The structural behaviour of sustainable concrete that incorporate use of agro-industrial waste and recyclable construction materials

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The structural behaviour of sustainable concrete that incorporate use of agro-industrial waste and recyclable construction materials

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Abstract

This study emphasizes a sustainable approach on alternative green construction techniques that make use of agro-industrial waste and recyclable construction materials to overcome the greenhouse gas emissions and to protect the consumptions of natural resources. In this research experimental study is carried out to evaluate the structural characteristics of self-compacting concrete (SCC) by utilizing ground coal bottom ash (GCBA) as a cement substitute, coir fibre (CF) as a filler with self-consolidating precast concrete beam (PS-B). To determine the fresh state and hardened state properties, a concrete mix design with compressive strength of 45 MPa based on Eurocode-2 guidelines was carried out with different percentages of GCBA and CF. The outcomes revealed that the workability of SCC mix increases up to 10% addition and decreases between 10% and 20% with the incorporation of GCBA. However, it increased significantly by addition of 10% GCBA and 0.5% CF. In addition, the modulus of elasticity, compressive strength, and split tensile strength of SCC were improved substantially with addition of 10% GCBA and 0.5% CF. Lastly, the flexural capacity against four-point bending test in terms of load-deflection behaviour of PS-B was considerably increased by 62.96% by incorporating 0.5% CF - 10% GCBA- compared to the other shell beams, and observed the least deflection.

**Keywords:** Sustainable construction; coir fibre; coal bottom ash; mechanical Characterization; flexural behaviour.
1. Introduction

The building and construction sector is a significant contributor to today's climate catastrophes, accounting for 40% of human-caused greenhouse gas emissions (World GBC, 2017), 50% of global natural resource consumption, and 40% of global waste production, while the global population is expected to increase by 2.1 billion people by 2050 and expected to add area of 2.4 trillion ft\(^2\) (230 billion m\(^2\)) (IEA, 2021). To provide adequate infrastructure for the future generation we will have to construct the equivalent of 1 New York City every month (Archi. 2020). Concrete, on the other hand, causes a slew of environmental issues, with global cement use exceeding 4.058 metric tonnes in 2018. It also generates massive amounts of waste, which are difficult to handle. Since this construction industry must evolve to meet these sustainability goals.

The economic importance of converting garbage into a resource cannot be overstated. The challenge of transforming the construction industry in more sustainable is therefore huge challenging (Kalianan et al., 2018). To reduce gas emission, global construction waste and to minimise natural resource consumption new benchmarks are much needed. The significance of sustainable construction lies in the creation of comfort, health, and environmental protection during the entire process of construction (N. A. Misnon et al., 2021). The human settlement space environment has reduced resource consumption at all stages and at the same time paid attention to the sustainable utilization of construction resources (Sapuay et al., 2016).

Meanwhile, a massive amount of industrial coal waste is being created. The dumping and proper management of this garbage is a critical issue that results in a slew of environmental issues, including dumping, harmful gas release, and leachate generation. (W. L. Liew et al., 2015). The finest remedy to overcome for this issue is adopting this disuse trash as building substance (N. Mohamad et al., 2019). This research produced the SCC, incorporating coal bottom ash (GCBA) as skewed cement substitute. GCBA is considered as siliceous and...
aluminous substitute that develops the calcium silicate $\text{Ca}_2\text{SiO}_4$. This congeal bow significant
effect in cohesion and adhesion bonding between the particles in SCC concrete mixture (D.
Ramachandran et al., 2018). CBA is a coal-fired waste product. Coal ash is produced at the
base of a generation plant's furnace and makes up around 25% of the total trash produced
(Siddique and Singh et al., 2013). It can be used as a concrete constituent. Coal ash is more
permeable contrast to fly ash, and the grain dimensions are comparable to sand dimensions;
some scholars have reported while using coal bottom ash to substitute cement in concrete
manufacturing (Okaye et al., 2010). As concrete contains siliceous and aluminous substitute
substances and is exposed towards adverse aliment, (Chaipanich et al., 2017) came across that
it has a long life than anticipated. As a consequence, there is a paucity of innovative eco-
friendly pozzolanic substances that could be used to improve toughness of concrete. Coal
bottom ash in concrete reduces debris production and carbon exhalation out of fossil generation
power plants significantly (A. Islam et al., 2021). The coir fibers are accessible in large
quantities easily (M. A. Keerio at al., 2019). In consequence, coir fibre is utilized as substitute
to enhance tensile and flexural capacity of concrete.

This study is a step toward sustainable construction by using novel and environmentally
friendly agro-industrial waste to enhance concrete's tensile, flexural strength, and overall
structural performance and comparing it to traditional concrete's performance. In addition, this
research focused on the structural properties of coal bottom ash as filler and coir fibre as
cement substitute to predict the structural behaviour under flexural load.

2. Substantial and materials

2.1 Substantial

In this experimental work, the main substantial’s water, super plasticizer (SP), ground coal
base ash and coconut fibre were utilized to characterize the mechanical performance of self-
compacting concrete. Ground Coal base ash was accumulated from Coal power plant, situated 80km north of Rome, Italy with prior permission and coconut fibres were collected locally. Ordinary Portland cement was utilized as the cement (MS 522- Part II. 2003). The chosen aggregate was separated using a 4.85 mm sieve after being sieved through a 12 mm sieve. 10 mm was the maximum material dimension. In order to increase the workability of concrete mixes with lower water-to-cement ratios, Type E, SP was reportedly used (ASTM. 2020). For the preparation of the matrix for the concrete mix design, supplied tap water was used.

![Images of CBA, GCBA, and CF](image)

**Figure 1:** (a) CBA (coal bottom ash), (b) GCBA (ground coal bottom ash) and (c) CF (Coir fibre)

### 2.2 Ground coal bottom ash

Coal bottom ash CBA shown in **Figure 1 (a)** was collected from 65 km north of Rome, Italy. GCBA showed in **Figure 1 (b)**, was obtained by grinding raw GCBA using a grinder and then sieved through a 63 µm sieve.

The Mastersizer laser diffraction equipment was utilised to decisive the plane area and modal size of OPC and GCBA. OPC and GCBA exhibited median particle sizes (D$_{50}$) of 23 m and 33 m, respectively. OPC had a surface area of 4915 cm$^2$/g, while GCBA had a surface area of 4689 cm$^2$/g. The specific gravity of GCBA and OPC, on the other hand, was found to be 3.15 and 2.45, respectively.
2.3 Coir fibre

The local coconut stall supplied the CF used in this research. Figure 1(c) illustrates CF, a natural fiber, which was extracted from the coconut's surface. It was then cleaned of any unwanted substances and cut into the necessary lengths of 20, 25, and 30 mm. The maximum aggregate size to fiber length ratios are 3, 2.5, and 2, consecutively, and are all greater than 1.33. According to Li et al., (2020), in vibrated-compacting fiber-reinforced concrete, consequently, the ratio of fiber length to coarse aggregate size should be more than 1.33 in order to affirm a proficient reinforced effect of fibers.

3. Mix proportioning

Figure 2 represents the particle size distributions of coarse and fine aggregate. The mix ratios of SCC with GCBA and CF were developed in accordance with the (European guidelines 2005). To achieve the desired compressive strength of 45 MPa, multiple trial mixes of SCC were used. The cement, sand, and coarse aggregate ratio used in the mix design was 1:2:1.5, which was the result of the experimental mixtures for this intended strength. The SP: cement ratio was set at 1%, with a water: binder ratio of 0.40. As instructed by ESTOP, the SP supplier, the amount of SP utilized in the mix was between 0.5 and 2%. The SCC mixture ratio with various GCBA percentages (5%, 10%, 15%, and 20%) is shown in Table 1, along with the SCC-10%GCBA with two distinct CF percentages (0.5% and 1%). The weight of the major component of SCC calculated using the acquired ratio after adding GCBA and CF.
Figure 2: (a) Coarse aggregate grading, (b) Fine aggregate grading

Table 1: Mix proportions

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Total Binder (kg/m³)</th>
<th>GCBA</th>
<th>OPC</th>
<th>FA</th>
<th>CA</th>
<th>Water</th>
<th>CF</th>
<th>SP</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC-0%-GCBA</td>
<td>495</td>
<td>0</td>
<td>495</td>
<td>990</td>
<td>742</td>
<td>173</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>SCC-5%-GCBA</td>
<td>495</td>
<td>25</td>
<td>470</td>
<td>990</td>
<td>742</td>
<td>173</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>SCC-10%-GCBA</td>
<td>495</td>
<td>49</td>
<td>446</td>
<td>990</td>
<td>742</td>
<td>173</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>SCC-15%-GCBA</td>
<td>495</td>
<td>74</td>
<td>421</td>
<td>990</td>
<td>742</td>
<td>173</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>SCC-20%-GCBA</td>
<td>495</td>
<td>99</td>
<td>396</td>
<td>990</td>
<td>742</td>
<td>173</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>SCC-10%-GCBA-0.5%CF</td>
<td>495</td>
<td>49</td>
<td>446</td>
<td>990</td>
<td>742</td>
<td>173</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>SCC-10%-GCBA-1%CF</td>
<td>495</td>
<td>49</td>
<td>446</td>
<td>990</td>
<td>742</td>
<td>173</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
4. Fabrication of precast shell concrete beam

Figure 3 represents the complete mix design process and fabrications of precast shell concrete beam. Using plywood formwork with a 6 mm thickness, the PS-B samples were cast longitudinally. To ensure that the coarse aggregate and sand did not alter the water binder ratio, particles were properly dried. The shell beam samples were cured using water curing. Twelve (12) shell beams were cast, each measuring 500 mm in length, 100 mm in width, and 50 mm in depth. Three (3) control shell beams, three (3) shell beams with 10% GCBA added, assigned as PS-10%GCBA-B, three (3) shell beams with 10% GCBA and 0.5% CF added, assigned as PS-10%GCBA-0.5%CF-B, and three (3) shell beams with 10% GCBA and 1% CF added, assigned as PS-10%GCBA-1%CF-B, were among the specimens.

Figure 3: Mixing procedure and fabrication of SC beam.
5. Methodology

5.1 Dispersion rate of GCBA and CF

Dispersion of materials is quite challenging task to perform concrete mix design. Therefore, ultra-violet (UV) spectrometry process was carried out to disperse GCBA and CF in aqueous solution in the presence of organic surfactant Acacia Gum. Different magnetic stirring trials of 20-min, 30-min, 40-min, and 60-min respectively, were employed to obtain the optimum dispersion rate of GCBA and CF.

5.2 Flexural modulus

The tensile properties were determined on cube specimens with a diameter of 100 mm and a height of 200 mm. (BS EN 12390. 2013) is used to measure static tensile property of the epoxy mixture. In this experimental study, a significant amount of loading and unloading preceded to eliminate the creep effects. The load applied and axial strain data recorded in two phases during load application: (1) whenever a strain value of 0.00050 was obtained ($\varepsilon_1 = 50 \times 10^{-6}$), (2) when 30% of the ultimate load was reached ($\varepsilon_2$). The kinetic elastic parameter can then be determined as follows: Equation 1.

$$E = \frac{S_2 - S_1}{(\varepsilon_2 - \varepsilon_1)}$$  \hspace{1cm} \text{Equation 1}

As $E$, $S_1$, $S_2$, and $\varepsilon_2$ denote the longitudinal elasticity modulus, the pressure corresponding to a strain rate of 1 at 0.00050, the load relating to 30% of the mortar's shear capacity, and the transverse strain caused by $S_2$.

5.3 Compressive strength

Cubes with statutory sizes of 100×100×100 mm were moulded, then demoulded after 24 hours and placed them in curing room to cure for 28 days at room temperature. The strength properties of the cube specimens were obtained using the universal testing machine and the test protocol given in (BS EN 12390–3. 2002).
5.4 Splitting tensile strength

For each mix, three-cylinder specimens with a diameter of 100 mm and a height of 200 mm were fabricated to be tested against splitting strain according to (BS-EN 12390-6. 2009). The splitting tensile strength was determined by the Equation 2.

\[ f_{ct} = \frac{2P}{\pi dL} \]  

where, \( P \), \( L \), \( d \), \( f_{ct} \) are the maximum applied load, cylinder length, diameter of cylinder and splitting tensile strength, respectively.

5.5 Four points load test of SC beam

Figure 4 shows schematically how shell beam tests were carried out under four-point bending stress using UTM with capacity of 3000 kN. Experiment was carried out in compliance with (BS EN 12930–5. 2009). Three module of 100 mm Linear Voltage Displacement Transducers were mounted to measure the deflection of the beam at the mid-span and underneath the point load at the bottom half of the beam.

The load was distributed to the beam by a load distributor using a manually operated hydraulic jack at a loading rate of 5 kN/min while the beam was being set up. During beam testing, the load cell monitored the applied load. The applied load, as well as the related deflections and
stresses, were monitored using a sensor module attached to the load cell until the beam reached
its maximum bending strength. When the first crack developed, the load was noted and identify
the first crack strength. The maximum and the ultimate loads were noted before the tested beam
failed. The mode of failure of the beam was analysed after the beam failed. The data for the
flexural performance was recorded for further examination and discussion. Photos of the beam
before and after the testing were captured especially at failure.

Three linear adjustable divergent transducers (LVDTs) with a grid length of 100 mm were used
to measure the deflection of the beam. The LVDTs were connected at the half-beam, under the
focal pressure, and at the end of the beam. The steel plate served as the basis for the LVDTs.
The LDVTs' magnetic buttons were turned on and securely fastened to the steel frame during
testing to ensure an accurate deflection reading. When the LVDTs failed, they were not
mounted exactly under the beam to protect them from damage caused by significant deflection
or impact with the beams. At the mid-span and point loading, three steel hooks were installed
on the beam, with LVDTs installed beneath the hooks. In order to collect deflection data, the
LVDTs were next linked to the data logger. The LVDT rod was manually tested numerous
times to ensure that it moved freely and that there were no gaps in its secure attachment to the
hook. The LVDT rod was not pressed during attachment to the hook in order to allow proper
movement of the beam to deflect. This allowed the connected data logger to get the first
deflection readings. Prior to testing, these values were calibrated to zero. During the test, the
findings for beam deflection at each incremental load were continually recorded.
6. Results and Discussions

6.1 Chemical properties

From the XRF test, the chemical makeup of OPC and GCBA was examined. Which aimed to categorize the chemical composition of the material. In this research the industrial waste material, GCBA, was used as cement substitution in the mixture of SCC; therefore, the chemical analysis of GCBA is required. The content composition of GCBA and OPC is presented in Table 2.

Table 2: Mixture composition of GCBA and OPC

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>OPC</th>
<th>GCBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphur oxide (SO3)</td>
<td>4.83%</td>
<td>3.28%</td>
</tr>
<tr>
<td>Carbon (C)</td>
<td>0.11%</td>
<td>1.70%</td>
</tr>
<tr>
<td>Potassium oxide (K₂O)</td>
<td>1.32%</td>
<td>0.71%</td>
</tr>
<tr>
<td>Magnesium oxide (MgO)</td>
<td>1.51%</td>
<td>1.11%</td>
</tr>
<tr>
<td>Iron oxide (Fe₂O₃)</td>
<td>3.10%</td>
<td>6.70%</td>
</tr>
<tr>
<td>Aluminium Oxide (Al₂O₃)</td>
<td>3.80%</td>
<td>17.20%</td>
</tr>
<tr>
<td>Silica dioxide (SiO₂)</td>
<td>21.72%</td>
<td>58.80%</td>
</tr>
<tr>
<td>Calcium Oxide (CaO)</td>
<td>62.81%</td>
<td>5.59%</td>
</tr>
<tr>
<td>LOI</td>
<td>2.12%</td>
<td>4.46%</td>
</tr>
</tbody>
</table>

According to Table 2, GCBA contains a substantial amount of calcium oxide, aluminium oxide, and silica dioxide in high concentrations. The total amount of aluminium oxide, silica oxide, and ferric oxide (Al₂O₃ + SiO₂ + Fe₂O₃) in GCBA, or approximately 82.82%, represented the molar ratio of pozzolanic elements in GCBA. The maximum SO₃ and Loss of Ignition percentages are, respectively, 3.28% and 4.46%. A material can be categorized as a Class-F
6.2 Dispersion Behaviour of Concrete Mix

Ultraviolet (UV) spectrometry was performed to determine the concentration level, water absorption rate, and strength of GCBA and CF under magnetic stirring trials of 15-min, 20-min, 30-min, and 40-min, respectively. An organic surfactant Acacia Gum with a ratio 1:1 (powdered form) was used to achieve the dispersion level against each trail. A direct relationship between water absorption rate and dispersion of GCBA (5.5% and 98.5%; 6.78% and 94.66%) and CF (6.34% and 74.22%; 6.89% and 82.45%) was found with 20-min and 30-min magnetic stirring respectively, however there was a contrast behaviour of GCBA (3.5% and 66.19%; 2.65% and 51.76%) and CF (3.79% and 59.34%; 3.10% and 49.92%) was observed in the last two trails. This peculiar dispersion behaviour under different magnetic trails of GCBA and CF was attributed with the loss of intermolecular bond-strength started after 30-min trials. Thus, 30-min dispersion time was set to get the optimal dispersion rate of GCBA and CF in aqueous solution.

6.3 Workability of concrete with composition of GCBA and SSC

The workability of the concrete mixture was investigated using slump test, values for the various mixes are presented in Figure 5. The study revealed that the flow ability of concrete improved by 6.23% and 19.91% with the addition of 5% and 10% GCBA respectively, compared to the reference concrete matrix (SCC 0%-GCBA). After that, the flow capacity of concrete mix was reduced by -33.91% and -48.07% with addition of 15% and 20% GCBA, respectively. The possible reason behind is that due the presence of nano pores of GCBA helps concrete to absorb moisture faster, leaving less free water in the mix for its workability attributes, one of the possible causes for diminishing the concrete workability compared to cement and natural fine aggregates as illustrated by Dehong Wang et al, (2019) and Berra et
However, there was a significant improvement in workability of concrete mix observed by addition of CF. The workability of concrete was improved by 29.94% and 9.75% with addition of 0.5% and 1% CF, respectively compared to the reference concrete matrix. Thus, based on the obtained workability performance, SCC-10%-GCBA-0.5%-CF concrete mix was considered as the optimum concrete mix design among all other concrete matrixes.

![Slump values with different composition of GCBA and OPC](image)

**Figure 5:** Slump values with different composition of GCBA and OPC

### 6.4 Compressive strength

*Figure 6* presents the mean compression strength of the cylindrical specimens on 28 days prepared from the novel concrete mix design. A compressive strength of 52 MPa and 55 Mpa of SCC-10%-GCBA and SCC-10%-GCBA-0.5%-CF samples was obtained with the addition of 5% and 10% of GCBA which were increased by 9.61% and 14.54%, respectively. This is because GCBA contains silica dioxide, which helps to increase concrete's strength. Malhotra et al. (2018) similarly came to a similar result after looking at the composition and mechanical characteristics of pozzolanic materials. The findings showed that SiO$_2$ creates a calcium silicate gel that is specifically designed to improve the performance of concrete. It was plainly seen
that using 10% coal bottom ash in place of cement helped to improve the performance of concrete. The incorporation of CF, it is further established, enhances the functionality of SCC, which in turn increases the durability of concrete. The results showed that coir fiber improves interior binding between concrete components, which has a tendency to increase concrete strength, as shown in Lakhiar et al., (2021).

Ho et al. (2021) studied the pozzolanic material-containing concrete's durability behaviour. The results indicated that the chemical pozzolanic reaction depends upon the material’s chemical composition, where sometimes strength improved at early stage and some time for long duration. At 28 days curing, all SCC samples except SCC with 15% and 20% GCBA experienced rapid reduction of strength up to 6% to 19%. This is because the pozzolanic reaction of GCBA with 15% and 20%, had experienced the negative impact because ample amount of silica oxide needs the calcium oxide to generate of pozzolanic calcium silicate gel.

![Figure 6: Average compressive strength of SCC](image)

### 6.5 Splitting tensile strength

Figure 7 shows the results of splitting tensile strength of SCC-GCBA-CF at age of 28 days. It was reported that control sample attained 5.17 MPa split tensile strength at 28 days water...
curing. For the SCC with added 10% of GCBA as cement replacement, 6.28 MPa splitting
tensile strength was achieved which was 21.47% higher contrast to the mixtures. Addition of
GCBA at different percentage (15% and 20%) as cement replacement caused 15% to 34%
decrement in splitting tensile strength because of negative impact of pozzolanic reaction.
However SCC able to produce even higher splitting tensile strength up to 51% with 10% of
GCBA and 0.5% of CF. The tensile strength of SCC with 10% GCBA and 1% CF was
marginally lower than that of 0.5% CF but 27% higher than that of the control sample. This
demonstration demonstrated that the loss of adhesive connection between the particles occurs
when the CF percentage is increased over the optimal level, which lowers the splitting tensile
strength of concrete. (Savetlana et al. 2018), suggest that adding more CF to concrete than is
necessary weakens the internal bonding of the material and contributes to the decline in
splitting tensile strength.

Figure 7: Average splitting tensile strength of SCC
6.6 Modulus of elasticity

The outcomes from the elastic modulus tests are compiled in Figure 8. The outcomes demonstrate that with utilization of 10% GCBA, SCC had a higher elastic modulus than the sample, but when the proportion of GCBA increased, the elasticity of SCC also reduced as a result of the increased use of GCBA. According to Bechar & Zerrouki et al. (2018), the results show that the elasticity of concrete reduced when pozzolan components were added in excess of what was considered to be the ideal mix. Additionally, the addition of CF to a 10% GCBA sample in SCC led to an increase in MOE values. The best ratio of GCBA and CF that might be included in SCC is therefore thought to be 10% and 0.5%, respectively.

Figure 8: Average modulus of elasticity of SCC
6.7 Flexural performances of shell beam

6.7.1 Ultimate load

From the analysis on the performance of beams under flexural load, it was found that shell beams incorporating 10% According to Table 3 GCBA attained a flexural capacity that was marginally 11% greater than PS-B's.

The flexural test's ultimate load analysis show that PS-10%GCBA-0.5%CF-B, with a 46% strength improvement, had the highest ultimate load. The control sample, on the other hand, had the lowest ultimate load at 10 kN. It was observed that shell beams incorporating GCBA, and CF attained higher ultimate load compared to the control beam. PS-B with added GCBA and CF attained greater ultimate load due to pozzolanic reaction of GCBA which enhanced the strength ability due to the formation of C-H-S gel in the SCC mixture. Meanwhile, CF as filler caused the improvement in the cohesion bonding that was liable to enhance the flexural ability (N.Mohamd at al., 2018). As illustrated by Lakhiar et al., (2020), it was observed that CF has an evident effect on the fresh and hardened properties of concrete when it was incorporated in SCC. The outcomes demonstrated that the utilization of 0.5% CF in the SCC followed with the flexural ability of SCC improved more than 50 percent. According to a study conducted by (Li et al., 2006) the use of three layers of coir mesh matting as reinforcement in a slab subjected to a four point bending load improved the flexural stress by 40% and increased the flexural ductility by roughly 20%. The results of the experiments in this investigation were consistent with these earlier studies. According to the findings, adding 0.5% of CF increased the flexural strength by roughly 63%.
Table 3: Maximum loads induced by beams

<table>
<thead>
<tr>
<th>Samples</th>
<th>Ultimate Load (kN)</th>
<th>Flexural Strength Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS-B</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>PS-10%GCBA-B</td>
<td>22</td>
<td>54.54</td>
</tr>
<tr>
<td>PS-10%GCBA-0.5%CF-B</td>
<td>27</td>
<td>62.96</td>
</tr>
<tr>
<td>PS-10%GCBA-1%CF-B</td>
<td>24</td>
<td>58.33</td>
</tr>
</tbody>
</table>

6.8 Durability assessment of SSC Concrete with grounded coal bottom Ash and Coir Fibre

Prior to testing, the samples for the concrete permeability tests were cured for 4 weeks. In this investigation, two curing strategies were used: a few samples were totally immersed in tap water at a temperature of 19 degrees Celsius and a humidity level of 85%, while others were covered in moist fabric at a temperature of 19 degrees Celsius and a relative humidity of 80% percent. Surface saturation was used to examine the samples that had been treated in tap water. Prior to the curing process, all samples were labelled at four spots, evenly separated at 87 degrees. After 28 days of drying, surface resistivity measurements for surface saturated and air-dried samples were performed. Moisture on the surface of the specimens that had been treated in water was wiped away with a wet cloth.

Prior to testing air-dry samples, the resistivity probes were dipped to make adequate surface contact. All samples' resistivity measurements were obtained four times (for a total of eight observations on each sample) to verify quality assurance applications as described in the protocol. From Figure 9: When the concentration of coir fiber was 10% of the total, the axial compressive strength gradually decreased as the GCBA percentage increased, however the severe reduction was not immediately apparent. The axial loading strength increased initially when the coir fiber volume fraction was between 0.20% and 0.30%, but thereafter decreased...
as the GCBA volume fraction rose. The axial loading strength reached its maximum value at 0.10% coir volume fraction and 0.033 GCBA, which is 16.7% greater than that of SSC without coir fiber. Because the peak stress and peak strain of HPC SSC with different fiber proportions are different, normalization was used in the stress-strain curves. The stress-strain curves are transformed into calibration curve by setting $x = \varepsilon_c = \varepsilon_{c0}$ and $y = \sigma / (f_c \times f_c)$, where $f_c$ and $\varepsilon_{c0}$ are the compressive strength of GCBA-SSC and the strain associated to the peak stress, respectively.

In addition, as reported by Ho et al. (2021) the durability behaviour of concrete mix containing pozzolanic materials were examined. The results indicated that the chemical pozzolanic reaction depends upon the material’s chemical composition, where sometimes strength improved at early stage and some time for long duration. At 28 days curing, all SCC samples except SCC with 15% and 20% GCBA, experienced rapid reduction of strength, up to 6% to 19%. This is because the pozzolanic reaction of GCBA with 15% and 20%, had experienced the negative impact because ample amount of silica oxide needs the calcium oxide to generate of pozzolanic calcium silicate gel.

![Figure 9: Compressive stress-strain relation of SSC Concrete with grounded coal bottom Ash and Coir Fibre](image-url)
6.9 Load-deflection (P-Δ) profile

Figure 10 shows the load deflection profile of shell beams at mid-span. SSC-10%GCBA with 0.5 % CF seem to have greater ductility than other control shell beams. Shell beams PS-SSC-0%GCBA and SSC-5%GCBA on the other hand attained less ductility compared to the other beams. This result does not concur with the outcomes obtained by Li et al., (2006) that resulted that incorporation of CF mesh in a slab enhanced its ductility by about 20%. In the concrete mixture, CF fillers and CF mesh both had opposite effects, acting as reinforcement and filler, respectively. Additionally, the SCC mixture's water content decreased as it dried, making the concrete more brittle, as the CF added absorbed more water.

6.10 Ductility

The ductility of concrete is an essential parameter for the analysis of concrete structures due to its brittle nature. It is the material's degree of capability to assist significant plastic deformation before failure. As given in equation (3), the ductility of precast self-compacting prisms was calculated from the stress-strain curve. As showed in Table 4, PS-10%GCBA-0.5%CF-B achieved the highest ductility (2.79) compared to the reference specimen (1.51). This can be
concluded that addition of GCBA and CF significantly enhances the total plastic deformation of precast self-compacting prisms under flexural loading before failure, which results in higher ductility.

\[ \mu = \frac{\Delta \varepsilon_1}{\Delta \varepsilon_2} \]  
Equation 3

Where \( \Delta \varepsilon_1 \) is the strain corresponding to the horizontal line intersected by tangent during pre-peak behavior, while \( \Delta \varepsilon_2 \) is the strain obtained against the 80% of the compressive strength during post-peak behaviour.

Table 4: Ductility of self-compacting prisms.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Ultimate Load (kN)</th>
<th>Ductility (( \mu ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS-B</td>
<td>10</td>
<td>1.51</td>
</tr>
<tr>
<td>PS-10%GCBA-B</td>
<td>22</td>
<td>2.05</td>
</tr>
<tr>
<td>PS-10%GCBA-0.5%CF-B</td>
<td>27</td>
<td>2.79</td>
</tr>
<tr>
<td>PS-10%GCBA-1%CF-B</td>
<td>24</td>
<td>2.50</td>
</tr>
</tbody>
</table>

6.11 Concrete Sustainability Assessment

The environmental impact analyses for all mixtures incorporated with multiple replacement materials of PC with ground coal bottom ash (GCBA) and fine aggregate with coir fibre (CF), both independently and blended, are used to investigate the embodied CO\(_2\), embodied energy, and eco-strength efficiency of the concrete mixtures. Equations (4) and (5) are used to determine the embodied carbon and embodied energy values for all concrete mixtures. In Equations (4) and (5), the symbols CO\(_2\)e, \( E_e \), \( I \) and \( W_i \) represent the total embodied carbon, embodied energy, and weight per unit volume (i.e., kg/m\(^3\)) for each concrete mixture, respectively. Furthermore, the symbols CO\(_2\)i and \( E_i \) represent the ecological footprint and low emissions of cementitious materials, as shown in Table 5.
Equation 4

\[ CO_{2e} = \sum_{i=1}^{n}(W_i \times CO_{ui}) \]

Equation 5

\[ E_e = \sum_{i=1}^{n}(W_i \times E_i) \]

Table 5: Carbon and energy encapsulated in concrete components

<table>
<thead>
<tr>
<th>Material</th>
<th>Embodied Carbon (kgCO2/m³)</th>
<th>Embodied Energy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Aggregate</td>
<td>0.0322</td>
<td>0.0058</td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td>0.0214</td>
<td>0.0042</td>
</tr>
<tr>
<td>Portland Cement</td>
<td>0.85</td>
<td>5.20</td>
</tr>
<tr>
<td>GCBA</td>
<td>0.08</td>
<td>1.22</td>
</tr>
<tr>
<td>CF</td>
<td>0.004</td>
<td>0.031</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5 shows the ecological footprint of cementitious materials integrated with various PC with GCBA and FA with CCA replacements. Portland cement produces the most carbon, followed by fine and coarse aggregate. Even so, the impact of GCBA as a substitute for Portland cement and CF as a substitute. As a result, the impact of these components to embodied carbon is negligible. Moreover, personified carbon is measured as 3.81%, 8.22%, 10.99%, and 14.12%, with GCBA levels of 4%, 11%, 14%, and 22%, respectively, and CCA levels of 11%, 22%, 31%, and 41%, respectively, less than that of Portland cement-prepared concrete.

Moreover, the environmental effectiveness of concrete is determined using Equation 6 based on compressive strength.

\[ Eco \text{ – strength efficiency} = x = \frac{\text{Average 28 – Days Compressive}}{\text{Strength of Concrete Total Embodied Carbon of Concrete}} \]

Equation 6
The environmental efficiency of concrete has been estimated using GCBA as a cement content and fine aggregate replaced with Coir fibre in a mixture. The finest environmental efficiency is 0.09789 MPa/kgCO2.m3 with 102% GC replacing portland cement, 0.09088 MPa/kgCO2.m3 with 3029% CF replacing FA, and 0.12 MPa/kgCO2.m3 with GCBA replacing both PC and FA. Correspondingly, the lowest is 0.08591 MPa/kgCO2.m3 for 22% GGBFS, 0.079 MPa/kgCO2.m3 for 38% CCA, and 0.081 MPa/kgCO2.m3 for GCBA.

7 Conclusion

The mechanical characteristics and structural performance of a precast self-compacting concrete shell beam integrating grounded coal bottom ash and coir fiber were studied in a comprehensive experimental research. The following conclusion was made in light of the results:

1- An optimum dispersion rate of GCBA and CF in aqueous solution was achieved on 30-minutes dispersion time in the presence of organic surfactant with ratio (1:1).

2- The fresh state properties of concrete mix were significantly improved and attributed to addition of GCBA and CF. The workability of concrete mix was improved by 29.94% with addition of 10% GCBA and 0.5% CF compared to the reference concrete mix.

3- The mechanical properties such as elastic modulus, split tensile strength, compressive strength, and split tensile strength were improved by 14.54%, 51%, 63%, and 34.86% respectively, with addition of 10% GCBA and 0.5% CF compared to the reference specimen.

4- Specimen PS-10%GCBA-0.5%CF achieved the highest flexural capacity and ductility under flexural loading with 27 kN and 2.79 compared to the reference specimen PS-0%-GCBA-0%-CF which demonstrates the optimum level of addition of 10% GCBA and 0.5% CF in concrete mix.
5- Based on durability assessment, substantial effect of the coir fibre volume fraction was found on the mechanical performance of concrete mix design. Highest axial performance was achieved on 0.2% volume fraction of coir fibre.

6- As the proportions of GCBA by weight of Portland cement increment, the embodied energy and carbon emissions levels in concrete decrease. Correspondingly, the embodied carbon of cementitious materials is lowered when fine aggregate is replaced with coir fiber, but the embodied energy of cementitious materials is improved when coir fiber is used as fine aggregate. Furthermore, the embodied carbon and energy are lowered, while the content of GCBA in the concrete mixture increases due to the weight of Portland cement and fine aggregate replaced with coir fiber. According to the results of the experiments, using GCBA up to 12% as a replacement for Portland cement and coir fiber up to 32% as a sand replacement separately and in combination in concrete produces the best results for construction materials.

Credit authorship contribution statement

Muneer Ahmed: Conceptualization, Methodology, Data curation, Visualization, Writing – original draft, Writing – review & editing.

Suliman Khan: Investigation, Resources, Visualization, Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that the research conducted in this study has no conflict of interest.

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