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A Study on Spent Catalyst-Based Self - Compacting Concrete RC Beams with Conventional and GFRP Rebars

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Abstract: This study focuses on creating an effective waste utilization strategy by incorporating spent catalyst (SC), a byproduct from oil refineries, into the production of self-compacting concrete (SCC) of C30 grade. The objective is to explore both waste management solutions and the material behavior of the resulting concrete. The whole work is divided into preliminary study and main study parts 1 & 2. In the early phase of the study, self-compacting concrete (SCC) mixes were prepared by partially replacing cement with spent catalyst (SC) at replacement levels of 3%, 6%, 9%, and 12%. The compressive strength was assessed using standard 150 mm concrete cubes, tested by British Standards, utilizing a 1000 kN capacity universal testing machine. The mixture containing 9% SC combined with 3% superplasticizer and a water-to-cement ratio of 0.58 was found to offer the most favourable performance. In the first segment of the main study, full-scale blocks measuring 400 × 200 × 200 mm were cast using both conventional C30-grade concrete and SCC incorporating SC. These blocks were cured and tested for compressive strength at 7 and 28 days. It was observed that SCC blocks incorporating SC exhibited an increase of approximately 15% in compressive strength compared to those made with standard concrete. The second segment of the study focused on the flexural behaviour of four reinforced concrete beams sized 1500 × 125 × 200 mm, reinforced either with traditional steel bars or glass fibre-reinforced polymer (GFRP) bars. These beams were subjected to flexural testing using a 500 kN loading frame. The SCC beams reinforced with GFRP showed a reduction in ultimate load-bearing capacity by 33%, an increase in deflection by 48%, and a decrease in ductility by 56%, relative to their steel-reinforced counterparts. Additionally, beams with conventional steel reinforcement demonstrated 40% greater stiffness and exhibited no signs of brittle failure, unlike those reinforced with GFRP. The test results confirm that the combination of 9% SC and an appropriate dosage of superplasticizer leads to enhanced overall performance of strength. While the incorporation of SC contributes positively to compressive strength, the use of GFRP reinforcement in flexural elements should be approached with caution due to its tendency to reduce ductility and promote brittle failure.

Keywords: SCC, SC, SP, Flexural behavior, GFRP rebar

1. Introduction

The increasing building of megastructures worldwide has led to a spike in the general usage of SCC. Primary structural member reinforcement congestion presents difficulties, particularly in cyclonic and seismic zones. SCC is considered a significant advancement in concrete, offering the only practical solution in scenarios where conventional concrete placement methods are not feasible. Because of its better performance, it can be used for a variety of purposes, from delicate portions to sturdy constructions, and it is soon to replace ordinary concrete. Standard materials are used in SCC, but stricter supervision is needed to ensure workability. Balancing between flowability, deformability, filling capacity, and segregation resistance is critical to its success. Because of its compatibility and flowability, SCC is a recommended choice, especially for delicate concrete features and repair work. Its application is essential for complicated forms and dense reinforcements, guaranteeing effective building techniques. Spent catalysts are waste materials that are frequently challenging to dispose of because of their hazardous nature; they are usually employed in the petrochemical sector. Using these components in SCC is a new way to recycle and build sustainably. In addition to reducing waste and lessening environmental impact, the reuse of spent catalysts has the potential to impart novel mechanical and chemical properties to concrete mixtures.

Integrating spent catalyst into SCC could open promising research pathways by revealing its effects on flowability, segregation resistance, and structural performance. By investigating SCC with non-traditional additives (such as spent catalysts), concrete technology and building methods are better understood. Most research on reinforced concrete (RC) beams has focused on the use of conventional steel reinforcement. However, GFRP rebars offer several advantages, such as a high strength-to-weight ratio, resistance to corrosion, and non-magnetic properties. Studying the flexural behaviour of RC beams reinforced with both GFRP and traditional steel rebars can provide valuable insights and potentially lead to the development of innovative and durable construction solutions.

In this study, a hybrid reinforcement approach is proposed by combining GFRP and traditional steel rebars within the same structural element. The innovative aspect of this hybrid system is knowing how it functions under different loading scenarios, including shear or bending stresses, and how long it can last in harsh settings. In corrosive settings where steel reinforcement may decay over time, combining GFRP rebars with a spent catalyst as part of the concrete mix may result in a more sustainable and long-lasting building method. Long-term performance advantages, including increased durability, lower maintenance requirements, and lower life-cycle costs, may be highlighted in the study. This is especially important for infrastructure that is subjected to hostile environments. Sustainable building materials are receiving more attention. Using modern materials (GFRP rebars) and a waste product (spent catalyst), this study supports worldwide efforts to lower the carbon footprint of building operations and promote the circular economy. Not much research has been done on the behaviour of beams constructed with GFRP rebars with spent catalyst-based SCC. The experimental findings from this investigation (such as load-bearing capacity, cracking behaviour, and deflection characteristics) would add new information to the field by offering fresh perspectives on their structural performance. This idea is unusual because it combines modern concrete technology (SCC), sustainable waste material (spent catalyst), and creative reinforcing methods (GFRP and traditional rebars). This interdisciplinary approach is beneficial for improving reinforced concrete structures' performance, longevity, and sustainability.

The potential for renewing spent catalysts was examined using both pure SC-CO_2 and SC-CO_2 modified with polar co-solvents, under conditions ranging from 343 to 423 K and pressures between 10 and 30 MPa. The regeneration mechanism of catalysts in the presence of SC-CO_2 has been analysed in detail (Gumerov et al., 2016). The properties of SCCs and the acceptability of substituting recycled aggregates (RA) for Natural River sand in various coarse-mix percentages in SCC. An attempt is made in this study to combine the SCC combinations with the recycled and quarry dirt mixtures. The energy was evident when opportunity materials such as recycled aggregates and quarry dirt rose by up to 20% in replacements (Kumar et al., 2020). Construction is one of Oman's primary industries, and it requires the creation of extremely safe and long-lasting concrete structures. SCC is one method for creating sturdy concrete structures (Patil et al., 2016). The effects of partially replacing cement with waste catalysts from the petrochemical industry on the performance of an environmentally sustainable, ultra-high-performance self-compacting mortar. Cement was substituted with spent catalyst in varying proportions, ranging from 0% to 50%. The research provides a comprehensive analysis of how the incorporation of used catalyst influences key properties of the mortar, including mechanical characteristics (compressive and flexural strength), microstructural features (such as porosity, hydration behaviour, calcium hydroxide content, and residual unhydrated cement), and overall mix performance (Abdolpour et al., 2022).

A comparative study was carried out to examine the compressive strength of SCC made with either traditional cement or red mud as a partial replacement. To evaluate the potential of red mud in enhancing mechanical properties, standard cube specimens (150 mm × 150 mm × 150 mm) were tested for compressive strength after 28 days of curing in water. The objective was to determine whether the inclusion of red mud could improve the performance of SCC compared to mixes using only cement (Singh & Laheriya, 2019).

Additionally, this research explores how GFRP rebars and polypropylene fibres affect the flexural behavior of high-performance concrete (HPC) beams containing waste glass powder and micro silica. The HPC mix design incorporated 25% waste glass powder as a fine aggregate replacement and 10% micro silica as a partial cement substitute to improve mechanical performance. Findings revealed that beams with conventional steel reinforcement demonstrated superior flexural strength compared to those reinforced exclusively with GFRP. However, when 1.5% polypropylene fibres were added to GFRP-reinforced beams, the flexural capacity remained on par with steel-reinforced beams. This combination also offered additional benefits, including a 4% reduction in beam weight, lower production costs, and decreased CO_2 emissions (Jabbar & Farid, 2018).

The longevity and structural integrity of ageing concrete infrastructure are often compromised by durability issues, particularly the corrosion of embedded steel reinforcement (Rajeev Devaraj et al., 2023). Self-compacting concrete (SCC) addresses these challenges by eliminating the need for mechanical compaction or internal/external vibration. It can flow freely into complex formwork, navigating congested reinforcement areas and filling voids without segregation or bleeding, all while maintaining its homogeneity and stability. SCC achieves full compaction solely under its weight, making it an ideal solution for enhancing construction quality and durability (Abunassar et al., 2023; Ofuyatan et al., 2022; Domone, 2007).

The significance of self-compacting concrete (SCC) lies in its capacity to fill formwork and flow smoothly around reinforcement without the need for vibration or concern over bleeding (Khaleel & Abdul Razak, 2014). The development of SCC was driven by the need to achieve an optimal balance between deformability and stability. Various mix design approaches have been proposed to accomplish this, including (a) combining water-reducing admixtures with increased volumes of mineral additives, and (b) pairing water-reducing admixtures with viscosity-modifying agents to enhance flow and cohesion (Dinakar, 2012).

The use of self-compacting concrete (SCC) contributes to improved working conditions and significantly reduces noise levels during casting operations (Li et al., 2005; Parra et al., 2011; Shi & Wu, 2005; Diamantonis et al., 2010). SCC is particularly essential in heavily reinforced structural elements such as columns and beams within moment-resisting frames, especially in seismic regions, to ensure complete filling of all voids in the formwork (Mansour et al., 2013). The rheological properties of cement pastes can be optimized by incorporating fine limestone powder, which enhances flowability, while combining limestone powder with fly ash increases the overall packing density of the mix (Saak et al., 2002). Air-entraining agents are used to producing air-entrained SCC, resulting in moderate compressive strength alongside excellent compaction levels. Unlike conventional concrete, the design of SCC necessitates the inclusion of pozzolanic materials, superplasticizers, and/or viscosity-modifying agents to achieve the desired performance characteristics (Abo Dhaheer et al., 2015; Hu & Wang, 2011; Wang et al., 2014).

Several factors significantly influence the properties of self-compacting concrete (SCC), including packing density, the characteristics of chemical admixtures and mineral additives, aggregate type, aggregate-to-cement ratio, raw material composition, mix design approaches, and the water-to-cement ratio. Among these, a coarse aggregate content of 33% by volume has been found to yield superior compressive strength compared to other proportions. Rheological parameters such as yield stress and viscosity increase as the proportion of coarse and fine particles rises (Gupta et al., 2020). SCC produced under conditions optimizing blocking and liquid phase content allows for reduced superplasticizer dosage, minimal paste volume, and low drying shrinkage, resulting in enhanced durability and cost-effectiveness (Kumar & Kumar, 2022). Prior research has demonstrated that recycled plastic self-compacting concrete (RPSCC) exhibits fresh and mechanical properties suitable for structural use, offering an environmentally sustainable alternative by replacing natural aggregates with recycled plastic materials (Baali, 2021). Furthermore, the incorporation of industrial waste materials such as glass, copper slag, tyre rubber, and foundry sand as substitutes for fine aggregates in SCC presents promising opportunities for sustainable construction practices (Balamuralikrishnan et al., 2023).

The flexural capacity of self-compacting concrete (SCC) beams is notably enhanced through the incorporation of hybrid steel fibers. Specifically, a blend of 0.5% hooked-end steel fibers combined with 0.25% micro-steel fibers delivers superior flexural performance compared to other fiber ratio combinations. Incorporating these hybrid fibers in reinforced concrete (RC) SCC beams results in increases of approximately 40.64% in load-carrying capacity and 40% in moment capacity relative to beams without fiber reinforcement. Additionally, crack spacing and crack widths are reduced by ranges of 16–45% and 25–75%, respectively (Ramkumar et al., 2023). In high-strength self-compacting concrete (HSSC) cementitious composites, the enhanced toughness and post-peak behavior are largely attributed to the bridging action of fibers and the improved bond strength at the interfacial transition zone, which is strengthened by increased silica fume content. Unlike plain high-strength concrete (HSC) specimens that typically fail suddenly and catastrophically, those containing alkali-resistant glass fibers (AR-GF) demonstrate progressive crack development as fiber content rises, indicating improved ductility and reduced abrupt fracture occurrence (Dalvand & Ahmadi, 2021). Moreover, specimens reinforced with corrugated and hooked-end steel fibers exhibit multiple microcracks near primary fractures, due to mechanical interlocking, resulting in more controlled failure mechanisms compared to those with straight fibers. To predict the flexural behavior of hybrid fiber reinforced concrete (HFRC), mathematical models have been developed that relate flexural loads, deflections, and toughness to a comprehensive fiber reinforcing index that accounts for varying fiber characteristics (Hilles & Ziara, 2019).

Increasing both the fibre volume fraction and the aspect ratio of steel fibres enhances the post-peak ductility of concrete and reduces the rate of strength degradation. Specimens reinforced with hooked-end and corrugated fibres demonstrate superior failure modes compared to those with straight fibres, exhibiting numerous microcracks near major fractures due to mechanical interlocking of the deformed fibres. Additionally, mathematical models have been developed to predict the flexural loads, deflections, and toughness of hybrid fibre reinforced concrete (HFRC), incorporating a comprehensive fibre reinforcing index that accounts for varying fibre properties (Li et al., 2018). The role of self-compacting concrete (SCC), fibre reinforcement, cementitious replacements, and artificial neural networks (ANN) in optimizing SCC mix designs has been extensively reviewed. The primary objective is to synthesize existing research to better understand the diverse characteristics of SCC in both fresh and hardened states, particularly when combined with fibre reinforcement and cement substitutes (Ramkumar et al., 2020).

Repairing concrete pavements using traditional concrete often demands thorough compaction, which can introduce stress in the already placed sections and potentially shorten their lifespan. In contrast, Self-Compacting Concrete (SCC) eliminates the need for mechanical compaction or vibration after placement. This characteristic makes SCC particularly beneficial for repairing rigid pavements. Additionally, SCC naturally forms a smooth and even surface, minimizing the need for further surface treatment and thereby conserving both time and labour (Jindal, A et al., 2023). Self-compacting concrete (SCC) is particularly effective for pump-based concrete placement, as it aligns well with the pumping and placement rates. Its properties make it an excellent match for use with ready-mix concrete systems, largely due to the reduced idle time for transit mixers. As a result, turnaround times are shortened, which in turn improves the overall efficiency and output of each mixer unit (Abhay Patil et al., 2024). A defining feature that sets SCC inclusion of filler materials in its mix. Numerous studies have explored how these fillers impact the properties of SCC. Findings indicate that incorporating fillers improves the concrete's flowability while reducing the amount of cement required. Additionally, fillers, especially pozzolanic types, can help achieve lower heat of hydration and minimize the risk of shrinkage-related cracking. Research also highlights that using fine particles with diverse sizes and shapes contributes to better packing density and long-term durability, ultimately decreasing the cracks caused by thermal effects (Jawad Ahmad et al., 2023).

1.1 Why Use Self-Compacting Concrete?

SCC is a type of concrete that can flow under its weight, fill formwork, and achieve full compaction even in congested places. The higher deformability of SCC mixes, which enables them to preserve homogeneity in a fresh state, is the cause of these properties. SCC allows for quick placing of concrete, quicker building timeframes, and easier flow around crowded reinforcement. High levels of homogeneity, few voids, and homogeneous concrete strength in situ are made possible by SCC's fluidity and segregation resistance, presenting the potential for increased levels of durability.

SCC makes it possible to reduce noise at the site, which improves health and safety there. Because SCC reduces worker exposure to sound levels as low as one hundredth of those produced when placing typical vibrated concrete, it is truly a silent revolution in concrete. SCC takes less labor than traditional concrete. SCC placement requires substantially less physical effort than typical vibrated concrete placement. The creation of more inventive designs, intricate shapes, and thin sections. SCC enables quick concrete pumping. SCC has an even, homogeneous surface that is free of voids, honeycombs, and other surface flaws thanks to its effective filling capabilities. SCC is a competitive alternative to traditional concrete because of its good fluidity and deformability, which improve the aesthetics of the finished product and the surface polish.

1.2 Applications of SCC

SCC has many applications, particularly useful in situations where traditional concrete would be difficult or impossible to place, such as in complex forms or areas with limited access, and where a high-quality surface finish is required. SCC is used in construction for a variety of reasons. It is also known to have better durability, flowability, and homogeneity compared to normal concrete. Self-compacting concrete is commonly used in building foundations, walls, columns, as well as in precast concrete structures.

1.3 FRP

Fiber Reinforced Polymer (FRP) has emerged as a highly advantageous substitute in the building sector, providing a multitude of structural benefits. It's a common option for reinforcing concrete beams, slabs, and shear walls because of its capacity to improve flexural and shear capabilities. However, the absence of natural ductility in FRP is a crucial factor to consider when utilizing it in building. The total ductility of the composite system is decreased when reinforced concrete is mixed with it to generate FRP-FRP-reinforced concrete (FRPRC). It is advised to install more steel rebar in FRPRC systems to remedy this. The brittleness of FRP rebars is partially offset by the addition of steel reinforcement, which increases the composite structure's ductility. This method of improving the ductility of FRPRC systems necessitates a careful balancing act between the steel and FRP component qualities.

1.4 Advantages and Disadvantages of FRP Bars in Load-Bearing Members

Advantages:

Corrosion resistance: Ideal for marine, chemical, or de-icing salt environments.
Lightweight: Easier handling, lower transport and labour costs.
High tensile strength: Often stronger (in tension) than steel per unit weight.
Electromagnetic neutrality: Useful in hospitals, research labs, or near electrical equipment.

Disadvantages:

High cost: Significantly more expensive than steel, especially carbon FRP.
Limited availability: Not as widely produced or standardized.
Brittle failure: No yielding before rupture - this is a major structural safety concern.
Low modulus of elasticity.
Poor performance in compression: Often only used where tensile reinforcement is needed.

1.5 Clarification on Design and Loading Standards

During the preliminary testing phase, beams reinforced with GFRP bars were fabricated by directly substituting steel rebars with an equivalent quantity of GFRP, without modifying the beam design to accommodate the unique characteristics of GFRP reinforcement. The load-bearing performance of these beams was subsequently assessed and compared against that of beams reinforced with traditional steel. In a proposed second phase, not covered in this study, it is suggested that the beams should be redesigned according to ACI 440.1R-15 to properly account for the unique mechanical characteristics of GFRP reinforcement.

In this study, GFRP rebars were used as a direct replacement for conventional steel rebars without redesigning the beam according to the mechanical properties of GFRP. While this approach may provide preliminary insights into load-carrying capacity, it does not reflect proper design practice. GFRP has distinct properties such as a lower modulus of elasticity and no yielding point, which require specific design considerations as outlined in standards like ACI 440.1R-15. Simply substituting one material for another without recalculating structural requirements may lead to misleading conclusions about structural performance. Additionally, the assumption that a high number of references equates to a stronger or more comprehensive study is not necessarily correct. Instead, the quality, relevance, and critical integration of the cited literature are more important than sheer quantity. The number of references should be adjusted to reflect meaningful engagement with existing research, not to artificially enhance the perceived weight of the article. The study should clearly explain the practical application of producing reinforced concrete members using GFRP bars and spent catalyst-based SCC, especially given the limitations such as reduced ductility, brittle failure modes, higher material costs, and the relatively lower load-carrying capacity observed in GFRP-reinforced beams. Without a defined application context, the research risks being viewed as purely experimental.

Therefore, the authors should discuss specific use cases where these materials and methods offer clear advantages - for example, Structures exposed to corrosive environments (e.g., marine infrastructure, chemical plants), where GFRP’s corrosion resistance is beneficial. Applications where non-magnetic or electrically non-conductive reinforcement is required (e.g., hospitals, labs, or certain industrial facilities). Environments that prioritize lightweight construction or sustainability, where using industrial waste (such as spent catalyst) aligns with green building goals. If no immediate practical application is intended, the study should position itself as foundational research aimed at developing knowledge for future implementation, while also identifying the challenges that must still be addressed before field use.

1.6 Aim and objectives

This study aims to explore environmentally sustainable self-compacting concrete blocks incorporating locally sourced spent catalysts, alongside the development of both corrosion-resistant and conventional structural components. To developing SC based SCC beams with conventional reinforcement (rebar) and non-corrosive reinforcement (GFRP rebar), and solid block with NC and SC based SCC. 4 beams of size [1500 mm (L) × 125mm (B) × 200 mm (D)] with conventional rebar and non-corrosive rebar (GFRP rebar) using SC based SCC and 12 solid blocks of size (400mm × 200mm × 200mm) by using (NC) and (SCC).

To accomplish the project's goal, attention should be directed towards the following key objectives:

- To develop C30-grade concrete by partially replacing cement with spent catalyst (SC) and to identify the optimal replacement level by assessing mix proportions of 3%, 6%, 9%, 12%, and 15%.
- To develop C30-grade self-compacting concrete (SCC) incorporating spent catalyst (SC) as a partial cement replacement, and to determine the optimum SC content for achieving the desired water–cement ratio and superplasticizer dosage.
- To assess the early-age mechanical behavior of C30-grade self-compacting concrete containing spent catalyst, with emphasis on strength characteristics and elastic modulus.
- To fabricate SCC blocks (400 × 200 × 200 mm) incorporating spent catalyst as a partial cement replacement.
- To cast C30-grade SCC beams with conventional steel reinforcement using spent catalyst-based concrete.
- To cast C30-grade SCC beams reinforced with fibre-reinforced polymer (FRP) bars using spent catalyst-modified concrete.
- To investigate the flexural performance of spent catalyst-based self-compacting concrete (SCC) reinforced with both conventional steel and FRP rebars.

2. Experimental Investigations

Figure 1 below shows the details of the experimental program followed.

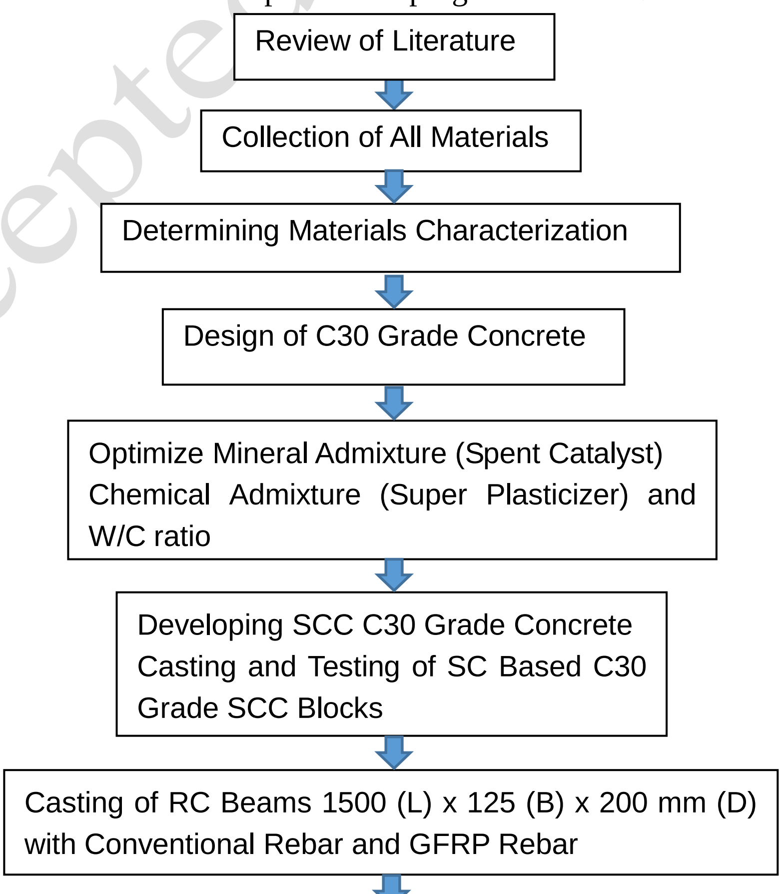


Figure 1. Experimental Program

2.1 Cement

Throughout the research, 33-grade Ordinary Portland Cement (OPC) supplied by Oman Cement Company, a prominent manufacturer in the Sultanate of Oman, was used

2.2 Aggregates

Aggregates are typically regarded as inert materials, comprising approximately 60-80% of the total volume and 70-85% of the overall weight of concrete. Replacing conventional natural aggregates with alternative or recycled materials offers a viable strategy to conserve natural resources and promote sustainability in concrete production. Fine aggregate, defined as material with particle sizes less than 4.75 mm, plays a crucial role in the concrete mix (Figures 2 and 3).

Figure 2. Fine Aggregates

Figure 3. Coarse Aggregates (10mm)

2.4 Spent Catalyst

In order to lower the oil's sulfur level and enhance its ability to burn, petroleum is cracked in oil refineries, producing spent catalysts as a by-product (Figure 3). These minerals are produced in large quantities by the Omani refineries in Mina Al3-Fahl (MAF) and Sohar (SR). These items are discarded at specifically created dumping sites without being put to good use and are categorized as waste materials. In Oman's oil refineries, at least two different types of wasted catalyst are created. Zeolite catalyst (ZCat) and equilibrium catalyst (ECat).

Figure 3. Spent catalyst (SC)

2.5 Superplasticizers

Enhance the performance of concrete, particularly in producing high-strength mixes using superplasticizers (SPs), also known as high-range water reducers, which are chemical admixtures (see Figure 4). These additives significantly improve workability while reducing water demand. While standard plasticizers can lower the water content by approximately 15%, superplasticizers can achieve a reduction of 30% or more.

Figure 4. Superplasticizers

2.6 A Mixture Design of SCC

The mix design incorporated coarse aggregates with a maximum particle size of 10 mm. The fine aggregates had a fineness modulus of 2.8 and a specific gravity of 2.65, while the coarse aggregates had a specific gravity of 2.7. The bulk density of the 12 mm coarse aggregates was recorded as 1600 kg/m³. Based on the mix design calculations for C30-grade concrete, the finalized mix ratio was established as 1:2.04:2.52 with a water-to-cement (w/c) ratio of 0.47. For the self-compacting concrete (SCC) variant, the modified mix proportion recommended by Okamura (1986) is illustrated in Figure 5. This method suggests an adjusted mix ratio of 1:1.9:2.052 using 10 mm coarse aggregates, maintaining a w/c ratio of 0.58.

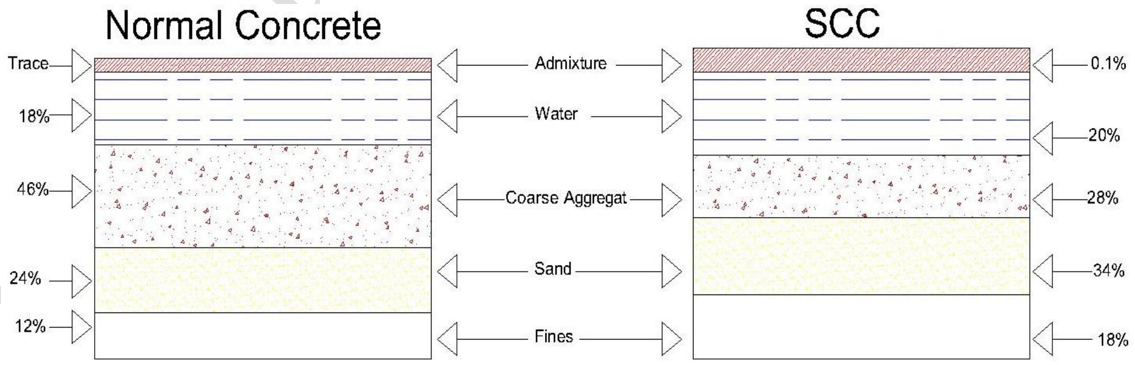


Figure 5. Convert NC into SCC (Okamura in 1986)

2.7 Tests for SCC

Slump Flow:

The slump flow test also provides an indication of the viscosity of self-compacting concrete (SCC) by measuring the time it takes for the concrete to spread to a diameter of 500 mm (20 inches) after the slump cone is lifted. The T20 (T50), also known as the SCC measurement, typically falls between 2 and 10 seconds. A higher T20 (T50) number indicates a more viscous mix that is better suitable for concrete in applications with crowded reinforcement or in deep parts. A lower T20 (T50) number may be sufficient for concrete that needs to reach significant horizontal distances unhindered (Figure 6).

Figure 6. Slump Apparatus

J-ring test:

It indicates the self-compacting concrete's capacity to pass. The J-Ring in conjunction with a slump cone mould, is used in this test technique to determine the self-consolidating concrete's capacity to pass (Figure 7). The test procedure is only applicable to concrete with aggregates no larger than 25 mm. This test technique outlines a process for determining if self-consolidating concrete mixes can pass. The difference between slump flow and J-Ring flow measurements serves as an important indicator of the concrete’s passing ability, particularly its capacity to flow smoothly through congested reinforcement without segregation or blockage.

Figure 7. J-ring test

U-box test:

Self-compacting concrete (SCC) segregation resistance is assessed using the U-box test (Figure 8). A specially made U-shaped box is used for the test, which is vibrated and filled with SCC to replicate the circumstances encountered during transit and placement.

Figure 8. U-Box test

L-box test:

Self-compacting concrete (SCC) flowability and passing capacity are both easily assessed using the L-box test (Figure 9). In this test, SCC is poured into a specifically made L-shaped box, and after the concrete has flowed through it, the height difference between the box's two legs is measured.

Figure 9. L-Box

V-funnel:

The apparatus comprises a funnel in a V shape, as is clear in the figure below (Figure 10). The filling ability (flowability) of SCC no larger than 20 mm is assessed using the V-Funnel test. There are around 12 litres of concrete in the funnel. Concrete may then be poured into the funnel and allowed to settle for five minutes. The flow time will dramatically lengthen if the concrete exhibits segregation

Figure 10. V-funnel

2.8 RC Beam Design

$Concretre\ grade:\ C30$

$f_{ck} = 30\ \mathrm{N/mm^2}$

$Steel\ grade:\ Fe500$

$f_{yk} = 500\ \mathrm{N/mm^2}$

$Depth\ (D)\ =\ 200\ mm$

Assume cover (d') = 25 mm

Effective depth (d) = D – d' = 200 – 25 = 175 mm

$$k = \frac{M}{bd^2\ f_{ck}}$$

$$A_s = \frac{M}{0.87\ x\ f_{yk}\ x\ Z}$$

A_s *= 2 Nos.× Area of 8mm = 2 × 50 = 100 mm²*

$Z_{max}\ =\ 0.95\,d\ =\ 0.95\ x\ 175\ =\ 166.25mm$

$M\ =\ 100\ x\ 0.87\ x\ 500\ x\ 166.25\ =\ 7231875\ Nmm$

$$k = \frac{7231875}{125\ \mathrm{x}\ 175^2\ \mathrm{x}\ 30} = 0.0629$$

$k' = 0.167$

$k < k'$

Therefore, ductile failure is achieved by designing an under-reinforced section where the tension steel yields before the concrete in compression reaches its ultimate strain, eliminating the need for compression reinforcement.

2.9 Result of SCC with SP and SC (As per BS EN 206-9, 2010)

The outcomes of testing on newly mixed self-compacting concrete, including slump flow, V-funnel, L-box, U-box, and J-ring tests for four distinct mixes (designated A, B, C, and D) are presented in Table 1. These tests offer vital information about each concrete mix's workability and flowability properties. The concrete's horizontal flow is evaluated by the slump flow test; viscosity is measured by the V-funnel test; passing through narrow spaces is assessed by the L-box and U-box tests; and passing through reinforcing bars is examined by the J-ring test.

Table 1. Self-compacting concrete with SP and SC

SCC Mixes	**Water-cement ratio**	**SC %**	**SP %**	**Max Force (kN)**	**Compressive strength (N/mm²) (28 days)**
Mix-A	0.51		2%	787.5	35
Mix-B	0.54	9%	2.5%	810.0	36
Mix-C	0.58		3%	855.0	38
Mix-D	0.61		3.5%	742.5	33

2.10 Effect of SC and SP on Compressive Strength of SCC

The optimal SC dose is 9%, as shown in the previous study, and this dosage will be fixed in SCC with a variety of SP dosages, according to the study's findings, which are shown in (Figure 11) and outlined in (Table 2). Mix-C exhibited the maximum compressive strength of 38 MPa, suggesting that a dose of 9% SC and 3% SP would be ideal. The compressive strength of the remaining mixes was found to be lower than that of the mix containing the recommended dosages of superplasticizer (SP) and spent catalyst (SC). These findings guided the selection of optimal dosages for further testing on reinforced concrete (RC) beams to evaluate flexural strength. For this purpose, RC beams were cast in three groups: two samples with the control mix, two with 3% SP, and two with a combination of 9% SC and 3% SP. A comparative analysis of these samples indicated that the ideal dosages are 3% for the superplasticizer and 9% for the spent catalyst. The optimum dosage of spent catalyst, superplasticizer, and water-to-cement ratio was determined based on compressive strength results and self-compacting concrete (SCC) performance tests.

Figure 11. Compressive strength test after 28 days (SCC-SC&SP)

Table 2. Compressive strength results for SCC based on SC with SP and water cement ratio

Sl No.	Mixes	Slump Flow		V-Funnel		L-Box				U-Box				J-Ring	
		Dia (mm) Range (650-850)	$T_{500\ mm}$(s) Range (2-6)	Time (s) Range (6-12)	T_{5min} Range (more 0.3 for normal)	Time (s) Range (15-30)	H1 (mm)	H2 (mm)	H2/H1 (ratio) Range (0.8-1)	Time (s) Range (20-30)	H1 (mm)	H2 (mm)	H2-H1 (mm) Range (0-30 mm)	Dia (mm) Range (550-800)	Difference in height (mm) Range (0-10)
1	Mix-A	580	5.2	12	8.4	27	38	25	0.66	30	306	330	24	490	10.7
2	Mix-B	600	4.6	10	9.5	24	52	40	0.78	27	360	380	20	530	10
3	**Mix-C**	**680**	**3.4**	**8**	**12.5**	**21**	**40**	**34**	**0.85**	**24**	**340**	**340**	**10**	**600**	**9.3**
4	Mix-D	690	3.6	7	14.7	18	41	39	0.95	20	350	350	18	660	8.2

2.11 SCC and CC differ significantly in mix composition and durability

Higher Paste Content in SCC: SCC typically contains a higher volume of paste (cement + water + mineral admixtures) and fines to ensure flowability and segregation resistance. This increase in paste volume can improve the uniformity of the mixture, leading to better compaction and ultimately higher compressive strength if properly designed. Use of Admixtures: SCC relies heavily on superplasticizers to achieve flowability without increasing the water-to-cement ratio (w/c). This allows SCC to maintain or improve strength even with high workability. Lower Coarse Aggregate Content: SCC usually contains less coarse aggregate than conventional concrete. While this may reduce interlocking between particles and slightly affect compressive strength, the overall quality and packing density of the matrix often compensate. While SCC offers superior workability, potential strength benefits, and excellent surface finish, its durability and environmental performance need more in-depth, long-term, and holistic evaluation. Many studies comparing SCC and CC are limited by short-term focus, lack of lifecycle thinking, and variability in mix design. These limitations should be carefully considered when interpreting study results or applying them in practice.

3. Main Study

There are two sections to the Main study. Totally 12 nos. of solid blocks were cast and tested for 7 7-day and 28-day curing periods. Of which 6 nos. solid blocks for conventional C30 grade concrete, and the remaining 6 nos. are SC based SCC concrete. It was examined that SCC blocks have 15% more compressive strength than conventional blocks. The next phase involved performing a flexural study on beams measuring 1500 mm (L) x 125 mm (B) x 200 mm (D), which were reinforced with an SC based SCC mix that included conventional steel and fibre-reinforced polymer (FRP) rebar. For each mix, two beam specimens were cast and tested in the laboratory using a two-point loading setup with a 500 kN capacity loading frame. The FRP beam was equivalent to the amount of steel substituted. The SCC beam reinforced with FRP exhibited initial cracking approximately 40% earlier than the SCC beam with conventional steel reinforcement. Its load-bearing capacity was also found to be 33% lower than that of the steel-reinforced counterpart. In terms of deformation, the conventional rebar SCC beam demonstrated about 48% less deflection than the SCC-FRP beam, reflecting a 56% reduction in ductility for the FRP-reinforced beam. Additionally, the stiffness of the conventional SCC beam was roughly 40% greater than that of the SCC-FRP beam. While the FRP-reinforced beam exhibited a brittle mode of failure, the beam with traditional rebar displayed a more ductile response and did not fail prematurely.

3.1 Casting of spent catalyst-based concrete blocks

In the laboratory, both spent catalyst (SC)-based self-compacting concrete (SCC) blocks and conventional normal concrete (NC) blocks, each measuring 400 mm × 200 mm × 200 mm, were cast and subjected to evaluation. A total of 12 SCC and NC blocks were used for a 7-day and 28-day curing period. (Figures 12 to 15) depict the casting and testing of blocks.

Figure 12. Casting of blocks **Figure 13.** Finished NC blocks **Figure 14.** Finished SCC blocks

Figure 15. Testing of blocks

Table 3 presents the compressive strength results obtained after 7 and 28 days of curing.

Table 3. Block compressive strength (N/mm^2)

Description	Average compressive strength N/mm^2 (7 days)	Average compressive strength N/mm^2 (28 days)
NC Blocks 400 × 200 × 200 mm	7.50	10.75
SCC Blocks 400 × 200 × 200 mm	9.50	12.75

3.2 Casting of SC based SCC RC beams with conventional reinforcement and fiber reinforced polymer rebar.

In accordance with the EC2 design guidelines, four reinforced concrete (RC) beams measuring 1500 mm in length, 125 mm in breadth, and 200 mm in depth were cast using both conventional steel reinforcement and glass fiber-reinforced polymer (GFRP) rebars. The longitudinal and cross-sectional details of the RC beam are illustrated in Figure 16.

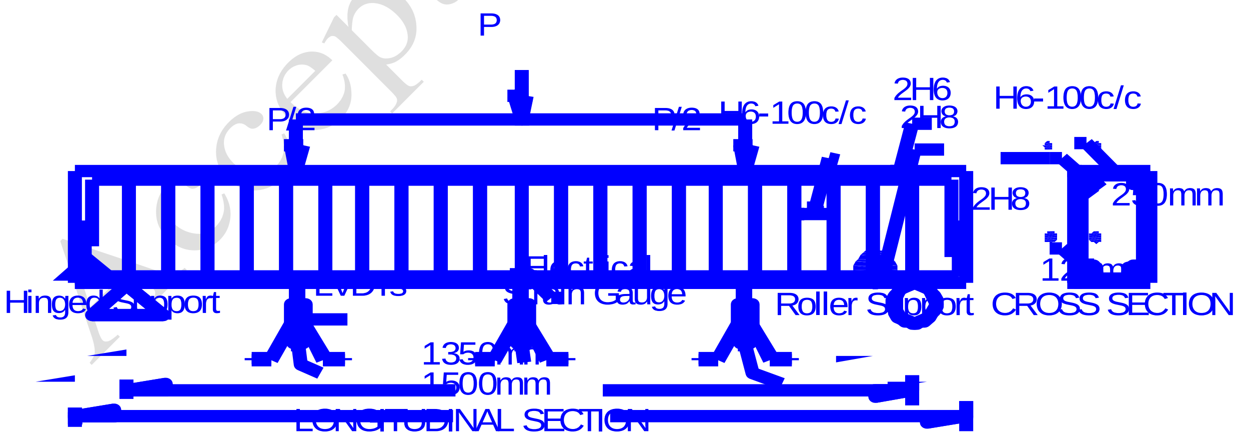


Figure 16. RC Beam Reinforcement Details

GFRP rebar replaced the equivalent amount of conventional rebar. Figures 17 to 20 depict GFRP rebar and traditional rebar grills.

Figure 17. GFRP rebar **Figure 18.** GFRP rebar 8mm and 6mm (closer view)

Figure 19. Conventional rebar grill **Figure 20.** GFRP rebar grill (coloured) (Same cross-sectional area of conventional rebar replaced with GFRP)

Table 4 compares the material properties of FRP rebar with conventional rebar.

Table 4. Properties of FRP Rebar

Material	Steel (Rebar)	GFRP rebar
Tensile strength, MPa	500	1100
Modulus of elasticity, GPa	200	55
Bond strength, MPa	10	12
Shear strength, MPa	380	181
Thermal conductivity, W/(m*°C)	46	0.35
Linear expansion coefficient, $\alpha*10^{-6}$/°C	13-15	9-12
Density, kg/m^3	7850	1900
Relative elongation, not more than, %	18	3
Compressive strength, MPa	250	350

Figures 21 & 22 depict the casting process for two RC beams and two GFRP beams, including the 28-day curing procedure

Figure 21. Casting process of conventional rebar and GFRP rebar RC beams

Figure 22. 28-day curing of conventional rebar and GFRP rebar RC Beams

Figure 23 illustrates the way the beams are cleaned and tested after 28 days of curing.

Figure 23. Conventional rebar and GFRP rebar RC beams ready for testing

Figure 24 depicts the flexural behavior of a SC-based SCC RC beam with conventional rebar and GFRP rebar conducted by a loading.

Figure 24. Testing of Conventional rebar and GFRP rebar SC bases SCC RC beam

4. Results and Discussions

This chapter presents the development and experimental evaluation of self-compacting concrete (SCC) beams incorporating spent catalyst (SC) as a partial cement replacement. Two types of reinforcement were employed: conventional steel rebars and corrosion-resistant glass fiber-reinforced polymer (GFRP) bars. A total of four reinforced concrete (RC) beams were cast using SC-based SCC, each with dimensions of 1500 mm in length, 125 mm in width, and 200 mm in depth. Two beams were reinforced with steel, while the remaining two utilized GFRP reinforcement, enabling a comparative assessment of the influence of reinforcement type on structural performance.

All beams were tested under a two-point loading system using a 500 kN capacity loading frame. Key performance parameters such as load-bearing capacity, mid-span deflection, crack initiation and propagation, and failure modes were closely monitored. In addition, twelve solid concrete blocks (400 mm × 200 mm × 200 mm) were cast using both normal concrete (NC) and SC-based SCC. These specimens were tested under a two-point loading setup using a 1000 kN capacity universal testing machine (UTM) to evaluate compressive strength and material behaviour. Special emphasis was placed on observing and analysing the development of cracks throughout the beam testing process. Crack formation and propagation patterns were documented in detail to gain deeper insights into the structural response and failure mechanisms associated with different reinforcement types and concrete compositions.

Analysis of Results and Discussion: As illustrated in Figures 24 to 26, the load–deflection behaviour of both conventionally reinforced beams and those reinforced with GFRP rebars exhibits three distinct stages before failure: the initial cracking stage, the yielding stage, and the ultimate failure stage. Key performance parameters analysed included the first crack load, ultimate load-carrying capacity, mid-span deflection, flexural stiffness, and ductility ratio. The results are discussed in the following sections to highlight the influence of reinforcement type on structural behaviour.

Crack: Table 5 indicates that the initial cracking in the SCC beam reinforced with GFRP occurred approximately 40% earlier compared to the SCC beam with conventional steel reinforcement.

Ultimate load: The effectiveness of reinforced concrete (RC) beams is primarily determined by their load-carrying capacity at the ultimate stage, which represents the maximum load the beam can sustain before failure. As shown in Table 5, the ultimate load recorded for the beams reinforced with GFRP is notably lower than that of the beams with conventional steel reinforcement. Specifically, the SCC beam with GFRP rebars exhibited a 33% reduction in load-carrying capacity compared to its steel-reinforced counterpart.

Deflection: As presented in Table 5 and Figures 25, 26, and 27, a direct proportional relationship exists between load and deflection; deflection increases progressively with applied load. Additionally, the SCC beam reinforced with conventional steel rebars exhibited approximately 48% less deflection at the ultimate load compared to the GFRP-reinforced beam, indicating higher stiffness and reduced deformation.

Ductility: Ductility is assessed through the load–deflection response of a structural element, typically quantified as the ratio of ultimate deflection to yield deflection. As shown in Table 5, the SCC beam reinforced with GFRP bars exhibited greater ductility compared to the conventionally reinforced beam. Specifically, the ductility of the conventional SCC beam was approximately 56% lower than that of the

GFRP-reinforced beam, indicating a more gradual failure mode and higher deformation capacity in the latter.

Stiffness: Beam stiffness refers to the flexural rigidity of a structural member under applied loading, particularly distributed loads. It is a critical factor in determining how much a beam resists deformation. While stiffer beams undergo less deflection, they are not necessarily more flexible; in fact, increased stiffness typically corresponds to reduced flexibility. The stiffness of a simply supported reinforced concrete (RC) beams up to the steel yielding point is evaluated using a standard flexural stiffness equation. This equation allows for a comparative assessment of different reinforcement types in beams. Using this approach, it was observed that beams reinforced with glass fiber-reinforced polymer (GFRP) bars exhibited notably lower stiffness compared to those reinforced with traditional steel bars. Specifically, the SCC beam with conventional steel reinforcement demonstrated approximately 40% higher stiffness than its GFRP-reinforced counterpart. This greater stiffness contributed to superior structural behaviour under applied loads. Furthermore, the steel-reinforced SCC beam displayed ductile failure characteristics, with no evidence of sudden or brittle fracture. Conversely, the SCC beam reinforced with GFRP bars experienced brittle failure, reflecting reduced ductility and a diminished ability to dissipate energy prior to collapse.

$$\text{Stiffness} = \frac{PL^3}{56.25 \times \delta}$$

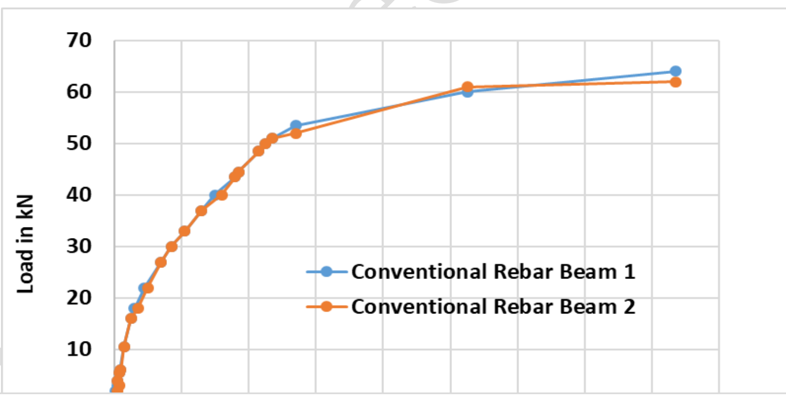
Where:

P= load at yielding point

L= effective span = 1350 mm

δ = deflection at yielding point

The load deflection behaviour of SC based SCC beam with conventional reinforcement and GFRP reinforcement are shown in Figure 25 and 26. The combined load deflection curve is shown in Figure 27.



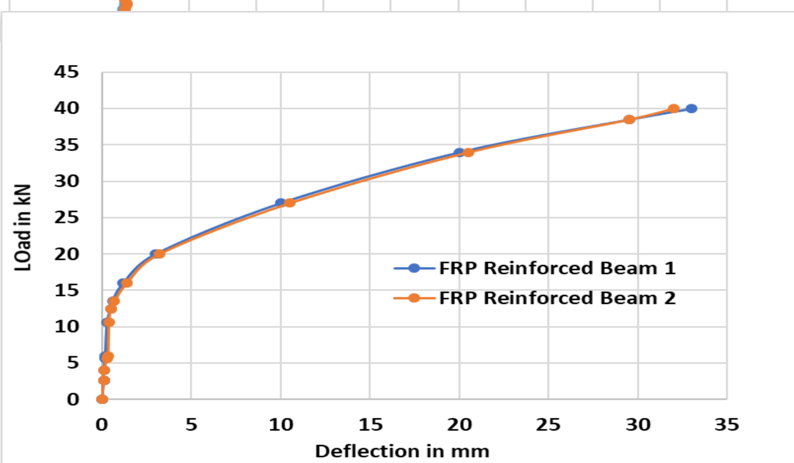


Figure 25. Load – deflection behaviour of conventional Rebar beam

Figure 26. Load – deflection behaviour of FRP Rebar beam

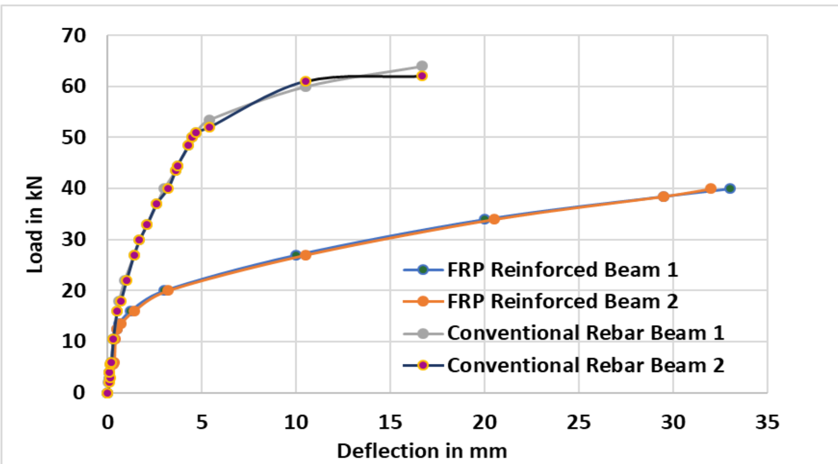


Figure 27. Load - Load-Deflection Behavior of Conventional Rebar and FRP Rebar Beams

Crack patterns that developed in the beams during testing were carefully observed and analyzed, as illustrated in Figure 28.

The initial cracks typically appeared in the tension zone near mid-span, progressing in width and number with increasing load. In beams reinforced with conventional steel, cracks propagated more gradually, exhibiting multiple fine cracks indicative of ductile behaviour. Conversely, GFRP-reinforced beams showed fewer but wider cracks that rapidly led to brittle failure (Figure 29).

The detailed crack mapping provided insight into the different failure mechanisms and structural responses associated with each reinforcement type.

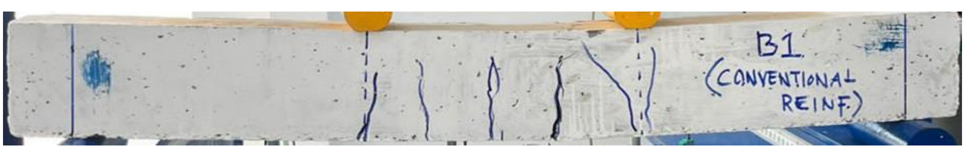


Figure 28. Crack Pattern of Tested (Conventional Reinforcement)

Figure 29. Crack Pattern of Tested (GFRP Rebar)

Table 5 displays the results of the beam tests as well as information that was produced for stiffness, ductility factor, and related data. Finally, 12 nos. of solid blocks (400 mm × 200 mm × 200mm) were cast using C30 grade conventional concrete (NC Blocks) and SC-based SCC for 7 days and 28 days curing. Figure 30 demonstrates that the compressive strength of SC base SCC concrete is 15% higher than that of conventional concrete.

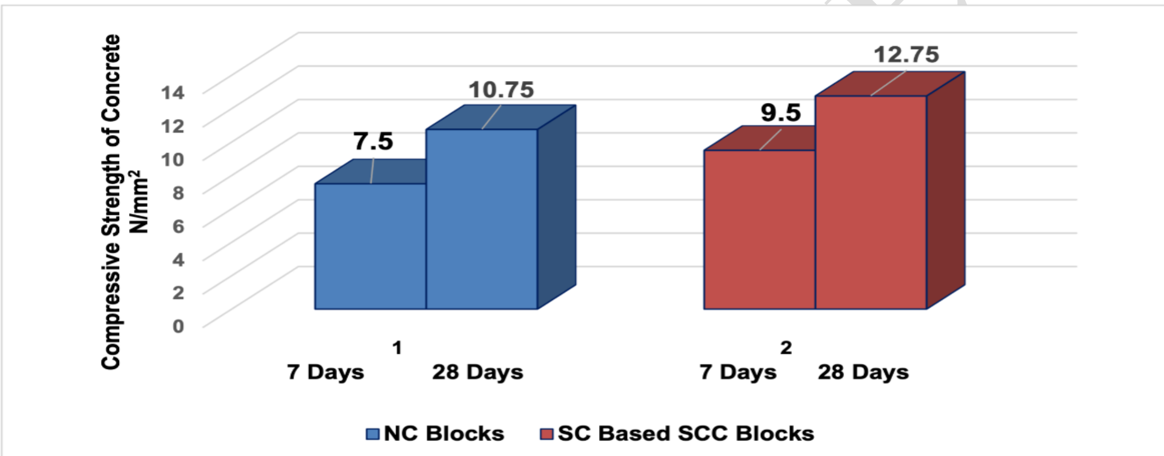


Figure 30. Compressive strength of NC blocks SC base SCC blocks

Table 5. Experimental data and derived information

Beam code	First crack stage		Yield stage		Ultimate stage		Ductility factor	Post cracking - pre-yielding stiffness (kNm^2)	Mode of failure	Average crack width	Type of loading
	Load (kN)	Central Deflection (mm)	Load (kN)	Central Deflection (mm)	Load (kN)	Central Deflection (mm)					
Conventional Rebar Beam 1	22.00	0.25	30	1.7	62	16.70	9.82	689	Flexure	0.11	Static monotonic loading
Conventional Rebar Beam 2	23.00	0.30	30	1.6	64	17.00	10.63	732	Flexure	0.10	
FRP Rebar Beam 1	14.00	0.10	16	1.4	40	33.00	23.57	446	Brittle	0.18	
FRP Rebar Beam 2	13.50	0.20	15	1.5	39	32.00	21.33	390	Brittle	0.19	

3. Conclusion

The following key observations were drawn from the experimental investigation on the partial replacement of cement with spent catalyst (SC) in self-compacting concrete (SCC) and its flexural behaviour:

- Preliminary investigations indicate that partially replacing cement with spent catalyst (SC) in C30-grade control concrete results in approximately a 10% improvement in compressive strength after 28 days of curing, compared to other replacement levels.
- Various tests including slump flow, J-ring, U-box, L-box, and V-funnel indicated that an optimum dosage of 3% spent catalyst (SC) met the criteria for self-compacting concrete (SCC) in accordance with BS standards, showing consistent and satisfactory performance.
- In self-compacting concrete (SCC) containing spent catalyst (SC) and superplasticizer (SP), the optimum dosages were found to be 9% SC and 3% SP, respectively. This combination yielded superior compressive strength at 28 days curing and met the SCC performance requirements of BS standards, as confirmed by various tests including slump flow, J-ring, U-box, L-box, and V-funnel.

- Flexural testing was conducted on beams measuring 1500 mm (L) × 125 mm (B) × 200 mm (D) cast with SCC and reinforced using either conventional steel or GFRP rebars. For each reinforcement type, two beams were prepared and tested in the laboratory using a two-point loading setup. In the case of GFRP-reinforced beams, the steel reinforcement was directly replaced with an equivalent amount of GFRP bars.
- The initial cracks in the SCC beam reinforced with GFRP appeared approximately 40% earlier than those in the conventional steel-reinforced SCC beam. Additionally, the load-carrying capacity of the SCC-GFRP beam at ultimate load was about 33% lower compared to the conventional rebar SCC beam.
- Compared to the SCC-GFRP beam, the conventional steel-reinforced SCC beam exhibited approximately 48% less deflection and 56% lower ductility. Furthermore, the stiffness of the conventional rebar SCC beam was about 40% higher than that of the SCC-GFRP beam. The steel-reinforced beam showed no signs of premature or brittle failure, whereas the SCC-GFRP beam failed in a brittle manner.
- Twelve solid blocks measuring 400 mm × 200 mm × 200 mm were cast using both C30-grade conventional concrete and SC-based self-compacting concrete (SCC), cured for 7 and 28 days. The compressive strength of the SC-based SCC was found to be approximately 15% higher than that of the ordinary C30-grade concrete.
- None of the conventionally reinforced beams showed premature or brittle failure; however, the reinforced beams with GFRP exhibited brittle failure modes.
- It can be concluded that using an optimum dosage of 3% superplasticizer and 9% spent catalyst enhances the performance of SCC. However, when GFRP reinforcement replaces an equivalent amount of steel, the beams exhibit a 33% reduction in load-carrying capacity compared to conventional steel-reinforced beams

4. Conflict of Interest

The authors declare no conflict of interest.

5. Declaration

I hereby declare that no AI tools or technologies were used in the preparation of this journal paper.

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