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EVALUATION OF FRESH PROPERTIES AND COMPRESSIVE STRENGTH OF SELF-COMPACTING CONCRETE REINFORCED WITH COIR FIBERS AND MODIFIED WITH CHEMICAL ADMIXTURES

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ABSTRACT:
In today's construction industry, there is a growing focus on sustainable concrete practices that involve utilizing various waste materials to enhance concrete's mechanical properties. Coir fiber (CF), derived from coconut husk and generally a waste material, stands as a promising fiber addition to concrete in this regard. This study has investigated the fresh and mechanical properties of self-compacting concrete (SCC) reinforced with CF. Dosage rates were 0%, 0.1%, 0.2%, and 0.3% of the total concrete volume with a definite CF length of 19-20 mm. To assess the suitability of SCC mixes, evaluations were carried out using slump flow, V funnel, L Box, and J-ring tests, and the resulting fresh properties were compared to the criteria outlined in the EFNARC Guidelines. Superplasticizer (SP) dosage depended on the desired results of fresh SCC properties. Additionally, compressive strength was evaluated after 28 days of curing the SCC specimens. The results indicate that the compressive strength increases with fiber content up to 0.2%, but excessive SP dosage is required at 0.3% CF dosage and shows an inverse effect on compressive strength. The highest compressive strength was achieved in the SCC mix having 0.2% CF, which was 8.9% greater than the control mix.

1. INTRODUCTION

Although concrete is widely recognized for its strength and durability, segregation problems may arise if it is poured into densely packed spaces with significant reinforcement. This is overcome by adopting self-compacting concrete (SCC), which ensures equal distribution, improves structural integrity, and flows smoothly into intricate forms without segregation. SCC is increasingly chosen for its ability to maintain concrete's strength and durability in demanding construction conditions (Lashari et al., 2021).

SCC is an advanced type of concrete that can be placed and compacted without vibration due to its high flowability (Ghazy, 2009; Rao and Ravindra, 2010). Originally developed in Japan for seismic regions, SCC is now widely used globally for its ability to fill complex forms and dense reinforcement without segregation. Its benefits include reduced construction time and labor costs by eliminating vibration, decreased noise pollution at construction sites, and improved structural performance in congested areas of reinforcement. These advantages make SCC a preferred choice for modern construction projects aiming for efficiency (Rao and Ravindra, 2010).

Cement production emits around 0.9 tons of CO2 per ton, contributing to 5-8% of global CO_2 emissions and ranking the cement production as the second-largest source CO_2 emissions (Ezekiel et al., 2024). To address the climate emergency, reducing these emissions is crucial, as any increase in CO_2 levels contributes to global warming (Pierrehumbert, 2019). One approach to mitigating this impact is the use of pozzolans as alternative cementitious materials in SCC mixtures, which help to decrease the reliance on Portland cement and its associated emissions (Sharma, 2019; Sun et al., 2021; Feng et al., 2021).

Despite the environmental concerns, the performance of SCC must also be considered. Fibers are commonly introduced to improve SCC's tensile and flexural properties (Hannant, 2003). The inclusion of fibers in SCC improves its mechanical properties by transitioning its behavior from strain-softening to strain-hardening. This enhances post-cracking performance and ductility, contrasting with fiber-free concrete that is susceptible to quicker crack initiation and propagation, leading to decreased stiffness and load-bearing capacity (Yehia et al., 2016). Karatas and Gunes (Karatas and Gunes, 2015) showed that using steel and polypropylene fibers in SCC significantly improved flexural strength, ductility, and durability; steel fibers enhanced crack resistance, while polypropylene fibers improved bending strength and lowered capillary absorption. Vidhya et al. (Vidhya et al., 2016) showed that inclusion of steel fibers with silica fume in SCC improved mechanical properties including compressive, tensile, and flexural strength. Similarly, Lad and Katiya (Lad and Katiya, 2019) showed that while the addition of glass and steel fibers increased compressive strength and reduced crack widths, it also led to decreased workability and slump values. Al-Hadithi and Hilal (Al-Hadithi and Hilal, 2016) used waste plastic fibers in SCC which revealed that while workability and flow properties decreased, the compressive and flexural strengths were improved. Ahmad et al. (Ahmad et al., 2021) investigated the impact of Nylon fibers (NFs) on fresh properties, durability, and mechanical strength of SCC. NFs were added at varying proportions (0.5%, 1%, 1.5%, and 2% by weight of cement). Results indicated reduced passing and filling ability but increased segregation and bleeding resistance with NFs. Mechanical tests showed significant strength improvement up to 1.5% NF addition, followed by gradual decline. NFs also enhanced durability parameters such as water absorption, permeability, carbonation resistance, and acid attack resistance compared to the control mix, highlighting their potential for improving SCC properties. However, many fibers are made from inorganic polymers that are non-degradable and contribute to CO2 emissions during their production (Zhang et al., 2022; Feng et al., 2022; Zhang and Tang, 2021). Natural fibers offer a more environmentally friendly alternative due to their biodegradability and lower production costs (Ramli et al., 2013; Tang et al., 2021; Luo et al., 2021).

Several studies have been conducted on different natural fibers. The study by Chairunnisa et al. (Chairunnisa et al., 2022) focused on investigating the effects of incorporating banana fibers into SCC. The result shows addition of 0.12% treated banana fiber enhances compressive strength by 44.36% and tensile strength by 17.78%, despite decreased workability. Study by Hasan et al. (Hasan et al., 2023) evaluated jute fiber (20 mm length) additions from 0.1% to 1% in (SCC). Results showed satisfactory rheological properties and improved mechanical strengths, with up to 2% higher compressive strength, 21% in splitting tensile strength, and 18% in flexural strength compared to conventional SCC. Among natural fibers, CF are notably the toughest (Ali et al., 2012).

Coconut fiber (CF), also known as coir fiber, which is a natural fiber is a waste material that has potential to be utilized in SCC to enhance its properties. CF is obtained from outer husk of coconut shell (Swamy et al., 2015). These fibers enhance post-cracking performance and increase its toughness. Coconut fibers are particularly notable for their toughness, enduring strains 4-6 times greater than other natural fibers. They are suitable for reinforcing low-cost concrete structures (Lakhiar et al., 2021). Swamy et al. (Swamy et al., 2015) and Baruah and Talukdar (Barauh and Talukdar, 2007) showed that coconut fibers increased the mechanical properties of self-compacting concrete. The previous studies have explored the CF as sustainable reinforcement in concrete. The effect of CF on compressive, tensile and flexural strength has been investigated in these studies (Abbasi et al., 2024; Ahmed et al., 2023; Ahmad et al., 2020; Ibrahim, 2023; Ahmad et al., 2021; Aslam et al., 2022). It has been revealed that the post-cracking behavior with CF improves at the greater extend. On the other hand, it is noted that, nothing is known about the use of CF in SCC, especially with regard to novel characteristics and the function of superplasticizers. In the existing literature, there is a lack of trials for the mix design of SCC in accordance with the CFs. Notably, the potential of CF in SCC applications has not been extensively explored, and this study aims to address this gap in the research. Moreover, the global coconut production reached approximately 62 million tonnes in 2019 (Azeta et al., 2021; Stelte et al., 2022).

The husk, comprising approximately 35% of the coconut's weight, contains around 30% coir, resulting in roughly 20 million tonnes of husks and a theoretical potential yield of 6 million tonnes of coir. However, global production of coir in 2019 was estimated at just 1.26 million tonnes (Stelte et al., 2022). These figures highlight the underutilization of coir, prompting environmental concerns. Integrating coir into SCC offers a sustainable solution that transforms waste into a valuable construction resource. Therefore, this study investigates the incorporation of CF into SCC in varying proportions by the weight of the total concrete volume. This study examines the effect of CF in SCC with an adjustable dosage of SP and provide assurance of required workability, while assessing its effect both on the fresh and hardened state, in contrast with the previous studies that employed fixed SP dosages. The experimental program includes evaluating the fresh properties using Slump Flow, V-funnel, L-box, and J-ring tests as per EFNARC guidelines, and evaluating compressive strength after 28 days of curing.

2. MATERIALS AND METHODS

Ordinary Portland Cement-Lucky Star by Lucky Cement having standard compliance ASTM-C150, and fly ash according to ASTM C618 from 5 Star Mining in Pakistan was used in this study. Locally available river sand with particle size ranging between 1.18 mm and 75 μm and locally available coarse aggregates having particle size from 4.75mm to 12.7mm were adopted for all the SCC mixes.

Table 1 shows the physical properties of both the fine and coarse aggregates. Fig. 1 shows the grading curves of fine and coarse aggregates. The superplasticizer (SP) used in this experimental work was MasterPolyheed 993. MasterPolyheed 993 is an admixture based on modified Poly Carboxylic Ether. It is free of chloride and low alkali. It had a light-yellow liquid aspect with a relative density of 1.02 ± 0.02 at 25°C. It had a pH level of ≥6 and a chloride ion content of less than 0.2%. It is certified by ASTM C-494 Type A, D, and G and BS 5075 part 1. Normal tap water was used both for the SCC mix and the curing process. The CF were manually extracted from the outer shell of coconuts, which were sourced locally from coconut traders. The fibers were then cut to lengths of approximately 19-20 mm using scissors.

Sr no:	Description	Fine Aggregate	Coarse Aggregates
1.	Water Absorption	2%	2%
2.	Specific Gravity	2.7	-
3.	Fineness Modulus	2.92	2.54
4.	Bulk Specific gravity (oven dried)	-	2.5

Table 1. Physical Properties of Fine and Coarse Aggregate

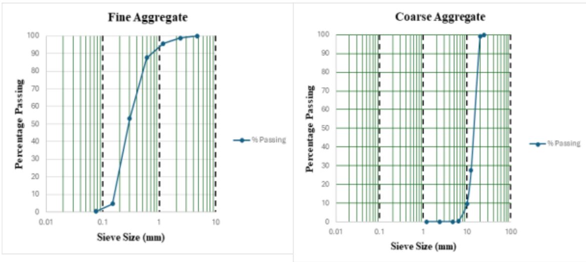

Figure 1. Gradation curves of fine and coarse aggregates

Fig. 2 shows the flow chart which visually illustrates the sequence of steps in the conversion of coconut husks into these desired fibers. The process begins with the collection of locally sourced coconut husks. These husks are then subjected to brushing, cleaning, and cutting to transform them into fibers, each measuring between 19 to 20 mm in length.

Figure 2. Process of conversion of coconut husks into desired fibers

2.1. Mix Design

This mix design for self-compacting concrete was designed in accordance with EFNARC SCC Guidelines (2002) (EFNARC, 2002). In this mix design, the cement binder content was proportioned at 550 kg/m3, coarse aggregate at 860 kg/m^3, fine aggregate at 850 kg/m^3, and water/binder ratio at 190 kg/m3. At initial stage in controlled mix (CM) the fly ash was added at a 10% replacement level for cement to improve workability, decrease the water-to-binder ratio, and enhance sustainability. Fly ash helps in the pozzolanic reaction, enhancing the long-term strength and durability of SCC, while also lowering CO_2 emissions associated with cement manufacture (Akbulut et al., 2024). The partial replacement of cement with fly ash in SCC has proven to be beneficial in its production and make it more suitable for the introduction of fiber reinforcement (Ahmad et al., 2021).

In this study, even at the high content of CF, the workability specially the flowing ability of the corresponding matrix was compensated by the addition of fly ash, and all mixtures satisfied the EFNARC guidelines.

The CF were added by volumetric fraction varying from 0.1%, 0.2%, and 0.3%. These proportions of contents were selected as per (Odeyemi et al., 2023), which revealed with this range of CF content enhances the mechanical performance while maintaining the required level of workability. The SP dosage was adjusted in accordance with the CF content to maintain the self-compacting characteristics of SCC. To make sure that every mix met with the workability criteria as per EFNARC and the SP dosage had to be varied. Higher content of fibers in SCC hindrances both the flowing and passing ability, however this modification is very much necessary for the proper comparisons. Moreover, Pervious Studies (Chairunnisa et al., 2022) have observed the SCC mixes with greater fiber content would not be able to reach at required level of workability and hence those mixes require more demand of SP. Here in this study the SP was added by the percentage of binder accordingly to achieve the slump value given by EFNARC (EFNARC, 2002). Table 2 shows the proportions of materials per cubic meter.

S. No.	Cement (kg/m^3)	Fly Ash (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Water/Binder Ratio	Coir Fibers (%)	Super-plasticizer (% of binder)
1	495	55	860	850	0.35	0	2.0
2	495	55	860	850	0.35	0.1	2.0
3	495	55	860	850	0.35	0.2	2.2
4	495	55	860	850	0.35	0.3	2.8

Table 2. Mix Proportions

3. RESULTS AND DISCUSSIONS

3.1 Fresh Properties of SCC with CF

After mixing the mixtures at initial stage the fresh properties of SCC were determined through their special characteristics; filling ability and passing ability. The filling ability was evaluated by the slump flow test and V-funnel test while passing ability was determined through the L-box and J-ring test. All the tests were carried out in accordance with the EFNARC specifications (EFNARC, 2002). Table 3 shows the all the values of each test for every mix.

As expected, the fresh properties of SCC, especially the flowing ability, has been affected with more content of CF. However, this requires a larger amount of SP to maintain the flowing ability. A similar trend was also observed by the different researchers, where natural fibers were added in SCC (Ahmad et al., 2022). While altering the dosage of SP influences the workability characteristics, this approach ensures that the fiber performance is assessed on the basis that the SCC's flowing ability should meet the required standards. It is suggested that the future studies may investigate the effect of fibers alone without altering the dosage of SP.

Mixes	SPD (%)	D (mm)	T (sec)	Average Height Difference (mm)	Blocking Ratio
Control Mix	2%	750	6	0.7	0.89
0.1%CFR-SCC	2%	670	11	1	0.83
0.2%CFR-SCC	2.2%	695	8.5	2	0.81
0.3%CFR-SCC	2.8%	725	8	1.5	0.85

Table 3. Results of Fresh Concrete Properties

3.1.1 Slump Flow test: Table 3 presents the values of slump flow te4st for each mix. The D represents the average final spread diameter of slump flow. Fig. 3 shows the variations of slump flow diameter with different dosages of SP and CF. The range of diameter of slump flow is from 670 mm to 750 mm (EFNARC, 2002). The diameter of CM is highest 750 mm because the fiber addition is zero percentage. Whereas, 0.1% CF mix's diameter decreased due to the inclusion of fibers. In 0.2% CF and 0.3% CF mixes, the SPD was increased with an increment of 0.2% until the desired SCC slump flow was achieved. By the addition of CF, the flowing ability of SCC was decreased which resulted in the increment of SPD.

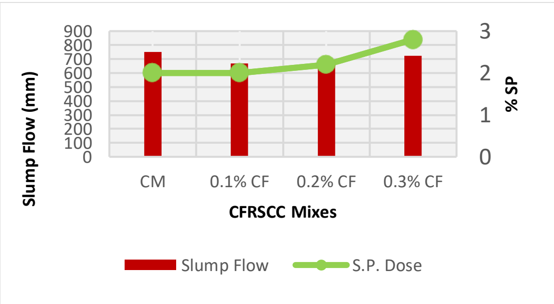

Figure 3. Effect of CF and SPD dosage on slump flow diameter

This research varied both CF and superplasticizer levels, unlike the study by Satheesh et al. (Satheesh Kumar et al., 2024), which kept the superplasticizer dosage constant while investigating the impact of CF on slump flow. However, both studies consistently found that the addition of CF increased slump flow diameter.

3.1.2 V-funnel test: : From table 3 T (sec) represents the time in seconds taken by SCC to flow out of the V-funnel. None of the mixes showed segregation or blockage. Fig. 4 shows both the pictorial view and graphical representation of different values of V-funnel time obtained from the test with respect to different dosages of superplasticizer. The given range for the time taken to flow out of V-funnel ranges from 8-12 seconds (EFNARC, 2002). The controlled mix took the least time to flow out of V-funnel due to zero percent of fibers. By adding fibers, the blockage increased but the trend shows the decrease in time because of increment of superplasticizer. Abhishek et al. (Abhishek et al., 2015) studied varying CF content in SCC while keeping the superplasticizer dosage constant. In contrast, this research varied both CF and superplasticizer dosages. Despite these differences, both studies observed that the addition of CF led to an increase in flow time. The superplasticizer was increased to achieve the desired value of T given by EFNARC (EFNARC, 2002).

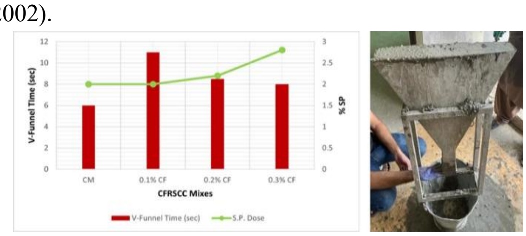

Figure 4. Effect of CF and SPD dosage on V-funnel time

3.1.3 J-ring test: The results from the J-Ring test provided insights into the passing ability of the different concrete mixes were presented in table 3 and figure 5.

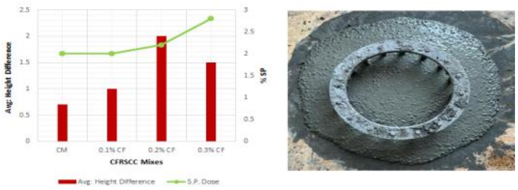

Figure 5. Effect of CF and SPD dosage on J-ring

In the controlled sample, the average height difference is 0.7 mm, indicating a remarkable level of uniformity. In contrast, the second mix, incorporating 0.1% fiber, shows a slightly increased average height difference of 1 mm, indicative of a slight reduction in workability due to the introduction of fibers. SCC mix containing 0.2% fiber, average height difference of 2 mm was observed, showing a significant impact on workability. The fourth mix, containing 0.3% fiber, falls between the second and third in terms of workability, with an average height difference of 1.5 mm. The range of height difference of j-ring test ranges from 0-10mm according to EFNARC (EFNARC, 2002). A notable observation is that the increase in superplasticizer content in the fourth mix showed a decrease in the average height difference, indicating the direct impact of superplasticizer on workability. The trend in the J-Ring test results shows that higher fiber content leads to reduced workability in concrete mixes. Similarly, a study by Tan et al. (Tan et al., 2019) reported no height difference in the control SCC mix, while a significant increase in height difference was observed with higher CF content. However, unlike this study, which varied the superplasticizer dosage, Tan et al. used a constant superplasticizer dosage. Conversely, an increase in superplasticizer levels is associated with improved workability. This indicates an inverse relationship between fiber content and workability and a direct relationship between superplasticizer levels and workability in concrete mixtures, highlighting the importance of balancing these factors for optimal performance.

3.1.4 L-box test: Figure 6 represents the physical and evaluated results obtained from the L-box test respectively. Blocking ratio is the ratio of heights. The whole test was performed within 5 minutes to the EFNARC SCC Guidelines (EFNARC, 2002). The range of blocking ratio is between 0.8-1, the closer the ratio to one, the lesser the blockage. Controlled mix showed the least blockage thus it has the blocking ratio of 0.89.

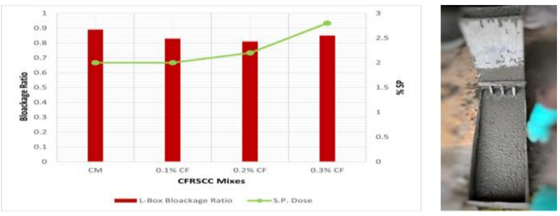

Figure 6. Effect of CF and SPD dosage on L-box blockage ratio

The values obtained by the L-box test decreased with the addition of CFs, as demonstrated by the study of Odeyemi et al. (Odeyemi et al., 2023). However, in this research, while the initial trend followed this pattern, the value later increased due to the excessive dosage of superplasticizer. 0.1% coconut fiber reinforced SCC (CFR-SCC) mix and 0.2% CFR-SCC blocking ratio value decreased due to increased proportion of coconut fibers. Whereas the blocking ratio value increased (blockage decreased) despite of CF proportion of 0.3% in the 0.3% CFR-SCC mix as compared 0.1% CFR-SCC and 0.2% CFR-SCC mix because of the greater dosage of superplasticizer in comparison with other mixes.

3.2 Compressive strength of SCC with CF

After completion of fresh properties, the compressive strength was determined through cube testing. The standard sized 6in x 6in were cast and tested. The average compressive strength of six specimen for each mix was determined at the age of 28 days curing. After the initial casting, these concrete cubes were allowed to remain undisturbed for a 24-hour period to undergo an initial drying stage. Following the 24-hour drying phase, the concrete cubes were then carefully immersed in water for an extended curing period of 28 days, as this is the standard curing period for structural concrete and provide the approximate indication towards the long-term strength. Even though the early strength of concrete at 3, 7, 14 days curing is apricated for the early strain gain, this experimental study is intensive on the long-term strength of SCC. The cubic specimens were removed from water after curing and cleaned with a dry cotton determine the concrete's compressive strength. An automatic compression testing machine (Tecnotest KE 300/CE) was used to carryout the compressive strength testing. The load was applied at the rate of 0.50 N/mm^2 per second. The specimens on the machine were arranged in such a manner that the load was distributed equally through the top and bottom. Figure 7 shows the pictorial view of the concrete specimen during testing.

Figure 7. Pictorial view of cube specimen under compression

Table 4 shows the values of average compressive strength with respect to SPD and CF content. From plotted results in figure 8 it is observed that the compressive strength increased with increment of CF up to 0.2% CF dosage by 8.9%. At 0.3% CF, compressive strength reduced by approximately 24% when compared to the control sample. The results are in agreement with the previous research by Iman et al. (Iman et al., 2020), which demonstrated that the compressive strength of SCC increased with the addition of CF up to a certain point, after which further additions of CF resulted in a decrease in strength.

Mixes	SPD	Average Compressive Strength (psi)
Control Mix	2%	6788
0.1%CFR-SCC	2%	7105
0.2%CFR-SCC	2.2%	7395
0.3%CFR-SCC	2.8%	5461

Table 4. Compressive Strength w.r.t SPD and CF

This behavior was similarly observed in this study where compressive strength peaked at 0.2% CF but declined at higher CF content due to excessive superplasticizer dosage. The recommended dosage for Master-Polyheed 993 is between 600 ml and 2000 ml per 100 kg of cement (BASF Corporation, 2023).

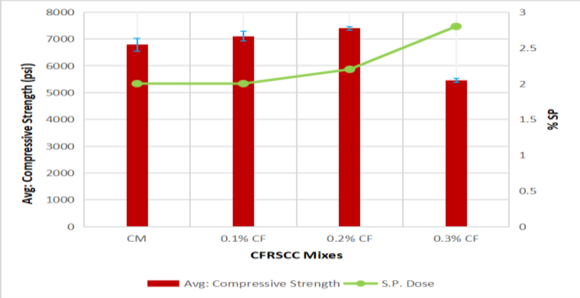

Figure 8. Effect of CF dosage and SPD on compressive strength

However, in this study, up to 2800 ml per 100 kg of cement was used to achieve the required slump flow. When less than 2800 ml per 100 kg of cement was used, the slump value did not meet the standards for SCC as defined by EFNARC (EFNARC, 2002). To achieve the desired slump value, an excessive amount of superplasticizer was required, which consequently led to a decrease in compressive strength. The decrease in compressive strength at 0.3% CF due to excessive superplasticizer dosage suggests that this mix may not be suitable for high-strength concrete applications. Therefore, precise optimization and careful supervision of SPD are needed to effectively balance workability and mechanical properties with such proportion of fibers. The width of cracks decreased by the increment of CF. The difference in crack widths between the 0.1% CF mix and the 0.3% CF mix was visually apparent. The cracks were considerably narrower in the 0.3% CF mix compared to the 0.1% CF mix. Hence, incorporation of CFs resulted in a noticeable reduction in crack width. Additionally, specimens with CFs did not fail as abruptly as the control mix and gave greater warning before failure.

3.3. Statistical Analysis

The statistical analysis was conducted to evaluate the significance of variations in SCC properties. The parameters include:

- **T_{50}:** Slump flow time for SCC to reach at 50 cm spread.
- **CS:** Compressive strength of SCC.
- **P:** Passing ability of SCC from J-ring test
- **d:** Diameter of fiber.

The correlation coefficient for dosage of superplasticizer and dosage of fiber was found equal to -0.8652 and -0.5578. The values show that the additives have inverse relation with compressive strength. Thus, increasing the dosage of the additives beyond certain limit will adversely affect the compressive strength. The same parameter for fresh properties, i.e., T_{50}, diameter and blocking ratio were recorded equal to 0.2667, -0.1819, and -0.3728 respectively. The values show that the diameter and blocking ratio again have inverse relation with the compressive strength but the T_{50} has direct relation with the compressive strength. Thus, without evaluating the compressive strength one can have the idea of the compressive strength from the parameters discussed above. Additionally, regression analysis is done using dosage of superplasticizer, T_{50} and diameter as independent variables to estimate the compressive strength. Compressive strength results are used as dependent variable. From the process following numerical equation is obtained.

$$CS = 32304.15 - 2858.61SP - 677.126T_{50} - 18.5131 \quad (1)$$

Significant F and p-values of the parameter were recorded nearly equal to zero (less than 0.005) which show best fit among the variable. Normal probably plot of the process is shown in figure 9. Further checking of the numerical equation shown very good correlation between the variable. Also, in another attempt it was observed that there was no effect of dosage of fiber and blocking ratio on the numerical evaluation of the compressive strength.

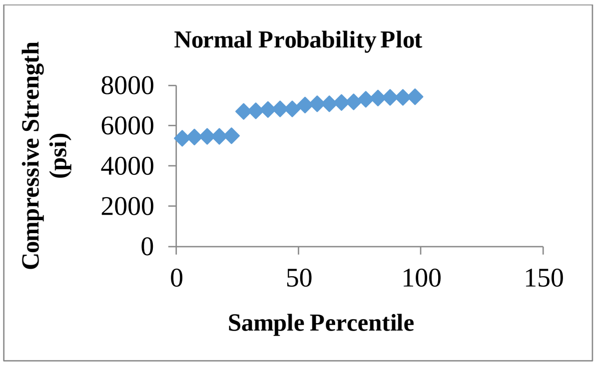

Figure 15. Normal probably plot

4. CONCLUSION

- This study investigated the effect of CF in SCC both at the fresh and hardened state.
- The addition of CF reduced SCC workability due to fiber-induced entanglement, requiring an increased superplasticizer (SP) dosage to maintain flowability. The slump flow diameter decreased from 750 mm CM to 670 mm (0.1% CF) but improved for higher fiber dosages with increased SP.
- The highest compressive strength (7395 psi) was achieved at 0.2% CF, representing an 8.9% improvement over the control mix. However, at 0.3% CF, excessive SP dosage negatively impacted strength, reducing it by approximately 24% compared to the control mix.
- While CF enhanced the hardened property (compressive strength) of SCC, excessive fiber dosage led to workability issues and strength reduction. This highlights the need for precise

mix optimization when using natural fibers in SCC.

It is further concluded that CF is a promising eco-friendly reinforcement for SCC when used within an optimized range. However, careful workability adjustments and strength optimization are required to maximize its benefits. Future studies should address the identified limitations to expand the applicability of CF-reinforced SCC in sustainable construction.

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