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SAMARRA JOURNAL OF ENGINEERING SCIENCE AND RESEARCH

S.J.E.S.R

# Fresh and Hardened Properties of Self-Compacting Concrete containing Waste Materials and Recycled Coarse Aggregate.

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**Article Information**

**Received: 30/06/2024**
**Accepted: 05/08/2024**

**Keywords:**

***Recycled aggregates; Ground-Granulated Blast-Furnace Slag, Wood Waste Ash; Self-compacting concrete; Strength; Workability.***

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**Abstract**

Currently, the use of waste materials and recycled aggregates in concrete production is increasing to achieve sustainability in the construction industry. This approach is essential because the resources for natural aggregates are decreasing worldwide. Using recycled aggregates and waste materials in self-compacting concrete (SCC) production is a promising strategy to address environmental concerns and enhance sustainability. This study investigates the combined impact of ground-granulated furnace slag (GGBS), wood waste ash (WWA), and recycled coarse aggregate (RCA) on the workability and strength of SCC. Recycled coarse aggregate (RCA) has been used as a substitute for natural coarse aggregate (NCA). In volume ratios of 0, 50, 100%, and for each of these percentages, 20% of the cement weight was replaced as following; 20% for WWA, 10% for WWA with 10% GGBS, 20% for GGBS, in addition to reference mixture which containing a cement percentage of 100%. The experimental program evaluates fresh properties (slump flow, V-funnel flow, and passing ability) and hardened properties (compressive strength and split tensile strength). Results indicate that increasing RCA content from 0% to 100% reduces slump value from 780 mm to 730 mm. Compressive and split tensile strengths decrease by 12.14% and 2.67%, respectively, with the increase of RCA from 0 to 100%. Using WWA and GGBS as cement replacements reduces compressive strength by 40.92% and 6.74%, respectively. Therefore, it is recommended to incorporate other waste materials with high pozzolanic reactivity to enhance SCC strength containing RCA.

## 1. Introduction

Concrete is the most used construction material worldwide and is applied in infrastructure and superior projects such as airports, tunnels, and high-rise buildings [1]. However, it has a negative impact on the environment due to use high cement amount in the production of concrete. The cement industry alone generates about 7% of global $CO_2$ emissions [2]. Besides, the large quantities of raw materials extracted to produce the concrete result in harm to the environment [3]. Therefore, the researchers used alternative materials to address these challenges and issues by using waste materials as sustainable materials in the production of concrete. Structural elements with heavy reinforcement, especially those located in places where vibrations are not possible, such as the beam-column connections, require appropriate materials and casting methods to prevent separation and ensure bonding, as well as filling the molds with concrete. Therefore, self-compacting concrete (SCC) is considered one of the suitable solutions to address these problems, as it is a high-flow, non-separable concrete that can fill formwork without the need for mechanical vibrators, making it mainly suitable for complex structural elements with dense reinforcement [4, 5].

The use of waste materials as cement replacement and recycled coarse aggregate (RCA) as natural aggregates was extensively investigated [6-8]. For instance, Uygunoğlu et al. [9] investigated the use of RCA as natural aggregate and marble waste (MW) in the production of SCC. While Duan et al. [6] used 10% and 20% recycled powder with RCA in the production of SCC. They found that the compressive and splitting tensile strengths of SCC mostly decline as RCA content increases. The use of waste materials as renewable construction materials has a double effect, may be improve the durability of concrete, as well as reduce the environmental effect of concrete due to reduced cement production [3].

Abhishek et al. [10] examined the influence of GGBS and RCA on the fresh and hardened properties of SCC. They used 20%, 25%, 30%, and 35% of natural coarse aggregate with RCA to obtain a design strength of 30 MPa. They found that the addition of RCA into the SCC mixes beyond 20% reduces the compressive strength of SCC. Nandanam et al. [11] used GGBS as a cement replacement with metakaolin (MK) and coal fly ash (CFA) to investigate the durability and mechanical properties of SCC. They observed that the use of GGBS resulted in enhancing the durability properties of SCC, while the addition of 15% MK as cement replacement shows better mechanical properties of SCC and increased strength up to 75 MPa. Tamanna et al. [12] conducted a comprehensive review on the potential use of WWA as a cement and/or aggregate replacement in the concrete mix. They concluded that the concrete containing WWA with other ashes has a better performance than that concrete without WWA. Recently, Wang et al. [13] used WWA with recycled fine aggregate as fine and coarse aggregates in the production of wood aggregate recycled concrete (WARC). They examined shrinkage, mechanical properties, and thermal insulation. They observed that the thermal conductivity was decreased by 81.9% and the shrinkage and mechanical properties of WARC were decreased due to the addition of WWA and recycled fine aggregate in concrete mixtures.

Despite numerous studies examining the influence of waste materials and RCA on the properties of SCC [6, 14]. However, most studies focus on the separate effects of these wastes on SCC, and there is limited research on the combined effect of recycled aggregate and these wastes in SCC. Also, no study investigated the combined effect of WWA and GGBS as a cement replacement with RCA as coarse aggregate on the properties of SCC. Therefore, this study was introduced to close this knowledge gap. This study aims to examine the combined effect of WWA and GGBS as cement replacement, as well as RCA as coarse aggregate, on the workability and strength of SCC. This study determines the fresh properties of SCC, like filling ability and passing ability, as well as compressive and splitting tensile strengths of SCC.

## 2. Experimental work

### 2.1 Materials description

Fine and coarse aggregates were used in this study with particle sizes as shown in Tables 1 and 2, respectively. Local Ordinary Portland Cement (OPC) with a specific gravity of 3.15, was used as a main binder material. Supplementary Cementitious Materials (SCMs) including GGBS and WWA with physical and chemical properties as in Table 3 were used with OPC as binder materials in the production of SCC. The potable water was used in the mix design in a water-cement ratio of 0.4. Sika Viscocrete-180 GS was used as a Superplasticizer (SP) to adjust the workability of SCC in a concentration of 1.5%. Natural sand was used as a fine aggregate, while two types of aggregates were used as coarse aggregate, namely normal and recycled coarse aggregates (RCA). Recycled coarse aggregate (RCA) was obtained locally from concrete debris from the roof of a demolished house more than 30 years old. After the process of crushing concrete blocks in the laboratory, a vibrating sieve was used to obtain aggregate of the required sizes, and each size was stored in special bags. The sieve analysis was adopted for the natural coarse aggregate (NCA) because it conforms to the specifications. Therefore, with regard to the recycled coarse aggregate (RCA), the same gradation ratios were adopted for the NCA to ensure the same gradation zone for the two types of aggregates, as well as its conformity with the Iraqi standard.

**Table 1.** Sieve size analysis of fine aggregate

| Sieve No. | Passing% | Iraqi standard limits, IQS No.45/2009 [11] |
|---|---|---|
| 3/8 in | 100 | 100 |
| No.4 | 98 | 90-100 |
| No.8 | 92 | 85-100 |
| No.16 | 86 | 75-100 |
| No.30 | 73 | 60-79 |
| No.50 | 37 | 12-40 |
| No.100 | 2 | 0-10 |
| PAN | 2 | Max 5% |

**Table 2.** Sieve size analysis of coarse aggregate

| Sieve Size (mm) | Percentage of Passing | | Iraqi standard limits, IQS No.45/2009 [11] |
|---|---|---|---|
| | Natural coarse aggregate (NCA) (%) | Recycled coarse aggregate (RCA) (%) | |
| 20 | 100 | 100 | 100 |
| 14 | 94 | 94 | 90-100 |
| 10 | 62 | 62 | 50-85 |
| 5 | 0 | 0 | 0-10 |

As shown in Table 3, the cement, WWA, and GGBS have a high Calcium oxide (CaO) content of 63.14, 40.42, and 34.16%, respectively. While the WWA has low Silica oxide ($SiO_2$) essential to produce further calcium-hydrate-silica (C-H-S) gels. Therefore, the GGBS rich in $SiO_2$ was added to enhance the WWA containing low-silica oxide. Table 4 shows the mix design of materials adopted in this study. Twelve SCC mixtures have been prepared based on numerous trial and error experiments in the concrete lab. These mixtures were divided into three groups according to the RCA content, 0% RCA, 50% RCA, and 100% RCA. Each group has four mixtures, three of them containing of WWA and GGBS and one mix as a control mix without WWA and/or GGBS.

**Table 3.** Chemical composition of Cement, WWA, and GGBS

| Compound | $SiO_2$ | $AL_2O_3$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $TiO_2$ | $K_2O$ | $SO_3$ | LOI | S.G. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cement | 20.05 | 4.76 | 3.25 | 63.14 | 1.65 | 0.35 | 1.04 | 0.29 | 2.44 | 2.25 | 3.15 |
| WWA | 7.31 | 1.48 | 3.21 | 40.42 | 7.46 | 0.23 | 2.50 | 5.20 | 1.06 | 26.1 | 2.32 |
| GGBS | 38.41 | 10.5 | 0.98 | 34.16 | 8.95 | 0.26 | 0.00 | 1.69 | 0.34 | 2.19 | 2.30 |

**Table 4.** Proportions of materials in mix design

| RCA (%) | Cement replacement (%) | | Concrete Mixture Quantity (kg/m$^3$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | WWA | GGBS | C | WWA | GGBS | W* | w/b | NFA | NCA | RCA | SP |
| 0 | 0 | 0 | 500 | 0 | 0 | 200 | 0.40 | 800 | 850 | 0 | 7.5 |
| | 20 | 0 | 400 | 100 | 0 | 200 | 0.40 | 800 | 850 | 0 | 7.5 |
| | 0 | 20 | 400 | 0 | 100 | 200 | 0.40 | 800 | 850 | 0 | 7.5 |
| | 10 | 10 | 400 | 50 | 50 | 200 | 0.40 | 800 | 850 | 0 | 7.5 |
| 50 | 0 | 0 | 500 | 0 | 0 | 230 | 0.46 | 800 | 425 | 393 | 7.5 |
| | 20 | 0 | 400 | 100 | 0 | 230 | 0.46 | 800 | 425 | 393 | 7.5 |
| | 0 | 20 | 400 | 0 | 100 | 230 | 0.46 | 800 | 425 | 393 | 7.5 |
| | 10 | 10 | 400 | 50 | 50 | 230 | 0.46 | 800 | 425 | 393 | 7.5 |
| 100 | 0 | 0 | 500 | 0 | 0 | 260 | 0.52 | 800 | 0 | 786 | 7.5 |
| | 20 | 0 | 400 | 100 | 0 | 260 | 0.52 | 800 | 0 | 786 | 7.5 |
| | 0 | 20 | 400 | 0 | 100 | 260 | 0.52 | 800 | 0 | 786 | 7.5 |
| | 10 | 10 | 400 | 50 | 50 | 260 | 0.52 | 800 | 0 | 786 | 7.5 |

WWA: Wood Waste Ash, GGBS: Ground-Granulated Blast Slag, C: Cement, W: Water, w/b water-binder ratio, NFA: Natural Fine Aggregate, NCA: Natural Coarse Aggregate, RCA: Recycled Coarse Aggregate, SP: Superplasticizer.

* The increase in water of concrete mixture is the additional water that was added to the mixture to ensure the saturated surface dry (SSD) condition of the recycled coarse aggregate at two percentages (50% and 100%).

## 2.2 The process of preparing, mixing and casting

Preparing, mixing and casting SCC from different SCM and RCA involved several main steps. Selecting the RCA and SCM to be used in the concrete mix is one of the important factors affecting the performance of SCC. The mix design of SCC mixtures adopted in the study was according to numerous experimental runs in the concrete lab and the results obtained from the previous studies. The SCC mixtures equipped were used to assess the workability, compressive strength, and splitting tensile strength of SCC with different cement replacements by GGBS and WWA, as well as RCA. Filling ability and passing ability using Slump flow, V-funnel, and L-box tests were employed to evaluate the effect of SCM and RCA on the workability of SCC according to the standards of EN 12350: Part 8-2010 [15]. The compressive and splitting tensile strength tests were conducted in two curing ages according to the specifications of IS 5816- 1999 [16] and IS 516-1959 [17], respectively. Mix the dry materials including cement, and fine and coarse aggregates, in a mixer. The water and superplasticizer have been added gradually to obtain a uniform and workable SCC. The fresh state tests, like slump flow, V-funnel, and L-box tests have been conducted, to assess the workability and flowability of the SCC.

### 2.3 Testing procedure

The fresh tests of SCC are conducted to identify the workability of SCC. A fresh SCC test was conducted. Slump flow, L-Box, and V-funnel tests were conducted for SCC mixtures. The slump flow test is measured for the diameter of the flow spread of the SCC mix, as shown in Fig. 1. V: The funnel test is the measure of the filling ability and plastic viscosity of the SCC mix. The Passing Ability of SCC can be determined using the L-box test in the fresh state of SCC.

The Compressive strength test was achieved on steel cubes with dimensions 100 $mm^3$, and the results obtained were considered from the average of three samples for each mixture at 28 days curing age. The splitting tensile strength is one of the hardened SCC tests, was determined using cylinders with dimensions of 100 mm diameter × 200 mm depth. Also, the results were obtained from the average of three samples for each SCC mix.

## 3. Results and discussion

### 3.1 Fresh properties results

The slump flow test was conducted on different SCC mixtures as illustrated in Table 5 and Figures 2 and 3. RCA was a coarse aggregate in different replacement levels, and it was detected that the slump flow time of SCC mixtures increased with the increasing proportion of RCA. For the control SCC mix (MS-1) the slump flow time and diameter were 1.84 sec and 780 mm, respectively. While addition 50% RCA as a coarse aggregate led to an increase in the slump flow time up to 2.83 sec and reduced the slump flow diameter up to 755 mm. The slump flow diameter decreased by 3.2% and 6.41% due to the use of 50 and 100% RCA as a coarse aggregate, respectively. The reduction in slump flow was due to the high-water absorption and angular shape of RCA compared to that of natural coarse aggregate [18, 19]. This result agrees with a study conducted by Mahakavi and Chithra [20], they used RCA in 25, 50, 75, and 100% as a coarse aggregate replacement with mining sand in the production of SCC. They observed that the flow diameter and flow time are affected by the RCA content. This effect is due to that the RCA contains a huge amount of impurities and has highly porous and heterogeneous. The use of RCA and SCM led to an increase in the V-funnel time and a decrease in the L-box ratio, as shown in Table 5 and Figures 4 and 5.

RCA= 0% RCA= 50% RCA= 100%

W00G00

RCA= 0% RCA= 50% RCA= 100%

W20G00

RCA= 0% RCA= 50% RCA= 100%

W00G20

RCA= 0% RCA= 50% RCA= 100%

W10G10

**Fig. 1.** Effect of waste materials and RCA on shapes of slump flow

**Table 5.** Fresh Proportions of SCC

| Coarse aggregate replacement (%) | Cement replacement (%) | | Filling ability | | | Passing ability |
|---|---|---|---|---|---|---|
| | WWA | GGBF | T50 slump (sec.) | Slump diameter (mm) | V-funnel (sec.) | L-box ratio |
| 0 | 0 | 0 | 1.84 | 780 | 4.77 | 0.96 |
| | 20 | 0 | 3.06 | 715 | 7.01 | 0.91 |
| | 0 | 20 | 2.28 | 746 | 6.45 | 0.94 |
| | 10 | 10 | 2.77 | 728 | 6.82 | 0.92 |
| 50 | 0 | 0 | 2.83 | 755 | 6.34 | 0.93 |
| | 20 | 0 | 3.72 | 708 | 10.22 | 0.87 |
| | 0 | 20 | 2.86 | 730 | 8.55 | 0.90 |
| | 10 | 10 | 3.08 | 714 | 9.56 | 0.88 |
| 100 | 0 | 0 | 3.30 | 730 | 9.29 | 0.87 |
| | 20 | 0 | 4.62 | 630 | 11.89 | 0.81 |
| | 0 | 20 | 3.88 | 685 | 10.67 | 0.85 |
| | 10 | 10 | 4.31 | 647 | 11.10 | 0.83 |
| EFNARC limitations | | | 2-5 | 600-800 | ≤ 12 | 0.8 - 1.0 |

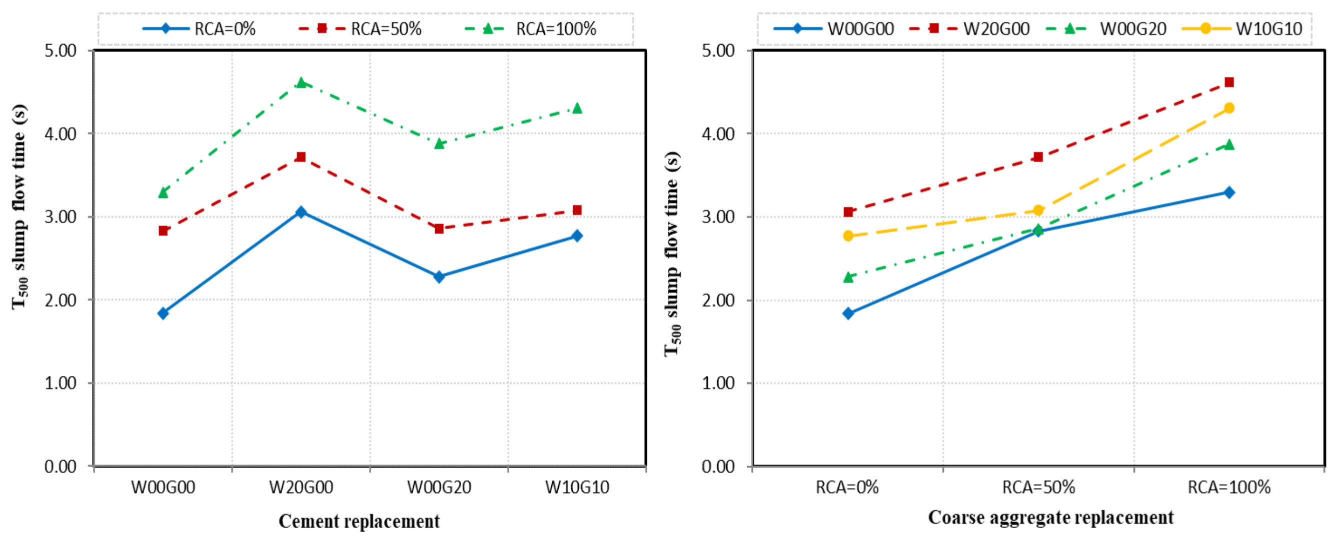


**Fig. 2.** Effect of cement and coarse aggregate replacement on slump flow time

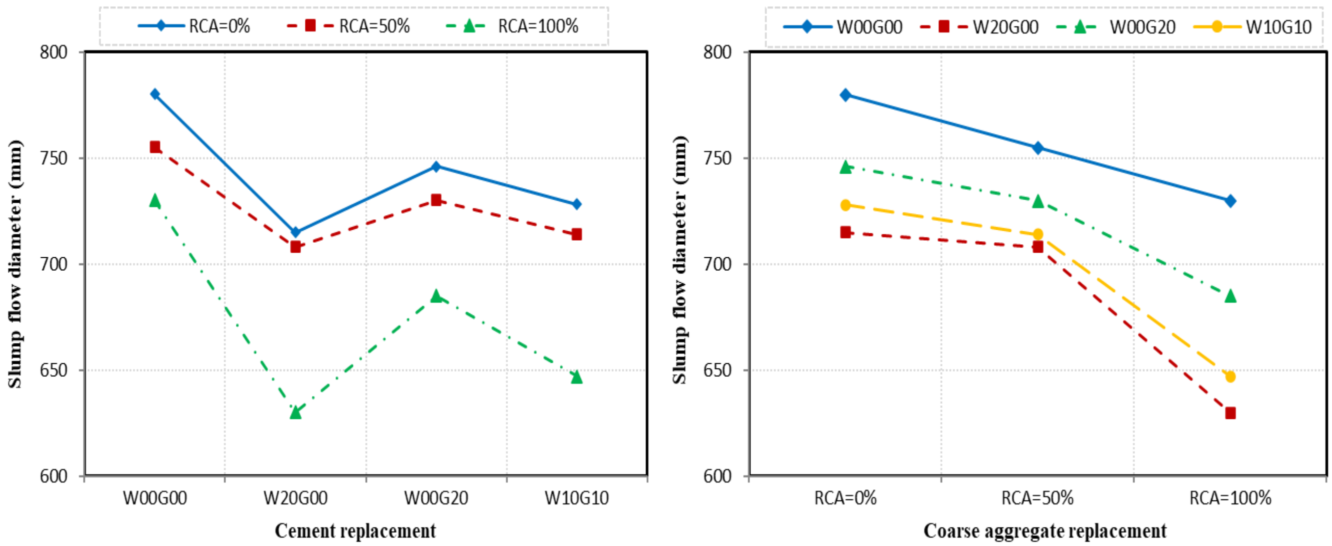


**Fig. 3.** Effect of cement and coarse aggregate replacement on slump flow diameter

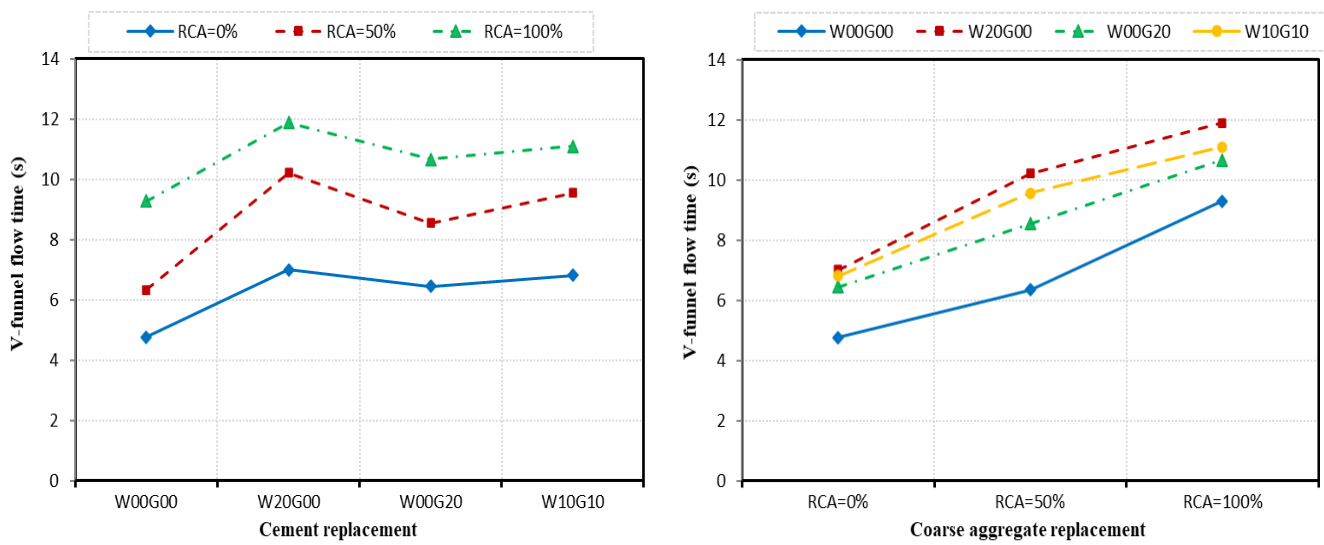


**Fig. 4.** Effect of cement and coarse aggregate replacement on V-funnel time

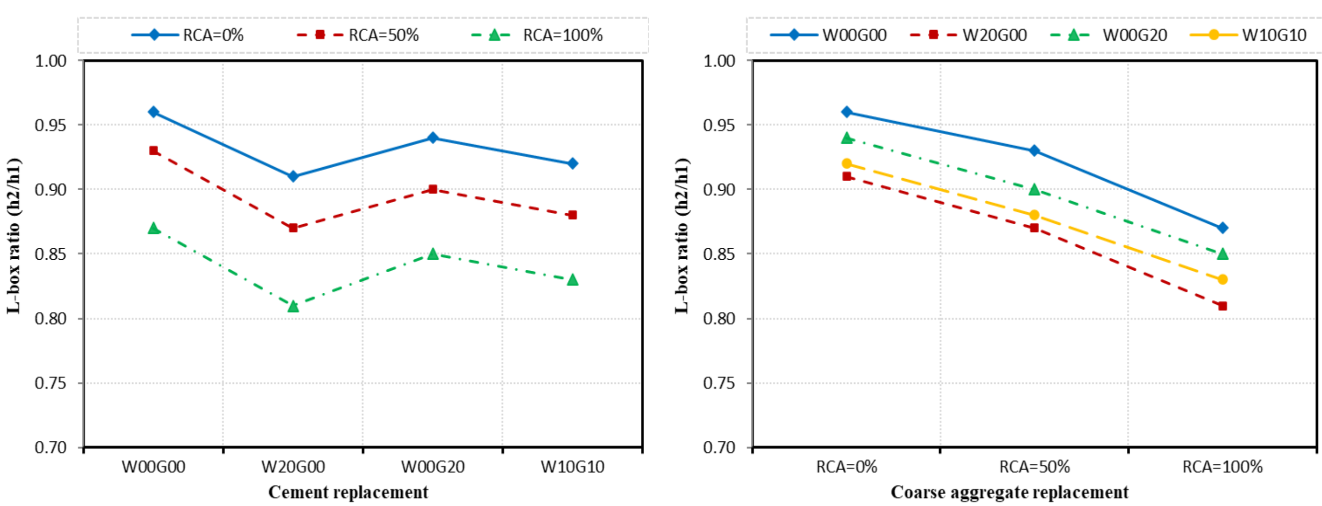


**Fig. 5.** Effect of cement and coarse aggregate replacement on L-box ratio

### 3.2 Hardened properties of SCC

#### 3.3.1 Compressive strength of SCC

The compressive strength of SCC mixtures with 0, 50, and 100% RCA as a natural aggregate is shown in Fig. 6. For the control SCC mixtures, the addition of 50% and 100% RCA as a natural coarse aggregate into SCC mixtures led to a decrease in the compressive strength of SCC from 66.7 MPa to 63.4 MPa and 58.6 MPa, respectively. These results agree with a study conducted by Kebaïli et al. [21] and Carro-López et al. [22]. They reported that the addition of RCA as a natural coarse aggregate hurts the compressive strength of SCC.

On the other hand, the addition of SCMs, namely GGBS and WWA into SCC mixtures has a significant effect on the compressive strength of SCC. For the SCC with natural coarse aggregate, the addition of WWA as a cement replacement into SCC mixtures led to reduce the compressive strength of the SCC mix by 40.9% for the mixtures containing 20% WWA, as shown in Table 6 and Fig. 6. While the addition of GGBS has a lower effect on the reduction of compressive strength of SCC. For instance, addition of 20% GGBS as a cement replacement in SCC mixtures resulted in reducing the compressive strength by 6.75%. The combined effect of WWA and GGBS in the MS-4 mix is having a moderate impact on the compressive strength, 10% GGBS and 10% WWA as a cement replacement led to reduce the compressive strength of SCC by 32.2%.

The effect of RCA and SCM namely (WWA and GGBS) on the compressive strength of SCC, has presented in mixtures (MS-5 to MS-12). The addition of RCA in 50 and 100% as natural coarse aggregate hurts the compressive strength, especially with 20% WWA. While addition of GGBS as a cement replacement into SCC mixtures made of RCA, has a lower effect than that of WWA on the compressive strength of SCC.

**Table 6.** Compressive and Tensile strength of SCC

| Coarse aggregate replacement (%) | Cement replacement (%) | | Compressive strength (MPa) | Tensile Strength (MPa) |
|---|---|---|---|---|
| | WWA | GGBF | | |
| 0 | 0 | 0 | 66.7 | 5.23 |
| | 20 | 0 | 39.4 | 4.86 |
| | 0 | 20 | 62.2 | 4.52 |
| | 10 | 10 | 45.2 | 4.35 |
| 50 | 0 | 0 | 63.4 | 5.21 |
| | 20 | 0 | 38.1 | 4.58 |
| | 0 | 20 | 57.2 | 4.41 |
| | 10 | 10 | 43.3 | 4.20 |
| 100 | 0 | 0 | 58.6 | 5.09 |
| | 20 | 0 | 35.9 | 4.34 |
| | 0 | 20 | 55.5 | 4.21 |
| | 10 | 10 | 42.7 | 4.05 |

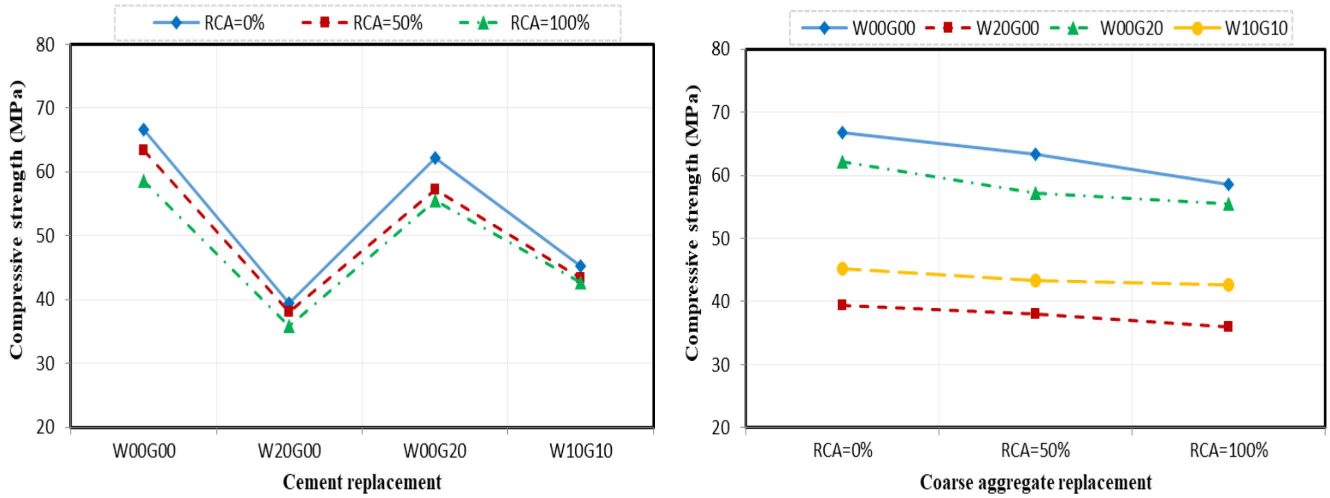


**Fig. 6.** Effect of cement and coarse aggregate replacement on compressive strength

### 3.3.2 Splitting tensile strength of SCC.

The splitting tensile strength test has been conducted for twelve SCC mixtures. The addition of RCA as a natural coarse aggregate with 100% cement in SCC mixtures led to reduce the splitting tensile strength of SCC by 0.38% and 2.67% only for the SCC mixtures containing 50% and 100% RCA, respectively. This reduction in splitting tensile strength is not high and can be neglected. While the addition of 20% WWA as a cement replacement in SCC mixtures led to reduce the splitting tensile strength by about 7.07%, 12.42%, and 17.01% for the SCC mixtures made of 0, 50, and 100% RCA, respectively, as shown in Fig. 7.

On the other hand, the addition of GGBS as a cement replacement into SCC mixtures has a higher effect on the splitting tensile strength than that of WWA. The addition of 20% GGBS results in reducing the splitting tensile strength of SCC mixtures by 13.57%, 15.67%, and 19.5% for the SCC mixtures containing 0, 50, and 100% RCA. Other researchers reported that the addition of RCA instead of natural coarse aggregate leads to reduce the splitting tensile strength of SCC [21, 22].

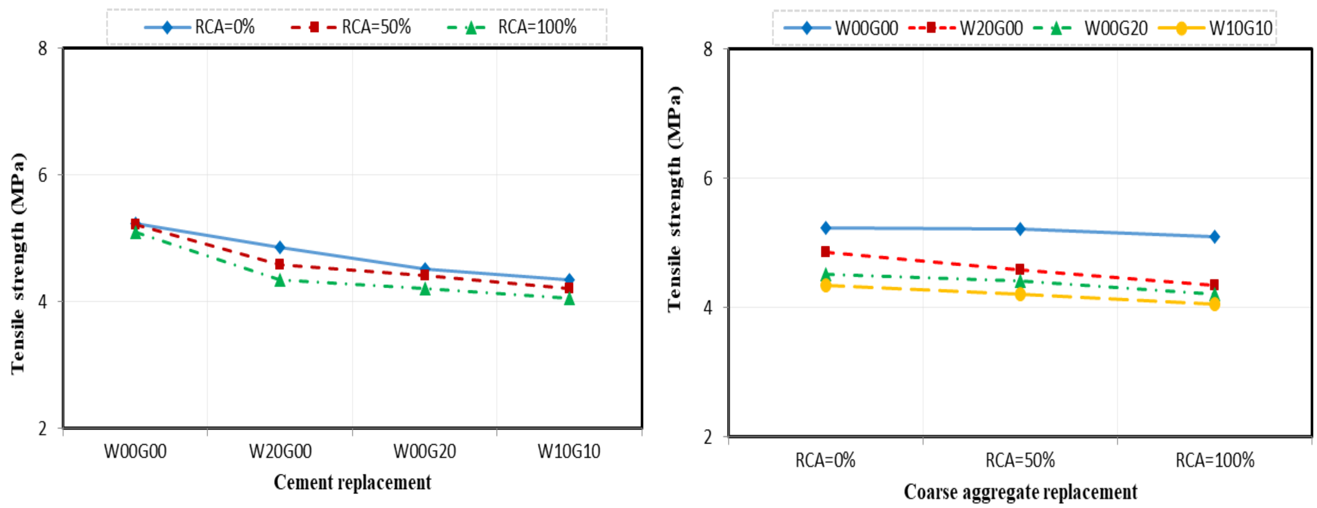

**Fig. 7.** Effect of cement and coarse aggregate replacement on tensile strength

## 4. Discussion of results

The current study investigated the combined effect of waste materials including (WWA and GGBS) and recycled coarse aggregate on the workability and strength of SCC. The results obtained showed significant information about sustainable concrete materials. The addition of waste materials, like GGBS and WWA, presented an important effect on the workability of SCC. As observed, the addition of 20% WWA and 20% GGBS reduced the slump flow diameter from 780 mm to 715 mm and 746 mm, respectively, while the $T_{50}$ slump increased from 1.84 to 3.06 and 2.28, respectively. In addition to that, the addition of RCA into SCC mixtures in replacement levels of 50% and 100% as a coarse aggregate resulted in a further decrease in the slump flow diameter from 780 mm to 755 mm and 730 mm, respectively.

On the other hand, the combined effect of WWA and GGBS has a lower effect on the workability. The addition of 10% WWA and 10% GGBS into the SCC mix led to a decrease in the slump flow diameter from 780 to 728 mm, and increase the $T_{50}$ slump from 1.84 to 2.77 sec. This development in workability can be attributed to the pozzolanic reactivity of GGBS, which assisted better particle packing and lubrication within the concrete matrix [23]. Subsequently, the addition of waste materials and RCA into SCC needs suitable additives to enhance workability for optimizing the rheological properties of SCC [24, 25].

The addition of RCA led to a decreased workability of SCC due to its rough surface texture and higher water absorption, which increased the demand for mixing water and hindered the flow of the SCC mix [26]. Nevertheless, through appropriate modifications in the mix design, like optimizing the aggregate/binder ratio and using suitable mineral admixtures, it was possible to mitigate the adverse effects of RCA on workability while keeping an acceptable flow slump diameter [27].

Furthermore, the results obtained showed that the compressive strength of SCC can be extensively affected by the combined existence of RCA and waste materials. The incorporation of waste materials namely WWA and GGBS mainly contributed to the reduce the compressive and splitting tensile of SCC. The addition of 20% WWA into the SCC mix led to a decrease in the compressive and splitting tensile strengths from 66.7 to 39 MPa and from 5.23 to 4.86 MPa, respectively. The addition of 20% GGBS into the SCC mix led to a decrease in the compressive and splitting tensile strengths from 66.7 to 62.2 MPa and from 5.23 to 4.52 MPa, respectively. On the other hand, the combined effect of WWA and BBGS as cement replacement in the SCC has been investigated. The addition of 10% GGBS and 10% WWA into the SCC mix resulted in decreasing the compressive and splitting tensile strengths from 66.7 to 45.2 MPa and from 5.23 to 4.35 MPa, respectively. Parallel, the addition of RCA as coarse aggregate also contributed to a decrease in the compressive and splitting tensile strength from 66.7 to 58.6 MPa, and from 5.23 to 5.09 MPa, respectively. This decrease in the strength of SCC might be due to the variability in the quality and properties of RCA caused challenges in getting constant strength properties [28-31].

In general, the results obtained highlight the potential combined effect between waste materials and RCA in improving the workability and strength of SCC. By carefully selecting suitable replacement levels for these constituents, it is reasonable to achieve sustainable concrete mixtures that demonstrate favorable workability and strength properties.

## 5. Conclusions and recommendations

This paper discusses the combined effect of RCA as a natural aggregate and the addition of WWA and GGBS as a cement replacement on the fresh properties and strength of SCC mixtures. The results obtained from this study can be summarized in the following points:

1. The T50 slump flow increased from 1.84 to 3.30 sec due to an increase in the RCA as natural coarse aggregate from 0% to 100%. The slump flow diameter was reduced from 780 to 730 mm for the SCC mixtures containing 0% and 100% RCA, respectively.
2. The addition of RCA as a natural coarse aggregate affected the passing ability of SCC mixtures. The addition of 50% and 100% RCA led to an increase in the V-funnel time from 4.77 sec to 9.29 sec, and a decrease in the L-box ratio from 0.96 to 0.87, respectively.
3. The addition of RCA as a natural coarse aggregate reduced the compressive strength of SCC mixtures. The addition of 50% and 100% RCA reduced the compressive strength by 4.94% and 12.14%, respectively.
4. The addition of RCA as a natural coarse aggregate reduced the splitting tensile strength of SCC mixtures. The addition of 50% and 100% RCA as natural coarse aggregate led to reduce the splitting tensile strength by 0.38% and 2.67%, respectively.

It is recommended to investigate the use of other waste materials with high pozzolanic materials and RCA in SCC to get better results and compare them with natural aggregate with optimized mix designs.

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