DE GRUYTER OPEN

DOI: 10.1515/sspjce-2015-0001

Flexural Fatigue performance of Alkali Activated Slag Concrete mixes incorporating Copper Slag as Fine Aggregate

Mithun B.M, Narasimhan M.C, Nitendra Palankar and Ravishankar A.U

National Institute of Technology Karnataka, Surathkal, Mangalore, India - 575 025
Department of Civil Engineering
e-mail: mithunbm@gmail.com, mattur.cn@gmail.com, nitendrapalankar@gmail.com and aurshankar@gmail.com

Abstract

The present investigation attempts a detailed study of mechanical properties and fatigue characteristics of a new class of Alkali Activated Slag Concrete (AASC) mixes incorporating Copper Slag (CS) as fine aggregates. The natural river sand is replaced with Copper Slag, upto 100% (by volume) as fine aggregate in these AASC mixes. The behavior of plain concrete prisms, cast with this range of AASC mixes under dynamic cyclic loads with sand/CS fine aggregates is studied and is compared with conventional OPC-based concrete specimens. The results indicate that incorporation of CS even upto 100% as fine aggregates, did not have any adverse effects on the mechanical properties of AASC mixes. The AASC mixes with CS displayed slightly better fatigue performance as compared to AASC mix with river sand. An attempt is also made herein to statistically describe the fatigue life data of AASC mixes using a 2-parameter Weibull distribution.

Key words: alkali activated slag concrete, copper slag, flexural fatigue, sustainable concrete

1 Introduction

The study on Alkali Activated Slag Concrete (AASC) as an alternative construction material to well-established Ordinary Portland Cement-based Concrete mixes (OPCC) have gained much importance recently. The use of large amounts of Ground Granulated Blast Furnace Slag (GGBFS), an industrial by-product from iron and steel industry, in the production of AASCs leads to reduced consumption of virgin, non-renewable resources like limestone, clay, coal etc. required for manufacture of Ordinary Portland Cement (OPC). With reduced consumption of energy and the associated reduction in CO_2 discharge in their manufacture, AASC mixes also have shown higher mechanical strengths at early ages, better resistance when exposed to either aggressive environments or elevated temperatures [1-3]. With such desirable properties, alkali-activated slag concretes can be considered as very promising alternatives to OPCC mixes from economical and technical points of view [3,4].

Copper slag (CS), a by-product obtained from the manufacture and decontamination of copper, can be identified as a potential replacement for sand [5]. The production of one ton of copper produces about 2 to 2.3 tons of CS as a by-product. About 2.5 million tons of CS is generated annually in India, which is to be disposed off as industrial waste.
Studies conducted on High Performance Concrete (HPC) mixes using CS as fine aggregates have recorded better workability and 28-day strength increments with mixes containing upto 50% CS as fine aggregates. However, replacement of sand with CS beyond 50% (by weight) has resulted in the decline in the strength properties [5]. Concrete mixes produced with 100% CS (by weight) have recorded better compressive strength when constant workability was maintained [6]. The high density and glassy surface texture with shape ‘rough’ of CS may often lead to undesirable effects in concrete mixes such as excessive bleeding leading to weaker top surface layers and the formation of water pockets below bigger particles of coarse aggregate. Such adverse effects are known to increase with higher contents of CS in the concrete mixes. However, it has been shown that, by limiting the CS content up to 40% or by adding fines, in the concrete, the extent of bleeding can be controlled [7].

The fatigue property is a key factor in the design of rigid pavements since the pavements structures are subjected to many cyclic loads during their service life. ACI 215R-74 defines Fatigue as - a process of progressive permanent internal structural change in a material subjected to repetitive stresses. These changes may be damaging and result in progressive growth of cracks due to repeated application of traffic loads, progressive fatigue damage takes place in the cement concrete slab in the form of gradual development of micro cracks and complete fracture if the stress repetitions are sufficiently large. Fatigue failure is generally a time dependent process which initiates due to progressive development of cracks followed by further crack propagation, thus leading to permanent material failure under repeated loading. Fatigue failure usually occurs at a lower flexural stress than the modulus of rupture of the concrete material determined by static tests under the prolonged influence of cyclic loads [8]. The fatigue failure depends upon several other parameters namely material characterization, magnitude of the applied stress, frequency of load applications etc., [9, 10]. The fatigue data of concrete structures may be represented using the S-N curves which provide a graphical representation of the number of cycles required for the concrete structure to fail against the applied stress level [11].

Despite of satisfactory performance of CS in conventional PC based concrete mixes; there is no literature available on the use of CS in AASC mixes. The present study aims to study the mechanical and fatigue characteristics of a class of AASC mixes with varying replacement levels of sand with CS as fine aggregates.

2 Experimental Investigations

1.1 Materials

1.1.1 Cement

43 Grade OPC conforming to IS 8112 – 2013, was used for preparing the reference concrete mix. The cement was having a fineness of about 340 m^2/kg (Blaine) and specific gravity of 3.14. Compressive strengths of cement at 7 and 28 days were 40.2 and 57.0 MPa respectively.

1.1.2 GGBFS

In the present investigation, Ground Granulated Blast Furnace Slag (GGBFS) conforming to IS: 12089 – 1987 was used as the starting material to produce alkali-activated slag concrete mixes. The same was obtained from M/S Jindal Steel Works, Bellary, India. The slag had a fineness of about 370 m^2/kg (Blaine) and specific gravity of 2.9, basicity coefficient [$K_b=(CaO+MgO)/(SiO_2+Al_2O_3)$] of 0.88 (acidic slag).

2.1.3 Aggregates

Locally available crushed granite chips of maximum nominal size of 20 mm were used as coarse aggregate. The specific gravity and water absorption of the coarse aggregate were 2.69 and 0.4%, respectively. The specific gravity, water absorption and fineness modulus (FM) of local river sand used in control concrete mixes were 2.64, 1.55% and 2.58, respectively. The specific gravity, water absorption and fineness modulus (FM) of CS used were 3.6, 0.50% and 2.61 respectively. The results show that grading of both sand and CS used herein conform to Zone II, as per IS: 383– 1970.

2.1.4 Alkali solution

The alkali activator solution used herein is a mixture of liquid sodium silicate and sodium hydroxide, with SiO_2/Na_2O ratio (modulus, Ms) of 1.25 and Na_2O concentration of 4% (by weight of GGBFS). Commercial grade Sodium Hydroxide (NaOH) flakes (97% purity) and Liquid Sodium Silicate (LSS) (14.7% Na_2O + 32.8% SiO_2 + 52.5% H_2O by mass, and density = 1570 kg/m^3), were used in the preparation of this alkali activator solution. The desired modulus was obtained by adding NaOH flakes to appropriate amount of LSS. Tap water available in the institute laboratory was then added to bring the total water to binder (binder=GGBFS in AASC) ratio to 0.4, for all AASC mixes, taking into account the amount of water readily present in the LSS. Alkali solution was immediately transferred to a container with air tight cap, left for at least 24 hours to cool, before using in a concrete mix.

2.1.5 Super plasticizers

A commercially available, chloride-free Naphthalene sulfonate-based admixture (Conplast SP 430) with 40% solids in solution was used to increase the workability of the OPC-based control concrete mix.

2.2 Mix design

The guidelines specified by IS: 10262-2009 were used for the mix design of OPC based concrete mix. With a binder content of 440 kg/m^3 and total water/binder ratio of 0.4, the mix was targeted to achieve a slump of 50-75 mm. The ratio of volume of coarse aggregate content to fine aggregate content was maintained at 36% and 64% of the total aggregate volume respectively. The mix design for AASC mixes with river sand fine aggregate, were based on trials with systematic modifications in the design parameters of OPC-based control mix. The total binder content and w/b ratio for AASC mixes were kept same as that of OPCC (440 kg/m^3 of GGBFS and w/b of 0.4) and the remaining volume was adjusted for aggregates.

The GGBFS binder was activated using an alkaline activator at a constant Na_2O dosage of 4% with an activator modulus ($Ms = SiO_2/Na_2O$) of 1.25.

After the finalization of the quantities of all ingredients, AASC mixes with CS are prepared by replacing natural fine aggregates up to 100% (by volume of fine aggregates) keeping the total volume of fine aggregates constant. Due to higher density of CS, the mass of CS used was more than that of sand of equal volume at each replacement level. Details of mix proportions of all the six trial mixes tested herein are presented in Table 1. All concrete mixes had a nominal compressive strength of 65±4 MPa at 90 days

Table 1: Details of Mix proportions of concrete mixes (All ingredient contents are in kg/m^3)

Mix ID	OPC	GGBFS	Fine Aggregates		Coarse Aggregate	LSS	NaOH flakes	Added water	Total water	SP	Density kg/m^3
			Sand	CS							
OPCC	440	-	650	-	1178	-	-	174.4	176	2.64	2445
ACS-0	-	440	630	-	1141	67.1	10	140.8	176	-	2429
ACS-25	-	440	473	216	1141	67.1	10	140.8	176	-	2488
ACS-50	-	440	315	432	1141	67.1	10	140.8	176	-	2547
ACS-75	-	440	156	648	1141	67.1	10	140.8	176	-	2606
ACS-100	-	440	-	864	1141	67.1	10	140.8	176	-	2665

Note: OPCC - Portland cement based control mix; ACS-**X** - represents AASC mixes with X (% by volume) of sand replaced with copper slag. LSS – Liquid Sodium Silicate, SP - Superplasticizer

2.2.2 Sample preparation, curing and testing

Concrete cube samples of 100mm size and prism samples of 100mm x 100mm x 500mm size were prepared with each of the above mixes, to determine their compressive strengths and flexural strengths respectively. Concrete specimens were demoulded after 24 hours; OPC concrete cubes were cured in water, while alkali-activated slag concretes were kept at ambient laboratory condition having 85±10% relative humidity at 27±3°C until testing in order to prevent leaching and tested as per the guidelines in IS: 516-1959.

The fatigue tests for concrete specimen were conducted using an MTS SERVO hydraulic testing machine with 5 ton capacity, on prism specimen of size (100x100x500) mm. The fatigue tests were performed on prisms of OPCC, ACS-0, ACS-50 and ACS-100 mixes. The effective span of prism (400mm) and the position of loading points were maintained similar to those for static flexural tests (third point bending test). The static flexural strengths of the concrete mixes at 90 days were evaluated before beginning the test. The fatigue tests were carried out after 90 days in order to reduce the errors due to strength development with age of the various concrete mixes. The specimens were tested at constant amplitude of loads, without any rest periods in between, at a frequency of 4 Hz using half sinusoidal wave form. The maximum load was applied according to the desired stress level, however the minimum load was kept zero. The tests were performed at different stress levels 'S' (ratio of applied stress to modulus of rupture) of 0.85, 0.80, 0.75, 0.70 and the fatigue life 'N' (number of cycles to failure) for each sample was recorded. A total of 80 samples were tested with five specimens for each mix at every stress level. The entire data set of obtained fatigue lives for all the mixes are represented using S-N curves, however one set of readings are tabulated in Table 2.

2 Results and Discussions

2.1 Static Flexural strengths of AASC prisms

Average 90 days flexural strength of 7.05MPa, 7.54 MPa, 7.6 MPa and 7.65 MPa was obtained for OPCC, ACS-0, ACS-50 and ACS-100 respectively. It is observed that the AASC mixes with sand/CS fine aggregates display higher flexural strengths than the reference OPCC. No appreciable variation in flexural strengths can be noticed with the increasing replacement of sand with CS in AASC mixes at all ages. This may have to be attributed to the possible development of distinct microstructure and the presence of dense and uniform interfacial transition zone in AASCs as compared to OPCC [12].

2.2 Flexural fatigue behaviour of AASC concrete prisms

Table 4 presents the results of fatigue tests conducted herein on the standard prism specimens cast with OPCC and the AASC mixes, with decreasing amplitude of the repeated load. The load applied on the specimens is represented in terms of the 'stress ratio' which is the ratio of stress applied to the modulus of rupture obtained for the mix during the static flexural testing. The usual way of representing the fatigue data is by plotting the S-N curve. In a fatigue experiment, the S-N curves i.e. the graphs of stress ratio S v/s number of cycles up to failure N (on log scale) are plotted as shown in Fig. 1. The best-fit straight- line relation between Stress Ratio S and number of fatigue cycles (N) obtained from the experimental results for all the concrete mixes are then obtained as listed in Table 3.

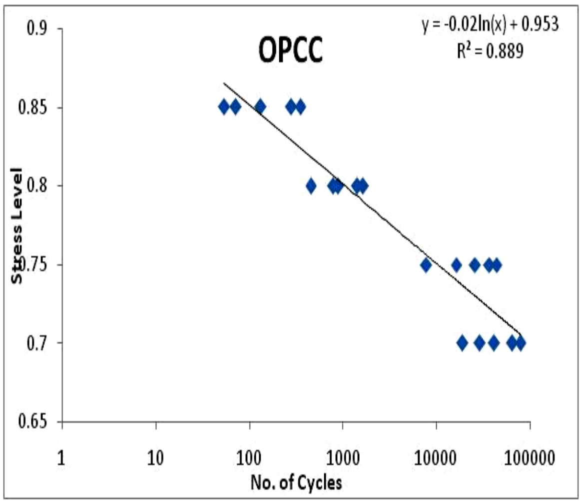
Table 2: Fatigue life of OPCC and AASC specimens

Stress Ratio	Mix ID (No. of Cycles to failure of the specimen)			
	OPCC	ACS-0	ACS-50	ACS- 100
0.85	350	410	459	481
0.80	1634	1991	1887	1712
0.75	43684	49876	56789	51476
0.70	78956	85476	88789	96178

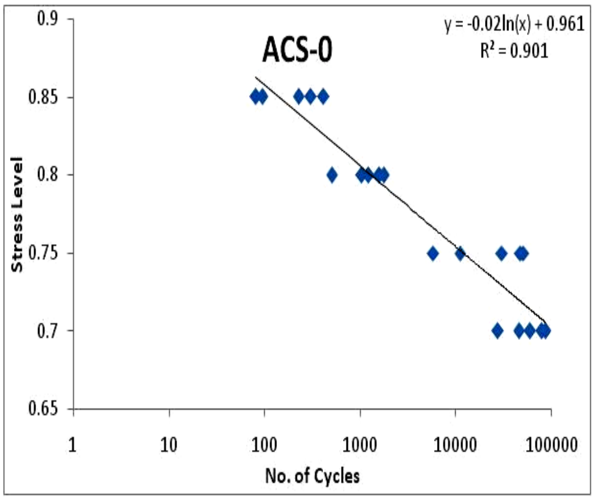
Table 3: Relationship between fatigue cycle (N) and stress level (SR)

Mix ID	Equations	R^2
OPCC	ln(N)=(0.953-SR)/0.02	0.885
ACS-0	ln(N)=(0.961-SR)/0.02	0.961
ACS-50	ln(N)=(0.954-SR)/0.02	0.879
ACS-100	ln(N)=(0.963-SR)/0.02	0.894

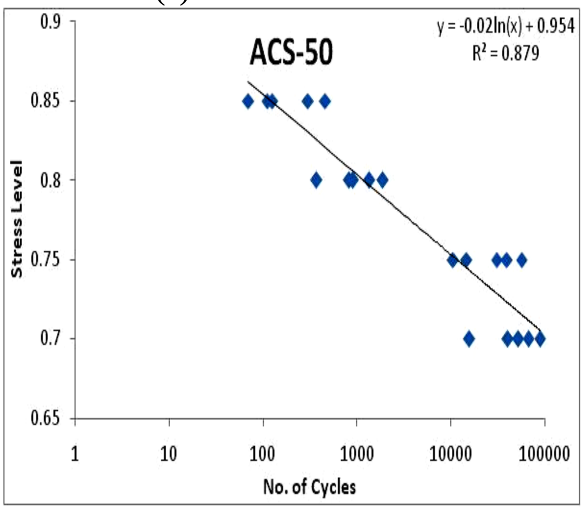
The fatigue life of concrete mixes is found to decrease drastically at higher stress levels (stress ratio=0.85) i.e. lower number of cycles to failure; however at lower stress levels (stress ratio=0.70) the number of cycles exponentially increase.



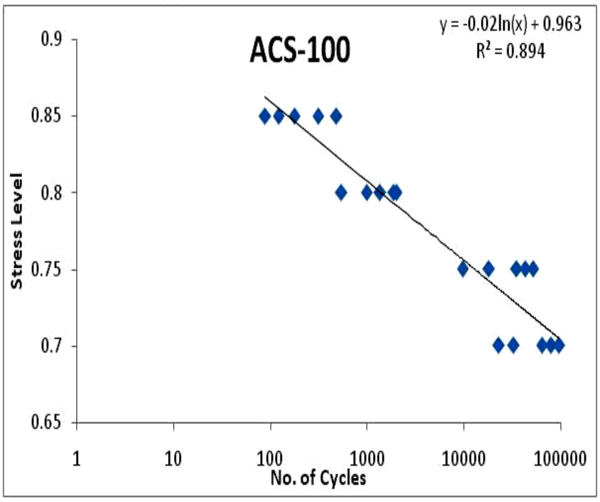
(a) S-N curve for OPCC



(b) S-N curve for ACS-0



(c) S-N curve for ACS-50



(d) S-N curve for ACS-100

Figure 1. S-N curves for various concrete mixes

From Table 2, it can be seen that AASC mixes display higher fatigue lives as compared to OPCC, which can be attributed to the possible presence of denser interfacial zone between the aggregate and paste [12], resulting in delayed formation and slower propagation of cracks under the action of repeated loads. The ACS-100 displays better fatigue life than OPCC, ACS-0 and ACS-50 at all stress levels. As cracks tend to travel through paths of minimum resistance, the properties of ITZ turn out to be of key significance. A stronger and thinner ITZ between the CS and paste and better packing would effectively take part in transmitting higher stresses through the composite [13], resulting in an improved fatigue resistance as compared to OPCC and AASC mixes with sand.

From Fig. 1, it can be observed that the variation of fatigue data of all concrete mixes, both OPCC and AASC mixes, show a similar trend with increasing stress levels. It can also be noticed that all the mixes generally display scatter in their S-N Curves. However, quite satisfactory correlation coefficients (R^2) in the range of 0.88-0.90 have been recorded for the best-fit lines plotted in Fig.1.

2.3 Probabilistic analysis of fatigue test data

Due to the heterogeneity of the material strengths and the applied loads, the fatigue data of concrete mixes generally display wide variability even under controlled testing conditions which lead to uncertainties in the fatigue data and its interpretation. It is necessary to resort to probabilistic analysis of the fatigue data to make better predictability of fatigue life of structures subjected to cyclic loadings. Hence in the present study, the use of statistical methods for analysis of fatigue data is adopted to obtain the fatigue equations with survival probability [14]. The two parameter Weibull distribution is widely accepted for analysis of fatigue data due to its relative simplicity in use, well established statistics and strong experimental verifications [15]. The Weibull distribution considers two parameters ‘α’ and ‘μ’ which describe the shape and characteristic life of the distribution respectively. An effort is made to verify that the fatigue data of OPCC and AASC follows Weibull distribution at a particular stress level. The graphical method is used to estimate the values of the parameters ‘α’ and ‘μ’ of the pertinent Weibull distribution.

2.4 Estimation of Weibull distribution parameters using Graphical method

The survival function of Weibull distribution can be expressed as follows:

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

n represents specific value of a random variable, α represents shape parameter or Weibull slope at stress level ‘S’ and μ, the characteristic life at stress level ‘S’.
Taking logarithm twice, on both sides of Eq. 1

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

Eq. 2 may be written in the following form:

$$Y = \alpha X - B \tag{3}$$

where $Y = \ln[\ln\left(\frac{1}{L_N(n)}\right)$, $X = \ln(n)$ and $B = \alpha \ln(\mu)$.

The fatigue data is considered to follow Weibull distribution if the relation between X and Y in Eq.3 is linear, and the values of distribution parameters α and μ can be obtained from the straight line. Therefore linear regression analysis is conducted for fatigue data to obtain the relationship for each stress level ‘S’ as in Eq.3.
The empirical survivorship function $L_N(n)$ at a particular stress level for each fatigue life data is calculated using the following Eq.4 [16].

$$L_N(n) = 1 - \frac{i}{k+1} \tag{4}$$

where 'i' represent failure order number and 'k' represents sample size under consideration at a particular stress level.

The distribution parameters α and μ can be obtained from the plot between $\ln[\ln\left(\frac{1}{L_N(n)}\right)$ and ln (n). The parameter 'α' be obtained from slope of the line while the characteristic life 'μ' can be obtained from the equation, B= α ln(μ). Weibull distribution parameters are calculated by plotting the graphs between $\ln\left[\ln\left(\frac{1}{L_N(n)}\right)\right]$ and ln (n) for all concrete mixes at different stress levels. A sample plot for ACS-0 at stress level of 0.85 is depicted in Fig. 2.

The Weibull distribution parameters for OPCC, ACS-0, ACS-50 and ACS-100 at different stress levels are presented in Table 4. It can be noticed from the Table 7, that the statistical coefficient of correlation ranges from 0.91 to 0.99 at different stress levels which signify that the Weibull distribution to be reasonable assumption for the distribution of fatigue data of OPCC and AASC mixes sand/CS.

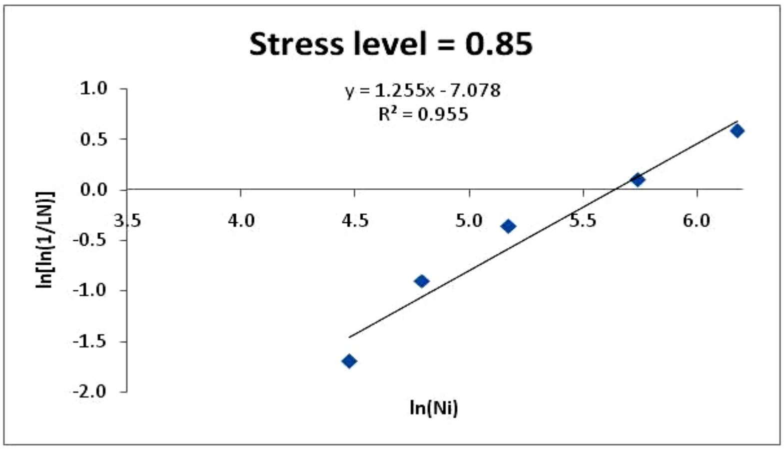


Figure 2: Graphical analysis of fatigue for ACS-100 at stress level of 0.85

Table 4: Values of Weibull parameters for concrete mixes at different stress levels

Mix ID	OPCC			ACS-0		
Stress Level	α	μ	R^2	α	μ	R^2
0.85	1.044	215	0.938	1.191	271	0.927
0.80	1.711	1234	0.97	1.739	1451	0.938
0.75	1.266	31677	0.971	0.909	35388	0.945
0.70	1.518	55396	0.987	1.893	69676	0.977
Mix ID	ACS-50			ACS-100		
Stress Level	α	μ	R^2	α	μ	R^2
0.85	1.100	255	0.916	1.255	281	0.955
0.80	1.420	1289	0.965	1.685	1551	0.913
0.75	1.241	36890	0.967	1.265	38305	0.965
0.70	1.308	65226	0.955	1.412	71877	0.959

2.5 Goodness-Of-Fit test for fatigue data

From the previous section, it has been established that the fatigue life data of OPCC and AASC with or without copper slag can be modelled using Weibull distribution at various stress levels. However, in order to further validate this, Kolmogorov-Smirnov test to find the goodness-of-fit was performed. The goodness-of-fit tests would indicate whether Weibull distribution is a valid distribution model for statistical description of fatigue life of OPCC and AASC mixes [16]

The Kolmogorov–Smirnov test can be performed by using Eq.5.

$$D = \max_{i=1}^{k} [|F^{+}(X_i) - F_N(X_i)|] \tag{5}$$

Where: $F^{+}(X_i) = i/k$ = observed cumulative histogram.

i= order number of the data point.

k = total number of data points in the sample under consideration at a given stress level.

$F(X_i)$ = hypothesized cumulative distribution function given by Eq.6 [28]

$$F_N(n) = 1 - \exp\left[-\left(\frac{n-n_0}{\mu-n_0}\right)^{\alpha}\right]; n \geq n_0 \tag{6}$$

Where: n is the specific value of a random variable N;

α=shape parameter or Weibull slope at stress level S;

μ=scale parameter or characteristic life at given stress level S; and

n_0 = location parameter or minimum life at stress level S.

Table 5 shows the results calculated by Kolmogorov–Smirnov test of fatigue life for ACS-0 at stress level S=0.85.

Table 5: Kolmogorov–Smirnov test of fatigue life for ACS-0 at S=0.85

Stress Level	i	X_i	$F^{+}(X_i) = i/k$	$F(X_i)$	$\lvert F^{+}(X_i) - F(X_i)\rvert$
0.85	1	81	0.2	0.2113	-0.0113
	2	94	0.4	0.2467	0.1533
	3	225	0.6	0.5512	0.0488
	4	302	0.8	0.6794	0.1206
	5	410	1	0.8055	0.1945

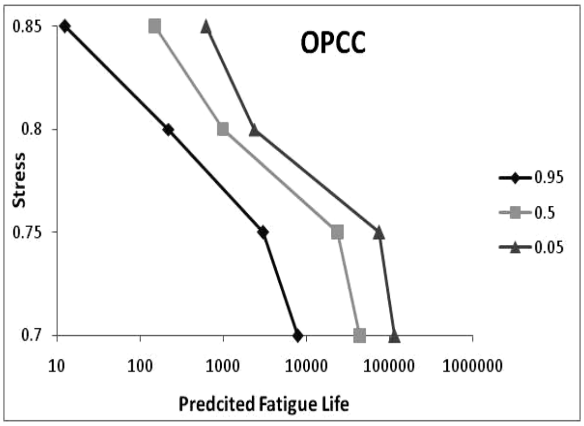
From the Table 5, it can be noted that the maximum difference is 0.1945 (for i=5) for ACS-0 at stress level of 0.85. From Kolmogorov–Smirnov Table, the critical value D_c for n=5 and 5% significance level is found to be 0.563. Since $D_t < D_c$ (0.1945< 0.563), the present two parameter Weibull distribution model for fatigue life at stress level S=0.85 is acceptable at the 5% significance level. The goodness-of-fit test is performed for the fatigue life data for OPCC, ACS-0, ACS-50 and ACS-100 at different stress levels and the model was found to be acceptable at 5% level of significance.

2.6 Survival probability and S–N relationship

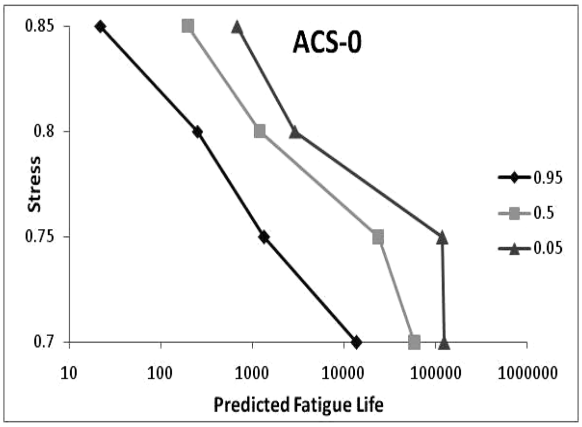
The parameters attained from Weibull distribution analysis might be used for predicting the fatigue life of concrete samples. The fatigue life for different probability of failure can be expressed as follows:

$$n= exp\left[\frac{\ln\left\{\ln\left(\frac{1}{1-P_f}\right)\right\}+\alpha\ln(\mu)}{\alpha}\right] \tag{7}$$

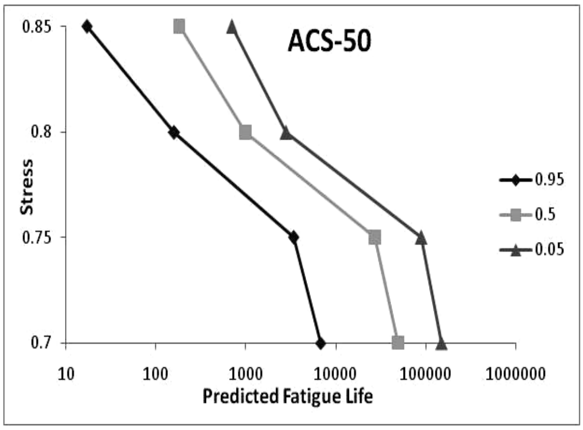
where P_f is probability of failure.



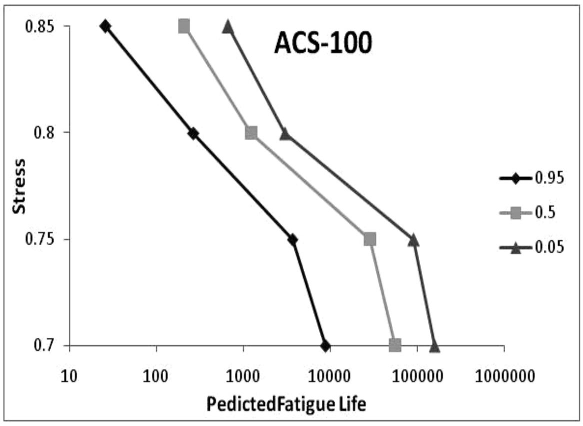
(a) Predicted fatigue life for OPCC



(b) Predicted fatigue life for ACS-0



(c) Predicted fatigue life for ACS-50



(d) Predicted fatigue life for ACS-100

Figure 3: Predicted fatigue lives corresponding to different survival probabilities for various concrete mixes

The values of α' and 'μ' attained from Weibull distribution analysis are substituted in the Eq.7 to predict fatigue lives of concrete samples at different probabilities of failure (P_f). The expected fatigue lives at different survival probabilities i.e. (0.05, 0.5 and 0.95) are calculated for OPCC, AASC mixes with sand/CS and the resulted are depicted in fig 3. It is apparent form the fig 3, at a specific stress level with decrease in probability of failure, the number of cycles for failure increases. The possible fatigue life of concrete mixes to be expected better at lesser probability of failure i.e. at 0.95 (failure probability=5%). The fig.3 can be used to forecast the probable fatigue life of OPCC, AASC mixes with sand/CS at any picked stress level at a specific probability of failure.

3 Conclusions

The major conclusions obtained from the present experimental and theoretical investigation carried out on the flexural fatigue strength behavior of AASCs with 0%, 50% and 100% of CS as replacement to river sand are summarized here. The flexural strength of AASC mixes with sand/CS is also higher compared OPCC of similar compressive strength. The AASC mixes with sand/CS shows better fatigue life as compared to that of OPCC due to dense and uniform interfacial transition zone. All the concrete specimens were found to fail in the flexure zone. The two parameter Weibull distribution has been utilized for the statistical analysis and it can be used for approximate modeling of fatigue data of OPCC and AASC mixes with sand/CS statistical correlation higher than 0.87. The parameters obtained from Weibull distribution may be utilized for carrying out prediction modeling with survival probability for OPCC and AASC with sand/CS mixes. The goodness-of-fit test is performed for the fatigue life data for OPCC, ACS-0, ACS-50 and ACS-100 at different stress levels and the model was found to be acceptable at 5% level of significance The expected fatigue lives at different survival probabilities i.e. (0.05, 0.5 and 0.95) are determined for OPCC, AASC mixes with sand/CS and it was found that at a specific stress level; the number of cycles for failure increases with decrease in probability of failure.

References

[1] Roy D. (1999). Alkali-activated cements – opportunities and challenges. *Cement and Concrete Research*. Vol.29, no.2, pp.249–254.

[2] Shi, C., Krivenko, P.V. and Roy, D. (2006). *Alkali-activated cements and concretes*. United Kingdom: Taylor Francis, Abingdon.

[3] Talling, B. and Krivenko, P.V.(1997). Blast furnace slag – the ultimate binder. In: S. Chandra Editor. Waste materials used in concrete manufacturing. pp.235–289, Noyes Publications.

[4] Van Deventer, J.S.J., Provis, J.L., Duxson, P. and Brice, D.G. (2010). Chemical research and climate change as drivers in the commercial adoption of alkali activated materials. *Waste Biomass Valorization*. Vol. 1, no.1, pp.145–155.

[5] Al-Jabri, S.K., Makoto, H., Al-Oraimi, K.S. and Al-Saidy, H.S. (2009). Copper slag as sand replacement for high performance concrete. *Cement and Concrete Research*. Vol.31, no.7, pp.483–488.

[6] Al-Jabri, S.K., Hisada, M., Al-Saidy, H.S., Al-Oraimi, K.S. (2009). Performance of high strength concrete made with copper slag as a fine aggregate. *Construction and Building Materials*. Vol. 23, pp.2132–2140.

[7] Shi, C.J., Meyer, C. and Behnood, A. (2008). Utilization of copper slag in cement and concrete. *Resource Conservation and Recycling*. Vol. 52, pp.1115–1120.

[8] Shoya, M., Nagataki, S., Tomosawa, F., Sugita, S. and Sukinaga, Y.T. (1997). Freezing and thawing resistance of concrete with excessive bleeding and its improvement. In: Proceedings of

the fourth CANMET/ACI International conference on durability of concrete. Vol.170, no. 45, pp.879–898, special publication.

[9] Kumar, B. (2012). Properties of pavement quality concrete and dry lean concrete with copper slag as fine aggregate. *International Journal of Pavement Engineering.* first article, pp.1–6.

[10] Hui, Mao-hua, Z. and Jin-ping, O. (2007). Flexural fatigue performance of concrete containing nano particles for pavements. *International Journal of fatigue*. Vol. 29. no 7, pp.1292-1301.

[11] Lee, M.K. and Barr, B.I.G. (2004). An overview of the fatigue behavior of plain and fibre reinforced concrete. *Cement Concrete Composites*. Vol.26, pp. 299–305.

[12] Jin-Keun, K and Yun-Yong, K. (1996). Experimental study of the fatigue behavior of high strength concrete. *Cement and Concrete Research*. Vol. 26, no.10, pp. 1513–1523.

[13] Hsu, T.C.C. (1984). Fatigue and micro cracking of concrete. *Materials and Structures.*Vol.17, no.97, pp.51–54.

[14] Wua, W., Weide, Z. and Guowei, M. (2010). Optimum content of copper slag as a fine aggregate in high strength concrete. *Materials and Design*. Vol. 31, no.6, pp.2878–2883.

[15] Wang, S.D. and Scrivener, K.L. (2003). ^{29}Si and ^{27}Al NMR study of alkali-activated slag. *Cement and Concrete Research*. Vol.33, no.5, pp.769–774.

[16] Bernal, S.A., Provis, J.L., Mejía de Gutierrez, R. and Rose, V. (2011). Evolution of binder structure in sodium silicate-activated slag-metakaolin blends. *Cement Concrete Composites*. Vol.33. no.1, 46–54.

[17] Ramakrishnan, V., Meyer, C., Naaman, A.E., Zhao, G. and Fang,.L. (1996). Cyclic behaviour, fatigue strength, endurance limit and models for fatigue behaviour of FRC. In: Spon E, Spon FN, editors. High performance fibers reinforced cement composites, Vol.2, pp. 101–48.

[18] Erdem, S. and Blankson, M. A. (2014). Chloride-Ion penetrability and mechanical analysis of high strength concrete with copper slag. *International Journal of Engineering Research and Applications*. Vol.4, no.5, pp.101-113.

[19] Oh, B.H. (1991). Fatigue life distributions of concrete for various stress levels. *ACI material Journal*. Vol. 88, no. 2, pp.122-128.

[20] Mohammadi, Y. and Kaushik, S.K. (2005). Flexural fatigue life distributions of plain and fibrous concrete at various stress levels. *Journal of Materials in Civil Engineering*. Vol.17, no.6, pp.650-658.