.; Lehman, D.E. Mechanical and Durability Properties of Sustainable Self-Compacting Concrete with Recycled Concrete Aggregate and Fly Ash, Slag and Silica Fume. *Constr. Build. Mater.* **2020**, *231*, 117115. [CrossRef]
2. Kuder, K.; Lehman, D.; Berman, J.; Hannesson, G.; Shogren, R. Mechanical Properties of Self Consolidating Concrete Blended with High Volumes of Fly Ash and Slag. *Constr. Build. Mater.* **2012**, *34*, 285–295. [CrossRef]
3. Pani, L.; Francesconi, L.; Rombi, J.; Mistretta, F.; Sassu, M.; Stochino, F. Effect of Parent Concrete on the Performance of Recycled Aggregate Concrete. *Sustainability* **2020**, *12*, 9399. [CrossRef]
4. Musa, A.A. A Review on Recycled Aggregate Concretes (RACs). *J. Phys. Conf. Ser.* **2022**, *2267*, 012003. [CrossRef]

ISSN 2063-5346

5. Amario, M.; Rangel, C.S.; Pepe, M.; Toledo Filho, R.D. Optimization of Normal and High Strength Recycled Aggregate Concrete Mixtures by Using Packing Model. *Cem. Concr. Compos.* **2017**, *84*, 83–92. [CrossRef]
6. Bahrami, N.; Zohrabi, M.; Mahmoudy, S.A.; Akbari, M. Optimum Recycled Concrete Aggregate and Micro-Silica Content in Self-Compacting Concrete: Rheological, Mechanical and Microstructural Properties. *J. Build. Eng.* **2020**, *31*, 101361. [CrossRef] 7. Song, X.; Li, C.; Chen, D.; Gu, X. Interfacial Mechanical Properties of Recycled Aggregate Concrete Reinforced by Nano-Materials. *Constr. Build. Mater.* **2021**, *270*, 121–446. [CrossRef]
8. Younis, A.; Ebead, U.; Suraneni, P.; Nanni, A. Short-Term Flexural Performance of Seawater-Mixed Recycled-Aggregate GFRPReinforced Concrete Beams. *Compos. Struct.* **2020**, *236*, 111860. [CrossRef]
9. Revilla-Cuesta, V.; Ortega-López, V.; Skaf, M.; Khan, A.u.R.; Manso, J.M. Deformational Behavior of Self-Compacting Concrete
Containing Recycled Aggregate, Slag Cement and Green Powders under Compression and Bending: Description and Prediction Adjustment. *J. Build. Eng.* **2022**, *54*, 104611. [CrossRef]
10. Shafiq, N.; Kumar, R.; Zahid, M.; Tufail, R.F. Effects of Modified Metakaolin Using Nano-Silica on the Mechanical Properties and Durability of Concrete. *Materials* **2019**, *12*, 2291. [CrossRef]
11. Anjos, M.A.S.; Camões, A.; Campos, P.; Azeredo, G.A.; Ferreira, R.L.S. Effect of High Volume Fly Ash and Metakaolin with and without Hydrated Lime on the Properties of Self-Compacting Concrete. *J. Build. Eng.* **2020**, *27*, 100985. [CrossRef]
12. Prakash, R.; Raman, S.N.; Divyah, N.; Subramanian, C.; Vijayaprabha, C.; Praveenkumar, S. Fresh and Mechanical Characteristics of Roselle Fibre Reinforced Self-Compacting Concrete Incorporating Fly Ash and Metakaolin. *Constr. Build. Mater.* **2021**, *290*, 123209. [CrossRef]
13. Yue, Y.; Zhou, Y.; Xing, F.; Gong, G.; Hu, B.; Guo, M. An Industrial Applicable Method to Improve the Properties of Recycled Aggregate Concrete by Incorporating Nano-Silica and Micro-CaCO3. *J. Clean. Prod.* **2020**, *259*, 120920. [CrossRef]
14. Wang, S.; Zhu, B. Influence of Nano-SiO2 on the Mechanical Properties of Recycled Aggregate Concrete with and without Polyvinyl Alcohol (PVA) Fiber. *Mater. Artic.* **2021**, *14*, 1446. [CrossRef]
15. Shi, C.; Wu, Z.; Lv, K.; Wu, L. A Review on Mixture Design Methods for Self-Compacting Concrete. *Constr. Build. Mater. J.* **2015**, *84*, 387–398. [CrossRef]
16. Grdic, Z.J.; Toplicic-Curcic, G.A.; Despotovic, I.M.; Ristic, N.S. Properties of Self-Compacting Concrete Prepared with Coarse Recycled Concrete Aggregate. *Constr. Build. Mater.* **2010**, *24*, 1129–1133. [CrossRef]
17. Kou, S.C.; Poon, C.S. Properties of Self-Compacting Concrete Prepared with Coarse and Fine Recycled Concrete Aggregates. *Cem. Concr. Compos.* **2009**, *31*, 622–627. [CrossRef]
18. Sadeghi-Nik, A.; Berenjian, J.; Alimohammadi, S.; Lotfi-Omran, O.; Sadeghi-Nik, A.; Karimaei, M. The Effect of Recycled Concrete Aggregates and Metakaolin on the Mechanical Properties of Self-Compacting Concrete Containing Nanoparticles. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2019**, *43*, 503–515. [CrossRef]
19. Khodair, Y.; Bommareddy, B. Self-Consolidating Concrete Using Recycled Concrete Aggregate and High Volume of Fly Ash, and Slag. *Constr. Build. Mater.* **2017**, *153*, 307–316. [CrossRef]
20. Mohammed, S.I.; Najim, K.B. Mechanical Strength, Flexural Behavior and Fracture Energy of Recycled Concrete Aggregate Self-Compacting Concrete. *Structures* **2020**, *23*, 34–43. [CrossRef]
21. Meena, A.; Singh, N.; Singh, S.P. High-Volume Fly Ash Self Consolidating Concrete with Coal Bottom Ash and Recycled Concrete Aggregates: Fresh, Mechanical and Microstructural Properties. *J. Build. Eng.* **2023**, *63*, 105447. [CrossRef]

ISSN 2063-5346

22. Yu, F.; Wang, M.; Yao, D.; Yang, W. Study on Flexural Behavior of Self-Compacting Concrete Beams with Recycled Aggregates. *Buildings* **2022**, *12*, 881. [CrossRef]
23. Ignjatovic´, I.S.; Marinkovic´, S.B.; Miškovic´, Z.M.; Savic´, A.R. Flexural Behavior of Reinforced Recycled Aggregate Concrete Beams under Short-Term Loading. *Mater. Struct. Constr.* **2013**, *46*, 1045–1059. [CrossRef]
24. Mohseni, E.; Saadati, R.; Kordbacheh, N.; Parpinchi, Z.S.; Tang, W. Engineering and Microstructural Assessment of FibreReinforced Self-Compacting Concrete Containing Recycled Coarse Aggregate. *J. Clean. Prod.* **2017**, *168*, 605–613. [CrossRef]
25. Mo, K.H.; Ling, T.C.; Cheng, Q. Examining the Influence of Recycled Concrete Aggregate on the Hardened Properties of Self-Compacting Concrete. *Waste Biomass Valorization* **2021**, *12*, 1133–1141. [CrossRef]
26. Said-Mansour, M.; Kadri, E.H.; Kenai, S.; Ghrici, M.; Bennaceur, R. Influence of Calcined Kaolin on Mortar Properties. *Constr. Build. Mater.* **2011**, *25*, 2275–2282. [CrossRef]
27. *ECP 203*; Egyptian Code of Practice for Design and Construction of Concrete Structures, "Annex III", Manual Laboratory Tests for Concrete Material. Ministry of Housing, Utilities & Urban Communities: Cairo, Egypt, 2018.
28. Available online: https://egy.sika.com/ (accessed on 10 March 2021).
29. *ECP 203*; The Egyptian Code for Design and Construction of Concrete Structures. Ministry of Housing, Utilities & Urban Communities: Cairo, Egypt, 2018.
30. EFNARC. *Guidelines for Self-Compacting Concrete*; English ed.; European Federation for Specialist Construction Chemicals and Concrete Systems: Norfolk, UK, 2002.
31. *EN 196-1 (Equivalence EN 196-1)*; Methods of Testing Cement—Part 1: Determination of Strength. Turkish Standards Institution: Ankara, Turkey, 2002.
32. *ASTM C496/C496M-17*; Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. ASTM International: West Conshohocken, PA, USA, 2017.
33. *ASTM C78/C78M-18*; Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). ASTM International: West Conshohocken, PA, USA, 2018.
34. Manzi, S.; Mazzotti, C.; Bignozzi, M.C. Self-Compacting Concrete with Recycled Concrete Aggregate: Study of the Long-Term Properties. *Constr. Build. Mater. J.* **2017**, *157*, 582–590. [CrossRef]
35. Kebaïli, O.; Mouret, M.; Arabia, N.; Cassagnabere, F. Adverse Effect of the Mass Substitution of Natural Aggregates by Air-Dried Recycled Concrete Aggregates on the Self-Compacting Ability of Concrete: Evidence and Analysis through an Example. *J. Clean. Prod.* **2015**, *87*, 752–761. [CrossRef]
36. Behera, M.; Minocha, A.K.; Bhattacharyya, S.K. Flow Behavior, Microstructure, Strength and Shrinkage Properties of SelfCompacting Concrete Incorporating Recycled Fine Aggregate. *Constr. Build. Mater.* **2019**, *228*, 116819. [CrossRef]
37. Liu, K.; Wang, S.; Quan, X.; Duan, W.; Nan, Z.; Wei, T.; Xu, F.; Li, B. Study on the Mechanical Properties and Microstructure of Fiber Reinforced Metakaolin-Based Recycled Aggregate Concrete. *Constr. Build. Mater.* **2021**, *294*, 123554. [CrossRef]
38. Etxeberria, M.; Vázquez, E.; Marí, A. Microstructure Analysis of Hardened Recycled Aggregate Concrete. *Constr. Build. Mater.* **2006**, *58*, 683–690. [CrossRef]
39. Omary, S.; Ghorbel, E.; Wardeh, G. Relationships between Recycled Concrete Aggregates Characteristics and Recycled Aggregates Concretes Properties. *Constr. Build. Mater. J.* **2016**, *108*, 163–174. [CrossRef]
40. Li, K.F.; Yang, C.Q.; Huang, W.; Zhao, Y.B.; Wang, Y.; Pan, Y.; Xu, F. Effects of Hybrid Fibers on Workability, Mechanical, and Time-Dependent Properties of High Strength Fiber-Reinforced Self-Consolidating Concrete. *Constr. Build. Mater.* **2021**, *277*, 122325. [CrossRef]

ISSN 2063-5346

41. Yaowarat, T.; Horpibulsuk, S.; Arulrajah, A.; Mohammadinia, A.; Chinkulkijniwat, A. Recycled Concrete Aggregate Modified with Polyvinyl Alcohol and Fly Ash for Concrete Pavement Applications. *J. Mater. Civ. Eng.* **2019**, *31*, 04019103. [CrossRef]
42. Duan, Z.; Singh, A.; Xiao, J.; Hou, S. Combined Use of Recycled Powder and Recycled Coarse Aggregate Derived from Construction and Demolition Waste in Self-Compacting Concrete. *Constr. Build. Mater.* **2020**, *254*, 119323. [CrossRef]
43. Turatsinze, A.; Garros, M. On the Modulus of Elasticity and Strain Capacity of Self-Compacting Concrete Incorporating Rubber Aggregates. *Resour. Conserv. Recycl.* **2008**, *52*, 1209–1215. [CrossRef]