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Flexural fatigue life assessment of self compacting concrete containing recycled concrete aggregates by using probabilistic approach

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Abstract

Present investigation has been conducted to analyze the fatigue life of self compacting concrete (SCC) containing different quantities of coarse fraction of Recycled Concrete Aggregates (RCA) by using probabilistic method. Three SCC mixes were prepared constituting 0%, 50% and 100% RCA. In total 165 beam specimens of size 100 × 100 × 500 (all dimensions in mm) were tested under fatigue loading in order to obtain fatigue life data at different stress levels. Static flexure test was also conducted on 126 beams prior to fatigue test. Fatigue life data have been modelled by using Weibull distribution method and subsequently distribution parameters were evaluated. Further, fatigue lives in terms of design fatigue life and theoretical fatigue life have been estimated by using the distribution parameters by employing probabilistic approach. It has been found that the design and theoretical fatigue life shows a significant reduction with the addition of RCA content. A decrease of 80-85 percent has been observed in the design and theoretical fatigue life when SCC has been made with RCA only. Substandard properties of RCA cause defects in the concrete by forming weak interfacial transition zone which degrades the fatigue performance of SCC containing RCA.

Keywords: Flexural fatigue test, design fatigue lives, Recycled concrete aggregate, Self compacting concrete

1. Introduction

Construction industry is one of the major exploiter of natural resources as it fulfils its demand of construction aggregates and binder through the extensive mining of rock deposits. The profit making policies of the construction sector neglects the concept of sustainability. Coarse natural aggregates (CNA) are one of the major entities of the concrete as it accounts for three-fourth part of the concrete by volume [1]. Many emerging economies require substantial amount of CNA for their sustainment and expansion of their infrastructure requirements to meet out the demand of the increasing population. CNA have established itself as a most important commodity in the form of non-fuel mineral. Many engineering structures such as buildings, railways, canals, hydroelectric dams, parking lots, sewer system, bridges etc. that are made to facilitate the growing population of the countries require considerable amount of concrete and so CNA for its construction and maintenance. A significant growth in the global population with the passing years results in an exponential growth in the infrastructure demand and subsequently CNA. The demand of construction aggregates in 2014 was approximately 40 billion tons and is forecasted to reach the figure of 65 billion tons by 2022 [2, 3]. These figures have tempted the researchers to propose some alternative of the CNA which is practical, economical and obeys the principal of sustainability.

The quantum of CNA can be restrained by adopting coarse fraction of Recycled Concrete Aggregates (RCA) as a substitute of CNA. RCA can be sourced from the processing of Construction and Demolition Waste (CDW). RCA derived from CDW are economical than CNA and also helps to reduce the emission of green house by 25% to 30% [4]. These positive aspects of RCA have motivated the researchers to explore the properties of concrete containing RCA in order to promote its usage in concrete wherever possible. Construction and demolition of the structures are the two faces of the same coin. Increase in construction activities also results in the increase in the generation of CDW. Figures of CDW generation of some big economies present the current situation. Countries such as France, United Kingdom, United States and Japan generate 349 million tons, 90 million tons, 534 million tons and 77 million tons respectively whereas India produces 17 million tons annually [4]. Although, the CDW generated by India seems to be less as compare to other countries but it is second largest country in terms of population with least per capita floor area of 9.4m^2 [5]. Therefore, densely populated countries like India, cannot afford to lose the available living space for dumping of CDW. The quantity of CDW generation can also be controlled to considerable extent by using RCA as a substitute of CNA. The use of RCA possesses dual benefits i.e. controlling the

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quantum of NA demand as well as reduces the problems associated with the disposal of CDW.

The need of speedy construction and enhanced durability has increased the application of Self Compacting Concrete (SCC) in construction sector. SCC has several advantages over the Normally Vibrated Concrete (NVC). High deformability, low yield stress, non-segregating properties and an ability to maintain its homogeneity while passing through the obstacles are some of its unique characteristics which differs it from the NVC [6]. It can be efficiently used where there is congestion of reinforcement, no possibility of compaction, textured surface concrete elements and at noise restriction sites. The popularity and acceptability of SCC can be asserted from its market share of $9.2 billion in 2016 and is forecasted to rise at an annual growth rate of 6.1% till 2024 [7]. SCC has known to bring reform in the concrete industry and has influenced the researchers to explore its fresh state properties, study its strength and durability parameters under different loading and environmental conditions, with wide range of materials.

Intensive investigations done in the past have concluded that the fresh state properties of SCC degrade with the increase in content of RCA and thus required more Super Plasticizer (SP) in order to maintain its fresh state properties and the reason being the harsh surface texture of RCA due to the adhered mortar over its surface, which obstructs the flow of SCC [8]. Similar conclusions have been drawn when the mineral admixtures such as silica fume, metakaolin and fibres were introduced in SCC mix [9, 10]. Strength and durability of SCC also gets affected with the addition of RCA. However, limiting the percentage of RCA i.e. up to 20 percent in SCC does not show any significant change in strength and durability of concrete but at higher replacement level, the fall in the strength and durability of SCC is noteworthy [11]. The inferior properties of RCA such as lower relative density, higher water absorption and poor interfacial transition zone resulting from adhered residual mortar around the surface of the aggregates are mainly responsible for degrading the strength and durability of SCC containing RCA [12]. However, efforts have been done by the investigators to enhance the quality of RCA by using methods such as grinding, acid treatment, polymer emulsion, carbonation etc. out of which concrete made with carbonated RCA have been found to give most promising results as it increases the density and lowers the water absorption of RCA [13, 14]. Investigators have also tried to compensate the loss in durability of SCC due to addition of RCA by introducing mineral admixtures such as silica fume and metakaolin and observed improvement in the carbonation resistance and permeability of the resulting SCC mix containing RCA [15, 16].

Many concrete structures such as such as decks, bridge piers, off-shore structures, machine foundation, airport and highway pavements etc. are subjected to loading of cyclic or repetitive nature due to which fatigue stresses are induced in these structures. Therefore, it becomes necessary to conduct the fatigue analysis of the material before using the same in the structures susceptible to fatigue loading. Fatigue behaviour of NVC has been extensively studied by the researchers in terms of endurance limit, fatigue lives, strength estimation with respect to different failure probabilities. Statistics of the fatigue lives obtained for NVC at various stress levels have been found to show large scatter therefore it has been well analysed by adopting probabilistic approach as defined by two parameter Weibull distribution at various stress levels [17, 18]. Investigators have also concluded that amongst SCC and NVC, former has been found to show better performance under fatigue loading and the reason being the improved microstructure and fewer defects in the matrix resulting from inadequate compaction as in the case of NVC [19, 20].

An increase in the requirement of bridges and highways for smooth movement of traffic has inspired the researchers to determine the behaviour of concrete under fatigue loading as these structures experience millions of loading cycles during their service life. Bearing in mind, the fatigue strength as a key parameter for design of such structures, majority of the literature discussed in the former section shows that fatigue behaviour of NVC has been extensively studied and the same has been enhanced by adding mineral admixtures and fibres. Various Relationships between stress level (S), commonly expressed as ratio of maximum fatigue stress (lmax) to the average static flexure strength (lr) and number of load cycles (N) have been proposed by the investigators for SCC and NVC. But there is a lack of data and findings that can reflect the fatigue behaviour of SCC containing RCA. Hence present investigation has been conducted in order to study the effect of RCA addition on the fatigue life of SCC. A probabilistic approach has been employed in order to predict the fatigue life in terms of design fatigue life and theoretical fatigue life. It is anticipated that the present investigation will highlight the scope of using RCA in SCC for structures prominently under fatigue load.

2.Investigation and methodology

2.1Material properties and their proportions

SCC primarily consists of binder, aggregates (coarse and fine fraction), admixtures (SP and Viscosity Modifying Agent (VMA)) and water. Binder adopted in present investigation is a combination of fly ash (30%) and Portland cement (70 %). Portland cement of grade 43 and fly ash of type class F were adopted as binder. Properties of Portland cement and fly ash have been mentioned in Table-1 and Table-2 respectively.

Table-1: Characteristics of PC used for making SCC

Characteristic	Result obtained	Permissible Range (IS: 8112-1989)
Specific gravity	3.15	3.10-3.15
Fineness	2350 cm^2/gm	2250 cm^2/gm (minimum)
Soundness	3%	10% (maximum)
Normal consistency	33%	30%-35%
Initial setting time	70 min.	30 min. (minimum)
Final setting time	430 min.	600 min. (maximum)
Compressive strength	45.3 MPa	43 MPa (minimum)

Table-2: Physical and chemical properties of fly ash

Chemical Properties	Fly ash (FA)
Silica (SiO_2)	60.62%
Aluminium oxide (Al_2O_3)	26.97%
Ferrous oxide (Fe_2O_3)	5.03%
Magnesium oxide (MgO)	0.88%
Calcium oxide (CaO)	1.45%
Loss on ignition	1.87%
Specific gravity	2.37
Specific surface area (m^2/kg)	432
Color	Grey

Maximum size of both CNA and RCA was restricted to 12.5mm. Grading patterns of CNA and RCA were kept as close as possible as shown in Fig.-1 in order to avoid the errors in the final results that may arise due to different grading pattern of RCA and CNA. Physical properties of RCA and CNA are shown in Table-3. Locally available sand was employed as fine aggregate and the grading of sand is shown in Fig.-2. Admixtures i.e. SP (polycarboxylic ether based) and VMA were used to maintain the stability of the SCC whose quantity were varied as the content of RCA increases in the mix. Increase of RCA content increases the harshness of the mix hence demand more dosage of SP and VMA. Proportioning of various constituents of different SCC mixes are shown in Table-4.

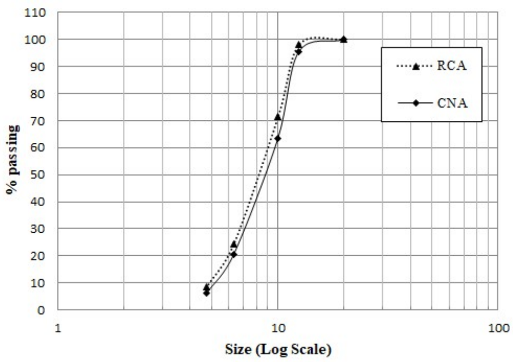


Fig.-1: Grading pattern of RCA and CNA

Table-3: Physical properties of RCA and CNA

Characteristic	Results obtained	
	RCA	CNA
Fineness modulus	6.73	6.98
Specific Gravity	2.47	2.64
Aggregate impact value	30.24%	16.32%
Aggregate crushing value	25.43%	15.81%
Water absorption	5.32%	0.67%

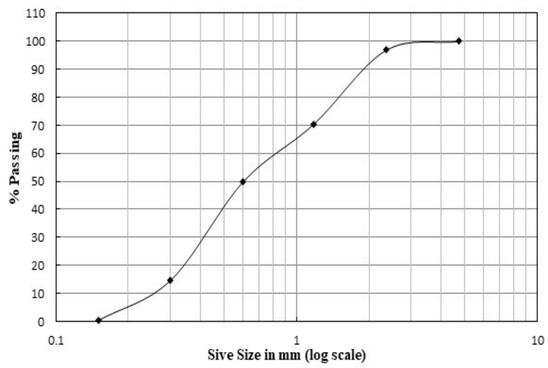


Fig.-2: Grading pattern of sand

Table-4: Mix proportion of SCC mixes (in kg/m^3)

Mix notation →	SCC-CM	SCC-50-RCA	SCC-100-RCA
Cement	430	430	430
Fly ash	185	185	185
CNA	602	301	-
RCA	-	282	563
Sand	845	845	845
Water	246	246	246
SP	1.80	2.15	2.60
VMA	1.72	1.72	1.72

Table-5: Workability test results for SCC mix

Mix notation →		SCC-CM	SCC-50-RCA	SCC-100-RCA
Slump flow	T500 (s)	2	2.3	3.5
	D (mm)	725	710	710
V-funnel (s)		6	7.1	9
L-box (h_2/h_1)		0.8	0.8	0.85
J-ring	Sj (mm)	700	680	680
	$T500_j$ (s)	302	3.8	4.3
	Bj (mm)	2	6	8
Whether conforms to EFNARC guidelines?		Yes	Yes	Yes

2.2 Workability tests and casting procedure

All the above-mentioned constituents in selected proportion were fed into the drum mixer and mixed thoroughly to obtain a homogeneous mix. Soon after the completion of mixing, freshly prepared SCC was examined for its fresh state properties. These properties were determined by conducting various tests such as L-box, V-funnel, J-ring and slump flow as per the guidelines laid down by EFNARC [21]. The test results should be within the limits as prescribed by EFNARC. If not, then the dosage of SP and VMA should be varied as per the requirement of mix. Test results for different SCC mixes have been shown in Table-5.

After determining the fresh state properties of SCC as per the guidelines of EFNARC, casting of specimens were initiated. Specimens were cast by employing systematic batching approach where each batch comprises of 7 beams and 3 cubes. Dimensions of the beams and cubes specimens were 100 × 100 × 500 and 150 × 150 × 150 (all dimensions in mm) respectively. After pouring the SCC in their respective molds, the molds were kept in open atmosphere for a time period of 48 hours and allowed to set gradually. After period of 48 hours, specimens were demolded and taken for the curing task. Cube specimens were cured for a duration of 28 days and then tested for the static compressive strength in order to check the quality of each batch while beam specimens were cured for a duration of 90 days. The reason for the extended curing of beam specimens is to curtail any possibility of strength increment during the course of fatigue testing.

Table-6.1: Fatigue life data for mix SCC-CM

Specimen No.	0.85	0.8	0.75	0.7	0.65
1	327*	2153*	39217	144561	625885
2	1364	9704	45591	168578	775726
3	1489	10622	49303	188948	952695
4	1698	11398	55718	205321	1132428
5	1824	12259	64860	222495	1341522
6	1965	13282	69786	244848	1458241
7	2153	14060	77713	273824	1631218
8	2267	15347	82096	307996	1735311
9	2551	16786	90709	329672	1952672
10	2720	19298	98364	355377	2000000##
11	2891	22612	101905	390761	-
12	-	-	105733	414474	-

** Rejected as outlier by Chauvenet's Criterion, not included in analysis*
Treated as run out

Table-6.2: Fatigue life data for mix SCC-50-RCA

Specimen No.	0.85	0.8	0.75	0.7	0.65
1	154*	527*	3029*	61881	411261
2	403*	6118	20547	69548	520429
3	1002	6751	25416	77652	609523
4	1283	7762	31891	91872	731724
5	1528	8748	36426	102642	912816
6	1592	10192	44953	119227	1154267
7	1782	11617	48821	132169	1273541
8	1862	13082	53623	151128	1424215
9	2085	13973	59942	159261	1497724
10	2260	14264	61481	181365	1519627
11	2371	15332	67283	205134	-
12	2537	16747	-	-	-

** Rejected as outlier by Chauvenet's Criterion, not included in analysis*
Treated as run out

Table-6.3: Fatigue life data for mix SCC-100-RCA

Specimen No.	0.85	0.8	0.75	0.7	0.65
1	293*	2866	9332	26582	128770
2	872	3162	11752	34982	137850
3	1034	4252	13512	47084	168304
4	1275	5042	17991	55441	215101
5	1330	5631	19610	71271	282727
6	1641	6226	23829	85343	323210
7	1788	6542	26845	97592	386575
8	2043	7830	30574	101220	445552
9	2091	8691	33162	110462	548192
10	2157	9374	35389	121440	637738
11	2215	-	35915	-	-
12	-	-	38852	-	-

** Rejected as outlier by Chauvenet's Criterion, not included in analysis*
Treated as run out

2.3 Methodology adopted for fatigue testing

There are three basic parameters required for performing fatigue test i.e. maximum fatigue stress (l_{max}), minimum fatigue stress (l_{min}) and frequency of applied load that are determined by using stress level ($S = l_{max}/l_r$) and stress ratio ($R = l_{min}/l_{max}$), where l_r denotes average static flexure strength. In order to determine the value of average static flexure strength, it is required to conduct static flexure test on the beams randomly chosen from each batch. Static flexure as well as fatigue tests were performed by using four-point loading method in which beam specimens were rested over the supports covering a distance of 450mm from center to center and the loads were applied at a distance of 150mm from both supports. Loading mechanism mainly consist of hydraulic actuator mounted over reaction frame of 2000kN capacity and is designed to operate in the close loop by servo controller. While conducting the fatigue test stress ratio and load frequency was fixed at 0.1 and 10Hz respectively whereas stress level was varied from 0.85 to 0.65. Loading was applied on the specimens in the form of continuous sinusoidal waveform and the number of loading cycles applied for the failure of the specimens were recorded from the controller of the fatigue testing machine. An upper boundary of two million cycles was selected to test large number of specimens in a given time period. Specimen under fatigue testing was tested until its failure or the loading cycles touches the value of two million. Fatigue life data obtained by testing specimens at several stress levels are shown in Tables-6.1-6.3.

3. Results and Discussion

3.1 Static compressive and flexure strength

As stated above that the static compressive strength is determined to check the quality of each batch whereas the static flexure strength of each batch serve as the input for conducting fatigue test. Static strength parameters shows a declination with the increase of RCA content. Static compressive and flexure strength of SCC containing CNA (SCC-CM) have been found to be 42.31 N/mm_2 and 5.13 N/mm^2 respectively. As the replacement of CNA has been done to a level of 50% in mix SCC-50-RCA, static compressive and flexure strength descends to 35.40 N/mm^2 and 4.92 N/mm^2 respectively whereas for mix with 100% RCA (SCC-100-RCA) static compressive and flexure strength observed were 31.35 MPa and 4.32 MPa respectively. Same has been represented graphically in Fig.-3. It can be concluded from the results of static tests that the increase in RCA content will result in the formation of weak interfacial transition zone which causes deterioration in the static strength of the resulting SCC.

3.2 Analysis of fatigue data by Weibull distribution

As it can be observed from the fatigue life values obtained at various stress levels that there is a significant randomness in the fatigue life values hence there is a need to apply some statistical method for the analysis of fatigue life of SCC mixes. Therefore, Weibull distribution method has been adopted for the analysis of fatigue life at different stress level. The conformity of the Weibull distribution for the fatigue life data has been ensured by using graphical method. The expression for reliability function (L_N) for Weibull distribution is given as follow [19, 22]:

$$L_N = \exp\left[-\left(\frac{n}{u}\right)^{\alpha}\right] \quad (1)$$

The expression can be simplified by taking logarithm on both the sides.

$$\ln\left[\ln\left(\frac{1}{L_N}\right)\right] = \alpha\ln(n) - \alpha\ln(u) \quad (2)$$

where, α and u are Weibull distribution parameters called as shape parameter and scale parameter, n is random variable. In present investigation random variable is fatigue life (N).

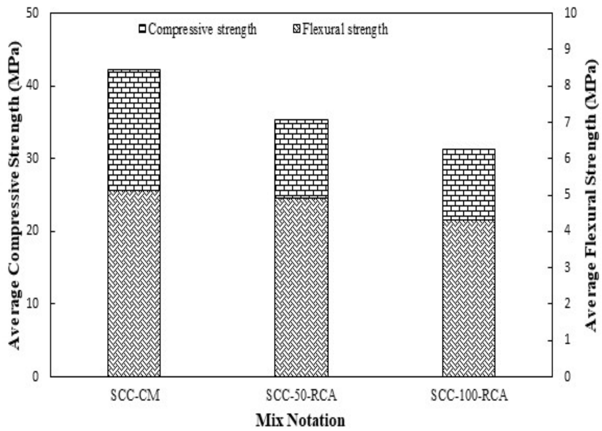


Fig.-3: Average static compressive strength and flexural strength of SCC mixes

By using the above equation (2), a graph is plotted between $\ln\left[\ln\left(\frac{1}{L_N}\right)\right]$and ln(N) for the obtained values of fatigue life data at various stress levels for each SCC mix and if the plots set a linear trend at stress levels under consideration then it confirms the applicability of Weibull distribution for that particular stress level and SCC mix. Reliability function (L_N) can be evaluated by employing following relation [19].

$$L_N = 1 - \frac{i}{k+1} \quad (3)$$

Where, i and k are total number of fatigue data and failure order respectively at particular stress level. Graphical plots of SCC mixes are shown in Figs.-4.1-4.3. It can be observed from the graphical plots that the fatigue life data for various SCC mixes under consideration sets a linear trend and is in agreement with the Weibull distribution with correlation coefficients greater than 0.9. Therefore, distribution parameters (α and u) were evaluated by conducting regression analysis over the obtained values of fatigue life at considered stress levels. Distribution parameters were also evaluated by using method of moments and method of maximum likelihood estimation. Details of these methods have been discussed by authors elsewhere [23]. Average values of distribution parameters obtained by abovementioned methods are listed in Table-7.

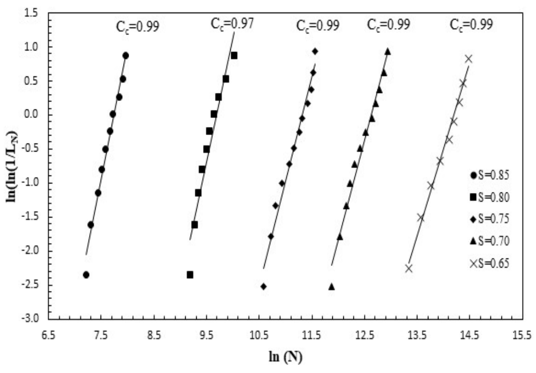


Fig.-4.1: Analysis of fatigue life data of SCC mix SCC-CM

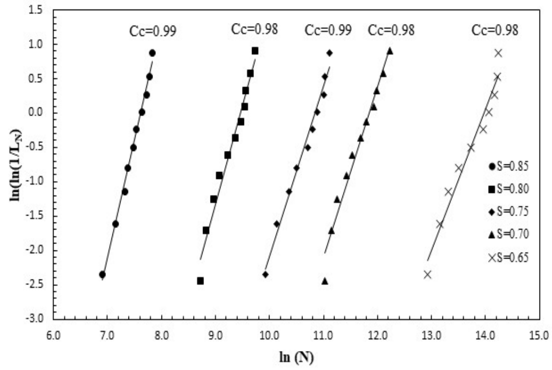
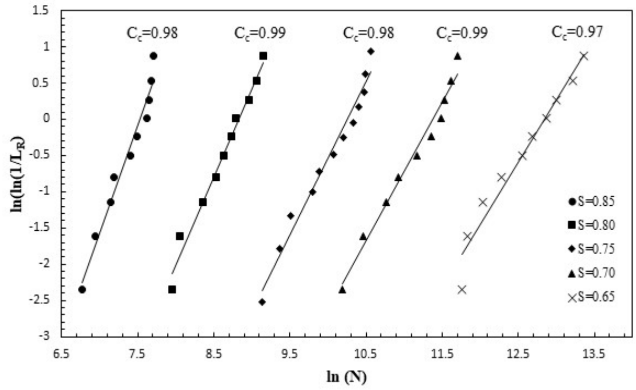


Fig.-4.2: Analysis of fatigue life data of SCC mix SCC-50-RCA



3.3 Estimation of design fatigue life

It has been observed that the even if the fatigue testing is conducted under carefully controlled testing environment, then also it can result in randomness in the fatigue data at a particular stress level. Therefore, a probabilistic approach is required to estimate the design fatigue life of SCC. A term called as failure probability (P_f) has been introduced along with the fatigue life. Fatigue life corresponding to a particular value of failure probability is called as design fatigue life (N_D). For a structure subjected to fatigue loading, its serviceable fatigue life should be less than the design fatigue life for a particular value of failure probability i.e. structure should be serviceable till the number of loading cycles is less than the design fatigue life or in other words at ($P_f = P$), $N < N_D$. Design fatigue life with respect to required failure probability can be estimated by using following relationship.

$$N_D = u\left[ln\frac{1}{1-P_f}\right]^{\frac{1}{\alpha}} \quad (4)$$

Design fatigue lives have been estimated at failure probabilities varying from 0.01 to 0.25. Mean value of Weibull distribution parameter (α and u) derived from the abovementioned methods has been employed for estimation of design fatigue life at different failure probability and at different stress levels. Design fatigue lives for different SCC mixes at varying stress levels have been mentioned in Tables-8-10. A comparison between the design fatigue lives for different SCC mixes at failure probability of 0.25 has been shown graphically in Fig.-5. It can be observed that the design fatigue life increases for the higher value of failure probability. Where higher reliability is required i.e. lower acceptable probability of failure, lower value of design

Table-7: Values of shape parameter α and characteristic life u for fatigue life data of different SCC mixes

Mix notation	Stress level	Graphical Method		Method of Moments		Maximum Likelihood		Average Value	
		α	u	α	u	α	u	α	u
SCC-CM	0.85	3.916	2308	4.517	2292	4.774	2288	4.402	2296
	0.80	3.603	16119	3.954	16048	3.934	16033	3.830	16067
	0.75	3.038	82667	3.510	81584	3.827	81500	3.458	81917
	0.70	2.974	303785	3.317	301558	3.530	301465	3.274	302269
	0.65	2.545	1472331	3.108	1441743	3.457	1439405	3.037	1451160
SCC-50-RCA	0.85	3.421	2043	4.132	2015	4.556	2009	4.036	2022
	0.80	2.886	12798	3.401	12606	3.744	12592	3.344	12665
	0.75	2.482	51499	3.056	50326	3.412	50392	2.983	50739
	0.70	2.503	139727	2.803	138007	2.997	138112	2.768	138615
	0.65	2.069	1165974	2.553	1132607	2.828	1134020	2.483	1144200
SCC-100-RCA	0.85	2.978	1854	3.692	1823	4.208	1818	3.626	1832
	0.80	2.455	6815	2.909	6682	3.166	6682	2.843	6726
	0.75	2.115	28568	2.594	27833	2.843	27865	2.517	28089
	0.70	1.912	87162	2.426	84733	2.669	84821	2.336	85572
	0.65	1.726	380987	1.958	369278	2.115	371625	1.933	373963

Table-8: Design fatigue lives at different failure probabilities for mix SCC-CM

Stress level	Design fatigue life, N_D				
	$P_f = 0.01$	$P_f = 0.05$	$P_f = 0.1$	$P_f = 0.15$	$P_f = 0.25$
0.85	807	1169	1377	1520	1730
0.80	4834	7398	8928	9998	11605
0.75	21659	34701	42731	48437	57135
0.70	74163	122011	152014	173530	206598
0.65	319027	545725	691688	797789	962831

Table-9: Design fatigue lives at different failure probabilities for mix SCC-50-RCA

Stress level	Design fatigue life, N_D				
	$P_f = 0.01$	$P_f = 0.05$	$P_f = 0.1$	$P_f = 0.15$	$P_f = 0.25$
0.85	647	969	1158	1289	1485
0.80	3200	5210	6462	7356	8726
0.75	10854	18745	23861	27592	33414
0.70	26306	47401	61480	71901	88375
0.65	179433	345934	462271	550430	692764

Table-10: Design fatigue lives at different failure probabilities for mix SCC-100-RCA

Stress level	Design fatigue life, N_D				
	$P_f = 0.01$	$P_f = 0.05$	$P_f = 0.1$	$P_f = 0.15$	$P_f = 0.25$
0.85	515	808	985	1110	1299
0.80	1334	2366	3048	3550	4339
0.75	4517	8631	11488	13647	17122
0.70	11943	23996	32656	39313	50200
0.65	34617	80446	116743	146085	196294

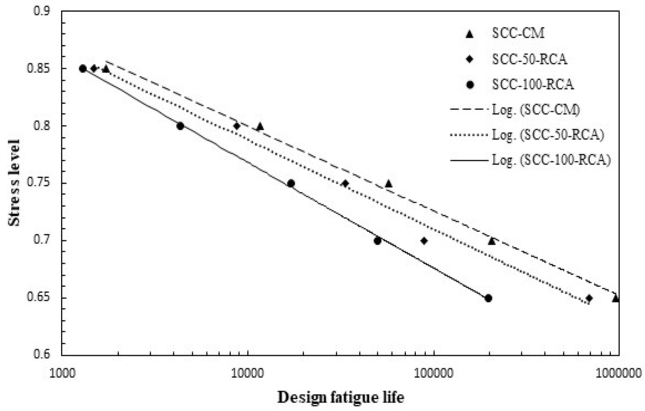


Fig.-5: Comparison of design fatigue lives of SCC mixes at $P_f = 0.25$

fatigue life has been obtained which correlates with actual practical conditions. It can also be concluded that for the same value of failure probability, design fatigue life decreases for increase in the content of RCA hence RCA degraded the design fatigue life of SCC.

3.4 Estimation of theoretical fatigue lives at 10% failure probability

Fatigue life data for SCC mixes have been found to be in accordance with the Weibull distribution. Expression derived from the reliability function defined by Weibull distribution in Eq. (2) can be further used to calculate the fatigue life at required failure probability known as theoretical fatigue life. Eq. (2) has been recalled here for reference.

$$\ln\left[\ln\left(\frac{1}{L_N}\right)\right] = \alpha \ln(n) - \alpha \ln(u) \quad (2)$$

By substituting $L_N = 1 - P_f$, the above equation can be reframed as

$$N = ln^{-1}\left[\frac{ln\left\{ln\left(\frac{1}{1-P_f}\right)\right\}+\alpha\ln(n)}{\alpha}\right] \qquad (5)$$

By substituting the value of failure probability (P_f) and distribution parameters the value of fatigue life corresponding to desired failure probability can be determined. In present study failure probability of 10% is considered for discussion. Fatigue lives calculated from Eq. (5) for different SCC mixes at failure probability of 10% at various stress levels are shown in Table-11.

Theoretical fatigue lives for SCC mixes have been evaluated by employing single log equation as mentioned below [24, 25]:

$$S = \frac{l_{max}}{l_r} = E_1 + E_2\, log_{10}(\text{N}) \qquad (6)$$

Where E_1 and E_2 are experimental constants which are determined by plotting the fatigue life (N) on a logarithmic scale on X-axis against the stress level (S) on Y-axis and subsequently linear regression analysis has been done to calculate the values of constants E_1 and E_2 for SCC mixes as shown in Fig.-6. Final forms of Eq. (6) for different SCC mixes have been shown in Table-12. Constants E_1 and E_2 have their respective significance i.e. greater the value of E_1 greater is the theoretical fatigue life provided if E_2 remains constant whereas change in the value of E_2 reflects the sensitivity of the theoretical fatigue life for change in the stress level. Theoretical fatigue lives estimated for different SCC mixes at various stress levels have been mentioned in Table-13 and same has been represented graphically in Fig.-7. A significant decrease has been observed in the theoretical fatigue life with the addition of RCA in SCC. Theoretical fatigue life reduces by 49% when 50% CNA were substituted with RCA. Similarly, a declination of 85 % has been observed when 100% RCA have been employed for making SCC. This decline in the theoretical fatigue life is due to the second-rate properties of RCA which induces micro defects in matrix by forming weak interfacial transition zone in SCC.

Table-11: Fatigue lives corresponding to failure probability of 10% for different SCC mixes

Mix Notation	Stress Level (S)				
	0.85	0.80	0.75	0.70	0.65
SCC-CM	1377	8928	42731	152014	691688
SCC-50-RCA	1158	6462	23862	61480	462271
SCC-100-RCA	985	3048	11488	32656	116743

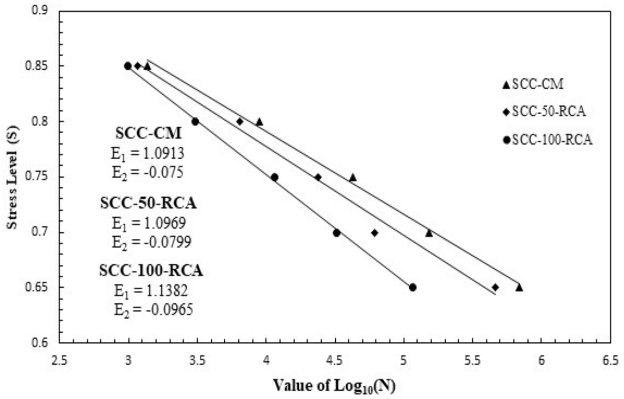


Fig.-6: Calculation of coefficients E_1 and E_2 for SCC mixes

Table-12: Experimental coefficients E1 and E2 of Eq. (13) for different SCC mixes

Mix Notation	Experimental Coefficients		$S = \frac{l_{max}}{l_r} = E_1 + E_2 \log_{10}(N)$
	E_1	E_2	
SCC-CM	1.0913	-0.075	$S = 1.0913 - 0.075 \log_{10}(N)$
SCC-50-RCA	1.0969	-0.0799	$S = 1.0969 – 0.0799 \log_{10}(N)$
SCC-100-RCA	1.1382	-0.0965	$S = 1.1382 – 0.0965 \log_{10}(N)$

Table-13: Theoretical fatigue lives for various SCC mixes

Mix Notation	Stress Level ⟶	0.85	0.80	0.75	0.70	0.65
SCC-CM	Theoretical Fatigue life	1649	7656	35536	164943	765597
	Percentage Change*	0	0	0	0	0
SCC-50-RCA	Theoretical Fatigue life	1231	5199	21962	92781	391960
	Percentage Change*	-25.39#	-32.10#	-38.20#	-43.75#	-48.80#
SCC-100-RCA	Theoretical Fatigue life	969	3196	10539	34748	114569
	Percentage Change*	-41.25#	-58.25#	-70.34#	-78.93#	-85.04#

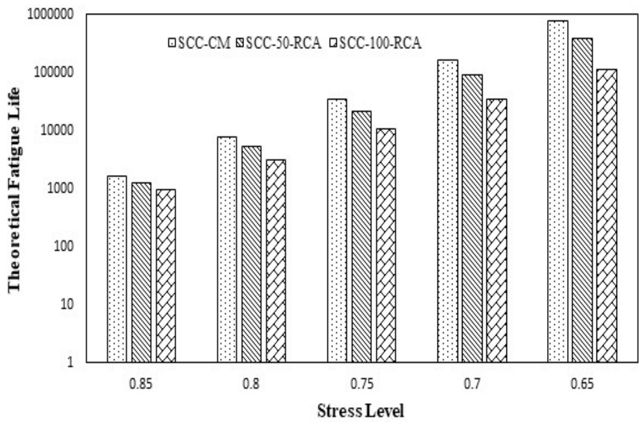


Fig.-7: Theoretical fatigue life for different SCC mixes

4. Conclusion

Fatigue life analysis of SCC containing different proportion of RCA has been done in the present investigation by employing probabilistic approach. Fatigue lives of different SCC mixes have been analyzed by using probabilistic approach and have been estimated in terms of design fatigue life and theoretical fatigue life at different failure probabilities. Both static compressive strength and flexure strength decreases with the increase in RCA content. For mix SCC-50-RCA static compressive and flexure strength decreases by 16% and 4% respectively whereas for mix SCC-100-RCA static compressive and flexure strength decreases by 26% and 16% respectively. It can be concluded from the obtained values of shape parameter (α) for SCC mixes that the shape parameter decreases with the increase in RCA content which indicates an increase in the variability in fatigue life of SCC. Similar conclusion can be drawn from the estimated design fatigue life and theoretical fatigue life. Design fatigue life at same failure probability also decreases with the increase in RCA content. Maximum decrease in the design fatigue lives of order 28% and 80% have been observed at failure probability of 0.25 for mix SCC-50-RCA and SCC-100-RCA respectively as compare to control mix (SCC-CM). Theoretical fatigue lives decrease by 48% and 85% at stress level of 0.65 for mix SCC-50-RCA and SCC-100-RCA respectively as compare to control mix. Such a decline in the fatigue performance of SCC containing RCA is mainly attributed to the inferior properties of RCA as compare to CNA which imparts defects in the concrete due to formation of weak interfacial transition zone. However, investigation is in progress at the authors institute to improve the fatigue performance of SCC containing RCA by effective and economical means.

Disclosures

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