Available online at www.CivileJournal.org

# Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 9, No. 05, May, 2023


# An Investigation on Eco Friendly Self-Compacting Concrete Using Spent Catalyst and Development of Structural Elements

Balamuralikrishnan R. [1*], Ranya Al-Balushi [1], Asima Kaleem [1]

[1] *Civil & Environmental Engineering, College of Engineering, National University of Science and Technology, Muscat, Oman.*

Received 22 February 2023; Revised 17 April 2023; Accepted 26 April 2023; Published 01 May 2023

**Abstract**

The theme of this initiative is "*Waste to Wealth*." Construction materials, particularly concrete, need to have better qualities, including strength, rigidity, durability, and ductility, because Oman's construction industry is expanding. Self-compacting concrete (SCC) has more benefits than regular concrete, including better workability. The major focus of this study is the C30-grade SCC for the control mix, spent catalyst (zeolite catalyst)-based SCC, and the development of the RC beam's flexural behavior employing control and spent catalyst-based SCC. The preliminary study and the main study are the two study outcomes included in this project. Preliminary research involves creating four mixtures with various dosages of 3%, 6%, 9%, and 12% in order to optimize spent catalyst in C30 grade concrete. All of the cubes undergo a 28-day curing test. The cubes' compressive strength is tested in order to establish the ideal dosage, which is 9%. Develop a C30 grade control modified design mix in accordance with SCC and optimize chemical admixtures such as superplasticizer (SP) at different dosages, like 2, 2.5, 3, and 3.5%, using various trials and tests (slump flow, L-box, J-ring, V-funnel, and U-box tests), as well as the optimized dosage of spent catalyst (SC). The main study includes six singly reinforced RC beams with dimensions of 750 (L)×100 (B)×150 mm (D) that were cast and tested in the laboratory. After a 28-day curing period, two specimens were placed under a two-point loading setup, with the remaining two samples receiving the optimum dosages of spent catalyst and superplasticizer. All of the beams were tested using a Universal Testing Machine (UTM) with a 1000 kN capability. From the preliminary study, partial substitution of cement in control concrete of grade C30 using spent catalyst (SC), it was found that the 9% optimum dosage produces greater compressive strength compared to other doses, which are almost 10% rises at 28 days of curing period. Based on a different test, it was discovered that the optimum dose of 3% SP gave closer agreement and satisfied the need for SCC as per the BS standard. The load-carrying capability of the SCC beams is almost 21.7% higher than that of the control beams. Comparing the SCC beams to the control beams, their deflection was reduced by about 26% at the same load level, and their ductility rose by almost 33%. Comparatively to the control beam, the stiffness of 21.6% of SCC also rises. According to test results, the SCC beam performs better in every way when superplasticizer and spent catalyst are used at the recommended dosage.

*Keywords:* SCC; Control Beam; RC Beam; Superplasticizers; Spent Catalyst; Two-Point Loading; Flexural Strength.

## 1. Introduction

This proposal is being submitted to show how waste materials may be used in Oman as abundant renewable and sustainable energy sources, as well as how they could be used to make concrete. The idea is to detect the many refinery waste sources, manage them using high-performance concrete and corrosion effects in RC members, and produce eco-friendly material as a byproduct. A vibration machine is used to disseminate and eliminate air and bubbles from the concrete so that it can reach every nook and cranny of the structural component. Self-compacting concrete can be put and compacted under its own weight without the requirement for mechanical vibration because of its excellent flowability feature. It is crucial to keep it durable and maintain its solid qualities. Superplasticizers and viscosity rates are added to the mixture, which lessen bleeding, preserve liquidity, and prevent isolation [1].

* Corresponding author: balamuralikrishnan@nu.edu.om

http://dx.doi.org/10.28991/CEJ-2023-09-05-08

### 1.1. Application of Self-Compacting Concrete (SCC)

Self-compacting concrete is frequently utilized in precast sections and in bridge construction due to its filling and passing properties. Drilled shafts, columns, earth retention systems, locations with a lot of pipelines and ducts, and other places where reinforcement is crowded are examples of these conditions. However, there are significant uses for self-compacting concrete, including the construction of structures with intricate reinforcement, repair, restoration, and construction renovation and rehabilitation, the construction of earth and water retaining structures with high stability and durability, and the foundational work for rafts and heaps [2].

### 1.2. Origin of the Research Problem for Eco-Friendly Self-Compacting Concrete (SCC)

The idea of the project is "waste to wealth." Massive amounts of natural resources are being used to make cement, which in turn is using up resources faster than it can be replenished. Finding such materials and methods that either partially or completely replace the constantly in demand substance cement has frightened concrete experts all over the world. Oman, a growing nation, has undergone and is undergoing massive infrastructure projects, all of which make use of enormous quantities of cement and other resources used to make concrete.

One of the main causes of the greenhouse gas (GHG) effect is the emissions produced by Portland cement. About 5% of the carbon dioxide produced by humans worldwide comes from the production of Portland cement, which is used to make concrete. 377 million metric tons of carbon were produced in the past years according to recent estimates of emissions from cement manufacturing; this means that emissions from burning fossil fuels and producing cement have increased by more than twice as much since the middle of the 1970s. Although steps can be taken to limit carbon dioxide production in cement kilns, the amount of carbon dioxide released per ton of cement is still in the range of 600 kg, of which 400 kg are due to the calcination of limestone. It is necessary to shift the building industry away from its disproportionate reliance on Portland cement by creating alternate binder systems in light of the major environmental effects of carbon dioxide as well as the predicted continuous rise of industrialization and urbanization. The partial substitution of cement using refinery waste, such as used catalyst, is one of the possibilities that has garnered interest. The use of such blended cements has been made possible by a wealth of information regarding the properties of freshly laid and hardened concrete when cement has been replaced in part.

Concrete is among the most commonly used construction materials. Each person in the world produces about one ton of concrete a year. Large amounts of raw materials, energy, and heat are used in the cement-making process. Along with that, it causes significant releases of gas pollutants and solid waste. Because the manufacturing of cement is one of the most energy-intensive industrial processes and because fuel is required for the extraction and transportation of raw materials, there are more carbon dioxide emissions in particular. One of these pollutants that is particularly noticeable is dust, whose total particle emissions per ton of cement produced are 360 pounds [3]. As a result, a significant amount of air pollution is released. Due to this, this topic will create self-compacting concrete by lowering the cement content of the concrete and incorporating waste catalyst with silica fume. The fluid catalytic cracking (FCC) waste catalyst will be employed in this project as a butanol addition to the production of SCC during the oil refining process. This catalyst lessens the impact of the cement business on the environment by reducing the amount of solid waste disposed of in landfills and by turning contaminated waste into a valuable product for the building materials industry. It is also preferable to use these wastes and lessen the negative effects of cement because they are currently produced in roughly 500 kilotons in oil refineries all over the world.

### 1.3. Origin of the Research Problem for Spent Catalyst

The majority of the solid waste produced by the Sohar and Mina Al-Fahl Petroleum Refineries is made up of spent Fluid Catalytic Cracking (FCC) catalyst, also known as spent catalyst because it contains active silica ($SiO_2$) and alumina ($Al_2O_3$) [4-6]. As waste products from the Sohar and Mina Al-Fahl refineries, respectively, more than 20 tons of spent catalyst and 200–500 kg of spent alumina catalyst are produced per day. These waste products are deposited in landfills, harming the environment. To address this issue and conserve energy and natural resources, numerous research projects are being conducted on the reuse of used catalysts. Experimental studies on the impact of adding used catalyst as a partial replacement for cement and sand lower concrete production costs and conserves natural resources. Depending on the source of the spent catalyst, the amount of replacement, the water-to-binder ratio, and the distribution of particle size, different conclusions were reached. As a result, this study explores the possibility of using used catalysts in concrete to completely or partially replace cement.

### 1.4. Status of Self-Compacting Concrete (SCC)

In the past decades, the development of self-compacting concrete has been one of the biggest technological breakthroughs in the field of concrete materials. Because self-compacting concrete has many benefits, such as its ability to address environmental and performance problems in an integrated manner, this study examines the feasibility of using waste fluid catalytic cracking (wFCC) catalyst from the oil refining industry as a pozzolanic addition to produce self-compacting concrete (SCCs). As such, an experimental program was conducted to design mixture proportions and assess the acceptable range of cement substitution level with a wFCC catalyst. It was carried out in two phases to suit a mixture of SCC. In the first stage, the mortars were prepared to meet the adequate flow requirements for each level of replacement of the cement test by mini slump-flow and mini V-funnel testing in order [7].

The appropriate percentage of fly ash and silica smoke in SCC gives the highest value of concrete compressive strength. As well as studying the effects of different curing conditions. 450 cylinders with a diameter of 100 mm and a length of 200 mm have been tested to check the compressive strength of concrete in SCC with different percentages of fly ash, silica fume, and the combination of fly ash and silica fume, respectively. Three types of mixtures were made in this study, as the first mixture is a combination of plain concrete (PC) and fly ash (FA), the second is a mixture of PC and silica fumes (SF), and the last is a mixture of PC, FA, and SF.

The slump-flow test and V-funnel test are being performed on the fresh SCC to assess the SCC's ability to flow and viscosity. The cone is filled with concrete, then lifted vertically, and time measurement begins, so the slump test is performed. The FA and SF together, at 10% each in SCC, gave the highest compressive strength value [8]. To evaluate the performance of fly ash and silica fume when they are replaced in the self-compressed concrete for the operability, durability, and strength of the concrete using OPC (53 grade). Cement replacement materials, along with mineral and chemical admixtures, improve the properties of concrete's strength, workability, and durability. The reason for developing this type of concrete is to shorten the construction period, ensure pressure in the structure, and eliminate noise due to vibration. Cement, fine aggregates, coarse aggregates, fly ash, silica fume, and superplasticizer are the materials used in this study. To achieve the optimum level of SCC in this experimental study, the cement was partially replaced by different levels of fly ash and silica fumes to obtain the optimal mix design. Nine mixtures were made, as the fly ash was replaced by three different percentages of 15, 20, and 25, while the added silica fume was replaced by percentages of the cement of 6%, 9%, and 12%. Slump flow, L-box, J-ring, V-funnel, and U-box tests. Finally, compressive strength and split tensile strength are maximum for 25% fly ash + 6% silica fumes [9]. To overcome the problems associated with pouring concrete on site, SCC is being developed.

This type of concrete is characterized by its high fluidity and resistance to segregation, as it can be pumped over longer distances and is not affected by the skills of workers. This study seeks to develop self-compacting concrete using silica fume. In this experimental study, materials are tested to determine the optimal mix for SCC according to EFNARC guidelines and the Nan-Su method. Initially, the design mixture was designed using the Nan-Su method, and then the developed ratio was taken as an experimental mixture ratio. The cement is replaced with silica fume (0–15%) at an interval of 2.5%. Then the mixture is tested to determine the rheological and hardening properties of the concrete. Ordinary Portland cement 43 grade has been used with fine aggregate, which is 4.75mm river sand. A 12 mm coarse aggregate was used for SCC mixes, and to improve workability and reduce segregation, Glenium TMB233 was used in combination with mineral admixture micro-silica. On the basis of laboratory investigations, it can be concluded that self-compacting concrete mixtures with silica fume can be developed without affecting strength. It also requires a high percentage of powder and every equal amount of coarse and fine aggregate proportions. SCC density increases slightly for cubes and cylinders with the addition of silica fume. Finally, increasing the percentage of silica fume in the range of 2.5–15% in a separation of 2.5% reduces the flow ability of concrete [10].

The technology of high-strength self-compacting concrete (SCC) containing ultra-pulverized fly ash (UPFA) and superplasticizer (SP). Ordinary Portland cement 525 was used with the fine aggregate from the Xiangjiang River, while coarse aggregate is crushed stone or broken gravel with a maximum symbolic size of 20 mm. On the basis of fluorinated naphthalene formal, a superplasticizer (SP) is used in the mix. With a fly ash vibrating ball mill, UPFA is pulverized, and by using Jianxi expansion agent, the SCC drying shrinkage caused by many cement materials is reduced. Ordinary concrete exposed to vibration (OC) and SCC are subjected to the same mixture proportions. To evaluate the compression strength, cubes are used that contain the following dimensions: 100×100×100 mm, while the dimensions used for unrestricted drying shrinkage are 100×100×515 mm. After determining the parameters of the mixture proportions, SCC is developed with good operability, high mechanical properties, and high durability. This is done through the following tests: standard slump and slump flow, L-box test, Orimet method, segregation resistance, and passing ability [11].

SCC flows into every corner of a mold, passes reinforcement, and fills gaps without any need for internal or external vibration and compaction, simultaneously maintaining stability without segregation and bleeding of concrete. It has the ability to compact itself only by means of its own weight [12–14]. In the early 1990s, SCC was introduced in concrete technology [15]. The properties of SCC depend on the source and type of constituent materials and their properties [16]. The use of SCC eliminates the compacting effort, which results in reduced costs of placement; moreover, a decrease in the duration of construction improves productivity [17]. SCC is a concrete type with high workability, high flowability, and superior resistance to segregation [18]. The property of SCC to completely fill a formwork by filling gaps and to flow around reinforcement without the need for vibration or bleeding makes its use significant [19].

A good balance between deformability and stability resulted in the successful development of SCC. Different mix design procedures were proposed for SCC that include (a) combinations of a higher volume of mineral additives and water-reducing admixture, and (b) combinations of water-reducing admixture and viscosity-modifying agent [20]. The use of SCC reduces the noise during casting and provides better working conditions [17–21]. The application of SCC in densely reinforced sections, that is, columns and beams in moment-resisting frames in seismic areas, is necessary to ensure that all gaps in a formwork are filled [18]. The use of lime stone powder as a fine additive can improve the rheological behavior of cement pastes, and the combination of both lime stone powder and fly ash can result in a higher packing density [22]. Eco-SCC is a SCC with a maximum total binder content of 315 kg/m$^3$, which can include cement, silica fume, fly ash, and/or limestone filler [23]. Air-entrained SCC was designed with the use of air entraining agents; a high level of compaction and a moderate compressive strength were achieved.

The addition of pozzolanic ingredients, superplasticizers, and/or viscosity-modifying agents is necessary for SCC design in comparison to traditional concrete design [24–26]. In terms of strength, durability, shrinkage, and rheology, the qualities of SCC are significantly influenced by factors including packing density, chemical admixture and mineral additive properties, water to cement ratio, aggregate type, raw material composition, and design techniques [16, 27–29]. The formability, stability, and strength of SCC created using a factorial approach can be sufficient [24, 30]. The statistical approach makes sure that there is sufficient compressive strength, flowability, and passing ability [20, 31]. In comparison to other ratios, higher compressive strengths were attained with a 33% coarse aggregate volume. With a higher percentage of coarse and fine particles, rheological parameters, namely yield stress and viscosity, increase [27]. Low superplasticizer dosage, little paste volume, and minimal drying shrinkage were achieved using SCC built with blocking and liquid phase content criteria [32]. It also showed great durability and economic efficiency.

Recycled plastic self-compacting concrete (RPSCC), according to the findings of earlier investigations, is suitable for structural applications due to its favorable fresh and mechanical qualities. The use of plastic components in place of natural aggregates (NA) makes this type of concrete sustainable and environmentally beneficial [33]. The replacement of fine aggregate in the creation of green self-compacting concrete using industrial by-products such as used foundry sand, used tire rubber, used copper slag, and used glass. Sustainable development could result from the use of these industrial by-products in self-compacting concrete [34].

In order to address both workability and durability without compromising the concrete's strength, artificial intelligence techniques were used to provide a perspective on the flexural strength of High Strength Hybrid Fiber Self Compacted Concrete (HSHFSCC), which is regarded as a specific type of concrete. It has excellent deformability in the fresh state and a strong reluctance to segregation, which improves homogeneity and increases production by adjusting the construction duration [35]. The advantages of this new composited SCC fiber composition with appropriate rheological, physical, and mechanical qualities compared to those of conventional SCC concrete. The impact of discarded plastic fibers on the rheological and mechanical characteristics of SCC is evaluated. An alternate SCC composite that is ductile and has improved characteristics may be produced by incorporating plastic fiber reinforcement into the structural matrix [36].

The compressive strength of the SCC mixing fraction, including 0.6 µm eggshell, was measured during engineering. The material parameters of the concrete mixture were estimated using the tests of lump flow, L-box, and sieve segregation. In comparison to theoretical values, the ultimate flexural strength and fracture width of the SCC beams were measured. According to experimental results, Eurocode2 is comparable to the flexural strength of eggshell-filled SCC beams. In most instances, the crack width was less than the limit for Eurocode 2 crack control [37]. Self-Compacting Concrete (SCC) is a relatively new kind of concrete that has excellent workability, a lot of paste, and contains components that can substitute cement, like slag, natural pozzolana, and silica fume. Cement substitute materials offer a wide range of advantages, including lower costs, less natural resource usage, lower carbon dioxide emissions, and enhanced fresh and hardened qualities. SCC is employed in numerous applications, including high rise shear walls and sections with congested reinforcing, and it is necessary to forecast how well it would perform in these situations. In civil engineering, artificial neural networks (ANN) are frequently used to forecast the performance of specific engineering materials, such as compressive strength and durability [38].

### 1.5. Status of Spent Catalyst

Zeolite is the primary ingredient in the initial catalysts used in fluidized catalytic cracking units (FCCUs) at refineries, along with a few other additions [39–42]. 1/5 of all catalysts produced worldwide are made up of zeolite [43]. Refineries utilize fluid catalytic cracking (FCC) catalysts to increase the output of higher-octane petrol produced from crude oil during oil refining and cracking. The deactivated FCC catalyst must be changed out for an active (regenerated) or brand-new catalyst when its catalytic abilities deteriorate [44]. Since many years ago, it has been commercially viable to regenerate used catalysts for hydro processing, fluid catalytic cracking (FCC), and reforming. After multiple cycles, the catalyst activity has not recovered enough to justify regeneration [45].

It has been noted that the performance of wasted catalysts is satisfactory without having any negative effects when 15-20% of cement and 10% of sand are partially replaced [46]. It was shown that after 7 and 28 days of curing, compressive strength increased more than in the control mix. Because of its reaction with calcium hydroxide to form more hydrated calcium silicate gel, the spent catalyst's finer size is to blame for the increase in compressive strength. The powder catalyst also served as a pozzolanic material and pore filler, improving the cementitious characteristics and, as a result, the compressive strength of the mortar [47]. $SiO_2$ and $Al_2O_3$ together make up more than 68% and 77%, respectively, of the chemical composition of used catalyst from the MAF and SR refineries. As evidenced by the loss-on-ignition (LOI) value, the spent MAF catalyst contained more organic molecules. The comparatively high alkali concentration of the MAF waste catalyst could react with the silica and negatively impact the characteristics of mortars. Alumina is substantially more abundant in MAF waste catalyst than silica, which has a silica to alumina ratio of roughly 1:1 in SR. Both catalysts used contain a very small amount of lime [48].

### 1.6. History of SCC

Durability in concrete systems caused enormous problems in Japan before 1983. Because there weren't enough certified workers available at the time, the quality of the buildings was lower, and the concrete needed to be compressed sufficiently to produce lasting concrete. The use of self-compacting concrete by Japanese engineers allowed them to obtain a satisfactory outcome without the need for a wide variety of workers. Okamura was responsible for creating a solid need in this direction in 1986 [11]. Ozawa et al. contributed significantly to the work that was done at Tokyo University to make these improvements more workable [12]. In addition, there are several reasons why engineers like self-compacting concrete examples, including the lack of vibration on building sites, the poor quality of the job, the resistance to separation in concrete, the production of concrete with a low water/cement ratio, and the quicker processing of the structure.

### 1.7. Advantage of SCC

Compared to ordinary concrete, self-compacting concrete has many advantages, such as casting, which requires minimal vibration, which reduces labor, time, and costs. Moreover, by preventing any gap between the concrete and the reinforcement bar, it improves durability and flows into complex shapes. Compared to normal concrete, self-compacting concrete has a lower permeability and a higher insulation value.

### 1.8. Disadvantage of SCC

As compared to ordinary concrete, self-compacting concrete has several disadvantages. For instance, there are not many SCC production facilities, so this product is not widely available. The cost of SCC is higher than that of ordinary concrete. Further, SCC needs more maintenance than hardening normal concrete. The high fluidity of this material may also cause problems in mold fabrication due to hydrostatic pressure.

### 1.9. Applications of SCC

There are several applications of self-compacting concrete such as:

- Foundations piles and rafts;
- Repair and retrofitting constructions;
- Structures with complex rebar distributions;
- Use in columns and beams.

### 1.10. Aim and Objectives

This project aims to study the flexural behavior of RC beams using spent catalyst-based self-compacting concrete. The main purpose of this project is to study the flexural behavior of RC beams using catalyst-based self-compacting concrete. Prepare a C30-grade construction mix and design a singly reinforced RC beam of size 750mm (L) × 100mm (B) × 150mm (D). Study the single-reinforced RC beam without spent catalyst and with spent catalyst. Likewise, find the flexural behavior of RC beams without spent catalyst and with spent catalyst at differing dosages of 3%, 6%, 9%, and 12%, and for superplasticizers at 2%, 2.5%, 3%, and 3.5%. Find the optimum dosage and conduct a comparative study between control SCC and spent catalyst-based SCC in terms of flexural strength.

To achieve the aim of the project must focus on the following objectives:

- To develop C30 grade SCC for control mix.
- To optimize mineral admixtures (spent catalyst) and chemical admixtures (super plasticizer) with different dosages say 3%, 6%, 9% and 12% for spent catalyst and 2%, 2.5%,3% and 3.5% for super plasticizer with different trials and different tests (Slump flow, L-box, J- ring, V-funnel, U-box tests).
- To design singly reinforced RC beam.
- To determine the flexural strength of RC beam with control SCC mix under two-point loading set up.

- To determine the flexural strength of RC beams with optimum dosage of spent catalyst and super plasticizer SCC under two-point loading set up.
- Comparative study between control SCC and spent catalyst-based SCC in terms of flexural strength.

## 2. Experimental Investigations

The detailed experimental program is shown in Figure 1.

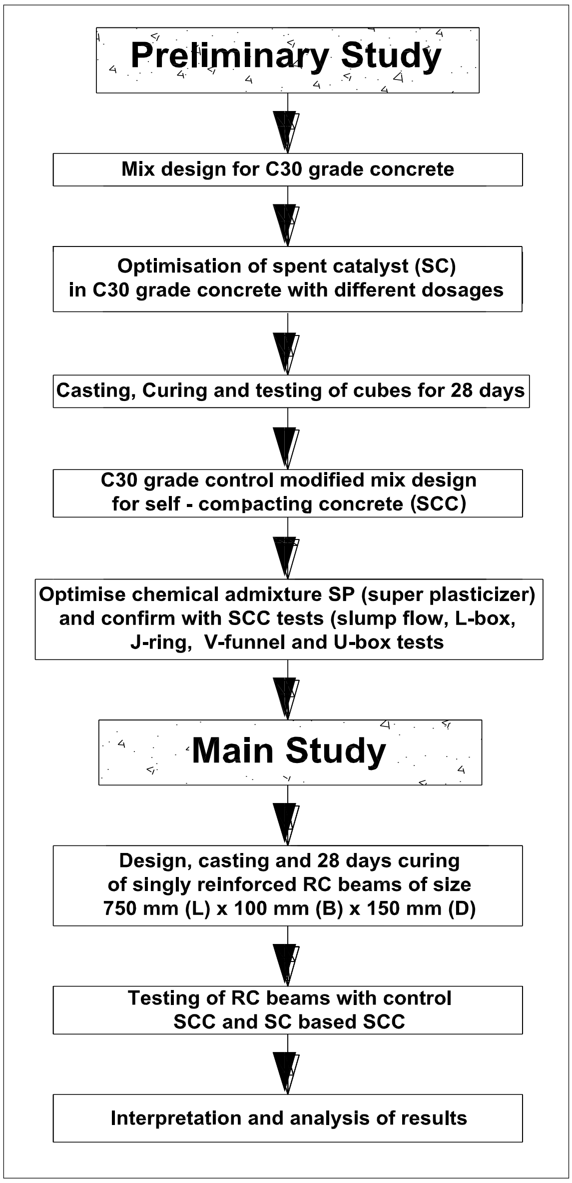


**Figure 1. Experimental program**

### 2.1. Cement

Worldwide, Ordinary Portland Cement (OPC) is the most widely used cement. In Oman, OPC is manufactured by the Oman Cement Company (OCC) in Al-Misfah by mixing limestone with clay, lime, and gypsum.

### 2.2. Fine Aggregate and Coarse Aggregate

Materials used in concrete aggregates include gravel, sand, and crushed stone. Additionally, the size of the particles determines whether they are finer than 0.125 or coarse aggregates. Aggregates are used to reduce manufacturing costs and improve the strength of concrete mixtures. However, the size of the coarse aggregate used in the SCC design cannot exceed 20 mm. In the case of crowded reinforcement, the aggregate size will be in the range of 10–12 mm. On the other hand, the fine aggregate used in SCC is either natural aggregate or manufactured aggregate, such as M sand, that is uniformly granulated. Typically, fine aggregates are used with a particle size of 2.75 mm.

## 2.3. Spent Catalyst

Used spent catalysts are a by-product of petroleum decomposition in petroleum refineries and are used to reduce sulfur levels and improve the combustion properties of petroleum (Figure 2 and Table 1). These materials are classified as waste and disposed of in specially designated landfills without meaningful reuse. There are two types of used catalysts such as equilibrium catalysts manufactured and zeolite catalysts manufactured. As the studies showed, they have a pozzolanic activity in which materials can be used as cement-based materials with Portland cement to improve the workability of concrete.

**Figure 2. Spent catalysts**

**Table 1. Spent catalysts (SC) Components**

| Composition (%) | Spent catalyst Mina Al-Fahal Refinary | Spent catalyst Sohar Refinary |
|---|---|---|
| $SiO_2$ | 1.71 | 39.21 |
| $Al_2O_3$ | 66.66 | 37.68 |
| $Fe_2O_3$ | 0.07 | 0.66 |
| CaO | 0.08 | 0.05 |
| MgO | 0.02 | 0.26 |
| $Na_2O$ | 8.29 | 0.43 |
| $K_2O$ | 0.26 | 0.06 |
| LOI | 26.13 | 2.43 |

## 2.4. Superplasticizers

Superplasticizers are applied to increase concrete strength, and plasticizers are chemical compounds that make concrete with a 15% lower water content (Figure 3). Therefore, SP is added to the concrete to improve fluidity. As well, it helps to reduce the water content in the concrete, which improves the strength and durability of the concrete and reduces the water content without compromising workability. Admix CF275 was added to cementitious materials in quantities of 500 to 2300 ml per 100 kg of cement, and an optimization process was made based on different tests with the BS standard.

**Figure 3. Superplasticizers (Admix CF275 Weber Saint-Gobain materials)**

## 2.5. Steel Reinforcements

Steel reinforcement represents one of the most important materials used while casting the beam due to its high tensile strength. It works together to resist deflection by increasing the low tensile strength of concrete and resisting the applied load. The steel used has a characteristic strength of 500 N/m$^2$. Steel reinforcements have diameters of 2H6 for the top steel and 2H8 for the bottom steel, while stirrups are H6 @ 100 mm c/c. The beam reinforcement used in casting the beam is shown in Figure 4. Both tension and compression faces are reinforced longitudinally. Stirrups and bent-up longitudinal bars are used as shear reinforcements.

**Figure 4. Steel reinforcements**

## 2.6. Mix Design of SCC

The design of the concrete mixture for casting RC beams was made according to the ACI method. In concrete type C30, the specified design strength indicates the characteristic strength after 28 days of curing to be 30 MPa. The following mathematical procedure was used to obtain the blend design ratio (Table 2).

Maximum size of the coarse aggregates = 12 mm; Fineness modulus of fine aggregates = 2.8; Specific Gravity of fine aggregate = 2.65; Specific Gravity of coarse aggregate = 2.7; Density of 12mm coarse aggregate = 1600 kg/m$^3$.

**Table 2. Mix design for concrete per m$^3$**

| Material | Cement | F.A | C.A | Water |
|---|---|---|---|---|
| Quantity per m$^3$ of concrete | 394 | 803 | 992 | 215 |
| Mix proportion | 1 | 2.04 | 2.52 | 0.47 |

Hence, the mix proportion = 1: 2.04: 2.52;

Water-cement ratio = 0.47;

Modified mix design for SCC based on Okamura [11] is shown in Figure 5 and Table 3.

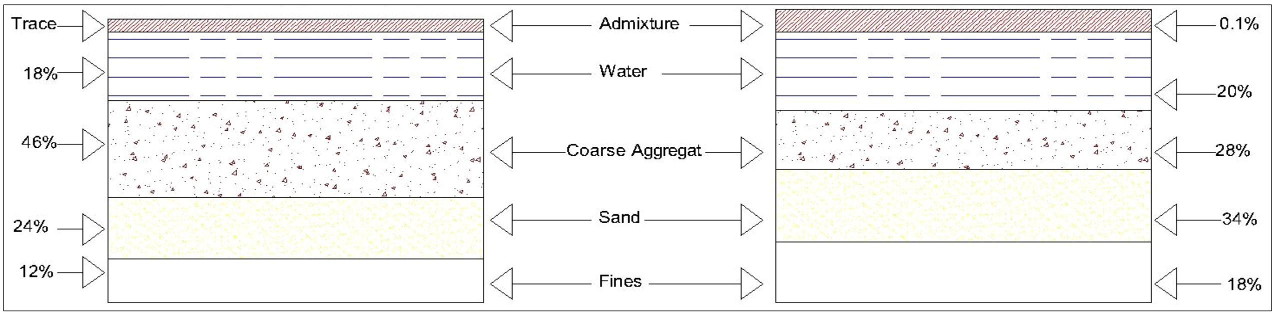


**Figure 5. Convert NC into SCC**

**Table 3. Modified mix proportion for concrete per m$^3$**

| Material | Cement | F. A | C.A | Water |
|---|---|---|---|---|
| Quantity per m$^3$ of concrete | 432 | 818 (2.75 mm aggregate) | 885(10 mm aggregate) | 215 |
| Mix proportion | 1 | 1.9 | 2.0 | 0.47 |

## 2.7. Tests for SCC

The following tests were conducted for SCC is shown in Figure 6.

Slump flow test J-Ring U-Box test L-Box V-funnel

**Figure 6. SCC tests**

### 2.8. Design of RC Beam as per EC2

Concrete mix of grade C30, $f_{ck}$ = 30 N/ mm$^2$, $f_{yk}$ = 500 N/ mm$^2$; Depth (D) = 150 mm; Depth cover Assume (d') = 25 mm; Effective depth (d) = D – d' = 150 – 25 = 125 mm; Steel Bar Diameter = 8 mm.

$$k = \frac{M}{bd^2 fck} \rightarrow As = \frac{M}{0.87 \times fyk \times Z} \rightarrow As = \frac{2 \times \pi \times D^2}{4}, Z_{max} = 0.95d \rightarrow \frac{2 \times \pi \times D^2}{4} = \frac{M}{0.87 \times fyk \times Z} \rightarrow \frac{2 \times \pi \times 8^2}{4} = \frac{M}{0.87 \times 500 \times 0.95 \times 125} \rightarrow M$$

$$= \frac{\pi \times 8^2}{4} \times 0.87 \times 500 \times 0.95 \times 125 \times 2 = 4775220.83\ N.mm \rightarrow k = \frac{4775220.83}{100 \times 125^2 \times 30} = 0.1 \rightarrow k' = 0.167 \Rightarrow 0.1 < 0.167 \rightarrow k < k'$$

Hence ductile failure, under reinforced section, tension steel yields, no compression steel is required. The beam is designed as an under reinforced beam (Singly reinforced beam).

### 2.9. Beam Testing Setup

This study is performed by testing a singly reinforced RC beam under two-point using Universal Testing Machine (UTM) 1000 kN capacity.

## 3. Specimens Preparations and Tests

### 3.1. Preliminary Study

The superplasticizer and spent catalyst are used to strengthen reinforced concrete beams and improve flexural performance. As a preliminary study, normal concrete is compared to self-compacting concrete in four different superplasticizer dosages of 2%, 2.5%, 3%, and 3.5% to determine the optimum dosage. Then, determine the best dosage of spent catalyst based on normal concrete, which is used as a partial replacement for cement; the dosages to be tested are 3%, 6%, 9%, and 12%. After that, using the optimum dosage of spent catalysts in self-compacting concrete with four different percentages of superplasticizer values (2%, 2.5%, 3%, and 3.5%) to find the optimum dosage, the RC beam is used, and the values are obtained based on the previous studies.

#### 3.1.1. Preparation of Concrete

- **Normal concrete (NC)**

Modified mix proportion for Normal concrete are presented in the Table 4.

**Table 4. Modified mix proportion for Normal concrete**

| Material | Cement (kg) | F. A (kg) | C.A (kg) | Water (Liters) |
|---|---|---|---|---|
| Quantity per m$^3$ of concrete | 432 | 818 (2.75 mm) | 885 (10 mm) | 215 |
| Mix proportion | 1 | 1.9 | 2.0 | 0.47 |

*Normal concrete mix:* For the C30 grade of the concert, the concrete mix was created using mixed design calculations with a ratio of 1:1.9:2.0 and a water-cement ratio of 0.47. Six concrete cubes measuring 150 × 150 × 150 mm were cast for 7 and 28 days, respectively. The materials used in ordinary concrete were fine aggregate, coarse aggregate, cement, and water, which were placed in a mixer and completely mixed until the concrete had a uniform color and consistency with no segregation. Further, the proportions of the individual substances used in the mixtures for normal concrete are represented in Table 5.

**Table 5. Modified mix proportion for Normal concrete**

| Mix / Materials | Cement | Superplasticizer | Water cement ratio |
|---|---|---|---|
| NC | 100% | 0 | 0.47 |
| SCC- Mix-A | 100% | 2% | 0.51 |
| SCC- Mix-B | 100% | 2.5% | 0.54 |
| **SCC-Mix-C** | **100%** | **3%** | **0.58** |
| SCC-Mix-D | 100% | 3.5% | 0.61 |

*Using the same normal concrete mix with Spent Catalyst to find the optimum dosages of spent catalyst:* Normal concrete was used to determine the ideal dosage of spent catalyst, which was replaced with cement in several dosages such as 3%, 6%, 9%, and 12% and named Mix-A, Mix-B, Mix-C, and Mix-D, which they prepared with a constant W/C of 0.47. Therefore, the weight of each percentage of cement and SC was calculated mathematically. The preparation and mixing of Mix-A, Mix-B, Mix-C, and Mix-D in a mixer machine after preparing each mixture separately and ensuring that the ingredients are properly mixed ensures a high level of concrete quality and uniformity. The proportions of the substance used in the mixtures for normal concrete mix with spent catalyst (SC) are shown in Table 6.

**Table 6. Modified mix proportion used in the mixtures for normal concrete mix with SC**

| Mix / Materials | W/C | Cement | Spent catalyst replacement percentage |
|---|---|---|---|
| NC | | 100% | 0% |
| Mix-A | | 97% | 3% |
| Mix-B | 0.47 | 94% | 6% |
| **Mix-C** | | **91%** | **9%** |
| Mix-D | | 88% | 12% |

- **Self-Compacting Concrete (SCC)**

*Self-compacting concrete with superplasticizer (SP):* Self-compacting concrete is made by adding superplasticizers to four different mixtures, which reduce the amount of water in the mixture, increasing strength and flowability. The four mixtures are Mix-A, Mix-B, Mix-C, and Mix-D, with superplasticizer dosages of 2%, 2.5%, 3%, and 3.5%, respectively. In Table 7, each mixture contains a different proportion of superplasticizer and a different water-cement ratio (W/C). Furthermore, each mixture is prepared separately and mixed in a mixer machine before being tested using the slump flow test, V-Funnel test, V-Funnel at T5min test, U-Box test, L-Box test, and J-Ring test. Afterward, the concrete was poured into molds, dried for 24 hours, and cured for 7 and 28 days, and its compressive strength was measured.

**Table 7. Proportions of the substance used in the mixtures for SCC**

| SCC Mixes / Materials | Cement | spent catalyst% (SC) | Superplasticizer% (SP) |
|---|---|---|---|
| Mix-A | | | 2.0% |
| Mix-B | 91% | 9% | 2.5% |
| Mix-C | | | 3.0% |
| Mix-D | | | 3.5% |

*Self-compacting concrete with several dosages of superplasticizer and optimum dosage of spent catalyst which is 9% represent in Table 7:* SCC, four mixtures, namely Mix-A, Mix-B, Mix-C, and Mix-D, were prepared. In addition, each mixture contains different amounts of superplasticizer (2, 2.5, 3, and 3.5%), spent catalyst dosages constant at 9%, cement content at 91%, and a constant w/c ratio of 0.58. In addition, Mix-A, Mix-B, Mix-C, and Mix-D were prepared and mixed using a mixer machine. Moreover, each mixture is prepared and mixed separately in a mixer machine until a uniform mixture is formed with a high level of concrete quality. After completing the mixer machine, the mixtures were tested in a variety of tests including slump flow, V-Funnel at T5min, L-Box, U-Box, and J-Ring tests. In order to determine the concrete's strength, it was poured into the molds, dried for 24 hours, cured for 7 and 28 days, and then tested for its compressive strength.

### 3.1.2. Test Methods for Fresh Concrete

To verify the performance of fresh SCC, several tests were developed, including the Slump-Flow test, the V Funnel test, the U Box and L Box tests, and the J-Ring test, as described and with results based on the study to find the optimum values of the superplasticizers and spent catalyst. For the normal concrete slump test was done.

- **Test for Normal Concrete**

*Slump test for normal concrete:* A slump test measures the consistency of a concrete batch to determine how easily it will flow. A concrete's overall slump can be measured in order to determine how much water is in the mix and whether it will be workable, as shown in Figure 7, and the result is represented in Table 8.

**Figure 7. Slump test for the normal concrete**

**Table 8. Slump test**

| Mix | Slump Height |
|---|---|
| **NC** | 50 mm |

*Slump test for normal concrete with spent catalyst:* A slump test was measured to determine the flowability of concrete with different dosages of spent catalysts. Table 9 shows the workability of normal concrete with spent catalysts by measuring slump flow.

**Table 9. Slump Flow test normal concrete with Spent catalysts results**

| Mix | Percentage of SC | Slump value |
|---|---|---|
| NC | 0% | 50 mm |
| Mix-A | 3% | 28 mm |
| Mix-B | 6% | 26 mm |
| Mix-C | 9% | 25 mm |
| Mix-D | 12% | 25 mm |

- **Test for Self-Compacting Concrete**

*Slump flow for SCC:* SCC flowability is determined by measuring the slump flow with coarse aggregates with a maximum size of 10 mm in SCC. However, the concrete placed in the mold is not tamped. As shown in Figures 8 and 9, the diameter of the spread is measured after the slump cone has been lifted and the sample has collapsed. Moreover, the slump flow of the SCC mix can range from 650 to 800 mm, and in this study, it is represented in Table 10 with SP and Table 11 with SP and SC for the several mixes. As observed during the flow, there was no fringe of water at the edge or on the surface and an even distribution of aggregates. The slump flow of concrete directly affects its filling ability.

**Figure 8. Slump flow**

**Figure 9. Measure diameter of slump flow**

**Table 10. Results of the self-compacting concrete with SP (As per BS EN 206-9, 2010)**

| Sl. No | Mixes | Slump Flow | | V- Funnel (s) | | L-Box (cm) | | | | U-Box | | | | J-Ring | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | D (mm) R (650-850) | $T_{500\ mm}$(s) R (2-6) | Time (s) R (6-12) | $T_{5min}$ R (more 0.3 for normal) | Time (s) R: (15-30) | H1 (mm) | H2 (mm) | H2/H1 (ratio) R (0.8-1) | Time (s) R (20-30) | H1 (mm) | H2 (mm) | H2-H1 R (0-30 mm) | D R (550-800 mm) | Difference in Height (mm) R (0-10) |
| 1 | Mix-A | 560 | 6.5 | 14 | 14.3 | 30 | 50 | 58 | 1.16 | 33 | 400 | 440 | 40 | 430 | 12.6 |
| 2 | Mix-B | 593 | 5.4 | 12.7 | 13 | 27 | 57 | 65 | 1.14 | 30 | 300 | 345 | 45 | 510 | 11.3 |
| 3 | Mix-C | 657 | 4.8 | 12 | 12.3 | 24 | 95 | 100 | 1 | 27 | 316 | 330 | 14 | 580 | 8.8 |
| 4 | Mix-D | 675 | 3.3 | 10.4 | 10.7 | 20 | 150 | 110 | 0.7 | 24 | 301 | 310 | 9 | 600 | 8.4 |

**Table 11. Results of the self-compacting concrete with SP &SC (As per BS EN 206-9, 2010)**

| Sl. No | Mixes | Slump Flow | | V- Funnel (s) | | L-Box (cm) | | | | U-Box | | | | J-Ring | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Diameter (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) | Diameter (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 | 330 | 340 | 10 | 600 | 9.3 |
| 4 | Mix-D | 690 | 3.6 | 7 | 14.7 | 18 | 41 | 39 | 0.95 | 20 | 332 | 350 | 18 | 660 | 8.2 |

***J-ring:*** SCC is tested both for filling ability and passing ability using the J-ring test, which is shown in Figures 10 to 12. Additionally, two different portions of the sample can be compared to determine the resistance of SCC to segregation. J-ring tests measure three parameters: flow spread, flow time T50J, and blocking step. Furthermore, the J-ring flow spread indicates the restricted deformability of SCC due to the blocking effect of reinforcement bars, while the flow time T50J indicates the rate of deformation within a defined flow distance. The results are represented in Table 10 with SP and Table 11 with SP and SC for the several mixes.

**Figure 10. J-Ring setup**

**Figure 11. J-Ring test**

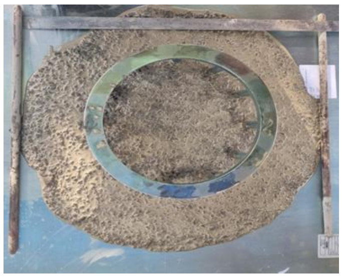

**Figure 12. Measure diameter of J-ring setup**

***V-funnel:*** In order to evaluate the segregation resistance of SCC, a V-shaped box with a narrow opening at the bottom is constructed. Further, a gate is attached to the bottom of the box and filled with concrete. The gate is opened, and as measured, the time it took for the concrete to flow out of the box was 10, as shown in Figures 13 and 14. However, the time required to empty the V-funnel of the SCC is 8–12 seconds, and the short flow time indicates a low plastic viscosity of the mixture. This test provides a qualitative indication of the viscosity of the SCC mixture. The results are represented in Table 10 with SP and Table 11 with SP and SC for the several mixes.

**Figure 13. V-Funnel test**

**Figure 14. After opening the gate of the V-Funnel test**

***L-box:*** This method aims to investigate the passability of SCC and measures the height reached by fresh SCC after passing through a specified gap in a steel bar and flowing within a defined flow distance, as shown in Figures 15 to 17. Also, regular 12mm-diameter rebars are placed in the gate at 50mm intervals, creating a 35mm gap between the rebars. Once this height is reached, the passing or breaking motion of the SCC can be estimated. However, to improve concrete flow, the barrier ratio (H2/H1) should be closer to one. The results are represented in Table 10 with SP and Table 11 with SP and SC for the several mixes.

**Figure 15. L-box fill with self-compacting concrete**

**Figure 16. After opening the gate of the L-box**

**Figure 17. Measuring the height**

***U-box:*** The U-Box test is a U-shaped box divided into two compartments that are separated by a door, and one side of the U-Box is filled with concrete with the door in place. However, the other side of the U-Box has rebar placed in it of a given size and spacing. Further, the door is removed, and the concrete flows through the rebar, reaching an equilibrium height on the other side of the U-box. The height of the concrete was measured at 0.2 mm. This test measures the filling ability of the concrete by flow through the rebar.

Furthermore, the higher the concrete flows on the other side of the U-box, the greater the ability of the concrete to flow through dense rebar and corners of the form, as shown in Figures 18 and 19. For better flow, the difference between the heights of concrete in the 1$^{st}$ and 2$^{nd}$ compartments should be nearly zero. The results are represented in Table 10 with SP and Table 11 with SP and SC for the several mixes.

**Figure 18. U-box fill with concrete**

**Figure 19. Measuring Height of SCC**

The range values as per BS Standard are presented in Table 12.

**Table 12. Range of values for all the tests followed in the study as per BS EN 206-9, 2010**

| Sl. No. | SCC tests | | Standard range as per BS EN 206-9, 2010 | |
|---|---|---|---|---|
| | | | Min | Max |
| 1 | Slump Flow (mm) | Flow Diameter (mm) | 650 | 850 |
| | | T500 mm | 2 | 5 |
| 2 | V- Funnel (s) | Flow time (s) | 6 | 12 |
| | | V- Funnel at T5 min | >0-0.3s of V-Funnel Flow time | |
| 3 | L-Box | Time (s) | 15 | 30 |
| | | H2/H1 | 0.8 | 1.0 |
| 4 | U-Box | Time (s) | 20 | 30 |
| | | H2-H1 | 0 | 30 mm |
| 5 | J-Ring | Flow Diameter (mm) | 550 | 800 |
| | | Difference in Height (mm) | 0 | 10mm |

### 3.1.3. Compressive Strength

Compressive strength is the capacity of concrete to withstand loads before failure, and it is the most important because it provides information about the concrete's properties. Furthermore, compressive strength results for the normal concrete mix, normal concrete with different dosages of SC, self-compacting concrete with several dosages of superplasticizers, as well as self-compacting concrete with several dosages of SP and the optimum dosage of SC, are shown in Figures 20 to 26, which are represented in Tables 13 to 15.

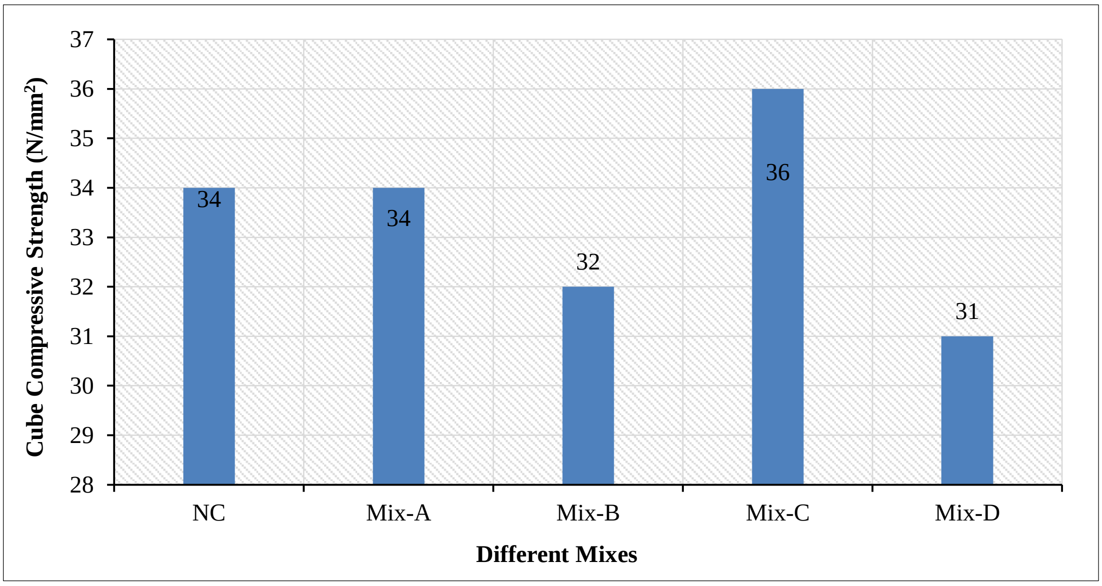


**Figure 20. Compressive strength results for NC with different dosages of SC**


**Figure 21. Failure condition of cube after 28 days (NC)**


**Figure 22. Failure condition of cube after 28 days (NC with SC)**

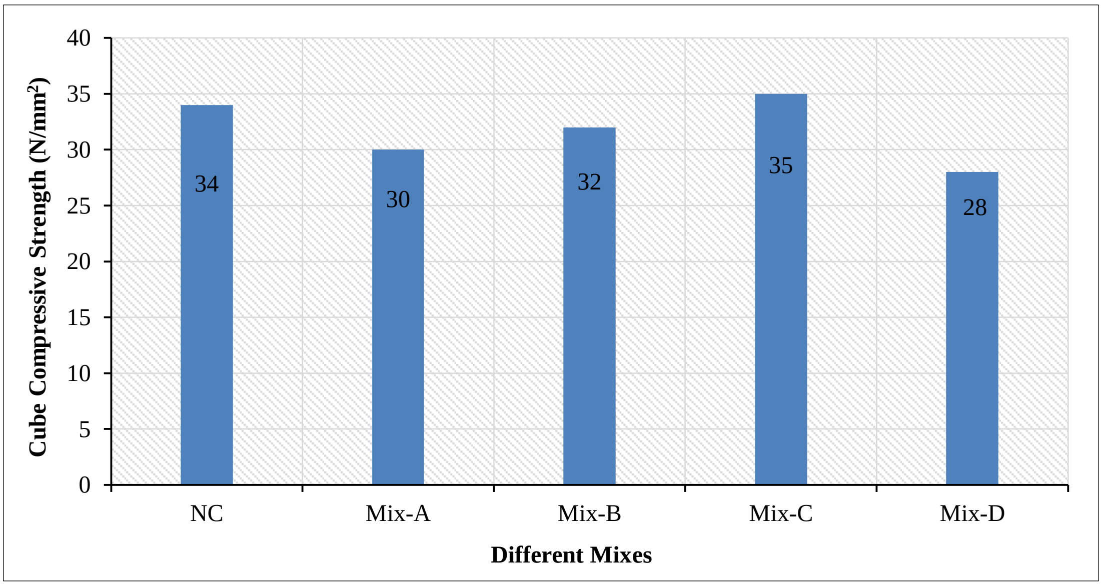


**Figure 23. Compressive strength results for NC and SCC with different dosages of SP**


**Figure 24. Failure condition of cube after 28 days (SCC-SP)**

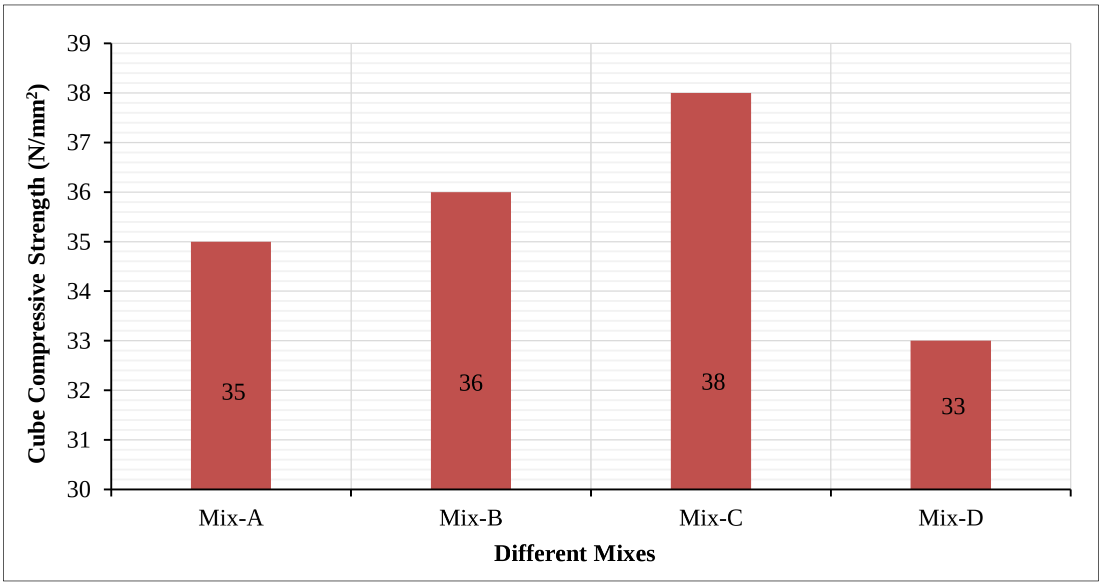


**Figure 25. Compressive strength results for SCC with different dosages of SP&SC**


**Figure 26. Failure condition of cube after 28 days (SCC with SC& SP)**

**Table 13. Compressive strength results for Normal concrete with different dosages of spent catalysts**

| Mix | Percentage of SC | Max force (kN) | Area ($mm^2$) | Compressive strength ($N/mm^2$) |
|---|---|---|---|---|
| NC | 0% | 765 | | 34 |
| Mix-A | 3% | 765 | | 34 |
| Mix-B | 6% | 720 | 150×150 | 32 |
| Mix-C | 9% | 810 | | 36 |
| *Mix-D* | 12% | 697.5 | | 31 |

**Table 14. Compressive strength results for NC & SCC-SP mixes**

| Mixes | Water cement ratio | SP % | Area (mm) | Max Force (kN) | Average Compressive strength ($N/mm^2$) for three cubes at 28 days curing |
|---|---|---|---|---|---|
| *NC* | 0.48 | 0 | 150 × 150 | 742.5 | 34 |
| *SCC- Mix-A* | 0.51 | 2% | 150 × 150 | 675 | 30 |
| *SCC- Mix-B* | 0.54 | 2.5% | 150 × 150 | 720 | 32 |
| ***SCC-Mix-C*** | **0.58** | **3%** | **150 × 150** | **765** | **35** |
| *SCC-Mix-D* | 0.61 | 3.5% | 150 × 150 | 630 | 28 |

**Table 15. Compressive strength results for SCC based on SC with SP**

| SCC Mixes | SC% | SP % | Max Force (kN) | Compressive strength ($N/mm^2$) (28 days) |
|---|---|---|---|---|
| Mix-A | 9% | 2% | 787.5 | 35 |
| Mix-B | | 2.5% | 810 | 36 |
| Mix-C | | 3% | 855 | 38 |
| Mix-D | | 3.5% | 742.5 | 33 |

## 3.2. Experimental Investigation on RC Beams Using Spent Catalyst Based SCC

The main aim of this work is to compare strengthened beams with the optimum superplasticizer dosage, as well as spent catalysts with ideal superplasticizer dosages, to a control beam. This experiment involved casting six RC beams with dimensions of 750 (L) × 100 (B) × 150 mm (D), two of which were used as control beams, two of which were used as the optimum dosage of superplasticizer 3% beams, and two of which were used as the optimum dosages of spent catalyst 9% with superplasticizer 3% beams, which were tested with tension zones for flexure failure.

### 3.2.1. Preparation of RC Beam

The mixture of concrete was prepared according to the calculations of the mixed design, in which the ratio of 1: 1.9: 2.0:0.47 was used for the control RC beam, which made two samples. Further, in the SCC mix design for two mixtures, the first mix was designed with an optimum dosage of superplasticizer as found in the previous study, which was 3%, and the second mix was designed with an optimum dosage of superplasticizer of 3%, as well as an optimum dosage of spent catalyst of 9%, as shown in the previous study used in RC beam casting each mix into two samples. Therefore, six numbers of reinforced steel were designed under the reinforced beam of size 725 (L) × 75 (B) × 125 mm (D), with the bottom steel being (2H8), stirrups being H6 @ 100 mm c/c, and the nominal top steel being (2H6), as shown in Figures 27 and 28. A 750 (L) × 100 (B) × 150 mm (D) mold was used to cast the RC beams, and each mixture was poured into two RC beams, so the total number of RC beams was six. Moreover, each mixture is separately placed in the mixer machine and then cast into the beam molds. The beam designation is presented in Table 16.

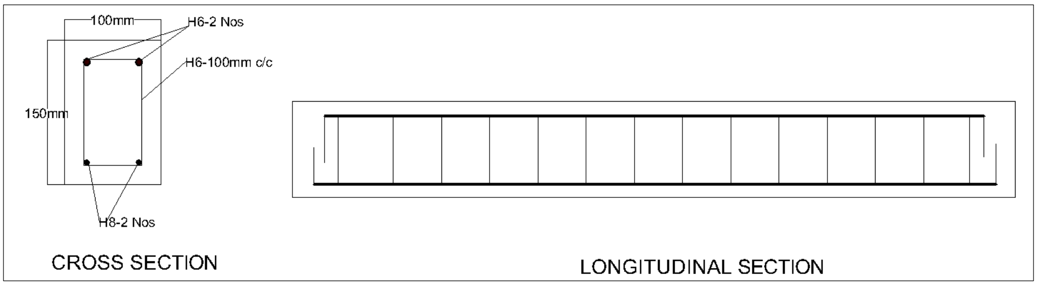


**Figure 27. Longitudinal and Cross Section of Strengthened**

**Figure 28. Reinforcement Steel**

**Table 16. Beam Designation**

| SI. No | Beam Number | Beam Type | Days | Superplasticizer SP | Spent Catalyst SC |
|---|---|---|---|---|---|
| | | | | Amount | |
| 1 | CB1 | Control Beam | 28 days | - | - |
| 2 | CB2 | Control Beam | 28 days | - | - |
| 3 | SCC-B1 | Self-compacting concrete RC beam with superplasticizer 3% | 28 days | 3% | - |
| 4 | SCC-B1 | Self-compacting concrete RC beam with superplasticizer 3% | 28 days | 3% | - |
| 5 | SCC-B2 | Self-compacting concrete RC beam with superplasticizer 3% and with spent catalyst 9% | 28 days | 3% | 9% |
| 6 | SCC-B2 | Self-compacting concrete RC beam with superplasticizer 3% and with spent catalyst 9% | 28 days | 3% | 9% |

### 3.2.2. Preparation of RC Beam

#### *Control Beam casting (Mix- CB)*

The concrete mix for the C30 grade of the concert was created using mixed design calculations with a ratio of 1:1.9:2.0 and a water-cement ratio of 0.47. Two control RC beams (750mm L × 100mm B × 150mm D) were used, and the materials for casting were fine aggregate, coarse aggregate, cement, and water, all of which were weighed using an electrical balance. The concrete was then placed in a mixer and rotated and mixed until it had a uniform color and consistency with no segregation. Further, we cleaned and oiled the RC beam mold size (750 mm L × 100 mm B × 150 mm D) to help prevent concrete from sticking to it, and we placed wood to fix the required size of the mold as shown in Figures 29 to 31. After leveling the top surface with the trowel, wait 24 hours, then carefully remove the sample from the mold and place it into a water tub for 28 days of curing.

**Figure 29. Mold is coated with oil**

**Figure 30. Self-Compacting Concrete mix**

**Figure 31. RC Finished Beams**

#### *SCC RC Beam Casting with SP (Mix- B1)*

In the second mix, the control RC beam procedures were repeated for all self-compacting concrete mixtures only without using mechanical vibration because it compacts itself and adds SP with the optimum dosage of 3% as shown in the previous study to increase its flowability as well as reduce its water content. To begin, 2 nos. of self-compacting concrete RC beams were cast with a superplasticizer, and the casting process is shown in Figure 32 with mold beam dimensions of 750 × 100 × 150 mm. After leveling the top surface with the trowel, wait 24 hours, then carefully remove the sample from the mold and place it into a water tub for 28 days of curing.

**Figure 32. SCC-RC beam with SP 3% after 24 hrs.**

***SCC RC Beam Casting with SP & SC (Mix-B2)***

For the last mixture, the self-compacting concrete RC beam procedures were repeated for casting two molds of RC beams only by adding the optimum value of superplasticizer 3% along with the cement replaced with the optimum value of spent catalyst 9% as per the previous study, which is used in casting RC beams of size 750 × 100 × 150 mm, and the casting process is shown in Figures 33 and 34. After leveling the top surface with the trowel, wait 24 hours, then carefully remove the sample from the mold and place it into a water tub for 28 days of curing.

**Figure 33. SCC-RC beam with SP 3%, SC 9%**

**Figure 34. SCC-RC beam with SP 3%, SC 9% After 24 hrs.**

## 3.2.5. Testing and Measurements

***Two-Point Loading Setup (Universal Testing Machines (UTM) Setup)***

The compressive strength of concrete refers to its ability to withstand loads without cracking or deflection. Furthermore, concrete's compressive strength can be determined by dividing the load on a beam (750mm L × 150mm D × 100mm B) by its cross-sectional area. Moreover, all beams were tested under two-point loading over a 650mm effective span as simply supported. As shown in Figure 54, the loads were applied 216.7mm apart on either side of the beam of 650mm in length. A study was conducted to determine how the control RC beams, the RC beam of self-compacting concrete with the superplasticizer (B1), and the self-compacting concrete with the spent catalyst as well as the superplasticizer (B2) performed in terms of flexure strength, as shown in Figures 35 and 36.

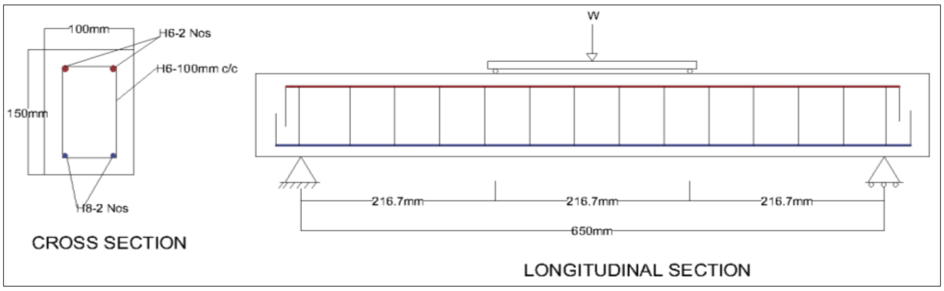


**Figure 35. Beam reinforcement details**

**Figure 36. Testing RC Beam into two-point load**

## 4. Results and Discussion

In this chapter, the design of the RC beams with three mixtures, and each mixture is made of two samples of the RC beam, such as the control beam, SCC with an optimum dosage of 3% of SP, which is mix-c, as well as the mixture of SCC-based spent catalysts with an optimum value of 9%, as well as adding SP 3% (mix-c), were tested under two-point loading and instrumented for measurement of mid-span deflections after 28 days by using UTM to measure flexural strength as deflection. Additionally, during the test, crack patterns in the beams were recorded and analyzed in detail.

### 4.1. Analysis of Results and Discussion

According to the load-deflection behavior shown in Figures 37 to 40, each CB, SCC-B1, and SCC-B2 go through four stages before failure: the first crack stage, the service stage, the yield stage, and the ultimate stage. There were several parameters evaluated, including first cracks, load-carrying capacity, deflection, stiffness, and ductility ratio.

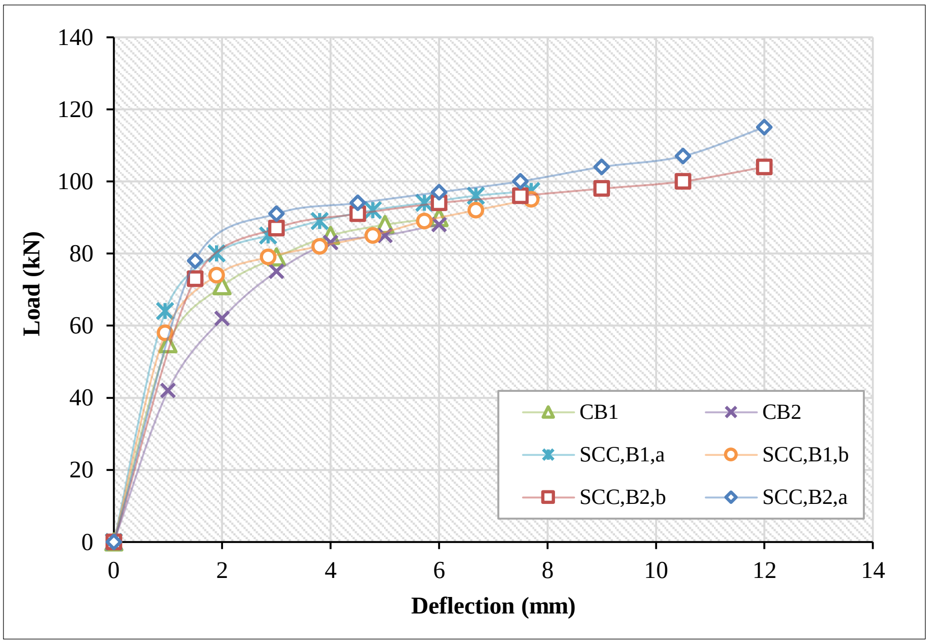


**Figure 37. Load-deflection for all specimen**

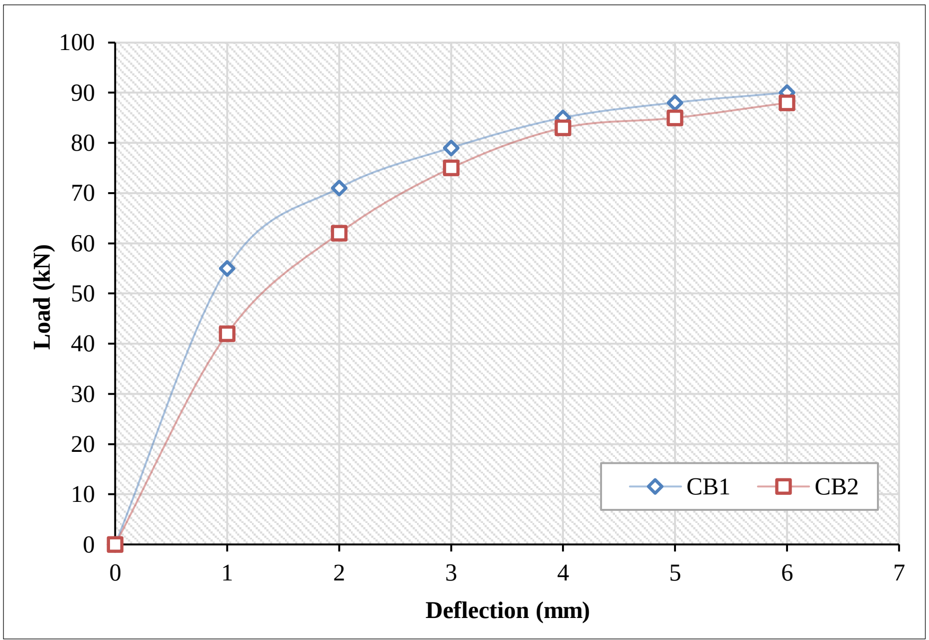


**Figure 38. Load-deflection curve for Control Beam**

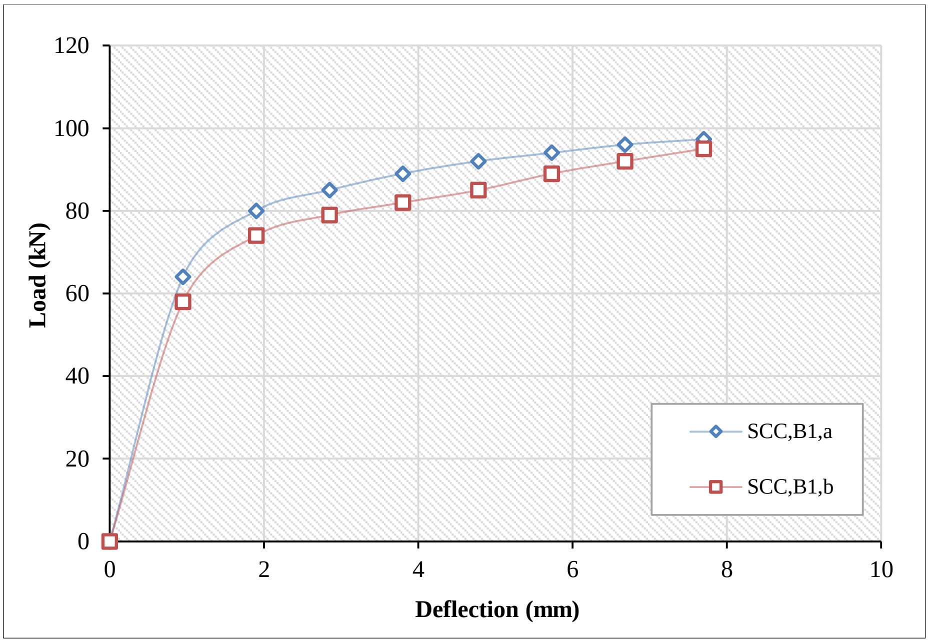


**Figure 39. Load-Deflection curve for SCC-B1**

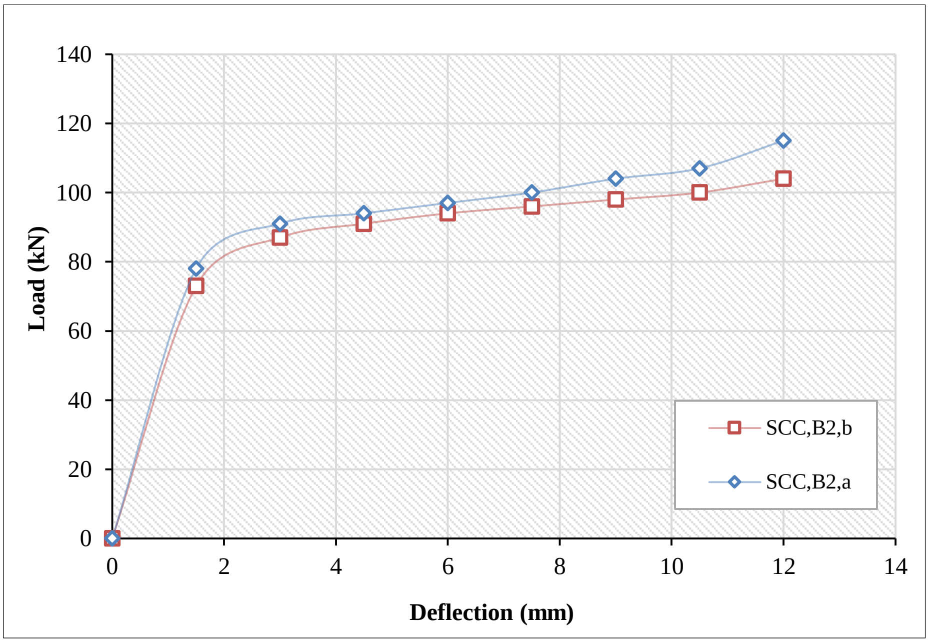


**Figure 40. Load-Deflection curve for SCC-B2**

### *Cracks*

Table 17 shows that the first cracks that appeared earlier in the Control Beam (CB) equal 52 kN, the SCC-B1 equals 60.5 kN, and the SCC-B2 equals 68 kN. Further, it seems that the first cracks appeared earlier in the control beam compared to the self-compacting beams (SCC), with nearly a 23.5% increase. Further Control beam. However, the crack in SCC beams with an optimum dosage of superplasticizer (SCC-B1) started early as compared with SCC beams with optimum dosages of superplasticizer as well as spent catalyst (SCC-B2) due to the strength of the spent catalyst on the RC beam.

### *Ultimate Load*

The load-carrying capacity of all RC beams at the ultimate stage, which indicates the maximum load the beam can bear before failing, determines their effectiveness. As a result, the B1 has a 7.5% greater load-carrying capacity than the CB, and the B2 has a 21.7% greater load-carrying capacity than the CB, proving that spent catalysts can strengthen reinforced concrete. Therefore, according to Table 17, the SCC beams exhibit an increase in the load-carrying capacity of nearly 21.7% as compared with the control beams.

### *Deflection*

The load is directly proportional to deflection, as shown in Figures 57, 58, 59, and 60 and represented in Table 17. Furthermore, the B1 has nearly 15% less deflection than the CB, and the B2 has 26% less deflection than the CB at the exact load level. Because the spent catalyst improves the reinforced beam's combined flexural behavior, the control beam deflects more than the strengthened beam under the same load.

### *Ductility*

To evaluate ductility, it must consider the load-deflection response. The ratio of ultimate deflection to yield deflection can be used to determine ductility. Table 17 shows that B1 has more ductility than CB, with ductility increasing by up to 19.2% with respect to CB. Furthermore, as shown in Table 17, the B2 has greater ductility than the CB, with the ductility increasing by up to 33% with respect to the CB.

### *Stiffness*

The stiffness of a beam is its flexural rigidity when loaded with distributed loads, with stiffer beams being more flexible. In order to determine the stiffness of a simply supported RC beam up to the yielding point, use the following equation, which is shown below. However, after applying the formula, it is possible to conclude that the control beam has a lower stiffness than B1 and B2. Furthermore, it demonstrates that the B1 has an increased stiffness of 12% compared to the control beam. As shown in Table 17, it can be concluded that the control beam has a lower stiffness than the B1. Therefore, the strengthened beam (B2) has an increased stiffness of 21.6% over the control beam, indicating that the optimum dosage of spent catalyst strengthened and made the beam more rigid, causing this to occur.

$$\text{Stiffness} = \frac{PL^3}{56.25 \times \delta} \tag{12}$$

where P is load at yielding point, L is effective span = 650 mm, and $\delta$ is deflection at yielding point.

Tables 17 show the results of the tests performed on the CB, B1, and B2. However, experimental results show that externally self-compacting concrete RC beams based on spent catalyst (B2) significantly increase strength at all load levels.

**Table 17. Summary of Test Results**

| Beam code | First crack stage | | Service stage | | Yield stage | | Ultimate stage | | Ductility factor | Post cracking - pre yielding stiffness (kNm$^2$) | Mode of failure |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Load (kN) | Central Deflection (mm) | Load (kN) | Central Deflection (mm) | Load (kN) | Central Deflection (mm) | Load (kN) | Central Deflection (mm) | | | |
| CB 1 | 52 | 0.63 | 60 | 1.2 | 58 | 0.9 | 90 | 6 | 6.7 | 314 | Flexure |
| CB 2 | 50 | 0.7 | 58.7 | 1.8 | 45 | 0.93 | 88 | 6 | 6.3 | 261.5 | Flexure |
| SCC-B1 | 60.5 | 0.74 | 64.9 | 0.7 | 68 | 0.93 | 97.3 | 7.7 | 8.3 | 357 | Flexure |
| SCC-B1 | 57 | 0.79 | 63.3 | 1.1 | 65 | 0.95 | 95 | 7.5 | 8.1 | 334 | Flexure |
| **SCC-B2** | **68** | **0.85** | **73.3** | **1.2** | **82** | **1** | **115** | **12** | **10** | **400.3** | **Flexure** |
| SCC-B2 | 63 | 0.88 | 69.3 | 1.4 | 78 | 1.02 | 104 | 12 | 9.2 | 373.3 | Flexure |

Crack patterns in the beams were noted and closely examined during the test, as shown in Figure 41.


**Figure 41. Crack Pattern of Tested Control Beams (CB)**

Crack patterns in the beams were noted and closely examined during the test, as shown in Figure 42.

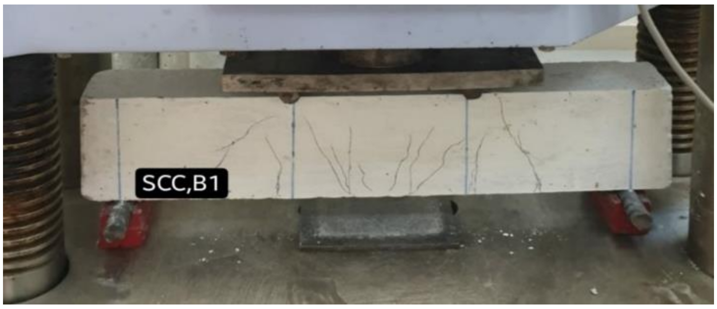


**Figure 42. Crack Pattern of Tested SCC with SP, RC-Beams (B1)**

Crack patterns in the beams were noted and closely examined during the test, as shown in Figure 43.


**Figure 43. Crack Pattern of Tested SCC with SC & SP, RC-Beams (B2)**

## 5. Numerical Analysis Using ANSYS

### 5.1. Finite Element Modelling and Description using ANSYS

*SOLID65* is used to simulate solids in three dimensions, either with or without reinforcing bars (rebar). The solid can fracture under strain and crumble under compression. For instance, in applications using concrete, the element's solid capacity may be used to simulate the behavior of the concrete, while the rebar capability could simulate the behavior of the reinforcement. Reinforced composites (like fiberglass) and geological materials (like rock) are two additional situations in which the element is also appropriate. Eight nodes that have translations in the nodal x, y, and z directions at each of their three degrees of freedom describe the element. Rebar requirements can be defined in up to three distinct ways (Figure 44).

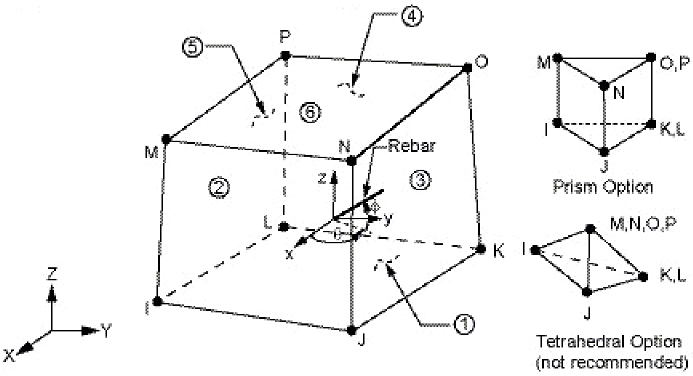


**Figure 44. Solid 65 Element**

The 3-D modeling of solid structures is done using *SOLID45*. Eight nodes that have translations in the x, y, and z dimensions as their three degrees of freedom each define the element. The element is capable of large deflection, large strain, creep, swelling, stress stiffening, and plasticity. Due to its unique cracking and crushing properties, this element is employed in laminates. The treatment of nonlinear material properties is this element's most crucial component. The concrete is capable of crushing, plastic deformation, creep, and three orthogonal orientations of cracking. Rebar can only be sheared in tension or compression. Additionally, they have creep and plastic deformation capabilities (Figure 45).

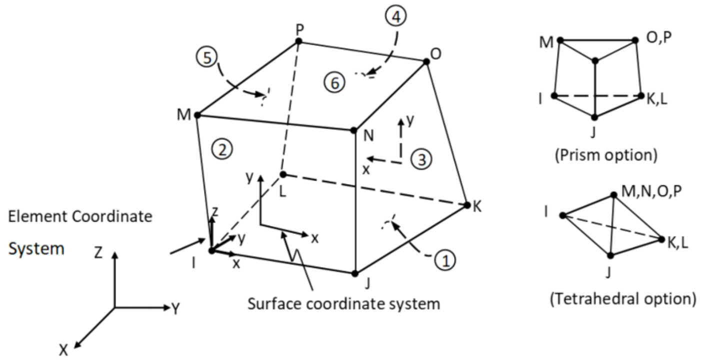


**Figure 45. Solid 45 element**

*LINK8* is a spar that may be used in a variety of engineering applications. This element can be used to model trusses, sagging cables, links, springs, etc. The 3-D spar element is a uniaxial tension-compression element with three degrees of freedom at each node: translations in the nodal x, y, and z directions. LINK8 for the steel element is shown in Figure 46.

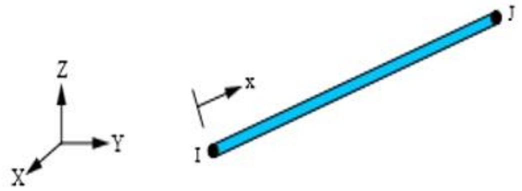

**Figure 46. LINK 8 element**

*PIPE16* is a uniaxial element with tension-compression, torsion, and bending capabilities. The element has six degrees of freedom at two nodes: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes. This element is based on the 3-D beam element (BEAM4) and includes simplifications due to its symmetry and standard pipe geometry. PIPE16 is used as a dummy element for rebar, as shown in Figure 47.

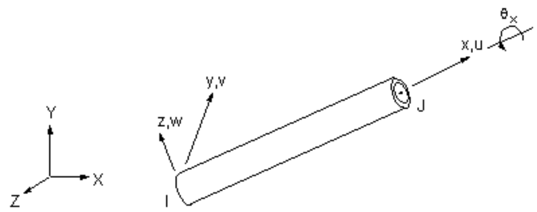

**Figure 47. PIPE16 element**

*SHELL99* may be used for layered applications of a structural shell model. It allows up to 250 layers. If more than 250 layers are required, a user - input constitutive matrix is available. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes (Figure 48).

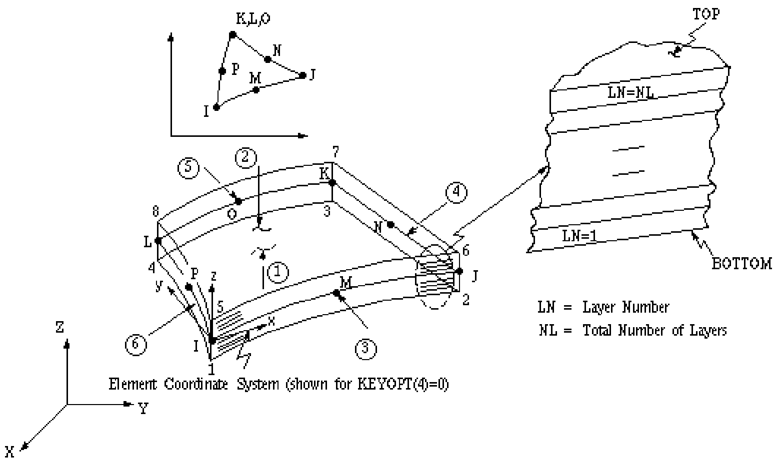


**Figure 48. SHELL99 element**

Input values for ANSYS are presented in Table 18. Element discretization, loading patterns, and boundary conditions are shown in Figures 49 and 50. Comparisons of ultimate loads and deflection for experimental and ANSYS (numerical) models are shown in Table 19.

**Table 18. Input values for ANSYS**

| SCC-B2 | | |
|---|---|---|
| Beam size | 100 width × 150 depth × 750 mm length | |
| Area of steel (Tension reinforcement) | $A_{st}$ = 100.53 mm$^2$ (2 Nos.-8 mm diameter) | |
| Characteristic strength of steel (Tension reinforcement) | $f_y$ = 500 N/mm$^2$ | |
| Hanger bars | 2 Nos - 6 mm diameter | $f_y$ = 500 N/mm$^2$ |
| Shear reinforcement | 6 mm diameter at 100 mm c/c | $f_y$ = 250 N/mm$^2$ |
| Modulus of elasticity of steel | $E_s$ = 1.95 × 10$^5$ N/mm$^2$ | |
| Poisson's ratio of steel | $\mu_s$ = 0.27 | |
| Mean strength of concrete | 33 MPa | |
| Modulus of elasticity of concrete | 28173 N/mm$^2$ | |
| Poisson's ratio of concrete | $\mu_c$ = 0.19 | |

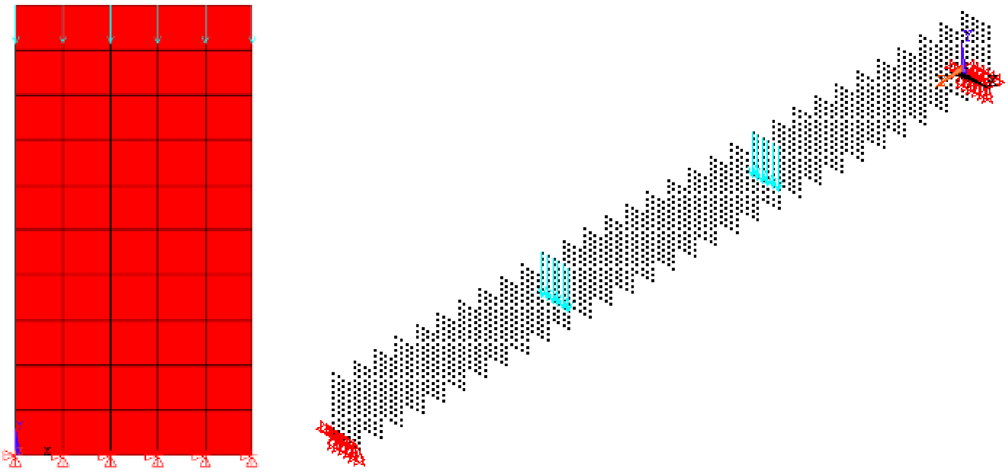

**Figure 49. Element discretization, loading pattern and boundary conditions in FEA - SCC-B2**

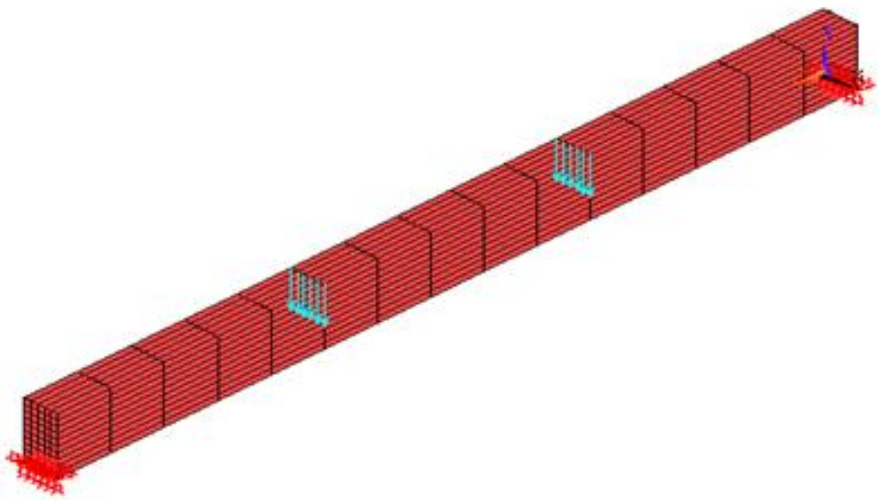

**Figure 50. Loading pattern and boundary conditions in FEA – SCC-B2**

**Table 19. Comparisons of ultimate load and deflection**

| Sl. No. | Detail of Beam | Ultimate Loads in kN | | Ultimate deflection | | Percentage difference in flexural capacity | Percentage difference in in ultimate deflection |
|---|---|---|---|---|---|---|---|
| | | Experimental | ANSYS | Experimental | ANSYS | | |
| 1. | SSS-B2 | 115 | 96.40 | 12 | 11 | 16.17 | 8.3 |

# 6. Conclusions

Based on the experimental investigation carried out on the partial replacement of cement using SC in SCC and flexural behavior, the following observations are made:

- From the preliminary study of partial replacement of cement in control concrete C30 grade using a spent catalyst (SC), it was found that the 9% optimum dosage gives better compressive strength compared to other dosages, with nearly 10 percent increases at the 28-day curing period.
- Conversion of control concrete to SCC without SC with superplasticizer (SP), and it is found that the optimum dosage of 3% gives closer agreement and fulfills the requirement of SCC as per BS standard based on a different test conducted (slump flow, J ring, U box, L box, and V funnel test).
- In SCC with SC and SP, it is found that the optimum dosage of 9% for SC and 3% for SP, respectively, gives better compressive strength compared to other dosages, resulting in a nearly 15% increase with respect to control concrete at the 28-day curing period and also fulfilling the requirement of SCC as per the BS standard based on a different test conducted (slump flow, J ring, U box, L box, and V funnel test).
- In a flexural study of a beam size of 750 (L) × 100 (B) × 150 mm (D), a control concrete mix and the optimum dosage of SCC mix were used. Each mix of two beams was cast and tested in the laboratory under a two-point loading setup.
- The first crack load started early in the control beams as compared with the SCC beams nearly 23.5% increase. The SCC beams exhibit an increase in load-carrying capacity of nearly 21.7% as compared with the control beams.
- The deflection of the SCC beams was reduced by nearly 26% at the same load level with respect to the control beam, and the ductility increased by nearly 33% with respect to the control beams.
- Similarly, the stiffness of 21.6% of the SCC increases with respect to the control beam.
- In the comparison of the experimental value with the numerical solution using ANSYS in terms of ultimate load and deflection, the percentage variation is 16% and 8%, respectively. It gives a closer agreement between the experimental and numerical parts.
- Based on the test results, the optimal dosage of the superplasticizer and spent catalyst in the SCC beam gives better performance in all aspects.
- All beams exhibited no premature or brittle failure.
- It could be concluded that the optimum dosage of the superplasticizer, 3% and 9% of the spent catalyst, gives better performance in SCC.

## 6.1. Limitations

This study is confined only to flexural strengthening of beams with spent catalyst-based SCC and congestion of reinforcement, which occur in the field. Further, this study is valid for isolated rectangular beams and not for beams that form part of structural systems.

# 7. Declarations

## 7.1. Author Contributions

Conceptualization, B.R.; methodology, B.R. and R.A.; software, A.K.; validation, A.K.; formal analysis, B.R.; investigation, B.R. and R.A.; resources, B.R.; data curation, R.A.; writing—original draft preparation, B.R.; writing—review and editing, A.K.; visualization, B.R.; supervision, B.R.; project administration, B.R.; funding acquisition, B.R. All authors have read and agreed to the published version of the manuscript.

## 7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

## 7.3. Funding and Acknowledgements

I am grateful to the Moheri, Sultanate of Oman for having funded 20,000 OMR under the Research Grant (RG) in Call 2021, during the year 2021-2022 and also thank Ms. Eman Mushier Adeen Al Hatali, Lab Instructor for the successful completion of the project.

## 7.4. Conflicts of Interest

The authors declare no conflict of interest.

## 8. References


[1] González-Aviña, J. V., Juárez-Alvarado, C. A., Terán-Torres, B. T., Mendoza-Rangel, J. M., Durán-Herrera, A., & Rodríguez-Rodríguez, J. A. (2022). Influence of fibers distribution on direct shear and flexural behavior of synthetic fiber-reinforced self-compacting concrete. Construction and Building Materials, 330, 1055–1070. doi:10.1016/j.conbuildmat.2022.127255.

[2] Adharsh, M., Mahadevaswamy, N., Nithin, S., Oriette Sharon Pinto, Arjun, V., & Kanmani, S. S. (2019). Assessment of Self Compacting Concrete Using Foundry Sand as Partial Replacement for Fine Aggregates. Journal of Ceramics and Concrete Sciences, 4(1), 35-41. doi:10.5281/zenodo.2634714.

[3] Afolayan, J. O., Wilson, U. N., & Zaphaniah, B. (2019). Effect of sisal fibre on partially replaced cement with Periwinkles Shell Ash (PSA) concrete. Journal of Applied Sciences and Environmental Management, 23(4), 715. doi:10.4314/jasem.v23i4.22.

[4] Rattanasak, U., Jaturapitakkul, C., & Sudaprasert, T. (2001). Compressive strength and heavy metal leaching behaviour of mortars containing spent catalyst. Waste Management and Research, 19(5), 456–464. doi:10.1177/0734242X0101900511.

[5] Tseng, Y. S., Huang, C. L., & Hsu, K. C. (2005). The pozzolanic activity of a calcined waste FCC catalyst and its effect on the compressive strength of cementitious materials. Cement and Concrete Research, 35(4), 782–787. doi:10.1016/j.cemconres.2004.04.026.

[6] Sun, D. D. (2003). Stabilization treatment for reutilization of spent refinery catalyst into value-added product. Energy Sources, 25(6), 607–615. doi:10.1080/00908310390195679.

[7] António, J., Silva, P., & Costa, C. (2013, September). Fresh properties and compressive strength of self-compacting concrete containing waste fluid catalytic cracking catalyst. 7th RILEM Conference on Self-Compacting Concrete (67th RILEM Week), 1-4 September, 2013, Paris, France.

[8] Abunassar, N., Alas, M., & Ali, S. I. A. (2023). Prediction of compressive strength in self-compacting concrete containing fly ash and silica fume using ANN and SVM. Arabian Journal for Science and Engineering, 48(4), 5171-5184. doi:10.1007/s13369-022-07359-3.

[9] Ofuyatan, O. M., Agbawhe, O. B., Omole, D. O., Igwegbe, C. A., & Ighalo, J. O. (2022). RSM and ANN modelling of the mechanical properties of self-compacting concrete with silica fume and plastic waste as partial constituent replacement. Cleaner Materials, 4, 100065. doi:10.1016/j.clema.2022.100065.

[10] Xie, Y., Liu, B., Yin, J., & Zhou, S. (2002). Optimum mix parameters of high-strength self-compacting concrete with ultrapulverized fly ash. Cement and Concrete Research, 32(3), 477–480. doi:10.1016/S0008-8846(01)00708-6.

[11] Okamura, H., & Ozawa, K. (1995). Mix design for self-compacting concrete. Concrete library of JSCE, 25(6), 107-120.

[12] Ozawa, K., Maekawa, K., & Okamura, H. (1992). Development of high performance concrete. Journal of the Faculty of Engineering, University of Tokyo, Series B; Japan, 41(3), 381-439.

[13] Okamura, H., Ouchi, M., & Concrete, S. C. (1999). Development, present use and future. Proceedings of the 1st International Symposium on Self-Compacting Concrete, 13-14 September, 1999, Stockholm, Sweden.

[14] Okamura, H., & Ouchi, M. (2003). Self-Compacting Concrete. Journal of Advanced Concrete Technology, 1(1), 5–15. doi:10.3151/jact.1.5.

[15] Domone, P. L. (2007). A review of the hardened mechanical properties of self-compacting concrete. Cement and Concrete Composites, 29(1), 1–12. doi:10.1016/j.cemconcomp.2006.07.010.

[16] Khaleel, O. R., & Abdul Razak, H. (2014). Mix design method for self-compacting metakaolin concrete with different properties of coarse aggregate. Materials and Design, 53, 691–700. doi:10.1016/j.matdes.2013.07.072.

[17] Dinakar, P. (2012). Design of self-compacting concrete with fly ash. Magazine of Concrete Research, 64(5), 401–409. doi:10.1680/macr.10.00167.

[18] Li, J., Yin, J., Zhou, S., & Li, Y. (2005). Mix proportion calculation method of self-compacting high performance concrete. Proceedings of the First International Symposium on Design, Performance and Use of Self-Consolidating SCC, 26-28 May, 2005, Changsha, China.

[19] Parra, C., Valcuende, M., & Gómez, F. (2011). Splitting tensile strength and modulus of elasticity of self-compacting concrete. Construction and Building Materials, 25(1), 201–207. doi:10.1016/j.conbuildmat.2010.06.037.

[20] Shi, C., & Wu, Y. (2005). Mixture proportioning and properties of self-consolidating lightweight concrete containing glass powder. ACI Materials Journal, 102(5), 355–363. doi:10.14359/14715.

[21] Sonebi, M. (2004). Medium strength self-compacting concrete containing fly ash: Modelling using factorial experimental plans. Cement and Concrete Research, 34(7), 1199–1208. doi:10.1016/j.cemconres.2003.12.022.

[22] Diamantonis, N., Marinos, I., Katsiotis, M. S., Sakellariou, A., Papathanasiou, A., Kaloidas, V., & Katsioti, M. (2010). Investigations about the influence of fine additives on the viscosity of cement paste for self-compacting concrete. Construction and Building Materials, 24(8), 1518–1522. doi:10.1016/j.conbuildmat.2010.02.005.

[23] Mansour, W. I., Yazbeck, F. H., & Wallevik, O. H. (2013). EcoCrete-Xtreme: Extreme flow, service life and carbon footprint reduction. Proceedings of the Fifth North American Conference on the Design and Use of Self-Consolidating Concrete, 12-15 May, 2013, Chicago, United States.

[24] Khayat, K. H., Ghezal, A., & Hadriche, M. S. (1999). Factorial design models for proportioning self-consolidating concrete. Materials and Structures/Materiaux et Constructions, 32(223), 679–686. doi:10.1007/bf02481706.

[25] Saak, A. W., Jennings, H. M., & Shah, S. P. (2002). New Methodology for Designing Self-Compacting Concrete. ACI Materials Journal, 98(6). doi:10.14359/10841.

[26] Abo Dhaheer, M. S., Al-Rubaye, M. M., Alyhya, W. S., Karihaloo, B. L., & Kulasegaram, S. (2015). Proportioning of self–compacting concrete mixes based on target plastic viscosity and compressive strength: Part I - mix design procedure. Journal of Sustainable Cement-Based Materials, 5(4), 199–216. doi:10.1080/21650373.2015.1039625.

[27] Hu, J., & Wang, K. (2011). Effect of coarse aggregate characteristics on concrete rheology. Construction and Building Materials, 25(3), 1196–1204. doi:10.1016/j.conbuildmat.2010.09.035.

[28] Wang, X., Wang, K., Taylor, P., & Morcous, G. (2014). Assessing particle packing based self-consolidating concrete mix design method. Construction and Building Materials, 70, 439–452. doi:10.1016/j.conbuildmat.2014.08.002.

[29] Bouziani, T. (2013). Assessment of fresh properties and compressive strength of self-compacting concrete made with different sand types by mixture design modelling approach. Construction and Building Materials, 49, 308–314. doi:10.1016/j.conbuildmat.2013.08.039.

[30] Van Khanh, B., & Montgomery, D. (1999). Mixture proportioning method for self-compacting high performance concrete with minimum paste volume. Proceedings of the 1st International Symposium on Self-Compacting Concrete, 13-14 September, 1999, Stockholm, Sweden.

[31] Sadeghbeigi, R. (2012). Fluid Catalytic Cracking Handbook. Gulf publishing company, Houston, United States. doi:10.1016/C2010-0-67291-9.

[32] Bukowska, M., Pacewska, B., & Wilińska, I. (2003). Corrosion resistance of cement mortars containing spent catalyst of fluidized bed cracking (FBCC) as an additive. Journal of Thermal Analysis and Calorimetry, 74(3), 931–942. doi:10.1023/B:JTAN.0000011025.26715.f5.

[33] Faraj, R. H., Hama Ali, H. F., Sherwani, A. F. H., Hassan, B. R., & Karim, H. (2020). Use of recycled plastic in self-compacting concrete: A comprehensive review on fresh and mechanical properties. Journal of Building Engineering, 30, 111–118. doi:10.1016/j.jobe.2020.101283.

[34] Gupta, N., Siddique, R., & Belarbi, R. (2021). Sustainable and Greener Self-Compacting Concrete incorporating Industrial By-Products: A Review. Journal of Cleaner Production, 284. doi:10.1016/j.jclepro.2020.124803.

[35] Kumar, B. N., & Kumar, P. P. (2022). Prediction on Flexural strength of High Strength Hybrid Fiber Self Compacting Concrete by using Artificial Intelligence. Journal of Artificial Intelligence and Capsule Networks, 4(1), 1–16. doi:10.36548/jaicn.2022.1.001.

[36] Baali, L., Belagraa, L., Chikouche, M. A., & Zeghichi, L. (2021). Study of the Effect of Plastic Waste Fibers Incorporation on the Behavior of Self Compacting Concrete. Annals of Chemistry: Material Science, 45(5), 417–421. doi:10.18280/acsm.450508.

[37] Md Zain, M. R., Oh, C. L., & Lee, S. W. (2021). Investigations on rheological and mechanical properties of self-compacting concrete (SCC) containing 0.6 μm eggshell as partial replacement of cement. Construction and Building Materials, 303, 200–212. doi:10.1016/j.conbuildmat.2021.124539.

[38] Serraye, M., Kenai, S., & Boukhatem, B. (2021). Prediction of compressive strength of self-compacting concrete (SCC) with silica fume using neural networks models. Civil Engineering Journal, 7(1), 118–139. doi:10.28991/cej-2021-03091642.

[39] Pinto, C. A., Büchler, P. M., & Dweck, J. (2007). Pozzolanic properties of a residual FCC catalyst during the early stages of cement hydration. Journal of Thermal Analysis and Calorimetry, 87(3), 715–720. doi:10.1007/s10973-006-7772-2.

[40] Dweck, J., Pinto, C. A., & Büchler, P. M. (2008). Study of a Brazilian spent catalyst as cement aggregate by thermal and mechanical analysis. Journal of Thermal Analysis and Calorimetry, 92(1), 121–127. doi:10.1007/s10973-007-8750-z.

[41] Singh, V., & Sangle, K. (2022). Analysis of vertically oriented coupled shear wall interconnected with coupling beams. HighTech and Innovation Journal, 3(2), 230-242. doi:10.28991/HIJ-2022-03-02-010.

[42] Furimsky, E. (1996). Spent refinery catalysts: Environment, safety and utilization. Catalysis Today, 30(4), 223–286. doi:10.1016/0920-5861(96)00094-6.

[43] Zornoza, E., Payá, J., & Garcés, P. (2008). Chloride-induced corrosion of steel embedded in mortars containing fly ash and spent cracking catalyst. Corrosion Science, 50(6), 1567–1575. doi:10.1016/j.corsci.2008.02.001.

[44] Bayraktar, O. (2005). Bioleaching of nickel from equilibrium fluid catalytic cracking catalysts. World Journal of Microbiology and Biotechnology, 21(5), 661–665. doi:10.1007/s11274-004-3573-6.

[45] Payá, J., Monzó, J., & Borrachero, M. V. (2001). Physical, chemical and mechanical properties of fluid catalytic cracking catalyst residue (FC3R) blended cements. Cement and Concrete Research, 31(1), 57–61. doi:10.1016/S0008-8846(00)00432-4.

[46] Chen, H. L., Tseng, Y. S., & Hsu, K. C. (2004). Spent FCC catalyst as a pozzolanic material for high-performance mortars. Cement and Concrete Composites, 26(6), 657–664. doi:10.1016/S0958-9465(03)00048-9.

[47] Su, N., Chen, Z. H., & Fang, H. Y. (2001). Reuse of spent catalyst as fine aggregate in cement mortar. Cement and Concrete Composites, 23(1), 111–118. doi:10.1016/S0958-9465(00)00074-3.

[48] Al-Dhamri, H., & Melghit, K. (2010). Use of alumina spent catalyst and RFCC wastes from petroleum refinery to substitute bauxite in the preparation of Portland clinker. Journal of Hazardous Materials, 179(1–3), 852–859. doi:10.1016/j.jhazmat.2010.03.083.