

A Probabilistic Approach to Estimating Hardened Properties of Self-Compacting Concrete

Amaranth Shetty¹, Shashank P², Naveen kumar S M³ and Manu Vijay H L⁴

¹Professor, Department of Civil Engineering, AJIET, Mangalore, VTU, Karnataka, India

²Assistant Professor, Department of Civil Engineering, ATME College of Engineering, VTU, Mysuru, India

³Assistant Professor, Department of Civil Engineering, AIT Chikkamagalur, VTU, Karnataka, India

⁴Associate Professor and Head, Department of Civil Engineering, ATME College of Engineering, VTU, Mysuru, India

Email: {¹amarnathshetty2003@gmail.com²shashank.psha@gmail.com³naveenkumarsm@aitckm.in, hlmanuvijay@gmail.com⁴}

Abstract—Concrete is the most popular material of construction around the globe. Advancement in structural engineering, architecture, and construction technology has led to the evolution of concrete with superior performance. One of the high-performance concretes is the self-compacting concrete (SCC), which can flow and compact under its own weight. With the need for narrow and sleek structural sections and congestions in the reinforcements, SCC has proved to be a game-changer in the field of concrete technology. The methodology of the present study can be divided into two phases. The first phase is the collection of developed experimental data. Ten different mixes of SCC (with variable amounts of Metakaolin as cement replacement and Nano-silica as additives) are subjected to tests at fresh and hardened states. The set state tests involve compression and split tensile strengths at 7, 28, and 56 days. The study's second phase is the probabilistic assessment of the results obtained from the experimental studies. For this purpose, the Monte-Carlo simulation method of random variable generation is used. The distribution of each mix is established from the Monte Carlo simulation, and strengths corresponding to 5% and 95% probability are shown.

Index Terms— Self-compacting concrete (SCC), Metakaolin – (MK), nano-silica-(NS), Monte-Carlo simulation, probability approach, Compressive Strength-(CS), Splitting Tensile Strength (ST).

I. INTRODUCTION

Concrete can be defined as the composite material made up of aggregates (fine and coarse) bonded in a matrix of cementations material produced out of cement and water. Other additives and admixtures are added to concrete to suit its performance requirements. Concrete is one of the most commonly used construction materials in the modern era. Concrete, with embedded steel bars (called reinforcements), forms new construction material called reinforced cement concrete (RCC), which has given a new dimension to the field of construction technology. Many kinds of structures, which were unthinkable in the past, have now been made possible with the advent of concrete.

Self-Compacting Concrete (SCC) is a type of concrete that can be placed and compacted without any external force or energy [3]. SCC should possess qualities such as high deformability, high segregation resistance, and suitable viscosity and flow ability. Constituents-wise, SCC is similar to conventional concrete. However, certain

modifications are required to achieve flowabilities, such as the increase in the Volume of fines and the application of supplementary cementations materials. Also, SCC uses high-range plasticizers and viscosity modifying agents to achieve flow ability and segregation resistance [4, 15&16].

Statement of Problem: The principal aim of the present experimental and analytical study can be summarized as below:

You are applying a probabilistic approach to predict hardened properties of concrete and to establish the statistics of set properties of concrete, using the experimental data on self-compacting concrete incorporating various mineral admixtures. A deterministic approach for predicting concrete strength has severe limitations since the variability involved with substantial strength development is many. There is a need to guard the structural behavior against the uncertainties associated with the strength characteristics of concrete.

II. LITERATURE REVIEW

Hossein Akbar Zadeh Kasani *et al.* (2016) has provided some case studies on the strength prediction of concrete based on previous test results. Using a database of 382 test results conducted over eight years, the author has come out with linear and power relations to estimate the strength of concrete. Equations have been developed to correlate seven days, 28 days, and 42-day strengths of concrete.

S. Shrihariand *et al.* (2015) have conducted experimental investigations on self-compacting concrete's properties by partially replacing cement with Metakaolin and sand with GGBS slag. The replacement of blast furnace slag is in the range of 10 to 60%, with the use of Metakaolin being about 10% to control the rate of strength development.

Robby Caspeele *et al.* (2014) have tried to study the influence of the estimate of concrete strength in evaluating the structural safety of existing structures. The influence of different methods for estimating the strength of concrete in the safety level of existing concrete columns was studied, considering both the application of partial factors not modified concerning the new structures and the partial characteristics adjusted according to the Factor Method.

Shamsad Ahmad *et al.* (2014) have attempted to provide a statistical approach to optimizing performance-based concrete mix designs. The data required for establishing the statistical procedure is obtained through a statistically planned experimental process. A total of 27 mixes consisting of 3 specimens each were considered, each with different key parameters that affect the strength development of the concrete, such as water-cement ratio, cementitious content, and aggregate ratios.

Debashis Das *et al.* (2013) have attempted to propose a statistical model to estimate the strength of concrete from a common sample space using the Monte-Carlo simulation technique. For this purpose, self-compacting concrete and usually compacted concrete of similar ultimate strengths have been cast, water cured, and tested after 7, 14, 60, 90, 120, and 150 days. Monte Carlo and RMSS simulation techniques have been used to develop a large set of simulated data.

Mahmoud Sayed-Ahmed *et al.* (2012) have presented a study on building a statistical model to predict compressive strength concrete containing different matrices at various stages of aging. The model considers eight other parameters for the matrix mixture, namely: time, water, cement, sand (S), aggregate (A), metakaolin (MK), silica fume (SF), and superplasticizer (SP).

Vahid. K. Alilou *et al.* (2010) have presented a study on the prediction of 28-day compressive strength of concrete on the third day using artificial neural networks. The data were collected from experimental samples, and the ANN was trained to predict the strength based on the input data. Out of 432 data, 300 were used as input, 66 were used for validation, and the remaining was used for final testing.

Paratibha Aggarwal *et al.* (2008) presented a procedure for the design of concrete self-compacting mixtures based on experimental research. In the water/dust ratio from 1180 to 1215, it was found that the results of the regulation flow test, of the V-funnel test, and of the L-box were satisfactory, i.e., the approval capacity; The filling capacity, and the resistance to segregation are within limits. SCC was developed without using VMA in this study.

II. MATERIALS AND METHODOLOGY

Although the characteristics of the materials used in the manufacture of SCC and their mixing proportions affect SCC, one of the challenges for SCC is that there is no proven mix design procedure. In this study, the experimental methodology adopted was divided into two phases. The first phase concerns collecting data on the

hardness properties of SCC mixtures using industrial by-products such as MK and NS. The second phase covers the statistical analysis of the collected data by the Monte Carlo simulation method [1,2,10&11].

A. Cement

Cement: Portland cement is one of the most widely used types of cement around the globe. Present study utilizes ordinary Portland cement of 53 grades. It confirmed to the requirements of Indian Standard Specification (IS: 269- 2016) [8]

B. Fine aggregate

Good quality river sand without any organic matter should be used as fine aggregate. Particles are angular in shape, passing 4.75mm and retaining on a 150-micron standard sieve. The sample should be water-washed to get rid of dust and should be dried for 48 hours. It confirmed to the requirements of Indian Standard Specification (IS: 383-2016) [6].

C. Coarse aggregates

The maximum size of aggregate should be restricted to 20mm for SCC. 12mm sized aggregates are utilized in places where reinforcement congestion is high. The aggregates should be well-graded and should be free from flocky and elongated particles.

D. Mixing water

Portable water with a pH value of less than seven is utilized for mixing and curing purposes.

E. Superplasticizers

Conplast SP 430 is different from conventional superplasticizers. It is based on a unique carboxylic ether polymer with long lateral chains. Used. conplast sp 430 is based on sulfonated naphthalene polymers and supplied as a brown liquid instantly dispersible in water conforming to IS1903-2000 code.

F. Nano-Silica

It is an amorphous (non-crystalline) polymer of SiO_2 and silica. It is an ultrafine powder collected as a by-product during silicon and Ferro-silicon alloy production [7]. The physical and chemical properties of Nano-Silica are listed below in Table I.

TABLE I: CHEMICAL COMPOSITION OF NANO- SILICA

Constituents	Percent
SiO_2	90-96
Al_2O_3	0.5-0.8
MgO	0.5-1.5
Fe_2O_3	0.2-0.8
CaO	0.1-0.5
Na_2O	0.2-0.7
K_2O	0.4-1.0
C	0.5-1.4
S	0.1-0.4

G. Metakaolin

Metakaolin is an artificial pozzolanic produced by subjecting kaolinite clay to within a specific temperature range (650 and 800 C). When heated to 700–900 C, kaolin calcifies, losing up to 14% hydroxyl water and changing into MK[7]. It has been found from previous studies that the inclusion of Metakaolin improves the quality of the gel, thereby improving the mechanical properties and durability of concrete. The properties of MK are shown in table II .

H. Mix design for SCC

Even though many mixed design procedures are available for SCC in the literature, there is no consensus among the codes as to which is the best method of mixed design. The present study uses the modified Nan Su mix design method for SCC [13&14]. The proportion of the mixture obtained from Nan-Su, the method is 1: 2.20: 2.26 and w / p ratio of 0.8 and final arrival of trial and error based on the above results, it was found that a mix of

TABLE II: PHYSICAL COMPOSITION OF METAKAOLIN

Colour	Dark Grey
Specific Gravity	2.5
Specific Surface Area	About 150000-180000 m ² /kg
Particle Size	Mostly fine spheres with a mean diameter of 2.5 micron

1:1.70:1.70 with water-cement ratio of 0.44 and 1.1% satisfies the requirements of flow as well as it is free from bleeding and segregation. Hence, it is adopted as a control mix.

I. Probabilistic Approach by Monte Carlo simulation method

The monte-Carlo method is a simulation technique. One of the usual objectives in using the Monte-Carlo technique is to estimate specific parameters and probability distributions of random variables whose values depend on the interactions with random variables whose probability distributions are specified. Monte-Carlo simulation builds models of possible results by substituting a range of values, a probability distribution function for any factor with inherent uncertainty. The following flow chart represents the procedure of the Monte Carlo simulation method [1,2, 10&11].

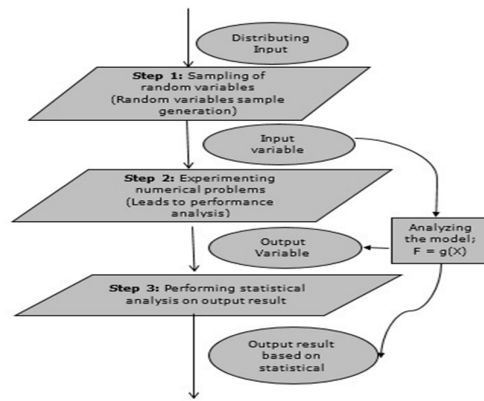


Fig 1: Flow chart for Monte Carlo Simulation

III. EXPERIMENTATION AND RESULTS

The SCC containing two different mineral admixtures, namely Nano-silica and Metakaolin are used in the present study as a replacement for cement. The following ten mixes are prepared using the control mix as a base. Where MK refers to Metakaolin and NS refers to Nano-Silica. The ten mixes are subjected to compressive and split tensile strengths [9] on the seventh, 28th, and 56th days after the casting. The results of the tests are explained below in Tables III and IV, respectively. An extensive set of experimental data is required to conduct a numerical analysis. In the present study, the data is collected from a previously performed experimental study. The experimental data collected from previous data is presented in tables Vth and VIth, respectively.

Observations: It has been observed that the compressive strength of SCC 7 days, 28 days, and 56 days produced with the combination of admixtures such as NanoSilica and Metakoline is almost the design strength. It is also observed that the strength increases as the NanoSilica and Metakoline increase. Furthermore, the maximum values are obtained for the mix 15%MK+1.5%NS compared to the little mix.

Observations: It has been seen that the Split tensile strength of SCC 7days, 28 days and 56days produced with the combination of admixtures such as Nano Silica and Metakaolin is almost the design strength. We can also see that the strength increases as the Nano Silica and Metakaolin increase. Moreover, the maximum value is obtained for 15%MK+1.5%NS mix proportions as compared to the nominal mix.

TABLE III: COMPRESSIVE STRENGTH RESULTS AT 7-DAYS, 28DAYS, AND 56 DAYS

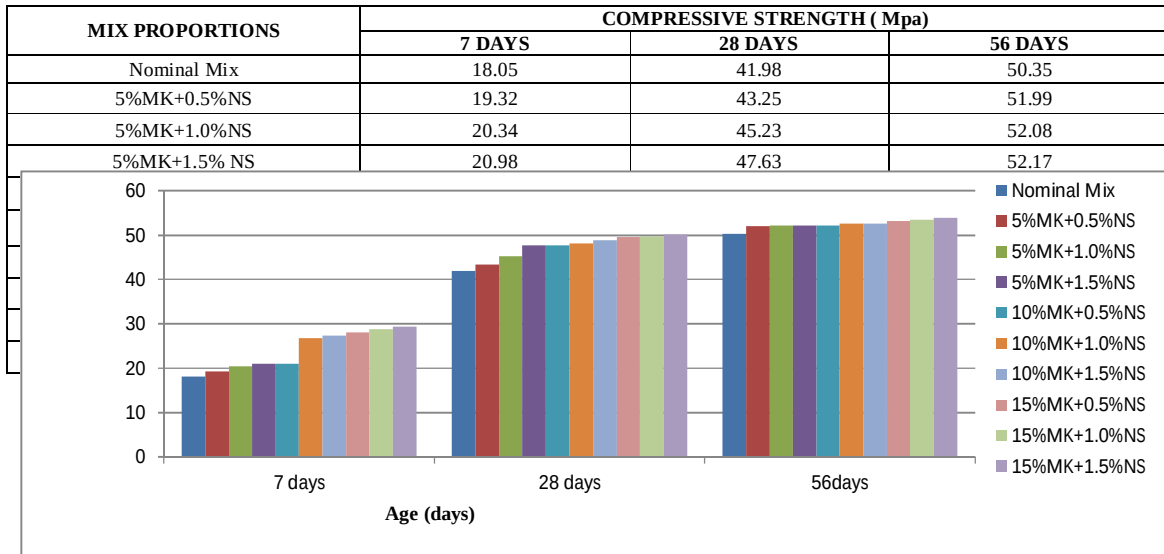


TABLE IV: SPLITTING TENSILE STRENGTH RESULTS AT 7-DAYS, 28DAYS, AND 56 DAYS

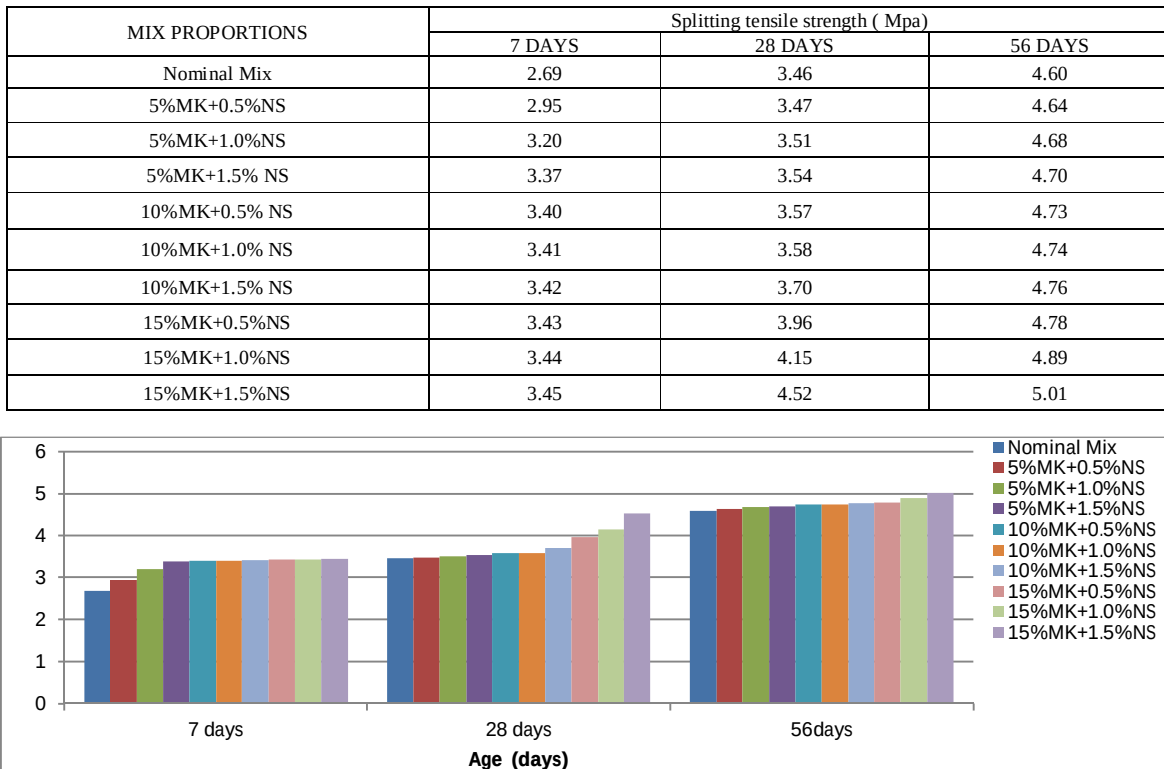
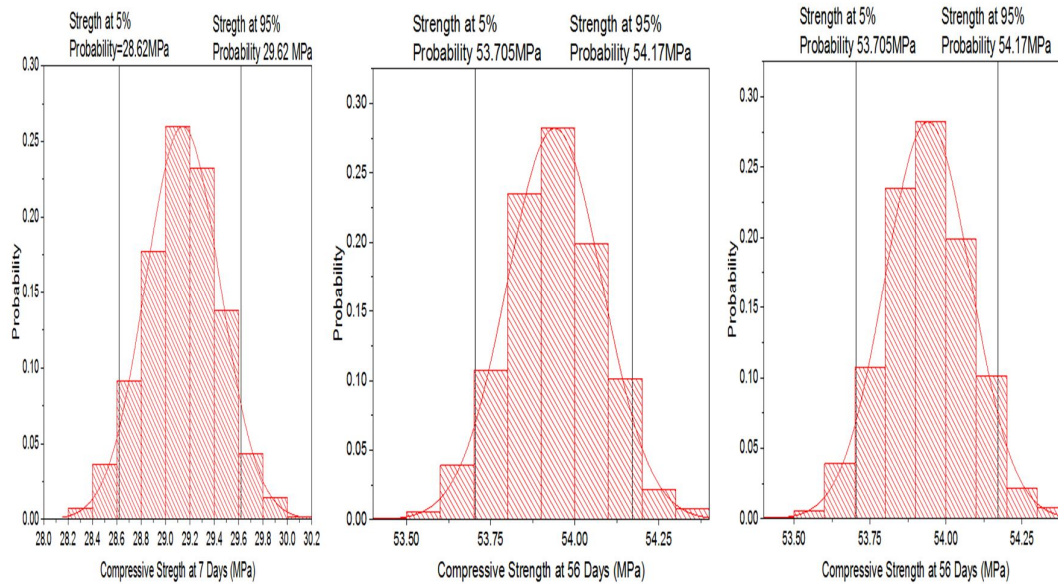


TABLE V: PROBABILISTIC ANALYSIS OF 7, 28 & 56-DAY COMPRESSIVE STRENGTH RESULTS

Mix proportions	Mean strength (Mpa)			Standard deviation			Strength at 5% Probability Mpa)			Strength at 95% Probability (Mpa)		
	7	28	56	7	28	56	7	28	56	7	28	56
Nominal mix	18.05	41.98	50.35	0.136504	0.27622	0.075498	17.83	40.64	50.23	18.27	41.55	50.46
5%MK+0.5%NS	19.32	43.25	51.99	0.14189	0.42724	0.13503	17.83	42.55 4	51.79	18.27	43.92	52.21
5%MK+1.0%NS	20.34	45.23	52.08	0.14177	0.68705	0.06807	20.07	44.05 5	51.96	20.56	46.38	52.194
5%MK+1.5%NS	20.98	47.63	52.17	0.14107	0.51316	0.02082	20.71	46.76	52.13	21.21	48.45	52.21
10%MK+0.5%NS	25.58	47.98	52.27	0.1893	0.56226	0.11533	25.26	47.01	52.07 4	25.89	48.94	52.464
10%MK+1.0%NS	26.76	48.20	52.48	0.40698	0.48429	0.06658	26.09	47.02	52.37 4	27.43	49.05	52.583
10%MK+1.5%NS	27.27	48.83	52.58	0.63906	0.04359	0.015275	26.4	48.76	52.55	28.54	48.89	52.604
15%MK+0.5%NS	28.15	49.59	53.26	0.45446	0.24583	0.05508	27.099	49.18	53.17 4	28.62	50.01	53.348
15%MK+1.0%NS	28.74	49.71	53.49	0.12662	0.06658	0.10066	28.52	49.6	53.32	28.94	49.83	53.656
15%MK+1.5%NS	29.35	50.03	53.94	0.31262	0.13868	0.14503	28.62	49.75	53.70 5	29.62	50.26	54.17



Graph 1.3:- 7,28and 56 -Day Compressive strength: 15%MK+1.5%NS

Observation:

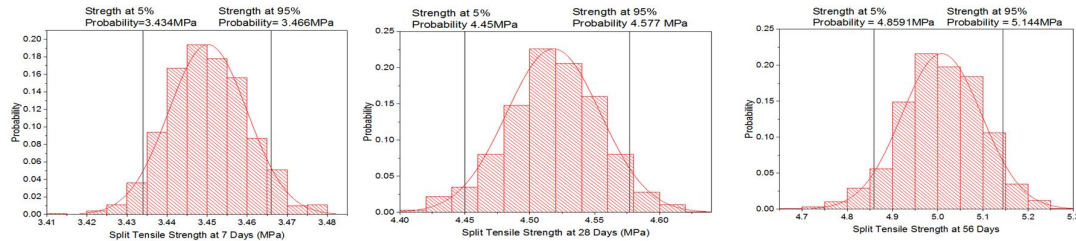
From the above table and graph 1.3, it has been observed that the compressive strength gradually increases and becomes higher at 15%MK+1.5%NS mix compared to the little mix. Similarly, strength at 5% probability and 95% probability follow the same trend as that as mean strength.

Observation:-

From the above table and fig 1.4, it has been observed that the split tensile strength gradually increases and becomes higher at 15%MK+1.5%NS mix compared to the little mix. Similarly, strength at 5% probability and 95% probability follow the same trend as that as mean strength.

TABLE VI: PROBABILISTIC ANALYSIS OF 7, 28 & 56-DAYS SPLITTING TENSILE STRENGTH RESULTS

Mix proportions	Mean strength (Mpa)			Standard deviation			Strength at 5% Probability (Mpa)			Strength at 95% Probability (Mpa)		
	7	28	56	7	28	56	7	28	56	7	28	56
Nominal mix	2.69	3.46	4.60	0.145716	0.00513	0.023094	2.448	3.45	4.56	2.93	3.468	4.638
5%MK+0.5%NS	2.95	3.47	4.64	0.091651	0.004	0.015275	2.791	3.463	4.615	3.097	3.476	4.664
5%MK+1.0%NS	3.20	3.51	4.68	0.066583	0.019731	0.015275	3.091	3.477	4.656	3.313	3.539	4.704
5%MK+1.5%NS	3.37	3.54	4.70	0.025166	0.003785	0.025166	3.329	3.533	4.658	3.409	3.546	4.746
10%MK+0.5%NS	3.40	3.57	4.73	0.049328	0.003785	0.015275	3.318	3.564	4.706	3.486	3.575	4.752
10%MK+1.0%NS	3.41	3.58	4.74	0.015275	0.020816	0.01	3.385	3.544	4.72	3.436	3.614	4.756
10%MK+1.5%NS	3.42	3.70	4.76	0.01	0.03	0.015275	3.403	3.651	4.73	3.437	3.749	4.784
15%MK+0.5%NS	3.43	3.96	4.78	0.01	0.055075	0.02	3.41	3.651	4.747	3.446	3.748	4.811
15%MK+1.0%NS	3.44	4.15	4.89	0.00577	0.064291	0.020816	3.431	4.047	4.859	3.449	4.248	4.925
15%MK+1.5%NS	3.45	4.52	5.01	0.01	0.036055	0.088881	3.434	4.45	4.859	3.466	4.577	5.144



Graph 1.4:- 7,28and 56-days split tensile strength: 15%MK+1.5%NS

IV. CONCLUSION

The present study is devoted to the experimental and probabilistic investigations of self-compacting concrete with Metakaolin and Nano-silica as additives. The first phase of the experiment is the experimental study of assessing the compressive and split tensile strength of concrete mixes with different percentages of Metakaolin and Nano-silica in concrete. The study's second phase is the probabilistic study of the experimental results using Monte-Carlo simulation [1, 2, 10&11]. The conclusions drawn from the study are listed below.

1. It is found from the probabilistic analysis of the collected experimental data on the compressive and split tensile strength of concrete that the distribution of concrete strengths on seven days, 28 days, and 56 days follows the normal distribution.
2. It has been observed that the compressive strength of SCC at seven days, 28 days, and 56 days produced with the combination of admixtures such as Nano Silica and Metakaolin is almost the design strength. We can also see that the strength increases as the Nano Silica and Metakaolin increase, and maximum values are obtained for 15%MK+1.5%NS mix proportions compared to the nominal mix.
3. It has been observed that the Split tensile strength of SCC at seven days, 28 days, and 56 days produced with the combination of admixtures such as Nano Silica and Metakaolin is almost the design strength. We can also see that the strength increases as the Nano Silica and Metakaolin increase, and maximum values are obtained for 15%MK+1.5%NS mix proportions compared to the nominal mix.
4. The compressive and split tensile strengths corresponding to 5% and 95% probabilities are found for each mix. It was found that these characteristic strengths follow the same trend as that of the mean strength.

5. The deterministic approach has severe limitations while dealing with concrete strength prediction. The Monte Carlo analysis method proves to be a useful probabilistic analytical tool for the strength prediction of concrete.

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