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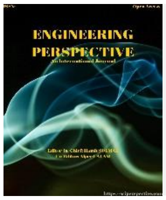

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Research Paper

Assessing Mechanical Properties of Free-Fall Self-Compacting Concrete and its Application in Concrete-Filled Steel Tube Columns

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ABSTRACT

The application of Self-Compacting Concrete (SCC) in the construction industry has been adopted over the years and its quality over normal concrete has been influential. The high-rise construction demands emphasize the necessity of concrete pumping technology due to limited working space. Concrete made from manufactured sand was produced and the variation of free fall height based on the experiment of SCC was studied. This study assesses both the mechanical properties of SCC cast after free fall from various heights and its applications in the CFST columns. The study specifically focuses on a varied height of free fall at 6m, 6.5m, 7m, 7.5m, and 8m. The workability performance of this SCC, batched from manufactured sand has been evaluated, and slump extension between 500-600 mm was obtained. The concrete cubes and prism specimens were tested for compressive and splitting, therefore the associate strength was obtained. Testing both normal and SCC reveals unfavourable effects in strength reduction with an increase in free fall height. At the final height of 8m, an observed decrease in strength of about 15%-20% using SCC was observed. At 6.5m, there is a 3% decrease in strength, and the reduction in cube-splitting strength ranges from 7% to 11% with SCC from natural sand. When the free fall height is 7m, the cubic compressive strength is reduced by about 4.3-5.4%, and its cube-splitting strength at a height of 7m decreases by approximately 7–11%. Despite the gradual decrease noted in this study, the application of SCC obtained at 7m in CFST has demonstrated reliable results in terms of combined strength, suggesting its use in columns not exceeding the same height.

Keywords: SCC, CFST, Free fall height, manufactured sand, compressive strength

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1. Introduction

Over the years, with the rapid development of concrete materials, the application of high-performance concretes with excellent properties has been widely adopted. SCC is one of the concretes with incomparable excellent working performance about other concretes. In the early 1980s, the Japanese research team prepared SCC with ordinary concrete materials for the first time and named it solid concrete [1, 2]. Since then, more and more researchers have begun to develop and widely use SCC in the construction of skyscrapers and modern houses.

SCC has been described as the most revolutionary development in concrete construction for several decades. It has continuously been adopted in the construction industry due to its added properties over ordinary concrete. The increase in use lies in the structural limitations of normal concrete considered as low resistance to tensile loading, cracking, vibration, density, strength development, final strength, and durability. SCC has been proven to have the best quality control thus flowing like honey, its ability to flow into a confined space is the added value when combined with steel reinforcements. The scenario that SCC can be manufactured in a site batching plant or a ready-mix concrete plant, and delivered to the site by truck can lead to the concrete free fall method especially when the working space is limited. Due to its self-vibration, SCC will have a stronger strength than standard vibrated concrete with a similar water-to-cement ratio. Then, this led it to be placed either by pumping or pouring into horizontal or vertical structures, some literature suggests, SCC can be poured above 5 m in height without any sort of segregation using a well-built SCC. On the other hand, some studies limit the standard maximum free drop height and maximum lateral flow distance should be around 5 m or less and 8 to l5 m or less, respectively s per EFNARC 2002 guidelines.

Currently, the use of SCC has gained popularity for its fluidity and anti-segregation properties thus being preferable in CFST columns. However, during high falls, before SCC is cast in designated columns can segregate, affecting its mechanical properties. The mix proportions in this case are critical, impacting compaction and CFST performance. The paste volume and aggregate ratios also affect the post-peak behaviour and ductility of these tubes. SCC's use in vertical structural members, like densely reinforced wall columns and nodal core areas, has been assured to cause segregation due to throwing out. The issues like displacement of reinforcements or damage of formwork, adhere to the construction codes and practices during concrete pouring, especially when allowing concrete to fall freely [3, 4]. Factors such as concrete ingredients, mixing, proportion, application method, and free fall height influence concrete compactness in the steel tubes. Empty spaces in steel tube may form thus, reducing its ability to confine the concrete core, thereby decreasing the load-carrying capacity and ductility of the structure [5, 6]. BS81101:1997 mandates precautions to prevent displacement of reinforcement, ducts, formwork, and damage to formwork faces during free falling of concrete, emphasizing the need for a cohesive, non-segregating mix while ACI standards do not specify a maximum free-falling height for concrete, the "Technical Regulations for the Application of SCC" limit pouring heights in reinforced column wall formwork to 5 m, extending to 9 m with the use of auxiliary devices like chutes and tandem tubes.

This study highlights the adaptability of free-fall SCC in hollow steel tube technology. Hou et al. [7] emphasized the significance of the construction stage in quality management for CFST members by highlighting the impact of construction methods on void formation, particularly during the prevalent pumping method. The method, commonly used, presents challenges as the air density within the steel tube rises with concrete height during pumping, risking voids if not promptly discharged. Despite the use of micro expansion agents, the shrinkage of high-strength core concrete may lead to voids between steel tubes and concrete over time, attributed to shrinkage and creep. Cao et al. [8] conducted a model test and theoretical analysis on core concrete filling in a CFST project. They found that the degree of void significantly affects the ultimate bearing capacity of such tubular members, more severe void reduces the bearing capacity. Chen et al. [9] analysed the axial compression process of hollow CFST and established the relationship between hollow degree and axial force. The void space in the tube increases initially with axial load, but beyond a critical value, it decreases with further axial load increase. Tests conducted by Zheng et al. [10], and Kumari et al. [11] revealed that the bearing capacity of CFST members with voids is lower than that of those without voids. The study found that insufficiently dense core concrete pouring can impact the coordinated stress between the steel tube and concrete, leading to a reduction in the bearing capacity of CFST members.

The steel tube and the infilled concrete work together to resist the applied external load, which is a fundamental assumption in the use of CFST columns. The factors affecting the compactness of concrete in steel tubes include concrete components, mixing, proportion, application method, and height of fall. Voids between the concrete core and outer steel tube can decrease confinement, reducing load capacity and utility. SCC is commonly used in CFST structures, but the compaction level within the steel tube is rarely studied. This study uses the common techniques for checking the quality of SCC in confined spaces like the percussion–acoustic method, well-known for its cost-effectiveness and high efficiency in detecting voids within concrete exposed to air. This method has been adapted for identifying voids in underwater concrete, considering the fluid-structure coupling effect. The Impact Rebound Method serves to indicate surface hardness, exhibiting correlation with concrete compressive strength. Additionally, the Vibration Test Method involves applying shock vibrations to prismatic specimens by hammering one end in the longitudinal direction. This method consolidates concrete in two stages: firstly, by displacing concrete particles and secondly, by eliminating trapped air (For Construction).

Shortage of working space mainly on small construction sites is likely and some methods of concrete casting can be adopted. This study is based on the experimental investigation of pouring concrete from heights, assessing the possible mechanical properties: compressive and tensile strength, and workability which is important in vibration and pouring to avoid segregation. This study aims to investigate the free fall properties of SCC made from artificial /manufactured sand. It applies artificial sand to demonstrate SCC's reliability in CFST columns within specified steel design sections. The free fall heights were varied at concrete batches from heights: 6m, 6.5m, 7m, 7.5m, and 8m based on the conflicts of existing literature. Additionally, the results from the best-performance batch were adopted into CFST for dual purposes: achieving the properties of hardened SCC and combined strength through its application. Finally, the use of percussion, Impact rebound, and Vibration testing were employed to ensure the distribution and quality of adopted SCC.

2. Materials and Methods

2.1 Materials

This study acknowledges the suitability of natural and man-made (manufactured) sand in concrete. These enhance binding with cement thus boosting strength and durability. Cement interacts with fine sands and various-sized gravels, enabling adaptable concrete mixes. Fly ash and mineral powder refine properties, contributing to workability and long-term strength. These materials enhance specific properties and reduce water content without affecting workability. Hallow steel tube columns filled with SCC mixes offer a unique blend of strength and lightness for high-rise buildings and large-span structures.

For this study, SCC and CFST were designed and tested to ensure the feasibility and extensive application in practice. The manufactured sand obtained from crushed gravel was used to make the quantity of SCC. The concrete, truck mixer has been used for mixing large volume quantity and quality concrete needed in the experiment.

Additionally, the SCC was tested using both cubes and prism formworks. The results from slump, compressive strength, and splitting strength tests were obtained. The hallow steel tube sections of square, rectangular, and circular shapes were employed, and used in application thus defining the purpose of this study.

2.2. Methods

2.2.1. Experimental Design

The experiment was conducted using artificial sand to make a C40 standard SCC; corresponding working performance (slump extension 500-600 mm) was taken as parameters to discuss the influence of manufactured sand on the working performance under a high drop of SCC. According to Table 1, SCC prepared using machine-made sand generally performs worse than natural sand. The main reason is that the fineness modulus of machine-made sand is small, usually only about 1.0, and the content of lime powder is large, which also reduces the cohesion of fresh concrete.

Table 1. Mix ratio of SCC with artificial sand

Number	cement	Artificial sand	Fine sand	5-10 gravel	10-16 gravel	10-20 gravel	fly ash	Mineral powder	admixtures	Bulking agent	water	water reducer	slump spread
I	294	660	219	88	442	355	63	63	8.32	42	165	1.8%	570
II	294	660	219	88	442	355	63	63	7.85	42	165	1.8%	600
III	294	917	-	85	443	339	63	63	8.32	42	165	1.8%	580
V	284	908	-	82	415	332	63	63	8.81	42	165	1.8%	570
IV	294	765	135	86	432	346	63	63	8.32	42	165	1.8%	500

From the observed SCC performance from the initial slump extension of 690mm, at T500 (time in seconds taken by the concrete to reach a spread diameter of 500mm after the cone is lifted) [12, 13] was 1.5s, 1.5 hours later, the slump of 630mm, at T500 was 2.25s, it indicated a significant loss of about 60mm; The initial falling time of the slump cylinder was 2.2s, and about 2.89s after 1.5 hours. There was no bleeding phenomenon around the collapse extension and inversion test of concrete.

In this comprehensive study, a thorough examination was conducted on a total of 48 CFST columns to provide a detailed analysis of their structural behaviour. Among these columns, 10 were designed with a circular cross-section, while the remaining 38 featured a rectangular configuration. It is noted that the steel tubes used in this research were fabricated from Q355B steel, known for its high strength and durability. The selection of Q355B steel ensures that the CFST columns exhibit robust mechanical properties, contributing significantly to overall structural integrity [14, 15]. The internal cavities of these steel tubes were uniformly filled with high-performance C40 concrete, further augmenting the columns' load-bearing capacity and overall performance. This incorporation of Q355B steel and C40 concrete not only aligns with contemporary construction standards but also represents a deliberate choice to achieve optimal strength and stability in the tested CFST columns as detailed in Table 2 and Figure 1.

It is therefore proven that in the construction of CFST columns with dense diaphragms, various methods can be employed. The utilization of the pipe jacking method for high or large one-time pouring heights, and achieving the required jacking pressure can be challenging. Alternatively, a method similar to underwater concrete tube pouring requires a special vibrator and complex safety measures when operating at high altitudes. However, the SCC tube method poured directly from the top of the column, utilizes the fluidity of SCC to eliminate the need for vibration. During the pouring process, a gap (free fall) is maintained between the duct end and the concrete surface.

Table 2. Information table of steel tube columns

Component member	Section size(mm)	Root number	Concrete strength class
GKZ 1	□1500*1000*40	16	C40
GKZ 2	□1600*1600*40	2	C40
GKZ3a	□1000*1000*40	6	C40
GKZ3b	□1000*1000*30	6	C40
GKZ4	□800*800*35	14	C40
GKZ5	□700*500*20	10	C40
GKZ6	□800*500*24	4	C40
GKZ7	○1000*30	10	C40

Note: □ represents rectangular/square steel columns, ○represents circular steel columns

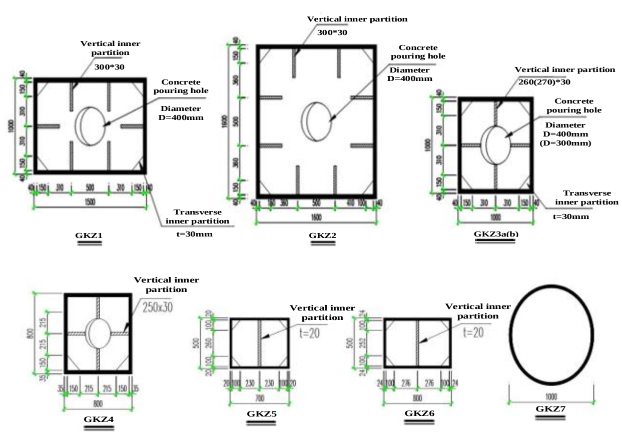


Figure 1. Detailed drawing of column section size

2.2.2. Experimental Methodology

The height from concrete drop was set to 6m, 6.5m, 7m, 7.5m and 8m, the mixture was set to unique and the variation in the properties based on height of drop were noted. The concrete truck was set to fixed station and the conduit was varied based on free-fall heights respectively. The purpose of undertaking these heights refer to the uncertain and challenges of different construction site conditions where accessing the concreting points is very complicated thus delaying the project and increase cost uncertainties. The difference in the five batches lies in the height of pump truck conduit, the results associated with the tests procedures were provided under slump test using slump cone, compressive strength tests using cube mould, and splitting tests using prism mould.

During the concreting process from concrete pump truck to ground base, it was required to pour 20mm of cement mortar with the same proportion, to prevent the rebound of the concrete falling process. A layer of soil was underlaid, rain canvas was laid on it, and concrete was freely dropped from different heights by placing booms, and then casted into the cube and prismatic test moulds. Even though the site was soft, there was a significance rebound phenomenon and the most obvious falling distance was 8m. According to the field observations, the rebound height was approximately 0.3 m horizontally. The field observation indicates that although there is a rebound, there is no great segregation.

2.2.2.1. Quality Detection Methods

Flowing of SCC in conduit results in minimum loss of strength depending on the quality of concrete produced, however, it is important to consider the concrete flow through conduit over height. The purpose of varying the heights of conduit from 6m to 8m explains the different strength obtained though seemed to have no practical restrictions when combined with steel. Concrete was applied in CFST columns of previously specified sizes and shapes which resulted in a very beautiful columns with less voids. The applications were adopted according to the code of practices regarding the uses of SCC in CFST with great care and the sound results were obtained. This section explains the 3 methods used for checking the hardened properties and qualities of casted CFST columns.

2.2.2.2. Percussion method

The incorporation of percussion method in CFST columns serves the purpose of ensuring optimal compaction and consolidation of the concrete. This technique employs percussion or vibration methods throughout the construction process to eliminate air voids, improve the bond between steel and concrete, and achieve a uniform density across the entire column [16, 17]. To assess the concrete's density within the column tube, a sound-based analysis was employed, utilizing a specialized Number 3 steel hammer designed specifically for quality inspections. The inspection process involves comprehensive percussion testing on each steel tube column. These inspections occurred at both 7 and 28 days, ensuring a thorough and accurate evaluation of concrete density within the columns. This method entails tapping at several equidistant points along the column's periphery, moving from the bottom to the top. Given that the two ends of the CFST column are fixed, there is a disparity in amplitude between them, resulting in inconsistent knocking sounds between the middle and the two ends of the column. Any deviation from the expected sounds, including the identification of a third kind of sound, is considered abnormal during this assessment.

2.2.2.3. Impact rebound method

The rebound hammer is a non-destructive testing apparatus, whereby the rebound of the spring-driven mass is measured after its impact with the concrete surface. The output of the rebound hammer is referred to as the rebound number and is correlated with the surface hardness of concrete [18]. When hammering the surface of the concrete structure, vibration will be induced on the surface. The elastic wave signal is continuously excited along the test concrete surface. By extracting the reflected signal and processing the corresponding image, the internal defects of the structure can be identified. In general, the following changes in vibration characteristics occur at the part where stripping occurs as shown in Figure 2:

(1) The bending stiffness decreases significantly, and the transcendence cycle increases;

(2) The escape of elastic wave energy becomes slow, and the duration of vibration becomes longer;

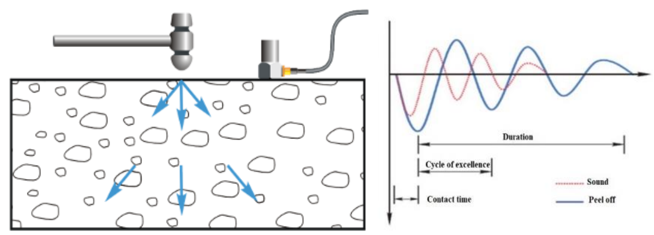


Figure 2. Variation characteristics of vibration parameters during peeling/emptying

When the structure is empty, the indexes (excellent period, duration) all tend to increase. Due to the lack of an absolute threshold, the induced vibration method involves many parameters, such as duration, predominance period, etc. To normalize relevant parameters, a void index can be introduced.

2.2.2.4. Vibration test method

The vibration test method in CFST construction aims to optimize mechanical properties by ensuring thorough compaction, uniform density, and void elimination within the concrete fill [19, 20]. This method enhances the material's strength and load-bearing capacity by eliminating air voids, promoting homogeneous distribution, and improving bonding between the steel tube and concrete. By focusing on compaction and uniformity, the vibration test method enhances the structural integrity and reliability of CFST columns, ensuring they meet standards while effectively supporting various loads and stresses within diverse structural applications. The signal acquisition system is selected, the appropriate acquisition parameters are set, the CFST structure is tested several times, and multiple acceleration response signals of the CFST under transient excitation are obtained.

3. Results and Discussions

This section details the results obtained from compressive and splitting tests performed using manufactured sand, demonstrating the influence of the studied free fall heights on the mechanical properties of SCC. It presents the results from 144 specimens – 54 for compressive strength and 54 for splitting strength of both normal concrete and SCC with cube moulds, while also presenting 36 specimens for both normal concrete and SCC with prism specimen.

3.1. Cube compressive test results

Table 3 shows the specimen numbers and cube compressive strength with the free-falling height of SCC as parameters. SCC stands for Self-Compacting Concrete, and NC stands for ordinary concrete. The second numbers, 0 and 1, represent the concrete at the test site to start the test. 0 represents the concrete to the site immediately used to start the test, and 1 represents the concrete to the site after waiting for 1 hour to start the test. On the other hand, 0, 6, 6.5, 7, 7.5, and 8 represent free-fall heights in m. For example, SCC-0-6 represents the test study of a 6m free fall from SCC to the site immediately.

Table 3. Cube compressive strength of each specimen

Specimen number	Concrete type	Time/h	Freefall height/m/m	Cubic specimen strength fcu /MPa			Efficient Value	Comparison with original
				Specimen1	Specimen2	Specimen3		
SCC-0-0	SCC	0	0	61	66	61	63	1.00
SCC-0-6	SCC	0	6	63	61	61	62	0.98
SCC-0-6.5	SCC	0	6.5	60	66	59	61	0.97
SCC-0-7	SCC	0	7	58	60	58	59	0.94
SCC-0-7.5	SCC	0	7.5	58	57	58	57	0.90
SCC-0-8	SCC	0	8	54	55	55	55	0.87
SCC-1-0	SCC	1	0	61	64	62	62	1.00
SCC-1-6	SCC	1	6	65	65	66	65	1.05
SCC-1-6.5	SCC	1	6.5	59	60	62	61	0.98
SCC-1-7	SCC	1	7	58	59	58	58	0.94
SCC-1-7.5	SCC	1	7.5	53	53	54	54	0.87
SCC-1-8	SCC	1	8	55	40	60	52	0.84
NC-0-0	NC	0	0	61	62	59	61	1.00
NC-0-6	NC	0	6	59	57	56	57	0.93
NC -0-6.5	NC	0	6.5	56	55	55	55	0.90
NC -0-7	NC	0	7	53	53	50	52	0.85
NC -0-7.5	NC	0	7.5	47	51	50	49	0.80
NC -0-8	NC	0	8	47	45	47	46	0.75

3.2 Cube-splitting test results

The corresponding cube-splitting strength of each test specimen in the first batch is shown in Table 4. Splitting strength is calculated according to Eq. (1):

$$f_{sp} = \frac{2F}{\pi A} = \frac{0.637F}{A} \tag{1}$$

In the Equation: f_{sp} is the splitting strength, F is the ultimate load, and A is the cross-sectional area of the cube.

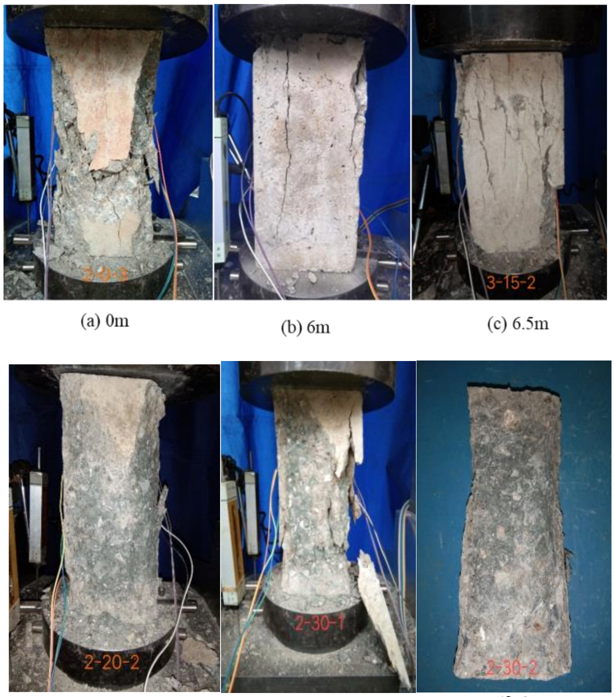
Table 3. Splitting tensile strength of cubic concrete

Specimen number	Concrete type	Time/h	Freefall height/m	Splitting tensile strength of cube specimen f_{sp}			Efficient	Comparison with original λh-cu
				Specimen1	Specimen2	Specimen3		
SCC-0-0	SCC	0	0	4.28	4.69	4.27	4.41	1.00
SCC-0-6	SCC	0	6	4.73	4.29	4.13	4.38	0.99
SCC-0-6.5	SCC	0	6.5	4.05	4.22	4.41	4.23	0.96
SCC-0-7	SCC	0	7	4.13	4.30	3.93	4.12	0.93
SCC-0-7.5	SCC	0	7.5	4.08	3.90	4.06	4.02	0.91
SCC-0-8	SCC	0	8	3.76	3.76	3.96	3.83	0.87
SCC-1-0	SCC	1	0	4.55	4.20	4.03	4.26	1.00
SCC-1-6	SCC	1	6	4.49	4.21	3.55	4.08	0.96
SCC-1-6.5	SCC	1	6.5	3.44	3.96	4.16	3.85	0.90
SCC-1-7	SCC	1	7	3.74	3.88	3.58	3.73	0.88
SCC-1-7.5	SCC	1	7.5	3.63	3.71	3.56	3.63	0.85
SCC-1-8	SCC	1	8	3.47	3.71	3.41	3.53	0.83
NC-0-0	NC	0	0	4.12	3.79	4.27	4.06	1.00
NC-0-6	NC	0	6	4.11	3.55	3.84	3.83	0.94
NC -0-6.5	NC	0	6.5	3.97	3.84	3.41	3.74	0.92
NC -0-7	NC	0	7	3.87	3.46	3.32	3.55	0.87
NC -0-7.5	NC	0	7.5	3.57	3.30	3.27	3.38	0.83
NC -0-8	NC	0	8	2.99	3.42	3.21	3.21	0.79

3.3 Test results of stress-strain curves of prisms under axial compression

This section focuses on the laboratory experimental phenomenon. Figure 3 shows the typical failure pattern of prismatic specimens under axial compression. It can be seen from the figure that the failure pattern of prismatic specimens under axial compression is generally similar to that of ordinary concrete. Still, the specimens with higher drop height have a more severe shedding phenomenon during failure, and the phenomenon of two inverted cones is evident.

The stress-strain curves of the prisms in each group are presented in Table 5 and plotted in Figure 4 and Figure 5. The stress-strain curves shown in the Figures illustrate the characteristic phases observed in the behaviour of each prism specimen. These curves typically exhibit distinct segments, including the elastic section, where the material undergoes reversible deformation; the splitting section, where the onset of failure or fracture is evident; the descending section, indicating the material's post-peak deformation; and finally, the residual section, representing the residual strength or stability after the peak stress has been reached



(a) 0m (b) 6m (c) 6.5m

(d) 7m (e) 7.5m (f) 8m

Figure 3. Failure modes of prisms under axial compression

3.4 Influence of free fall height on various mechanical properties

This section details the results of the relationship between compressive and splitting strengths based on the equations developed by the American Concrete Institute (ACI) in 1999, as have been modified by many scholars [21, 22]. To examine influencing factors such as free-falling height, time-loss, and slump extension of SCC corresponding strength reduction coefficients defined as λ. The specific algorithms are outlined in Eq. (2), Eq. (3), and Eq. (4) respectively.

$$\lambda_{h-cu} = \frac{f_{\mathrm{cu,h}}}{f_{\mathrm{cu,0}}} \quad (2)$$

$$\lambda_{h-sv} = \frac{f_{\mathrm{sp,h}}}{f_{\mathrm{sp,0}}} \quad (3)$$

$$\lambda_{h-c} = \frac{f_{\mathrm{c,h}}}{f_{\mathrm{c,0}}} \quad (4)$$

Where, λ_{h-cu}, λ_{h-sp}, λ_{h-c} represent reduction strengths of compressive, and splitting strengths for cube and prism specimens, respectively due to free fall height.

As the height increases, the cube's compressive and splitting strengths, as well as prismatic compressive strength, generally exhibit a downward trend. Figure 6 illustrates the decrease in the compressive strength of the cube with an increase in height. However, when compared with ordinary concrete, SCC shows a smaller decline range. In Figure 6 (b), as the height of free fall increases from 0 to 6.5m, the compressive strength of SCC only decreases by about 3%. Nevertheless, with further height increase, a gradual decrease is observed, reaching approximately 15% when the height reaches 8m. In contrast, the height increases in ordinary concrete from 0 to 8m resulting in a decline range of about 25%. The observed characteristics of SCC are primarily attributed to its high cement content, leading to a thicker water-cement slurry during the falling process. This, coupled with the substantial compressive strength of coarse aggregates, sets SCC apart from ordinary concrete, which typically has a slump of up to 180 mm. The increased use of powder admixtures in SCC results in a denser cement paste with weaker adhesion, causing a higher likelihood of separation between coarse aggregates and cement paste during movement. Figure 6 illustrates that, under the same free-fall height, the strength of a specimen subjected to a 1-hour delay before testing shows a similar decline as those tested immediately. This suggests that a delay of 1 hour has a minimal effect on the concrete's strength.

Table 5. Typical characteristic values of various prismatic specimens

Specimen number	Prism strength fc / MPa		λ_{h-c}	Peak strain εcu /με		λ_{h-c}
	53.6			2040		
SCC-0-0	54.8	53.2	1	2040	2046	1.0
	51.2			2060		
	53.8			1540		
SCC-0-6	48.9	51.9	0.98	1709	1650	0.81
	53.1			1702		
	52.9			1697		
SCC-0-6.5	52.0	51.6	0.97	1681	1833	0.90
	49.9			2121		
	54.4			1987		
SCC-0-7	44.8	49.2	0.92	1734	1850	0.90
	48.3			1829		
	44.7			1752		
SCC-0-7.5	45.0	46.7	0.87	1729	1794	0.88
	50.5			1902		
	43.3			1579		
SCC-0-8	43.0	42.2	0.79	1832	1674	0.82
	40.4			1612		
	51			1797		
SCC-1-0	53.6	50.1	1	1883	1720	1.0
	45.9			1481		
	51.3			1646		
SCC-1-6	46.1	51.3	1.02	1722	1756	1.02
	51.1			1899		
	50.5			1485		
SCC-1-6.5	48.6	49.2	0.98	1902	1810	1.05
	48.6			2043		
	45.5			1849		
SCC-1-7	49.8	48.0	0.94	1961	1981	1.15
	48.8			2135		
	48.4			1857		
SCC-1-7.5	47.9	47.0	0.92	1870	1702	0.99
	44.6			1379		
	45.6			1438		
	42.1			1853		
SCC-1-8	49.3	45.7	0.89	1600	1630	0.95
	49.5			1764		
	48.4			1723		

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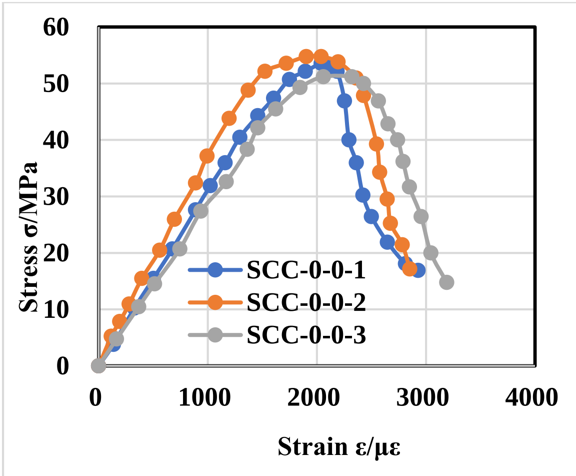
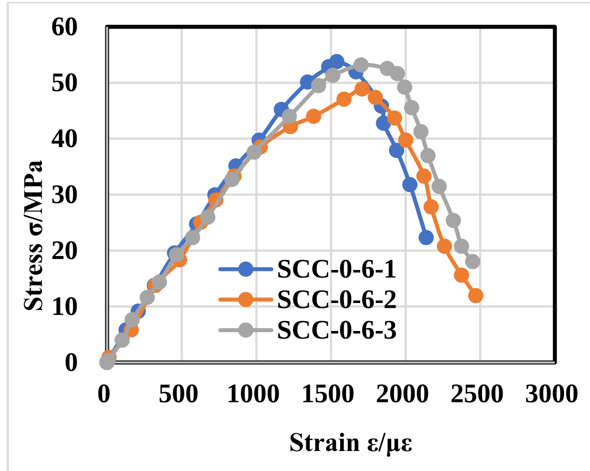
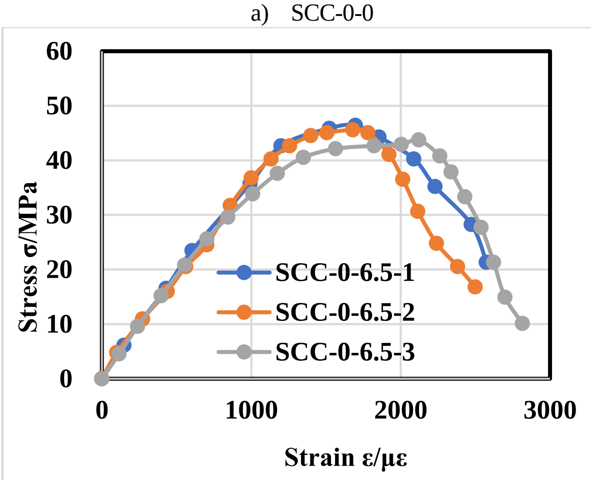


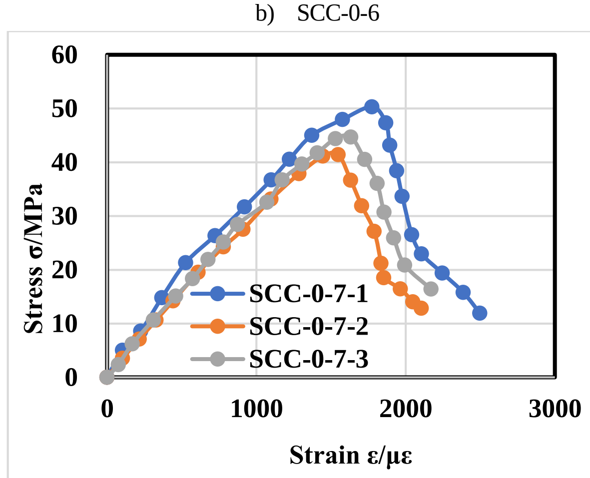
a) SCC-0-0



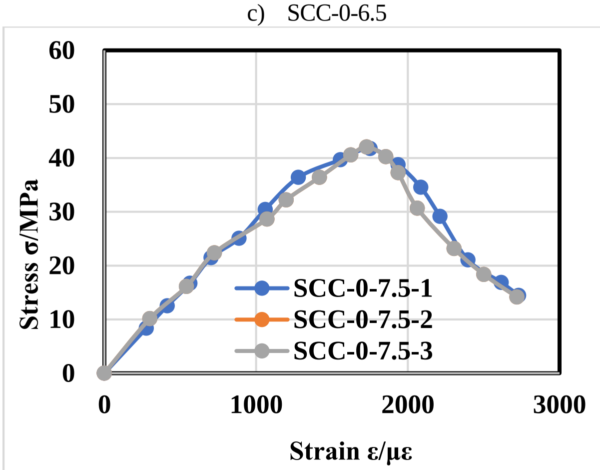
b) SCC-0-6



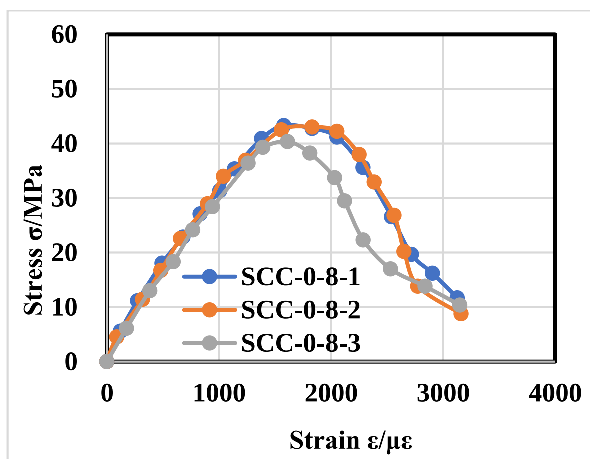
c) SCC-0-6.5



d) SCC-0-7

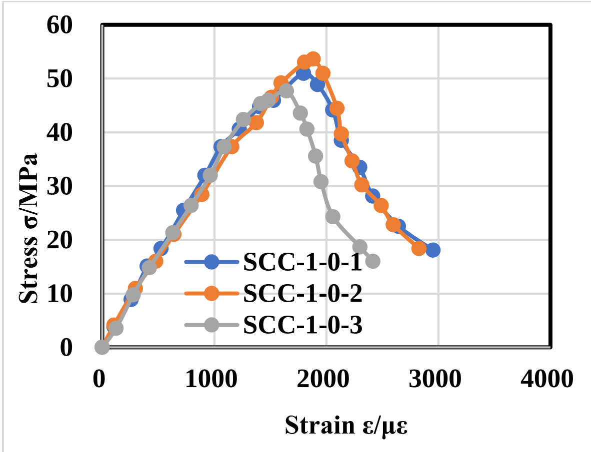


e) SCC-0-7.5

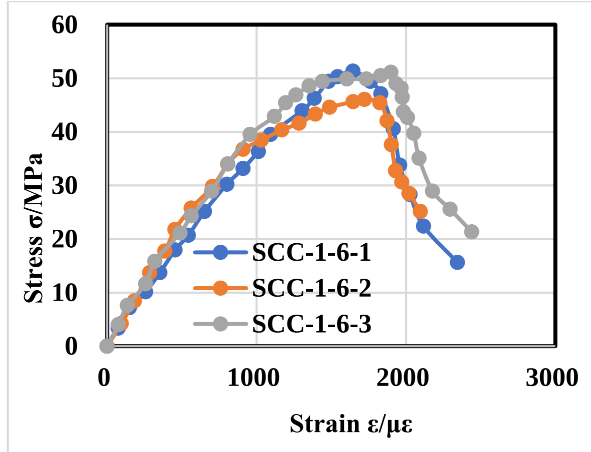


f) SCC-0-8

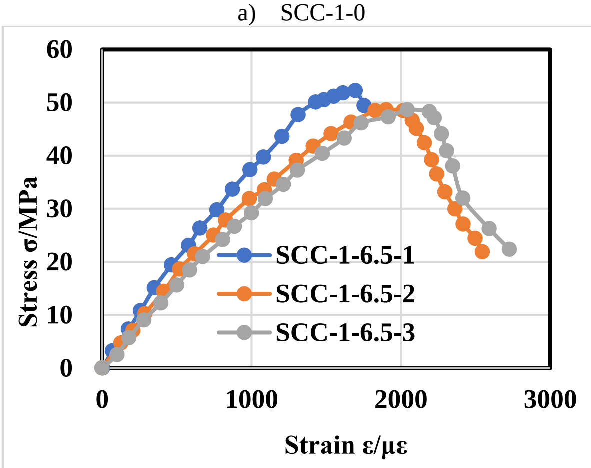
Figure 4. Relationship between stress and strain for specimens made of SCC



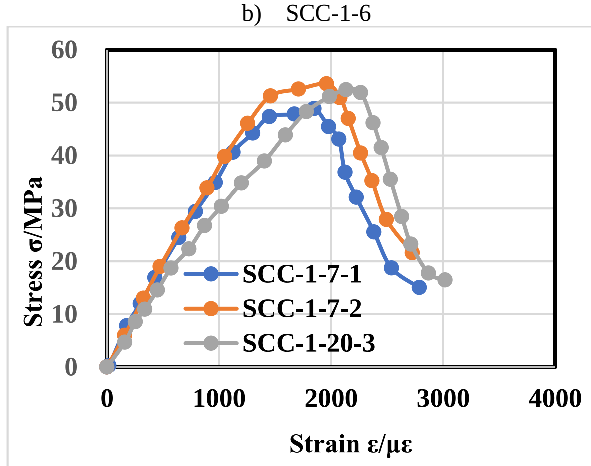
a) SCC-1-0



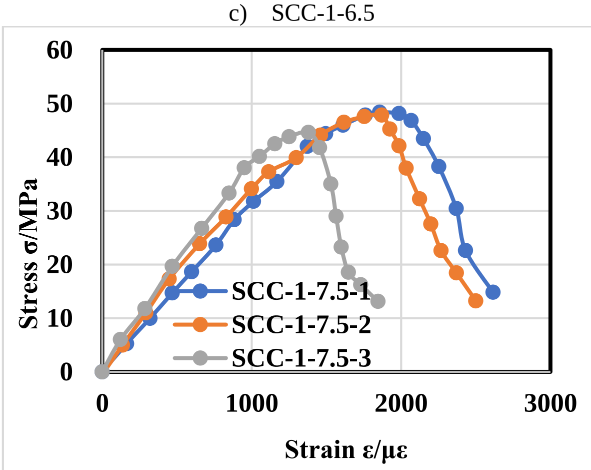
b) SCC-1-6



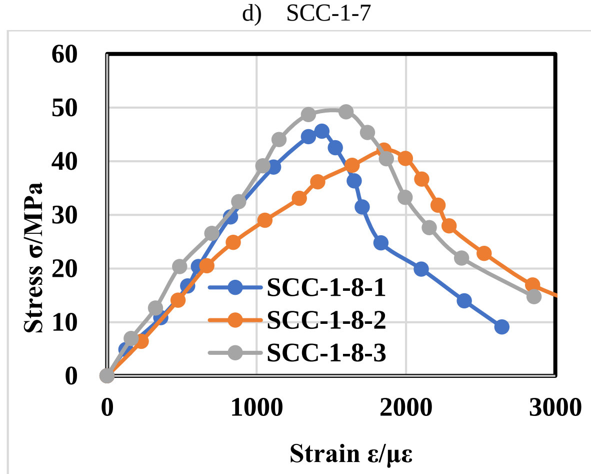
c) SCC-1-6.5



d) SCC-1-7

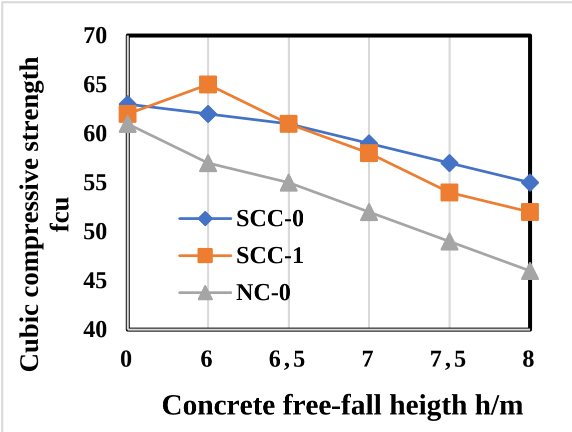


e) SCC-1-7.5

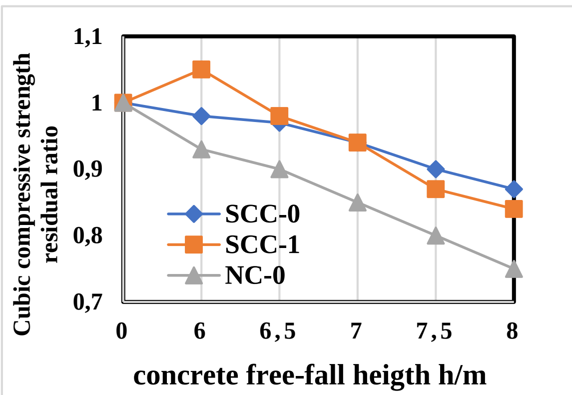


f) SCC-1-8

Figure 5. Relationship between stress-strain of specimens of SCC after standing for one hour.

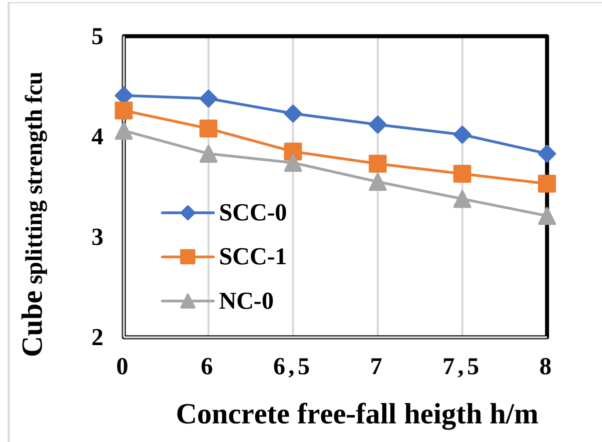


a) $f_{cu} - h$

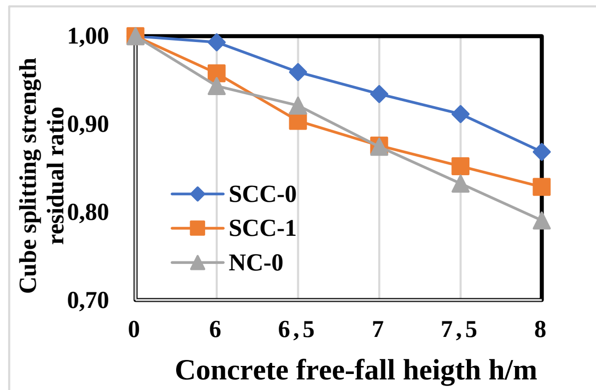


b) $\lambda_{h-cu} - h$

Figure 6. Influence of free fall height on compressive strength of cube



a) $f_{cu} - h$



b) $\lambda_{h-sp} - h$

Figure 7. Influence of free fall height on splitting strength of cube

Figure 7 shows that the correlation between the free fall height and the splitting strength of a concrete cube closely mirrors that observed in the compressive strength of a concrete cube. Both exhibit a similar decreasing trend, with the amplitude of decline roughly equivalent. Notably, when the free fall height of SCC specimens in two distinct groups reaches 8 meters, there is an approximate 17% reduction in the splitting strength of the concrete cube. This suggests a consistent and predictable impact of free fall height on the mechanical properties of the concrete, emphasizing the importance of understanding and controlling this factor in structural analysis and design.

3.5. Compressive properties of manufactured sand SCC cube after high throwing

The SCC is prepared with manufactured sand when the free fall height of the concrete is 7m, and its cubic compressive strength is reduced by about 4.3-5.4%, similar to the SCC prepared with natural sand. The reduction is roughly the same. Table 6 shows the compressive strength of SCC cube specimens with manufactured sand.

Table 6. Compressive strength of cubic concrete

Specimen number	Freefall height /m	Cube specimen strength f_{cu}/MPa				
		Data1	Data2	Data3	average value	Range of change
SCC-I-0	0	70	74	75	73	-5.4%
SCC-I-7	7	70	70	68	69	
SCC-II-0	0	64	69	68	67	-4.5%
SCC-II-7	7	63	65	64	64	
SCC-III-0	0	68	70	66	68	-4.4%
SCC-III-7	7	65	64	68	65	
SCC-V-0	0	68	69	67	68	-4.4%
SCC-V-7	7	66	65	64	65	
SCC-IV-0	0	70	68	70	69	-4.3%
SCC-IV-7	7	67	66	64	66	

3.6 Cube-splitting performance of manufactured sand SCC after free fall

From Table 7, it is evident that when SCC is prepared with manufactured sand, its cube-splitting strength at a height of 7m decreases by approximately 7–11%, which is slightly higher than that of SCC prepared with natural sand.

Table 7. Cube-splitting strength of SCC with manufactured sand after high casting.

Specimen number	Freefall heig	Data1	Data2	Data3	average value	Range of change
SCC-1-0	0	5.32	4.82	5.05	5.06	-7%
SCC-1-7	7	4.62	4.75	4.78	4.72	
SCC-2-0	0	4.65	4.53	4.62	4.60	-11%
SCC-2-7	7	4.02	4.08	4.16	4.09	
SCC-3-0	0	4.62	4.56	4.78	4.65	-10%
SCC-3-7	7	4.12	4.25	4.21	4.19	
SCC-4-0	0	4.75	4.62	4.71	4.69	-9%
SCC-4-7	7	4.32	4.25	4.28	4.28	
SCC-5-0	0	4.75	4.83	4.82	4.80	-9%
SCC-5-7	7	4.42	4.35	4.38	4.38	

In conjunction with the compressive strength, during the free-falling process, if the concrete does not undergo segregation, the free-falling height also has a relatively minor impact on the splitting strength of the concrete. Nonetheless, the reduction range is slightly greater than the compressive strength

The techniques employed for detecting and assessing SCC quality in CFST columns have consistently yielded reliable results. These results indicate the absence of voids, ensuring a seamless flow of concrete within the steel tube. This attests to the compactness and cohesion between SCC and CFST columns in terms of quality, strength, and durability – crucial measures for ensuring the structural integrity and resilience of high-rise buildings. The robust evaluation methods employed not only affirm the absence of voids but also underscore the essential attributes necessary for the optimal performance of these structures in the long term.

4. Conclusions

This study evaluates the mechanical properties by testing SCC at various free-fall heights. Subsequently, the concrete is applied to CFST columns, a scenario previously identified as challenging. The findings indicate that an increase in free fall height has detrimental effects on both normal concrete and SCC. The concrete's behaviour aligns closely with the obtained slump range, leading to a reduction in compressive and splitting strength. Specifically, SCC experiences a gradual decrease, with a notable drop of 15%-20% observed at a total height of 8 m. Interestingly, SCC prepared with manufactured sand remains suitable up to height of 7m. Notably, at a 6m free fall height, the study aligns with the results within the expected range, yielding void-free columns without segregation. The key conclusions drawn are as follows:

(1) The cube's compressive and splitting strength decreases with the increase in height of the conduit. However, compared with ordinary concrete, the decrease in strength of SCC is generally smaller. With the rise in the free fall height of concrete, the compressive strength of the prismatic body also decreases, which is similar to the compressive strength of the cube.

(2) The mechanical properties of SCC exhibit a nonlinear decrease as the free fall height increases. For total heights below 6.5m, there is an approximate 3% decrease in mechanical properties. However, as the total height increases further, the reduction range becomes more significant. Upon reaching a height of 8m, the reduction range for the mechanical properties indicates a substantial impact on the overall performance of the SCC.

(3) When considering a total height of 7m, the decline in cube compressive strength for SCC using manufactured sand is approximately equivalent to that observed in SCC prepared with natural sand. The reduction in cube splitting strength ranges from 7% to 11%, which is slightly higher than the corresponding decrease observed in SCC made with natural sand (7%).

(4) Through the verification test within 6m of free fall height, it is feasible that the maximum drop height of the core concrete of CFST should not be greater than twice the height.

The current research aims to comprehend the performance of SCC under significant height drops and its potential application in CFST columns. Despite previous studies, there is a critical need for further research to comprehensively explore various aspects of SCC, especially when incorporating manufactured (derived/artificial) sand in CFST columns. This includes investigating shrinkage performance, analysing the bonding properties between manufactured sand concrete and steel tubes, assessing flexural and creep behaviour, and evaluating the long-term behaviour associated with these columns.

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Conflict of interest declaration:

The authors declare that they have no conflicts of interest concerning this article.

Credit Author Statement

Jean de Dieu Ninteretse: Conceptualization of the study, devising the methodology, developing the necessary software tools for data analysis, interpretation of the results, and writing of the original draft.
Marc Nshimiyimana: Conceptualizing the research, devising the methodology, overseeing the project's progress, and interpreting the results. and writing the original draft, overall supervision.
Jovial Niyogisubizo: visual representations, and interpretation of the results.
Jean Claude Sugira: Writing, technical skills
Alain Niyongabo: Supervision

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