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RESEARCH ARTICLE

# Life cycle impact of concrete incorporating nylon waste and demolition waste

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**Abstract**

The large consumption of natural resources by the construction industry and resultant pollution have inspired the necessity to investigate the potential of eco-friendly materials, such as recycled aggregates and recycled fibers. In this study, the effect of different percentages of recycled coarse aggregate (RCA) and nylon waste fibers (NWFs) was investigated on engineering performance and performance-related carbon emissions of high-performance concrete (HPC). Engineering performance indices include compressive strength (CS), splitting tensile strength (STS), water absorption (WA), and chloride ion penetration (CIP). The environmental impact of designed mixes was evaluated using a cradle-to-gate life cycle assessment approach on the HPC mixes. The results showed that the incorporation of 0.25–0.5% yielded maximum STS for all percentages of RCA. The use of NWF helped overcome the negative impact of RCA on the STS of HPC. The use of the 0.1–0.25% volume of NWF was beneficial to the permeability-related durability indicators of HPC. CS-related emissions were minimum for concrete mixes incorporating 0.1–0.25% NWF with 0% and 50% substitution levels of RCA. While STS-related emissions were lowest for HPC incorporating 0.5% NWF with 50% and 100% substitution levels of RCA.

**Keywords** Recycled fibers · Concrete waste · Multi-criterion · Optimization · Sustainable concrete

## Introduction

On a global scale, the construction industry is responsible for 40% consumption of energy, 30% of raw materials, 25% of waste, 12% of land use, and about 35% of greenhouse emissions (Corominas et al. 2020). Activities such as the processing of raw materials and their transportation and installation of a structure made from a variety of materials consume a huge amount of energy. After the designed service life, the demolition of structures and disposal of building wastes are considered the main contributor to the detrimental effects on the environment. To lessen the demand for natural resources and the environmental impact of the construction industry, eco-friendly or recycled materials may not only meet the requirements of raw materials but also reduce their impact on the environment. In the construction industry, major environmental impact is contributed by the production and application of concrete. Portland cement is accountable for around 70–80% of the environmental impact of concrete mixes (Kurda et al. 2018). Moreover, coarse aggregate is the major component of concrete by volume, and its derivation from natural resources leaves devastating

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effects on the natural landscapes, causes air pollution and desertification, and destroys the habitat of flora and fauna (Qureshi et al. 2020).

The demand for construction aggregates was 52 billion tons in 2019 (Freedonia 2016). This demand can be partially substituted by recycled aggregates derived from demolition and construction wastes. The use of recycled coarse aggregate (RCA) in concrete as the partial or full replacement of natural coarse aggregates (NCA) has been studied by several researchers (Kurda et al. 2017, 2018). Not only the utilization of RCA saves the mineral resources of NCA, but it also manages the huge volumes of non-biodegradable construction wastes.

Both the mechanical and durability properties of RAC have been investigated widely. It is established that 20–50% replacement of NCA with RCA does not significantly harm the mechanical strength of concrete (Kou et al. 2011; Qureshi et al. 2020). However, at higher incorporation levels of RCA, both the mechanical and durability properties of concrete are affected negatively (Afroughsabet et al. 2017). The presence of low-density mortar causes a reduction in the mechanical strength of concrete and facilitates the permeability of chlorides and harmful chemicals (Ali and Qureshi 2019a). The performance of RAC can be upgraded using engineered fibers and secondary binding materials (Sasanipour et al. 2021; Yunchao et al. 2021).

Engineered or artificial fibers, such as steel fiber, glass fiber, polypropylene fiber, and nylon fibers can be used to supplement the ductility and tensile strength of RAC (Das et al. 2018; Kazmi et al. 2018; Ali et al. 2020b; Qureshi et al. 2020). Das et al. (2018) reported that at the addition of 0.5% volume of PPF, RAC showed higher splitting tensile strength (STS) and compressive strength (CS) than unreinforced NCA concrete. Afroughsabet et al.(2017) reported that at a 1% addition of steel fiber, the flexural strength of RAC was almost two times higher than the unreinforced NCA concrete. The compressive and flexural toughness of RAC also experienced substantial improvement due to the addition of artificial fibers (Kazmi et al. 2019; Ali et al. 2020b). Thus, fiber addition plays a positive role in enhancing the tensile strength of unreinforced concrete.

Although fiber addition is useful to the overall mechanical behavior of concrete, it is an expensive choice. Modern research efforts are inspired to explore eco-friendly or recycled fiber reinforcements to overcome the deficiencies of RAC. There are several waste materials like scrap tires, plastic bottles, fishnets, textile threads, plastic sacks, carpet fibers, and coir that can be used as fiber reinforcements since these consist of high tensile strength materials (Alshkane et al. 2017; Bui et al. 2018; Alrshoudi et al. 2020). Recycled fibers are not superior to artificial fibers, but some trade-offs can be accepted to conserve environmental quality. Recycled tire steel fibers (RTSFs) were found up to 75% efficient as compared to virgin steel fibers considering the STS and flexural strength of HPC (Ali et al. 2022). While Domski et al. (2017) stated the superiority of RTSF in tensile strength and toughness compared to artificial fibers. Recycled tire polymer fibers (RTPF) can be used as a replacement for virgin polypropylene fibers (Baricevic et al. 2018). The research advancement in the direction of recycled fibers would reduce post-consumer products and contribute to the sustainable production of reinforced HPC.

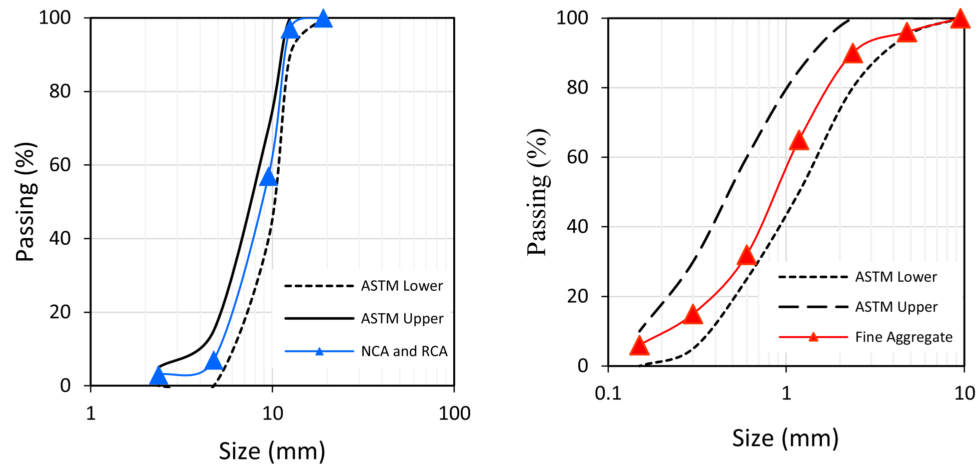
Many expired products can be processed into fiber reinforcements. For example, nylon waste fibers (NWFs) separated from expired brushes can be used as fiber reinforcement due to their high tensile strength. Globally massive quantities of nylon wastes are generated, and China solely generates around 80 million tons of expired nylon brushes in the form of toothbrushes, hairbrushes, and paintbrushes (Yin and Wu 2018). Recycling non-biodegradable nylon waste is necessary; otherwise, it can create severe land and water pollution (Wang et al. 2017). Similar to engineered polymer fibers (e.g., polypropylene, nylon, and polyvinyl fibers), NWF has high tensile strength, and toughness. NWF possesses about 400 MPa of tensile strength (Orasutthikul et al. 2017), while virgin nylon fibers possess a tensile strength of over 550 MPa (MatWeb 2021). Therefore, it can be studied as fiber reinforcement in concrete. Eco-friendly and inexpensive NWF can be used to supplement the strength and durability of RAC.

This research will evaluate the engineering and environmental performance of HPC produced with eco-friendly materials, i.e., RCA and NWF. Three groups of HPC were prepared with 0%, 50%, and 100% replacement of NCA with RCA. The effect of varying NWF content was studied on the properties of HPC. The performance of altered mixes was compared with that of the HPC containing 0% RCA and 0% NWF. For engineering performance, several properties like CS, STS, water absorption (WA), and chloride ion penetration (CIP) of mixes were measured. A simplified LCA analysis was conducted on the mixes from cradle to gate. Finally, the performance and environmental impact of mixes incorporating eco-friendly materials were compared with that of the conventional mix. For multi-criterion-based assessment, performance-related carbon emissions were calculated and compared for all the studied mixes.

## Materials and methods

### Constituent materials of concrete

For binding material, Portland cement of ASTM 53 grade was used. It complies with the “type I general purpose cement” according to ASTM C150 (2018). NCA consisted of crushed dolomitic sandstone. Whereas RCA was




(a) NCA and RCA (b) Fine aggregate

**Fig. 1** Gradation charts of aggregates

**Table 1** Properties of aggregates

| Aggregate | Aggregate size (mm) | | Absorption capacity (%) | Relative density | Fineness modulus (FM) |
|---|---|---|---|---|---|
| | Max | Min | | | |
| Fine aggregate-quarry sand | 4.75 | 0.075 | 0.78 | 2.67 | 2.92 |
| NCA-crushed dolomitic sandstone | 12.5 | 2.36 | 1.04 | 2.72 | - |
| RCA-crushed concrete waste | 12.5 | 2.36 | 3.61 | 2.54 | - |

manually prepared by crushing old concrete samples from the concrete laboratory. The gradation of RCA and NCA was kept similar. The maximum size of NCA and RCA was 12.5 mm, which is suitable for fibrous HPC mixes (Kizilkanat et al. 2015; Koushkbaghi et al. 2019). Natural fine aggregate was not replaced with recycled aggregates, due to high mortar content and poor strength of fine recycled aggregates (Fig. 1). Natural fine aggregate was derived from the local quarry in Lawrancepur. The engineering characteristics of aggregates are given in Table 1. NWFs were extracted from the expired paintbrushes. The handle and ferrule parts of the paintbrush were separated, and bundled nylon filaments were chopped in lengths between 25 and 40 mm. The diameter of fiber varied from 0.25 to 0.5 mm. The sample of NWF is shown in Fig. 2. Specific mass of NWF is 1.12 g/cm$^3$. Yin and Wu (2018) reported the tensile strength of expired nylon filaments as 357 MPa. For maintaining the workability at low water-binder ratio, Viscocrete 3110 was used as the water-reducer.

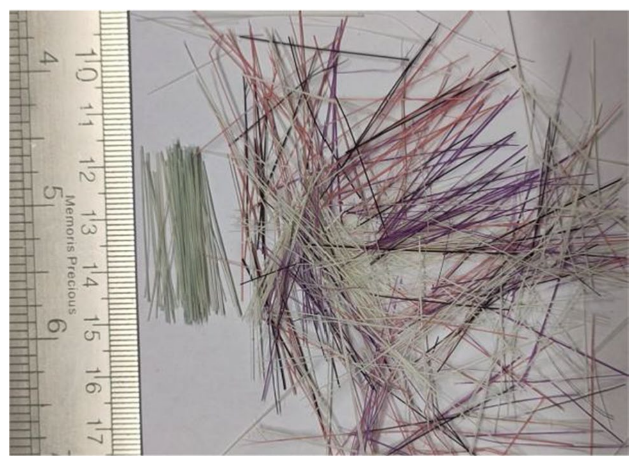


**Fig. 2** Sample of NWF

## Design of mixes

After several trials, basic or conventional HPC was designed for 60 MPa compressive strength and it served as a control or reference mix. The slump value of this HPC in the fresh state was chosen between 150 and 230 mm. Design strength and workability values were attained at a 0.3 water-cement ratio. Three groups of unreinforced HPCs were produced by 0%, 50%, and 100% substitution of NCA with RCA by volume. These three families were named 0RA, 50RA, and 100RA. In each of these three families, five different volume fractions of NWF, i.e., 0%, 0.1%, 0.25%, and 1% were individually incorporated. The formula for the calculation of NWF weight at a given volume fraction is shown in Eq. (1). Where, $V_f$ is the volume fraction (%) of fibers in the concrete mix, $W_f$ is the weight of fibers (kg) for the corresponding volume fraction, and $D_f$ is the density of fibers (1120 kg/

m$^3$). The details of the mix design are given in Table 2. The dosage of the plasticizer was changed to control the slump of fresh concrete in the 150–230 mm range.

$$W_f = \frac{V_f}{100} \times D_f \tag{1}$$

Concrete mixes were prepared in a drum mixer. First, aggregate and cement were dry for 2 min. Then, the required quantities of water and plasticizer were added to the dry mixed concrete and the mixing continued for 4 min. The mixing of unreinforced HPCs (0RA, 50RA, and 100RA) was done in two phases. For the preparation of fibrous HPCs, NWF was gradually added to the fresh plain HPC, and the mixing lasted for 4 min. Subsequently, the slump values of all batches were noted for the desired workability check. After meeting the workability requirement, all HPC mixes proceeded to the casting stage. No issue of fiber accumulation was observed, and the plasticizer softened fibrous mixes and aided the compaction.

## Testing methods

To assess the engineering performance of concrete mixes, mechanical and permeability-related durability was measured. Mechanical performance was judged based on the results of compressive strength (CS) and splitting tensile strength (STS). For CS assessment, 100 mm cubic samples of all mixes were tested as per the guidelines of BS EN 12,390. For STS, 100 mm × 200 mm cylindrical samples of mixes were tested following ASTM C496. Mechanical testing was conducted in a CONTROLS compression testing machine having a 3000 kN loading capacity in compression.

To assess the durability performance, the chloride ion penetration (CIP) and water absorption (WA) capacity of mixes were evaluated. CIP was assessed by the immersion method explained in a companion study (Ali and Qureshi 2019b). This test was performed on 100 mm cube samples of HPC cured for 28 days. WA test was executed on samples having 50 mm thickness and 100 mm diameter according to ASTM C948 (2016).

## LCA methodology

The life cycle assessment (LCA) of prepared concrete mixes was considered from cradle-to-gate, without considering the impact of their structural application, maintenance, and demolition. Nevertheless, the mechanical and durability parameters of the prepared mixes were investigated in this research, which depicts the performance of mixes in service. All the LCA calculations were systematically performed using the MS Excel program, considering mix design inputs, EI of raw materials, the impact of transportation, and mix preparations. The LCA analysis of mix preparations is performed similarly in previous studies (Kurda et al. 2018; Riekstins et al. 2020).

### Unit function

The functional unit in the present study is a unit cubic meter (m$^3$) of HPC with different amounts of RCA (0%, 50%, and 100%) and NWF (0%, 0.1%, 0.25%, 0.5%, and 1%) (Table 2). The volumetric environmental impact (EI) will be calculated in terms of carbon emissions per unit cubic meter of concrete (kg-$CO_2$/m$^3$). Performance-related emissions will be analyzed from the ratios between carbon emissions and performance indicators of concrete for different amounts of RCA and NWF, e.g., EI/CS, EI/STS, EI/WA, and EI/CIP.

**Table 2** Proportioning and identities (IDs) of HPC mixes

| Mix ID | NWF (%) | RA (%) | Cement (kg/m$^3$) | Fine aggregate (kg/m$^3$) | RCA (kg/m$^3$) | NCA (kg/m$^3$) | Water (kg/m$^3$) | NWF (kg/m$^3$) | Plasticizer (%) |
|---|---|---|---|---|---|---|---|---|---|
| 0RA | 0 | 0 | 457 | 755 | 0 | 1035 | 136 | 0 | 0.41 |
| 50RA | 0 | 50 | 457 | 755 | 485 | 518 | 136 | 0 | 0.41 |
| 100RA | 0 | 100 | 457 | 755 | 969 | 0 | 136 | 0 | 0.41 |
| 0.1NWF/0RA | 0.1 | 0 | 457 | 754 | 0 | 1034 | 136 | 1.12 | 0.54 |
| 0.1NWF/50RA | 0.1 | 50 | 457 | 754 | 484 | 517 | 136 | 1.12 | 0.54 |
| 0.1NWF/100RA | 0.1 | 100 | 457 | 754 | 968 | 0 | 136 | 1.12 | 0.54 |
| 0.25NWF/0RA | 0.25 | 0 | 457 | 752 | 0 | 1032 | 136 | 2.76 | 0.66 |
| 0.25NWF/50RA | 0.25 | 50 | 457 | 752 | 483 | 516 | 136 | 2.76 | 0.66 |
| 0.25NWF/100RA | 0.25 | 100 | 457 | 752 | 966 | 0 | 136 | 2.76 | 0.66 |
| 0.5NWF/0RA | 0.5 | 0 | 457 | 749 | 0 | 1029 | 136 | 5.52 | 0.72 |
| 0.5NWF/50RA | 0.5 | 50 | 457 | 749 | 482 | 515 | 136 | 5.52 | 0.72 |
| 0.5NWF/100RA | 0.5 | 100 | 457 | 749 | 963 | 0 | 136 | 5.52 | 0.72 |
| 1NWF/0RA | 1 | 0 | 457 | 742 | 0 | 1022 | 136 | 11.2 | 0.91 |
| 1NWF/50RA | 1 | 50 | 457 | 742 | 479 | 512 | 136 | 11.2 | 0.91 |
| 1NWF/100RA | 1 | 100 | 457 | 742 | 957 | 0 | 136 | 11.2 | 0.91 |

### Boundaries

For all constituent materials, the EI was considered from the cradle to the gate, which includes the EI from extraction, processing, and transportation of raw materials from the source to the concrete plant. The total EI for concrete was calculated by combining the cradle-to-gate EI of constituent materials used to produce a unit volume of concrete and the EI from the energy consumed for the mixing of concrete.

### Dataset

The EI of processing of constituent materials (cement, natural fine aggregate, RCA, NCA, and plasticizer), as carbon emissions generated per unit kilogram of material, was acquired from a European study (Kurda et al. 2018). A reliable framework to assess the EI potential of raw materials is absent in Pakistan, therefore, the EI of raw materials was taken from a reliable source (Kurda et al. 2018). The information on the EI of constituent materials is given in Table 3.

For NWF, EI was assessed for the first time in this study. For this purpose, the energy consumption in different processes to refine NWF was considered. The processes involved to recycle NWF are depicted in Fig. 3. Major carbon emissions from NWF processive were dependent on the shredding of extracted paintbrush filaments. Whereas other processes like manual separation of filaments and ferrule could not be quantified. For shredding, a typical plastic shredding machine shreds about 40 kg of plastic waste per hour and it requires a 2.5 kW power input (GIT 2022). The input power is supplied from a coal power plant in Sahiwal city. According to the US Energy information administration, about 1.05 kg of carbon emissions is released per kWh production of electricity (EIA 2022). Thus, 1 kg of NWF is produced with 0.066 kg of carbon emissions.

The transportation of processed constituent materials to the concrete batching plant contributes significantly to the total EI of concrete production. The EI of material due to transportation increases linearly with the distance between the source of material and the concrete batching plant. In this study, all materials were assumed to be transported by a 17.3-t capacity truck. For this type of truck, the EI is around $6.57 \times 10^{-5}$ kg of carbon emissions per unit kilogram of material for a 1-km distance. Thus, the distance of the sources of different materials from the concrete plant was noted. The impact of the empty returning vehicle was considered about 85% of the dispatching vehicle. The distances of different materials from the concrete plant are presented in Table 4. After including the EI from the processing and transportation of raw materials, the EI of the concrete mixing was considered as 4.65 kg-$CO_2$ per unit volume ($m^3$) constant for all mixes.

**Table 3** EI of constituent materials

| Processed material | Global warming potential (kg-$CO_2$/kg) |
|---|---|
| Cement | 0.898 |
| Fine aggregate | 0.002 |
| NCA | 0.053 |
| RCA | 0.005 |
| Superplasticizer | 0.002 |
| Water | 0.000 |

## Results and discussion

### Engineering performance

#### Compressive and splitting tensile strength

Compressive strength is one of the most important characteristics of hardened concrete and is widely used for the design of concrete structures. Figure 4 shows the effect of NWF and RCA incorporation on the CS value

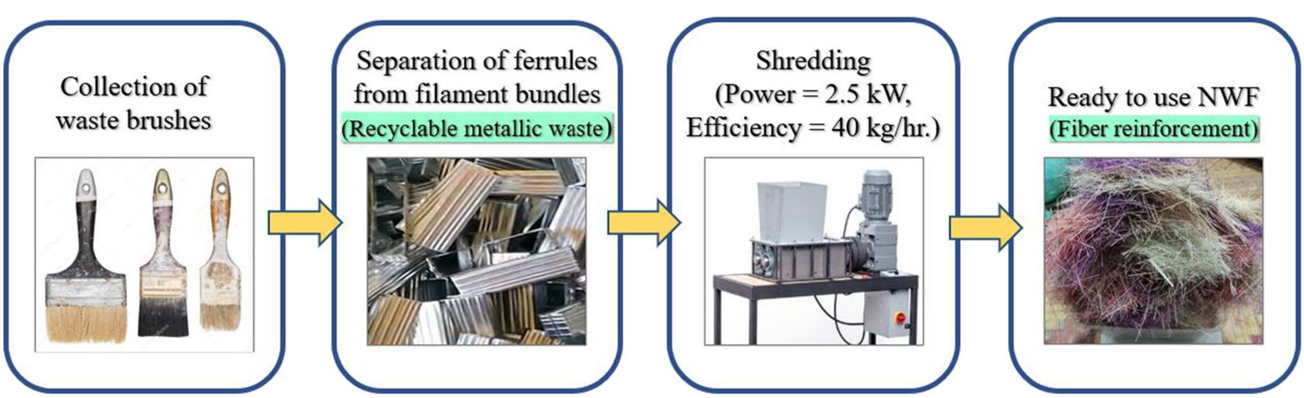



**Fig. 3** Recycling of NWF

**Table 4** Distance of materials' sources from concrete plant

| Material | Location | Distance from the plant (km) |
|---|---|---|
| Cement | Mianwali, Pakistan | 398 |
| Natural fine aggregate | Attock, Lawrancepur | 455 |
| NCA | Sargodha, Pakistan | 245 |
| RCA | Sahiwal, Pakistan | 3 |
| Superplasticizer | DHA, Lahore, Pakistan | 176 |
| NWF | Campus, Building | 0 |
| Water | Campus, Building | 0 |

of HPC. As anticipated, CS decreased noticeably with increasing RCA percentage. For example, at 50% and 100% replacement of NCA with RCA, CS dropped by 6% and 20%, respectively. Low-density attached mortar and inherent fissures in RCA negatively affect the CS. Depending upon the percentage, the addition of NWF showed mixed effects on the CS. Minor increments in CS values were observed at 0.1% volume of NWF. For example, around a 7% increase in CS of concrete was noticed at 0.1% NWF. Then, CS started to reduce gradually when NWF content exceeded 0.25%. Previous studies (Das et al. 2018; Ali et al. 2020a) have also found similar trends regarding the variation in CS results with fiber content. Fiber addition yields both positive and negative effects on the CS value. A positive effect comes from the bridging action of fiber filaments that improves the axial resistance of concrete. Whereas, the negative effect, especially in the case of lightweight fibers, comes from the low density of fibers. The use of high fiber volume tends to reduce the density and mechanical strength of concrete. The positive effect of fibers may be prominent at low doses, however, at higher fiber volumes, CS decreased due to a reduction in the density value of concrete.

The use of 50% RCA and 0.1% NWF yielded a CS value similar to the control mix. The positive effect of NWF helped in overcoming the difference between CS values of concrete with 0% and 50% RCA. Thus, NWF helped in supplementing the strength deficiency of concrete with a high volume of RCA. The CS value of 100% RCA concrete with and without 0.1% fiber was above 60 MPa, still falling in the range of high-strength/high-performance concrete (Neville and Aitcin 1998). The low water-binder ratio and plasticizer aided to achieve dense and high-strength RAC, and the addition of 0.1% NWF further enhanced the CS of 100% RCA concrete from 61 to 65 MPa.

Figure 5 shows the influence of different NWF and RCA contents on the STS of concrete. Compared to the control mix, STS of 50% RCA and 100% RCA concrete were 4%

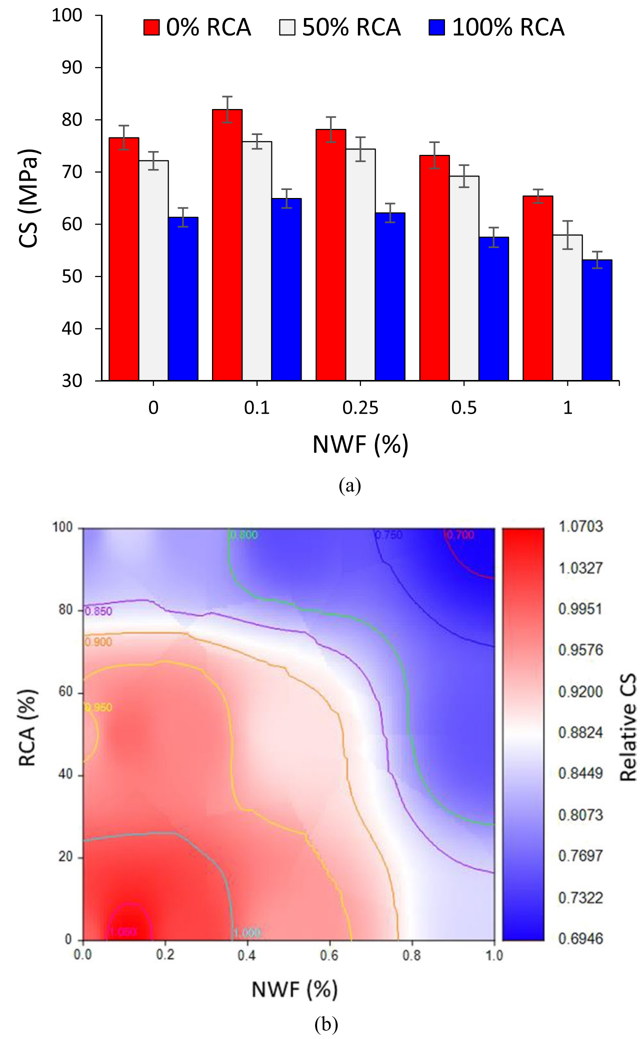



**Fig. 4** Compression performance. **a** Peak CS of HPC mixes. **b** Relative CS of HPC mixes with different amounts of NWF and RCA

and 15% lower. These reductions can be linked to the low-density attached mortar. Both CS and STS values were affected similarly upon the replacement of NCA with RCA. However, there was a substantial net increase in the STS of concrete due to the addition of NWF. The inclusion of 0.1%, 0.15%, 0.25%, 0.5%, and 1% NWF caused 8%, 18%, 20%, and 9% net increments in the STS. The optimum dosage of NWF is 0.25% causing about a 20% increase in the STS. Due to the incorporation of 0.25% NWF, 50% RCA concrete yielded about 11.3% higher STS than the control mix. Whereas concrete containing 100% RCA showed 6% more STS than the control mix. Thus, NWF was more beneficial to the STS as compared to its effect on CS. The utilization ratio or efficiency of fiber due to crack-bridging action is more under tensile load than compression load (Afroughsabet et al. 2017). Therefore, fiber addition is highly useful to the STS and ductility of concrete.

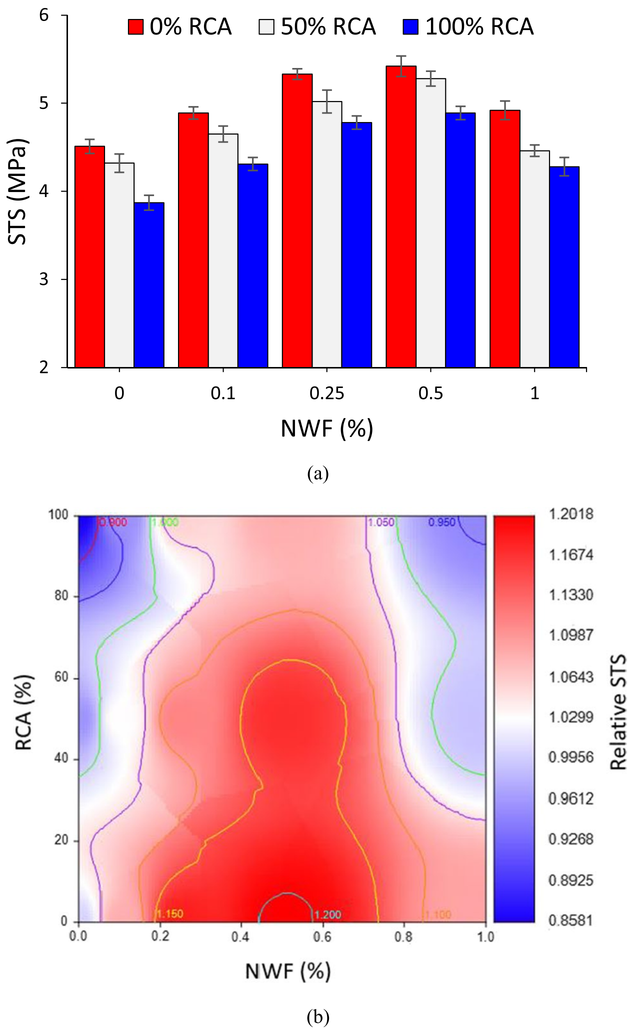



**Fig. 5** Tensile performance. **a** Peak STS of HPC mixes. **b** Relative STS of HPC mixes with different amounts of NWF and RCA

## Permeability-related durability properties

WA test results of HPC with or without NWF and RCA are illustrated in Fig. 6. As can be noticed in Fig. 6, the replacement of NCA with RCA caused an increase in the WA capacity of concrete. A net increase of 35% was observed at the incorporation of 100% RCA. The increase in the porosity originated from low-density mortar attached to RCA (Kurda et al. 2019). WA results also confirm the decrease in the density and increase in the porosity of concrete, which resulted in a decrease in the mechanical performance of concrete.

The results showed the incorporation of NWF at low volumes resulted in a decrease in WA capacity. The addition of NWF at 0.25% and 0.5% showed a 5% net reduction in the WA. This reduction can be ascribed to a reduction in the micro-cracks due to the shrinkage of cementitious paste. Thus, the permeability of water in plain concrete is reduced due to the micro-crack resistance of NWF at low volumes.

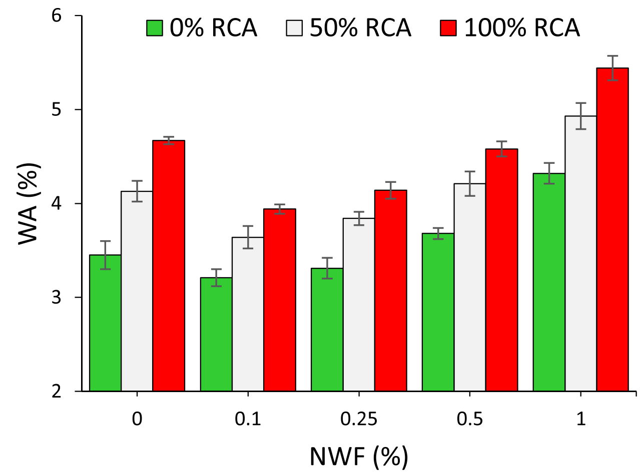



**Fig. 6** Water absorption capacity of HPC with or without NWF and RCA

The reduction caused by NWF is insignificant to improve the imperviousness of concrete. The incorporation of 1% NWF leads to an increase in the WA. This can be related to the reduction in compaction of concrete due to an increase in the harshness of concrete at 1% NWF content. Poor dispersion of fibers at high contents may increase the voids in concrete.

The resistance of steel rebars inside plain concrete against corrosion or chloride attack can be assessed through different tests. The chloride ion penetration (CIP) measurement through the immersion technique is a reliable method to assess the chloride durability of concrete as it stimulates almost the actual environmental conditions allowing for a natural penetration of chloride ions. Figure 7 shows the effect of different contents of NWF and RCA on the CIP of concrete. Higher values of CIP correspond to a decrease in the corrosion resistance of concrete and vice versa.

As can be seen in Fig. 7, the variation in CIP values with varying NWF and RCA levels is similar to that observed in WA results. The porosity increase in RAC allows for deeper penetration of chloride ions. The CIP value of concrete was increased by 58% due to the 100% replacement of NCA. While the incorporation of NWF showed no significant effect on controlling the CIP resistance of concrete. Notable reductions in CIP values were noticed at 0.1% and 0.25% volume of NWF. For instance, 50% RCA concrete experienced a reduction of 29% at 0.1–0.25% NWF. Similarly, 100% RCA concrete showed a 40% reduction in CIP value at 0.1–0.25% NWF. It is proved that the low fiber volumes were beneficial to the corrosion resistance of concrete. Contrary to the 0.1–0.25% dose of NWF, the higher doses of NWF showed an increase in the CIP value. This trend is similar to that observed in the results of WA. Thus, WA testing results can be used to predict the CIP values, see Fig. 8. Both WA and CIP values depend on the microstructural

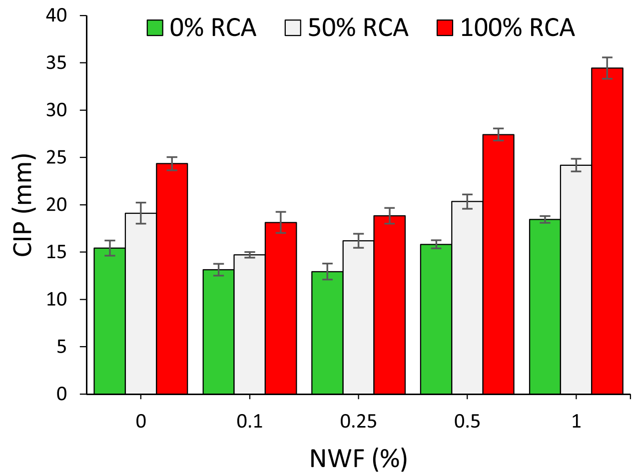



**Fig. 7** Chloride ion penetration inside HPC matrix with or without NWF and RCA

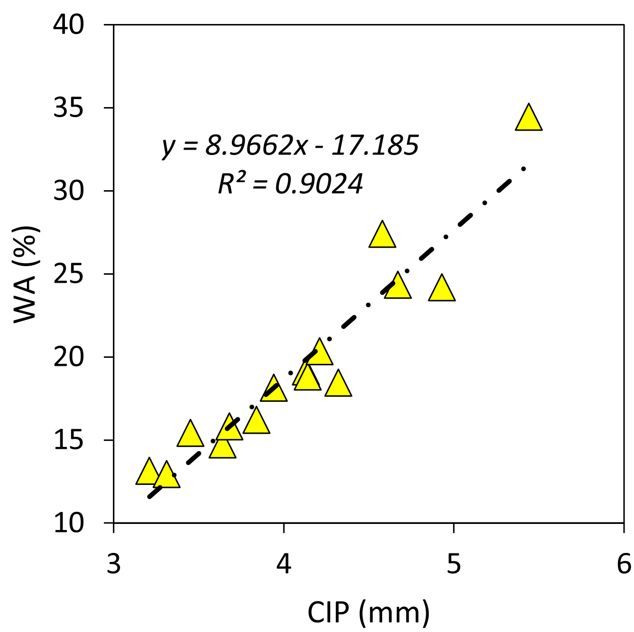



**Fig. 8** Relationship between WA and CIP

density and permeability. These can be related to a great degree of accuracy.

## Life cycle analysis results of concrete mixes

Based on cradle-to-gate LCA, the EI of concrete mixes with different amounts of NWF and RCA is presented in Table 5, while Fig. 9 presents the net change in EI of concrete mixes with varying amounts of NWF and RCA.

It can be noticed that, for all mixes, Portland cement contributes a major fraction to the total EI. For instance, Portland cement alone is responsible for 76% of the total EI of HPC containing 0% RCA. While, for mixes with 100% replacement of NCA, the cement accounts for about 90% of the EI of concrete. The addition of RCA showed notable reductions in the EI of concrete. For instance, for 100% replacement of NCA, the EI of concrete was reduced by almost 15%. This is because RCA preparation requires minimum energy for its processing. Besides, RCA is sourced from a site only 3 km away from the concrete plant; thus, its EI due to the transportation is minimum. RCA does not require energy for mining and conveyor systems. Besides consuming lesser energy, RCA saves natural resources of minerals and almost possesses zero abiotic depletion potential (Kurda et al. 2018). At 100% replacement of NCA, the EI of coarse aggregates is reduced by 95%. Thus, RCA caused notable reductions in the carbon footprint of concrete.

The EI of NWF is almost zero compared to that of cement and coarse aggregates. The incorporation of 1% NWF in concrete caused almost zero effect on the EI of concrete. This is because NWF is incorporated as by volume replacement of coarse aggregate. This means that when the quantity of coarse aggregate is reduced, the overall EI of concrete remained unaffected. NWF also yields no impact from transportation because of its nearness to the concrete plant. Contrary to the EI of engineered fibers, i.e., steel (2.65 kg-$CO_2$/kg), polypropylene (1.85 kg-$CO_2$/kg), and glass fibers (2.04 kg-$CO_2$/kg), the NWF (0.066 kg-$CO_2$/kg) possesses negligible EI. This is because NWF requires no processing of raw materials and if it can be recycled using an effective technique, it would be able to replace polypropylene and nylon fibers because NWF offered almost similar mechanical benefits.

## Performance-related emissions

As explained in the "Life cycle analysis results of concrete mixes" section, the incorporation of RCA with or without NWF showed noticeable reductions in the volumetric EI. However, the replacement of NCA with RCA also caused reductions in mechanical performance. Thus, a critical evaluation of HPC mixes with different amounts of NWF and RCA must be carried out. In this study, the performance-related EI (similar to the cost–benefit ratio) of the mixes was calculated. For example, the ratio between EI and mechanical parameters will enable deciding the optimum mix in terms of minimum EI per unit performance. Therefore, the EI/CS, and EI/STS ratios of all mixes were calculated, the results are presented in Fig. 10.

It can be noticed that the use of RCA does not reduce the emissions related to CS. It is because the use of RCA causes reductions in CS performance. Therefore, the deterioration of CS performance prevails over the environmental benefit of RCA. Concrete with 100% replacement of NCA, showed 7% higher EI than conventional mix containing 0% RCA.

**Table 5** Volume-related emissions of concrete mixes

| Mix ID | Cement (kg-$CO_2/m^3$) | Fine aggregate (kg-$CO_2/m^3$) | RCA (kg-$CO_2/m^3$) | NCA (kg-$CO_2/m^3$) | Water (kg-$CO_2/m^3$) | NWF (kg-$CO_2/m^3$) | SP (kg-$CO_2/m^3$) | Concrete production (kg-$CO_2/m^3$) | Total EI (kg-$CO_2/m^3$) |
|---|---|---|---|---|---|---|---|---|---|
| 0RA | 431.55 | 43.21 | 0.00 | 85.59 | 0 | 0.000 | 0.0094 | 4.65 | 565.0 |
| 50RA | 431.55 | 43.21 | 2.60 | 42.80 | 0 | 0.000 | 0.0094 | 4.65 | 524.8 |
| 100RA | 431.55 | 43.21 | 5.19 | 0.00 | 0 | 0.000 | 0.0094 | 4.65 | 484.6 |
| 0.1NWF/0RA | 431.55 | 43.15 | 0.00 | 85.51 | 0 | 0.072 | 0.0122 | 4.65 | 564.9 |
| 0.1NWF/50RA | 431.55 | 43.15 | 2.59 | 42.71 | 0 | 0.072 | 0.0122 | 4.65 | 524.7 |
| 0.1NWF/100RA | 431.55 | 43.15 | 5.19 | 0.00 | 0 | 0.072 | 0.0122 | 4.65 | 484.6 |
| 0.25NWF/0RA | 431.55 | 43.03 | 0.00 | 85.34 | 0 | 0.180 | 0.0152 | 4.65 | 564.8 |
| 0.25NWF/50RA | 431.55 | 43.03 | 2.59 | 42.63 | 0 | 0.180 | 0.0152 | 4.65 | 524.6 |
| 0.25NWF/100RA | 431.55 | 43.03 | 5.18 | 0.00 | 0 | 0.180 | 0.0152 | 4.65 | 484.6 |
| 0.5NWF/0RA | 431.55 | 42.86 | 0.00 | 85.10 | 0 | 0.361 | 0.0166 | 4.65 | 564.5 |
| 0.5NWF/50RA | 431.55 | 42.86 | 2.58 | 42.55 | 0 | 0.361 | 0.0166 | 4.65 | 524.6 |
| 0.5NWF/100RA | 431.55 | 42.86 | 5.16 | 0.00 | 0 | 0.361 | 0.0166 | 4.65 | 484.6 |
| 1NWF/0RA | 431.55 | 42.46 | 0.00 | 84.52 | 0 | 0.722 | 0.0211 | 4.65 | 563.9 |
| 1NWF/50RA | 431.55 | 42.46 | 2.56 | 42.30 | 0 | 0.722 | 0.0211 | 4.65 | 524.3 |
| 1NWF/100RA | 431.55 | 42.46 | 5.13 | 0.00 | 0 | 0.722 | 0.0211 | 4.65 | 484.5 |

However, the use of 0.1% NWF showed a minor about 5% reduction in the CS-related EI. This is because the incorporation of NWF showed a positive effect on the CS and it does not affect the volumetric EI of concrete. While, at volume fractions greater than 0.25%, the EI related to CS is significantly increased. For CS performance, the use of a high volume of RCA and NWF causes an increase in the EI of concrete. For instance, the mix incorporating 1% NWF and 100% RCA showed about 20% higher EI than the control mix, i.e., 0RA.

It is widely accepted that the use of RCA shows similar effects on STS and CS. Thus, both CS and STS-related emissions increased due to the negative effects of RCA on mechanical performance. On the other hand, the use of NWF is more beneficial to STS. Therefore, STS related-emissions of HPC were reduced drastically over the doses of 0.1–0.5% NWF, see Fig. 10b. The minimum emissions were observed for 0.5NWF/50RA and 0.5NWF/100RA, which were 21% lower compared to the 0RA mix. NWF offers more benefits

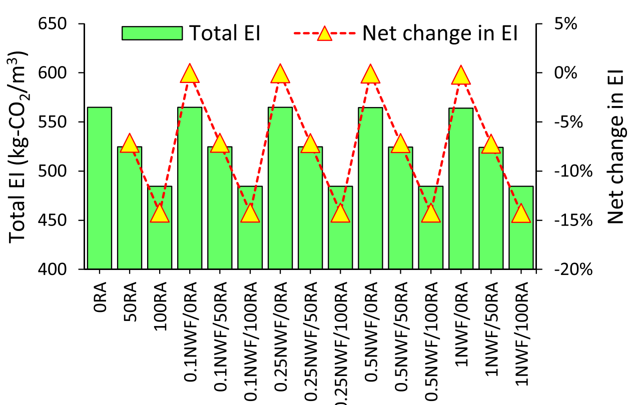



**Fig. 9** The net change in EI of concrete mixes with different amounts of NWF and RCA

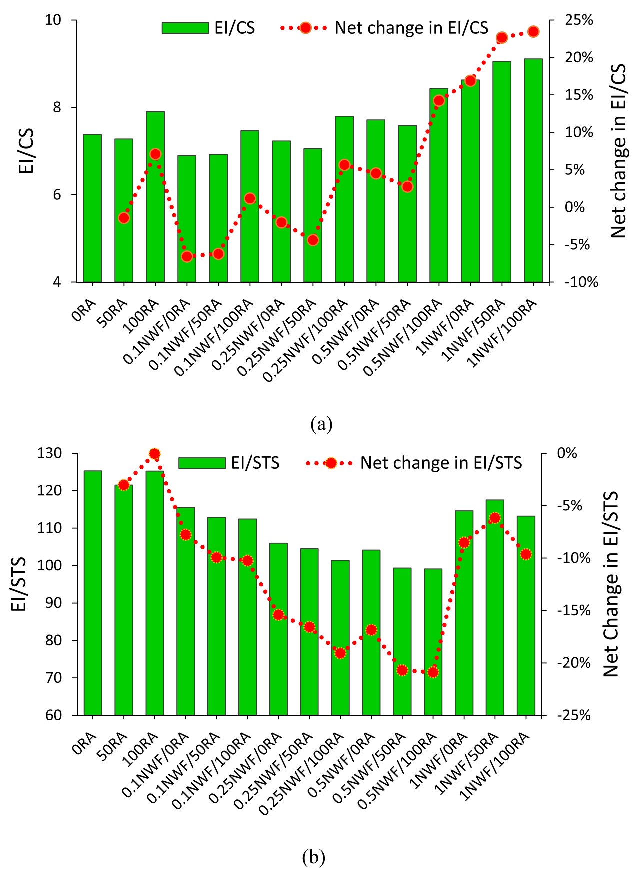



**Fig. 10** Mechanical performance-related EI (kg-$CO_2$/MPa). **a** EI related to unit CS performance. **b** EI related to unit STS performance

to the STS of concrete, and it caused no notable change in volumetric EI, consequently, it showed drastic reductions in the EI/STS ratio. These results showed that despite conservation benefits, the global warming potential of concrete with RCA incorporation may not be significantly reduced due to its performance issues.

The emissions related to WA resistance and CIP resistance of HPC with different amounts of NWF and RCA are illustrated in Fig. 11. No noticeable reductions in the EI relevant to durability indicators were observed. Fiber reinforcement is only beneficial to the STS, and it showed a marginal effect on the WA and CIP. While RCA incorporation caused a drastic increase in the WA and CIP values. The environmental benefits of RCA incorporation can be jeopardized due to its negative impact on the durability of concrete.

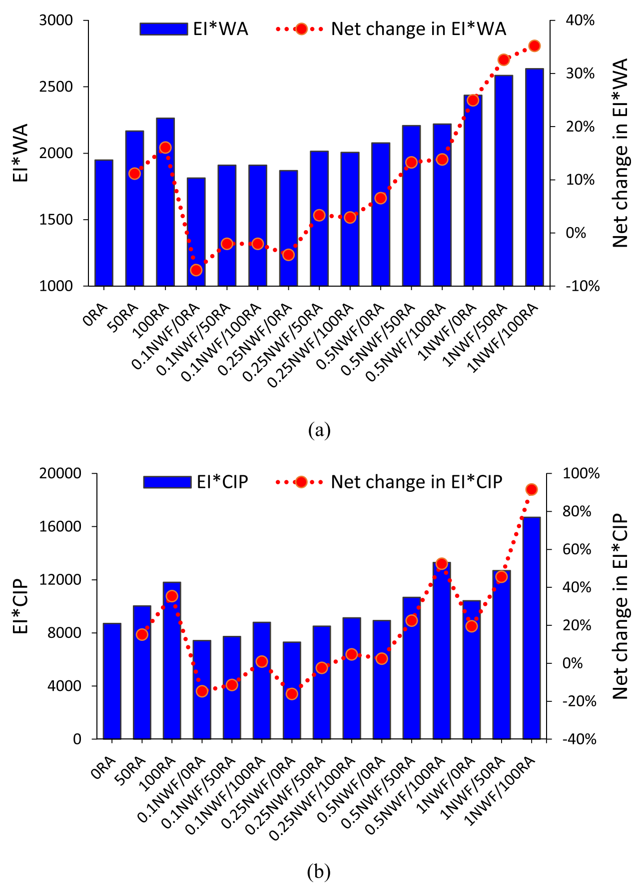



**Fig. 11** Durability performance-related EI. **a** EI related to WA resistance. **b** EI related to CIP resistance

## Conclusions

A comparative LCA study of high-performance concrete (HPC) with different amounts of nylon waste fibers (NWF) and recycled coarse aggregate (RCA) was conducted. Several engineering properties of HPC mixes were experimentally evaluated. The environmental impact (EI) related to the volume and performance of concrete was assessed. The following are the key findings of this study:

1. The RCA incorporation showed a negative effect on the compressive strength (CS) and splitting tensile strength (STS) of HPC. The use of NWF at 0.1% volume can minimize the negative effects of RCA on the CS. Whereas, 0.25–0.5% volume of NWF can lead to recycled aggregate concrete (RAC) having 8% higher STS than that of the control mix.
2. Considering the tensile strength results, the optimum dosage of NWF is 0.5% which caused about a 20% increase in the STS of plain concrete.
3. Both water absorption (WA) and chloride ion penetration (CIP) values of concrete increased with a rising volume of NWF and RCA. Low-density attached mortar in RCA leads to a noticeable increase in the porosity of HPC. NWF at 0.1% showed a positive effect on the imperviousness of HPC against CIP and WA. HPC made with 50% RCA and 0.1% NWF yielded similar imperviousness as that of the control mix.
4. The full replacement of NCA with RCA caused a 15% net reduction in the carbon emissions of HPC production as compared to the emissions of conventional HPC. While the inclusion of NWF at all studied levels caused an insignificant change in the EI.
5. The CS-related emissions were highest for mixes containing 100% RCA and 1% NWF. The use of high volumes of both RCA and NWF is not suitable to reduce CS-related emissions.
6. The STS-related emissions were minimum for mixes incorporating NWF with or without RCA. NWF is an eco-friendly material and highly useful in tensile strength. As compared to the control HPC mix, the STS-related carbon emissions were reduced by 21% at the incorporation of 0.5% NWF with either 50% or 100% RCA.

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**Data availability** All data is presented in this research.

## Declarations

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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