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Research Paper

Water Absorption, Impact Resistance and Strength Reliability of Concrete Incorporating Sintered Fly Ash Aggregate Under Drop Weight Impact Load

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ASTM and ACI methods were used to determine the water absorption and impact resistance of M30 grade concrete containing different percentages of sintered fly ash aggregate (SFA) ranging from 20%, 40%, 60%, 80%, and 100%. In the concrete laboratory, the parameters of the concrete mix, including fresh density, slump value, dry density, compressive strength, and impact resistance, were determined. The fresh and dry densities of concrete mix decrease as the quantity of SFA used as substitute increases. The 100% substitution of SFA in concrete results in a slump value of 200 mm, a fresh density of 1946 kg/m^3, a dry density of 1911 kg/m^3, and water absorption of 3.5%, with a compressive strength of 12.3 MPa. For the drop weight impact resistance test, reliability analysis was conducted to determine the level of reliability of each concrete mix for varying SFA. Using reliability analysis, the failure analysis owing to impact load determined the energy absorption of the concrete mix.

Keywords: sintered fly ash aggregates; water absorption; compressive strength; impact test; reliability analysis.

1. Introduction

Measuring water absorption in concrete is one of the durability tests used to assess the its water resistance [1, 2]. The water absorption of concrete is dependent on the aggregates used in its production, such as quarry dust and sintered fly ash aggregate [3]. Adding sintered fly ash aggregate (SFA) to concrete mix boosts their water absorption capacity [4]. The initial soaking of lightweight aggregates influences the transition zone [5]. The impact resistance of concrete can be determined in the laboratory for construction materials by using the aggregate impact testing machine [6]. The most common and straightforward test for determining the impact resistance and failure patterns of concrete mix can be conducted in line with American Concrete Institute (ACI) 544 procedure [7]. Increasing the impact resistance of concrete could protect large structures against earthquakes, tsunamis, and terrorist attacks [8]. SFA exhibits the same bonding properties in concrete as natural aggregates [9, 10].

Wallodi Weibull created the Weibull distribution to forecast the reliability of any composite engineering materials. According to the findings of researchers, the two parameters of the Weibull distribution are adequately suitable to analyze the drop weight impact resistance of concrete [11]. ACI Committee 544 has determined that the drop weight experimental results for a minimum of three specimens are not reliable and that there are enormous differences in test results. The following factors are examined for Weibull distribution:

(i) The crack initiation must be observed visually, which can occur in any direction.

(ii) The results of the drop weight test are obtained through impact strikes at a single location on the concrete's surface, either on a hardened substance containing a coarse aggregate or on the smooth interlayer of the cement matrix.

The tests require a 4.5 kg drop weight to be raised and dropped simultaneously from a height of 457 mm, which is a very tough task. In light of the aforementioned considerations, it can be inferred that a reliable statistical tool is required to examine the variations in test findings, which would be a good solution for the variances in drop weight impact outcomes [12].

The present experimental investigation seeks to determine SFA's durability and impact resistance in M30 grade concrete at replacement levels of 0%, 20%, 40%, 60%, 80%, and 100%. In addition, a reliability study is conducted for the impact resistance test on a concrete mix using different sintered fly ash aggregates.

2. Experimental analysis

2.1. *Concrete materials and their properties*

Cement, fine aggregate, natural coarse aggregate (NCA), sintered fly ash aggregate (SFA), and water are used to manufacture the concrete mix. Figure 1 depicts the ingredients required to produce concrete. Ordinary Portland cement 53 grade with a specific gravity of 3.15 was utilized. The laboratory-determined values for cement particle qualities, such as consistency [14], initial setting time, and final setting time [15], are 33, 52, and 300 minutes, respectively. According to IS 383 [16], the fine aggregate utilized was river sand with a specific gravity of 2.64 and a fineness modulus of 2.57. The largest particle size of the fine aggregate did not exceed 2.36 mm. According to IS 383 [16], the

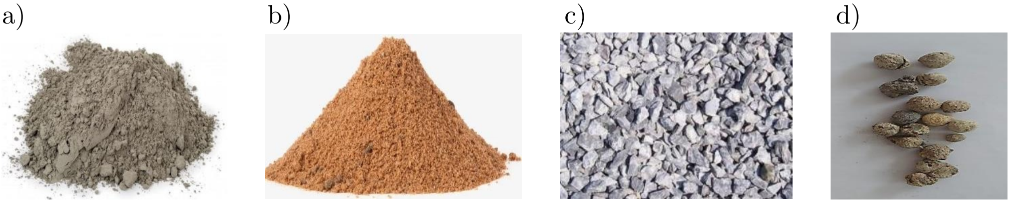

FIG. 1. Concrete material ingredients: a) cement, b) fine aggregate, c) NCA, d) SFA.

natural coarse aggregate (NCA) and SFA must have a maximum diameter of 12.5 mm. The NCA had a bulk density, specific gravity, and water absorption of 1650 kg/m^3, 2.02, and 1.25%, respectively. The utilized SFA was supplied by GBC, India, and its measured bulk density, specific gravity, and water absorption were 910 kg/m^3, 1.2, and 9%, respectively. The particle size distributions for fine aggregates, NCA, and SFA are depicted in Fig. 2. For making concrete, potable laboratory water was utilized, and specimens were cured in accordance with Indian standards [17].

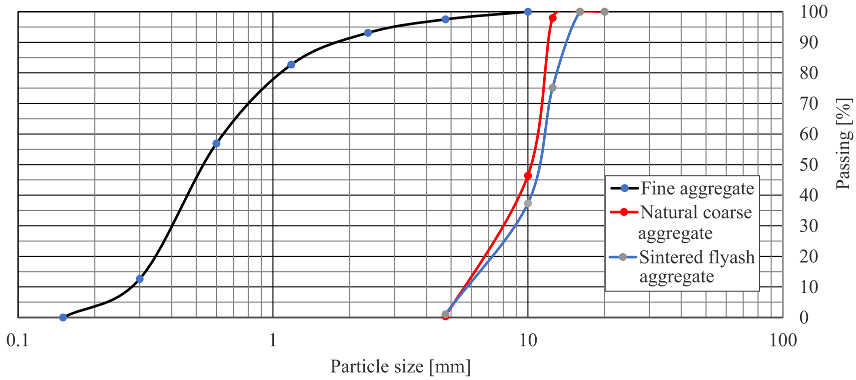

FIG. 2. Particle size distribution curve for fine aggregate, natural coarse aggregate and sintered flyash aggregate.

2.2. Concrete mixes

IS 10262 – 2019 [18] was utilized to develop the mix design for M30 grade concrete. To retain the same ratio of water to cement, the aggregates were utilized under surface-saturated dry conditions. To determine the fresh and dry density, impact behavior, and water absorption characteristics of concrete using various sintered fly ash particles, a total of six distinct concrete mixes were used. Table 1 displays the concrete mix utilized in this experiment. The Mix IDs SFA0, SFA20, SFA40, SFA60, SFA80, and SFA100 correspond to replacement levels of sintered fly ash aggregates.

Table 1. Concrete mixes.

Mix ID	Cement [kg/m^3]	Fine aggregate [kg/m^3]	Natural coarse aggregate (NCA) [kg/m^3]	Sintered fly ash aggregates (SFA) [kg/m^3]	Water [dm^3]
SFA0	332	644	983	0	138.5
SFA20	332	644	786	108	138.5
SFA40	332	644	590	217	138.5
SFA60	332	644	393	325	138.5
SFA80	332	644	197	434	138.5
SFA100	332	644	0	542	138.5

2.3. Casting and curing of specimens

The concrete was prepared using concrete mixing equipment with a 30-liter capacity. The mix started with fine aggregate and cement for 2 minutes, next natural coarse aggregate (NCA) and SFA for 3 minutes, and then water and 4 minutes waiting time to produce a homogeneous concrete mix. After this homogeneous mix slump test was performed, the concrete was poured into the corresponding molds including cubes and discs and kept for 24 hours. After 24 hours, the concrete molds were dispersed and placed in the curing tank until they reached the required age of 28 days. The concrete specimens must be stored at a temperature of 23°C and relative humidity close to 98%.

For each concrete mix utilized in the various tests, the following specimens were cast:

- Five 100 mm cubes, each for fresh density, dry density, water absorption and for 28 days cube compression strength.
- Five 150 mm diameter, 63.5 mm height discs for determining drop weight impact test as per the ACI recommendations.

2.4. Testing procedures

Bureau of Indian Standards (BIS) and American Society for Testing and Materials (ASTM) standards [7, 19, 20] were utilized to determine various parameters in the concrete specimens cast, including fresh and dry density, water absorption, compressive strength, and ACI drop weight impact test.

3. Test results and their discussion

3.1. Workability values

Figure 3 depicts the slump values for various levels of concrete mix with variable SFA. The workability measurements indicate that the slump value of

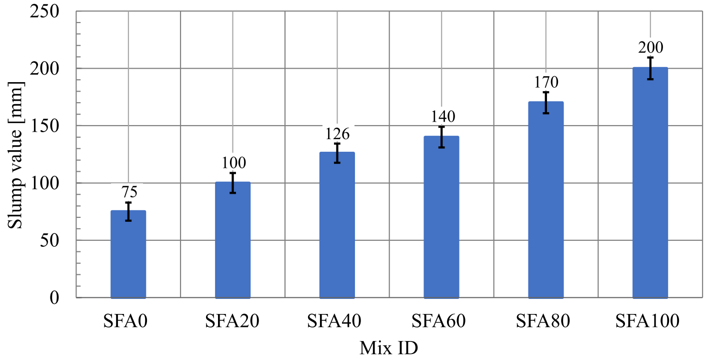

FIG. 3. Various levels of slump values for different percentages of SFA.

concrete mix increases as the percentage of SFA increases. This increase in slump values was caused by the effect of rounded aggregates in the concrete mix [21, 22].

3.2. Fresh and dry density

Figure 4 depicts the variation in fresh and dry density [kg/m^3] of the concrete mix. As the replacement percentage of sintered fly ash aggregates (SFA) in the concrete mix increases, the fresh density decreases, and 100% substitution of SFA in concrete mix results in a fresh density of 1946 kg/m^3.

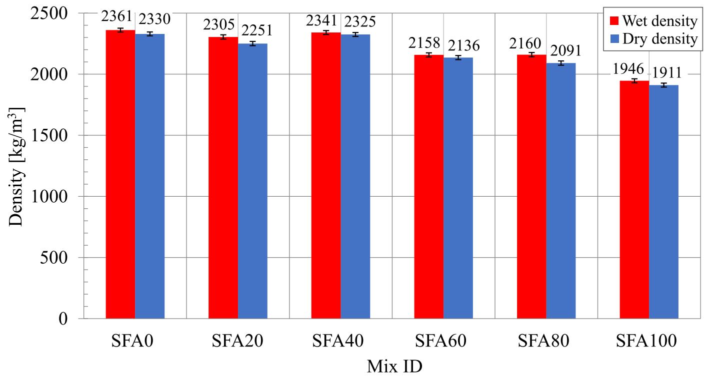

FIG. 4. Various levels of fresh and dry density for different percentages of SFA.

3.3. Water absorption

Figure 5 shows the variation in water absorption values computed based on ASTM C 642-13. Substituting SFA in concrete mix increased its water absorption properties. The water absorption percentage of concrete compositions

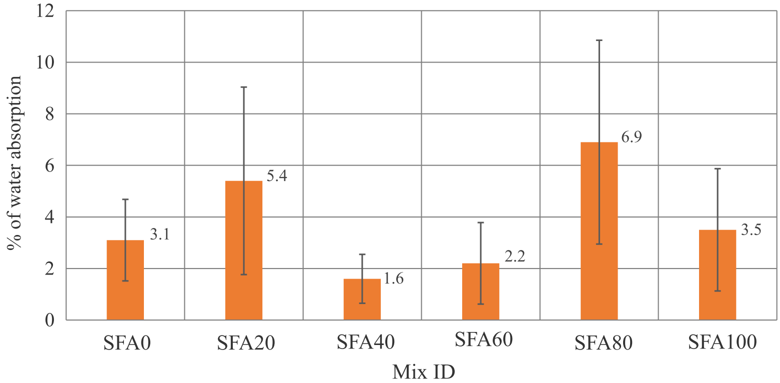

FIG. 5. Percentage of water absorption values for different percentages of SFA.

containing SFA ranged from 1.6% to 6.9%. The lowest water absorption percentage for a concrete mixture containing 40% SFA is 1.6%, and the highest water absorption percentage was 6.9% for SFA 80 concrete combination. The proportion of SFA in concrete had a significant impact on the durability of concrete mix containing SFA. The absorption of water by concrete does not affect its mechanical characteristics [1]. GOMATHI and SIVAKUMAR [29] also identified similar experimental trends on water absorption characteristics for concrete containing sintered fly ash aggregates.

3.4. Compressive strength

Figure 6 depicts the compressive strength of the concrete mix. Replacing concrete aggregates with sintered fly ash aggregates had a direct impact on the compressive strength of the concrete mix. As the percentage of replacement increases, compressive strength reduces. The highest compressive strength of the

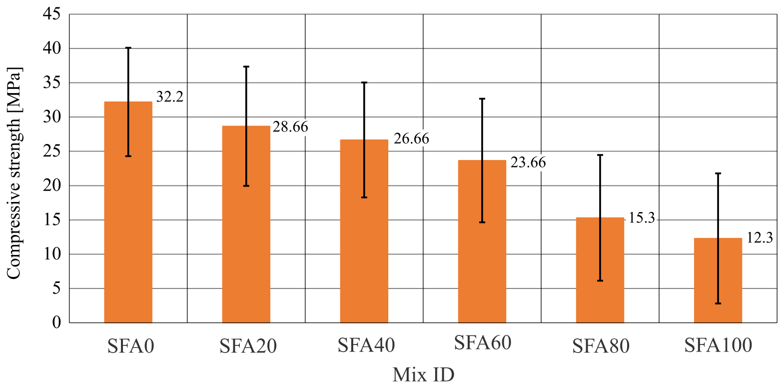

FIG. 6. Cube compressive strength values for different percentages of SFA.

concrete mixture is SFA0, which contains 0% SFA, and the lowest compressive strength is SFA100, which contains 100% SFA. Based on the compressive strength test findings, 60% SFA will be considered for structural lightweight concrete construction. The concrete mixture contains more than 50 % SFA with structural lightweight concrete characteristics as per ACI 213R-03 [24, 30]. The compressive strength of structural lightweight concrete must not be less than 17 MPa [23]. Figure 7 depicts the failure mode of concrete cubes. The failure of cubes is caused primarily by aggregate rupture [24].

FIG. 7. Typical failure of concrete cubes for concrete mixture SFA 100.

3.5. *Drop weight impact test*

The drop weight impact test was performed in accordance with ACI standards [7]. Figure 8 depicts the typical drop weight impact test performed to measure the impact resistance of concrete. A 4.56 kg hammer was built and utilized to drop from a height of 470 mm with the assistance of human force. The hammer should strike directly a steel ball with a diameter of 63.5 mm, which was set on top of a concrete disc with a diameter of 150 mm and a thickness of

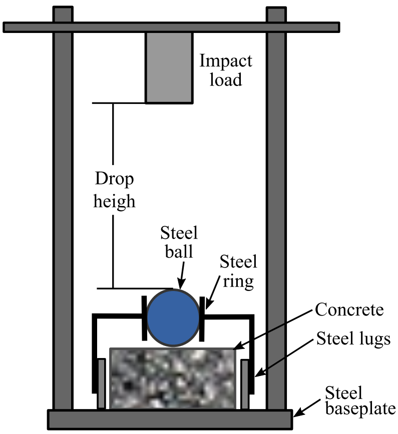

FIG. 8. A typical view of drop weight impact test [25].

63.5 mm. The number of drops at which the specimen showed beginning cracking (seen visually) and the number of drops at which the specimen broke into separate parts upon total failure were recorded. Based on the number of blows, the specimen's absorbed energy is estimated using Eq. (3.1). Figure 8 depicts the standard drop weight impact test suggested by ACI.

$$E = \frac{mv^2}{2} n = (mgh) \cdot n, \tag{3.1}$$

where E, m, v, g, h, and n are the energy absorption, drop mass, velocity at impact, gravitational acceleration, falling height, and the number of drops, respectively.

3.5.1. Impact resistance. Figure 9 depicts the impact resistance of concrete mix with increasing percentages of SFA. The number of blows required for the first crack was designated as N1, and the number of blows required for the failure of the specimen was designated as N2. Based on the average values of the failure blows N1 and N2, the impact resistance of concrete was increased by 60% when SFA was used as a replacement and decreased beyond that point. The results also indicate that the replacement percentage of SFA in the concrete mixture does not increase as the percentage of SFA in the concrete mixture increases from 80% to 100%. Table 2 shows the failure energy is associated with the number of blows required for failure N1 and N2 for each specimen. Table 2 shows that the average number of broken pieces of specimens for the concrete combinations SFA0, SFA20, SFA40, SFA60, SFA80, and SFA100 are 3, 3, 3, 2, 3, 2. The combination of SFA60 and SFA100 had a substantial effect on the impact resistance of concrete. The energy absorption values follow the same pattern as the number of blows required for the first crack and the number of blows required for failure. Figure 10 demonstrates the failures of the specimens.

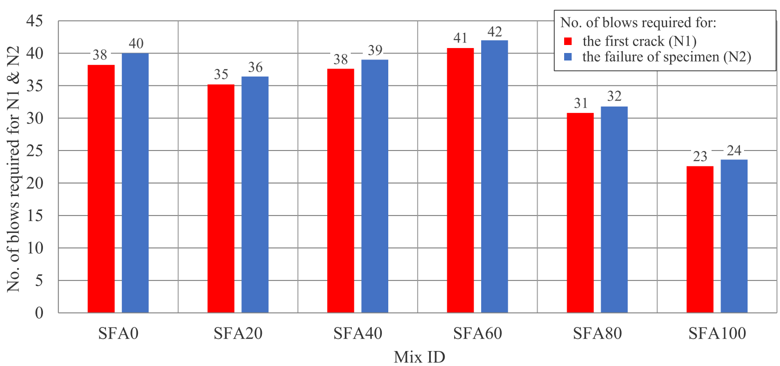

FIG. 9. No. of blows required for the first crack (N1) and no. of blows required for the failure of specimen (N2) for the percentage of varying SFA.

Table 2. Impact resistance measures for the percentage of varying SFA.

Mix ID	No. of blows required for the first crack (N1)	No. of blows required for failure of specimen (N2)	Energy absorption (N1) [N · m]	Energy absorption (N2) [N · m]	No. of broken pieces
SFA0	47	50	988.17	1051.24	3
SFA0	48	50	1009.19	1051.24	2
SFA0	37	38	777.92	798.94	2
SFA0	30	32	630.74	672.79	4
SFA0	29	30	609.72	630.74	2
Average	38	40	803	841	3
SFA20	37	38	777.92	798.94	4
SFA20	41	42	862.02	883.04	2
SFA20	39	40	819.97	840.99	3
SFA20	31	32	651.77	672.79	2
SFA20	28	30	588.69	630.74	4
Average	35	36	740	765	3
SFA40	31	32	651.77	672.79	4
SFA40	34	35	714.84	735.87	2
SFA40	44	46	925.09	967.14	2
SFA40	40	42	840.99	883.04	2
SFA40	39	40	819.97	840.99	3
Average	38	39	791	820	3
SFA60	37	38	777.92	798.94	2
SFA60	63	64	1324.56	1345.59	2
SFA60	47	48	988.17	1009.19	3
SFA60	29	30	609.72	630.74	2
SFA60	28	30	588.69	630.74	2
Average	41	42	858	883	2
SFA80	29	30	609.72	630.74	2
SFA80	31	32	651.77	672.79	3
SFA80	33	34	693.82	714.84	3
SFA80	31	32	651.77	672.79	3
SFA80	30	31	630.74	651.77	2
Average	31	32	648	669	3
SFA100	19	20	399.47	420.50	2
SFA100	20	21	420.50	441.52	3
SFA100	22	23	462.55	483.57	3
SFA100	23	24	483.57	504.60	2
SFA100	29	30	609.72	630.74	2
Average	23	24	475	496	2

Fig. 10. Failure specimens for the typical concrete mix:
a) SFA0, b) SFA20, c) SFA40, d) SFA60, e) SFA80, f) SFA100.

3.5.2. Reliability analysis and its discussion. The Weibull equation describes the relationship between the probabilities of drop weight impact failure energy and the impact test which is similar to the fatigue test on concrete [26]. The fatigue life of the concrete structures can be described using the Weibull function [27, 28]. In this investigation, the two-parameter Weibull distribution is adopted and a graphical method is used for six different concrete mixes for varying SFA. The cumulative distribution function is

$$F(C) = 1 - \exp\left(\frac{c}{b}\right)^{\alpha}, \tag{3.2}$$

where C represents the specific value of random variable N, b denotes the scale parameter, and α denotes the shape parameter.

Taking the natural logarithm twice on both sides of Eq. (3.2) [2] gives:

$$\ln\left(\ln\frac{1}{F_N(C)}\right) = \alpha\ln c - \alpha\ln b. \tag{3.3}$$

Thus, Eq. (3.3) can be used to verify whether the statistical distribution of the impact failure energy in the six groups of concrete mix for varying SFA follows the two-parameter Weibull distribution. In the Weibull distribution, only two steps are adopted. In the first step, the impact failure energy is arranged in ascending order, and then an empirical survivorship function is analyzed.

Several predefined empirical survivorship functions have been used in different sets of literature for evaluating the value of L_N [26]:

$$L_N = 1 - \frac{i - 0.3}{k + 0.4}, \tag{3.4}$$

where i is the failure order number and k is the total number of samples for a given specimen. If an approximately linear relationship is observed between $\ln\left(\ln\frac{1}{L_N}\right)$ and ln(impact failure energy), we can assume that the two-parameter Weibull distribution is a reasonable assumption for the statistical description of the impact resistance factor of the six types of concrete mix for varying SFA.

The probability of survivorship function (R) will be defined as:

$$R = 1 - F_N(C). \tag{3.5}$$

The probability of survival and U_{RN} denote the impact failure energy based on the reliability

$$U_{RN} = b\left[-\ln\left(R^{\frac{1}{\alpha}}\right)\right]. \tag{3.6}$$

The slope of the line for the concrete combinations SFA0, SFA20, SFA40, SFA60, SFA80, and SFA100 was 4.04, 6.91, 7.09, 2.94, 21.42, and 6.04, which corresponds to the values of the shape parameter (α) derived in Fig. 11 using the regression line of each concrete mix. Increasing levels are indicative of decreasing, consistent, and increasing failure rates. The scale parameter b for SFA0, SFA20, SFA40, SFA60, SFA80, and SFA100 concrete mix was calculated to be

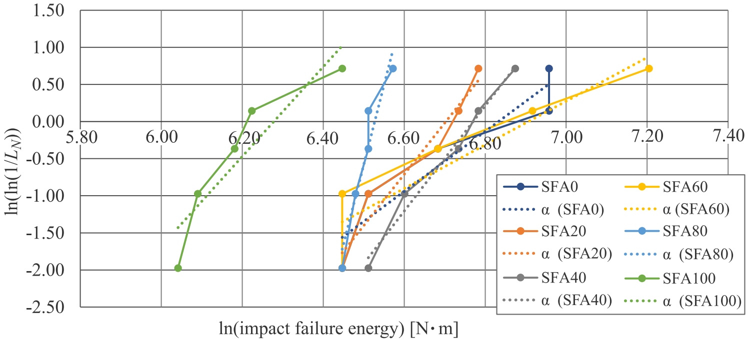

FIG. 11. Linear regression analysis based on the Weibull distribution for the percentage of varying SFA.

927.87, 814.82, 871.46, 999.00, 684.36, and 532.66, respectively. Equation (3.5) yields a reliability value of 0.368 based on the theoretical analysis. Therefore, 36.8% of the concrete mix had impact energy values of at least 927.80 J, 814.78 J, 871.42 J, 998.89 J, 684.35 J, and 566.63 J for various SFAs. The Weibull distribution determined that the impact energy of concrete mix containing 60% SFA has a substantial effect on drop weight impact testing. Figure 12 depicts the Weibull reliability chart for various impact energies for concrete mix.

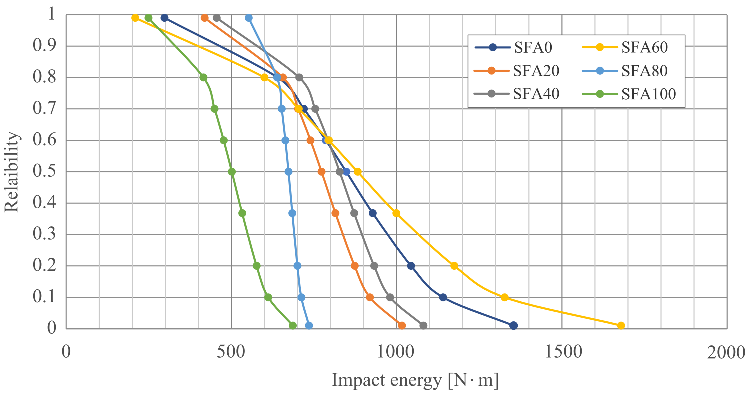

FIG. 12. Weibull reliability distribution.

4. CONCLUSION

The following are the drawn from the presented investigation for the concrete mix containing varying SFA:

The workability of concrete mix containing different percentages of SFA increases as the percentage of SFA increases, according to the findings of the current experiment. The slump value of 100% SFA in the concrete mix is 200 mm.

As the amount of SFA increases, the fresh density of concrete decreases. A similar tendency holds true for dry density as well. The fresh density drops for concrete mix SFA100, which is 21.3% less than that of concrete mix SFA0. Similarly, the dry density of the concrete mix including SFA was lowered by 22%.

The concrete mixtures SFA40 and SFA60 have a compressive strength of 26.66 MPa and 23.66 MPa, respectively. The dry density of the concrete mixture SFA60 was 8.13% smaller than SFA40, so it is more suitable for lightweight concrete application than SFA40 mix.

The drop weight impact resistance indicates that concrete mix containing 60% SFA has greater impact resistance than all other concrete combinations with SFA.

The Weibull reliability analysis demonstrates that the impact resistance of concrete mix and this model can be used to effectively predict the impact life of sintered fly ash aggregate concrete mixtures under different failure probabilities.

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