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A probabilistic fatigue failure analysis for FRSCC with Granite sawing waste

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Abstract. This paper investigates the compressive fatigue behaviour of polypropylene fibre reinforced self compacting concrete with Granite Sawing Waste (GSW). An experimental programme was conducted to obtain the fatigue lives of fibre reinforced self compacting concrete (FRSCC) at various stress levels. The stress ratio was kept constant as 0.3. Compressive fatigue test was conducted on 60 cubic specimens with 100mm edge length and 0.1% of polypropylene fibres at a frequency of 0.05Hz. The test results indicate that the fatigue lives of concretes containing granite sawing waste follow the double-parameter Weibull distribution. The fatigue strength equations have been developed based on different probabilities of failure.

Keywords: failure probability; FRSCC; Compressive fatigue; Granite Sawing Waste

1. Introduction

Most of the structures are often subjected to repetitive cyclic loads. The vibrations induced by machines, the impact of waves on offshore structures, vibration of vehicular traffic and forces of wind on structures are some cases in which the loading is repetitive and cyclic in nature .The exposure to repeated loading results in a steady decrease in the stiffness of the structure, which may eventually lead to fatigue failure. Although concrete is a widely used construction material, the understanding of fatigue failure in cementitious composites is still lacking in comparison to that of ferrous materials. This incomplete understanding is even more pronounced for composite materials such as fibre reinforced concrete. Fatigue may be defined as a process of progressive, permanent internal structural changes in a material subjected to repeated loading. In concrete, these changes are mainly associated with the progressive growth of internal micro cracks, which results in a significant increase of irrecoverable strain. Lee *et al.* (2004) have proved that at the macro level, this will manifest itself as changes in the material's mechanical properties.

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In recent decades, environmental considerations have become a main concern, and efforts to reuse industrial waste materials have been undertaken. The main aim of sustainable development is to reduce the usage of natural resources by proper recycling. In India more than 40 % of Granite Sawing Waste is produced in Tamilnadu, India, which is resulting from cutting and polishing processes. These processes result in mixture of water and fine particles which after drying becomes a potential problem to the environment. The granite polishing process yields fine granite powder which is disposed in the nearby areas without any treatment. Aarthi *et al.* (2014) have used this waste material as a replacement material for cement which is referred as Granite Sawing Waste (GSW).

Self-compacting concrete (SCC) is a concrete which can be placed and compacted under its own weight with little or no vibration and without segregation or bleeding. SCC is used to facilitate and ensure proper filling and good structural performance of restricted areas and heavily reinforced structural members. FRSCC is a high-performance building material that combines positive aspects of fresh properties of self-compacting concrete (SCC) with improved characteristics of hardened concrete as a result of fibre addition.

In this present work, polypropylene fibre is used which is very good for developing resistance against cracks and high temperatures. GSW is used as a filler material for FRSCC instead of cement. When such non conventional materials are utilised in concrete it is very much necessary to examine its strength and durability properties. The important mechanical property which often leads to failure of a structure is fatigue strength. According to Hui Li *et al.* (2007) the fatigue failure occurs when a concrete structure fails at less than design load after being exposed to a large number of stress cycles. Fatigue strength is an important design parameter for structures such as machine foundations, offshore platforms, chimneys, and bridges, which are subjected to repeated or cyclic loads.

Authors such as Ganesan.N *et al.* (2013), Goel.S *et al.* (2012), Youliang Chen *et al.* (2011), Yu Chen *et al.* (2013) have stated that the wave loading of off-shore structures, increased weight of vehicles crossing bridges originally designed to carry higher vehicles, and seismically induced strong motion, which may result in hundreds of load cycles, are some of the situations in which the structures are liable to induce fatigue degradation. Christopher *et al.* (2007), Zongcai (2005), Peng *et al.*(2000), Zhanga *et al.* (2002) have proved that in order to improve the failure behaviour, Fibre Reinforced Concrete (FRC) is made by adding discrete short fibres into the concrete matrix.

Authors like Paulo B. Cachim *et al.*(2002) have reported that the key to the success of improving the fatigue life of concrete with the addition of fibres seems to be related with the distribution of the fibres in concrete. It is also reported by Thomas. C *et al.* (2012) that the lack of a well-established test procedure for executing and evaluating fatigue tests makes it difficult to correlate or extend published test results. According to Feng Liu *et al.* (2013) fatigue performance is one of the most important aspects of study of the building materials. There may be inclined cracks in the prestressed concrete beams at lower loads due to fatigue loading and the static load carrying capacity of the component material may be altered as per Singh.S.P *et al.* (2003). The influence of stress ratio on fatigue performance has also been studied by Luis Saucedo *et al.* (2013).

The main objectives of this investigation were to evaluate the behaviour of FRSCC under compressive fatigue loading and to generate the S–N curves for the composites. The shape parameter (β) which is the Weibull slope at stress level S and scale parameter (η) are evaluated. These parameters represent the probable life of each type of concrete at particular stress levels. The above parameters are estimated by a graphical method which will be useful for fatigue design of structures made with GSW and polypropylene fibres.

2. Experimental programme

2.1. Materials and mix proportion

Ordinary Portland Cement of 43 Grade having specifications as per IS 8112:1989 reaffirmed in 2005 was used in the experiments. The fineness by Blaine's air permeability test as per IS 4031 (Part 2)-1988 was 299 m^2/kg, the specific gravity was 3.11 and the 28 day compressive strength was 48.5 N/ mm^2. The important consideration in the design of mix for SCC is to limit the coarse aggregate content. The coarse aggregate percentage was fixed as 50 % by volume. The crushed stone aggregates with 95 % of aggregates smaller than size 16mm was selected to avoid any blocking effect of SCC. Ordinary river sand with specific gravity 2.6 lying in Zone II was used.

Conplast SP430 was used as super plasticizer which disperses the fine particles in the concrete mix, enabling the water content of the concrete to perform more effectively. The very high levels of water reduction is possible which allow major increase in strength to be obtained. The GSW and Fly Ash (FA) were used as mineral admixtures. Class F Fly Ash was obtained from Mettur thermal power plant station near Mettur dam, India. The specific gravity of FA was found to be 2.1. The GSW from granite industries in Pudukotttai District, Tamilnadu, India was used. Since the granite powder was fine, hydrometer analysis was carried out on the granite powder to determine the particle size distribution. From hydrometer analysis it was found that the coefficient of curvature was 1.95 and coefficient of uniformity was 7.82. The specific gravity of the granite powder was found to be 2.59.

One of the best and popular methods for mix design of SCC was given by Okamura *et al.* (2003). This method initially depends on the cement paste and mortar tests before considering the properties of the super plasticizer, cement, fine aggregate and other mineral admixtures. EFNARC specifications and guidelines based on Okamura *et al.* (2003) were used to decide the mix proportions. One control and four mixtures with mineral admixtures and fibres were prepared and examined to quantify the fatigue properties of SCC.

Table 1 presents the composition and labelling of the SCC mixtures. In the mixtures, cement was replaced with GSW at the contents of 0 %, 5 %, 10 %, 15 %, 20 % and Fly Ash 25 % by mass of cement. After some preliminary experiments with varied powder content and super plasticizer dosage, the water–powder ratio by volume (w/p) was selected as 1.05 and the total powder content was fixed at 528 kg/m^3. Super plasticizer dosage by trial and error was 1.25 % by weight of powder. Based on the previous results of workability and strength, the polypropylene fibre content was limited to 0.1% by volume fraction.

Table 1 Mix Proportions

Materials in kg/m^3	G_0P_0	$G_5P_{0.1}$	$G_{10}P_{0.1}$	$G_{15}P_{0.1}$	$G_{20}P_{0.1}$
Cement	431	409.5	388	366.5	345
Fly Ash	97	97	97	97	97
Granite	0	21.5	43	64.5	86
Fine Aggregate	913	913	913	913	913
Coarse Aggregate	755	755	755	755	755
Water	194	194	194	194	194
Super plasticizer(by weight of powder i.e Cement, GSW and Fly Ash)	1.25%	1.25%	1.25%	1.25%	1.25%
Polypropylene fibre	0	0.1%	0.1%	0.1%	0.1%

Fig. 1 Slump flow

Table 2 Fresh and hardened properties of concrete

Mix	Slump Flow (mm)	V funnel (sec)	L Box	Compressive strength at 7 days N/mm^2 (with standard deviation)	Compressive strength at 28 days N/mm^2 (with standard deviation)
G_0P_0	730	6.5	0.92	16.0(0.5)	21.6(0.17)
$G_5P_{0.1}$	680	9.8	0.84	17.7(0.36)	22.7(0.34)
$G_{10}P_{0.1}$	580	12.7	0.71	18.6(0.72)	24.8(0.55)
$G_{15}P_{0.1}$	570	13.14	0.70	16.1(0.65)	20.6(0.26)
$G_{20}P_{0.1}$	595	12.9	0.77	15.2(0.43)	19.2(0.43)

2.2 Details of specimen

The experiments were conducted on 100mm×100mm×100mm cubic specimens. Totally 60 such specimens were cast to determine the compressive fatigue behaviour of FRSCC. Three specimens were cast and tested in each of the five mix proportions for four stress levels 100%, 95%, 90% and 85%. The minimum stress level was kept constant as 0.3. The stress range was adapted from 95% to 85% of the static compressive strength. The cyclic compressive loading was repeatedly applied at above stress levels until failure.

2.3 Details of test

2.3.1 Static compressive strength test

Initially the self compactability tests were completed and then the static compressive strength tests were conducted. The results of both are shown in Table 2. The standards specified for self compactability tests are given in Table 3. The slump flow obtained in SCC has been shown in Fig. 1. Three specimens were tested in each case and the average is reported as compressive strength of concrete. Fig. 2 shows the plot of static compressive strength of concrete.

Table 3 EFNARC specifications for SCC

Property	Test method	Typical range
Filling Ability	Slump flow	650-800mm
	T_{50}cm slump flow	2-7sec
	V funnel	8-12sec
Passing Ability	L- Box(H_2/H_1)	0.8-1
	U- Box(R_1-R_2)	0-30mm
Segregation Resistance	V funnel at T_{5min}	+3sec

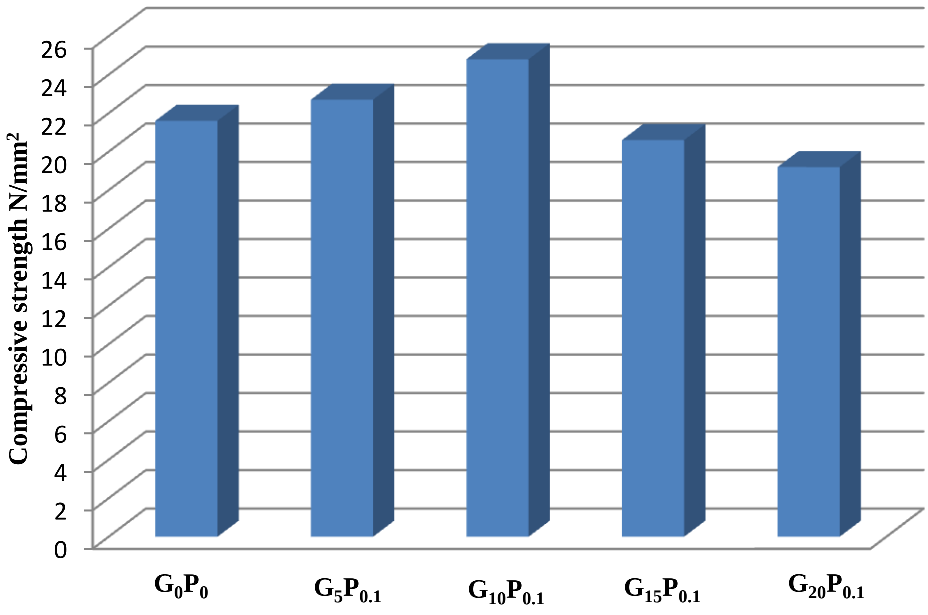

Fig. 2 Compressive strength

Fig. 3 Load setup

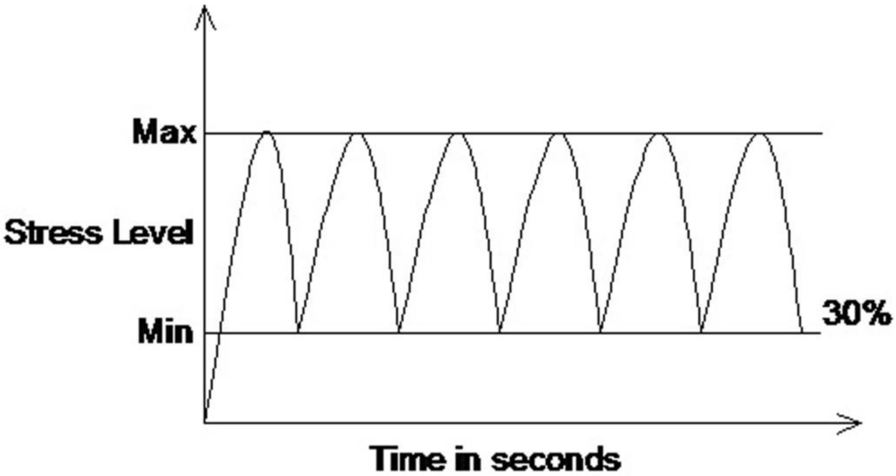

Fig. 4 Loading pattern

2.3.2 Fatigue test

The experiments were conducted on a servo hydraulic universal testing machine of 250kN capacity. The machine is capable of applying repeated cyclic loading. It is reported in the previous works by Arthur Medeiros (2015) that the number of cycles to failure at the lowest loading frequency (1/16 Hz) is at least one order of magnitude lower than that at the highest loading frequency (4 Hz). It is also reported that the number of cycles to failure decreases as the loading frequency decreases and, this decrease is more pronounced for plain concrete. Hence the loading was applied at a frequency of 0.05Hz. The experiments were conducted, as and when the failure of specimen was observed the loading is stopped. The objective of this work is to determine the fatigue strength using life data of the specimen at initial stress levels of 95% to 85% using two parameter Weibull distributions when the specimen is subjected to lowest loading frequency.

A minimum of 30% stress was applied first and then the haversine loading was applied. When the loads induced by the wheel of a vehicle is far from a specific point in the concrete pavement, stress is zero on that point and when the load is exactly on that point, the stress is maximum. Therefore, it is logical to assume that a stress pulse is a haversine. The input data to be entered in the machine are maximum and minimum stress levels and loading frequency. It has been suggested in the previous results that the fibre content influences only in the low cycle regions ($<10^3$) of fatigue which occurs only due to mortar cracking by Yin W(1995). In order to find the effect of addition of GSW and Polypropylene fibres the experiments have been conducted at low cycles and the probabilistic analysis have been used to study the performance at low stress levels. The loading set up and loading pattern is given in Fig. 3 and Fig. 4.

3. Results and discussion

3.1 Static compressive strength test

Table 4 Fatigue life of FRSCC

Mix Designation	G_0P_0	$G_5P_{0.1}$	$G_{10}P_{0.1}$	$G_{15}P_{0.1}$	$G_{20}P_{0.1}$
Stress level	Number of cycles to failure				
0.95	3 (4,2,3)	4 (5,4,3)	3 (4,2,5)	4 (3,3,5)	2 (2,2,1)
0.90	16 (16,17,15)	17 (19,17,15)	18 (17,17,20)	19 (20,21,16)	16 (17,18,13)
0.85	291 (322,287,264)	374 (384,376,362)	387 (395,371,395)	401 (410,407,386)	367 (370,352,379)

Table 5 Single logarithm fatigue equation

Mix Name	**Fatigue equation**	**R^2 Value**
G_0P_0	S=91.79-2.13 log N	0.976
$G_5P_{0.1}$	S=92.13 -2.11 log N	0.958
$G_{10}P_{0.1}$	S=91.67-2.01 log N	0.977
$G_{15}P_{0.1}$	S=92.21-2.09 log N	0.966
$G_{20}P_{0.1}$	S=90.91-1.89 log N	0.986

The results of static compressive strength show that the maximum strength is obtained at 10% of replacement of GSW. The utilisation of GSW beyond 10% is not improving the strength but gives an equivalent strength as that of control concrete. The main composition of GSW are SiO_2, Al_2O_3, CaO and Fe_2O_3 based components along with their tiny particle size inducing some pozzolonic action which ensure their use as a partial replacement material for cement in concrete. But at a GSW content of 15% and 20% this reaction becomes less effective due to the rough angular microstructure of GSW.

3.2 Fatigue test

The S-N curve or Wohler curve was used to characterise the fatigue behaviour of FRSCC with GSW. The stress level at which the load is applied is the ratio of maximum stress to the average static compressive strength of concrete. The curve relates the applied stress level and the number of cycles to failure. Fatigue strength of different mixes was obtained from single logarithm fatigue equation. The single logarithm fatigue equation given by

$$S = X - Y \log N \tag{1}$$

Alternatively the double logarithm fatigue equation can also be used as given below. It is also a perfect equation which agrees well with the test results.

$$\log S = \log X - Y \log N \tag{2}$$

But since the single logarithm fatigue equation is extensively used the same is followed in this work also.

The S-N curve for different mixes has been plotted and the resulting equations are given in Table 5.

The performance of concrete under fatigue loading depends on two important parameters X and Y of the S-N curve. The parameter X represents height of the curve and parameter Y represents slope of the curve. When the height of S-N curve increases it indicates better performance in fatigue. Hence the above equations show that the fatigue performance is better for FRSCC with GSW and Polypropylene fibres and the performance level decreases when the content of GSW increases. And the slope value indicates that the inclusion of GSW makes the fatigue life of such concrete as less sensitive to stress variations. Observing the fatigue life, the number of cycles to failure is high for GSW content of 15% at all stress levels. The inclusion of Polypropylene fibres improved the fatigue performance to a limited extent as regard to the previous researchers. But it depends on various parameters like loading sequence, loading frequency and testing composition etc. The results show that the inclusion of GSW along with polypropylene fibres improves the fatigue performance of concrete.

4. Double parameter Weibull distribution

Since concrete belongs to heterogeneous material group, the fatigue life data is very scattered in nature and it is necessary to apply a statistical tool to process the data. An engineer of Sweden Weibull, introduced a probability density distribution function to process the data of fatigue test so that the fatigue life at different failure probability can be obtained. The cumulative distribution function *P*(*n*) of double-parameter Weibull distribution can be expressed by

$$P(n) = e^{-(\frac{n}{\eta})^{\beta}} \tag{3}$$

Where β is the shape parameter which is the Weibull slope at stress level S and η is the scale parameter at stress level S. The graphical method is used to obtain the Weibull parameters since the sample size used in the investigation is small. Taking logarithm on both sides of the above equation

$$\log\left(log\frac{1}{P(n)}\right) = \beta \log\ n - \beta \log \eta \tag{4}$$

The above equation can be written in a different form

$$y = \ \beta x - c \tag{5}$$

In which y and x represents the following values

$$y = \log\ (\log\frac{1}{P(n)}) \tag{6}$$

$$x = \log\ n \tag{7}$$

$$c = \beta \log \eta \tag{8}$$

The another form of Eq. (5) reveals that the it is a linear equation and when the correlation coefficient R^2 approaches unity the Weibull parameters can be obtained from plotting the above equation as a straight line. Hence the fatigue life data was plotted and a linear regression analysis was carried out to obtain the above parameters from Eq. (5) at each stress level.

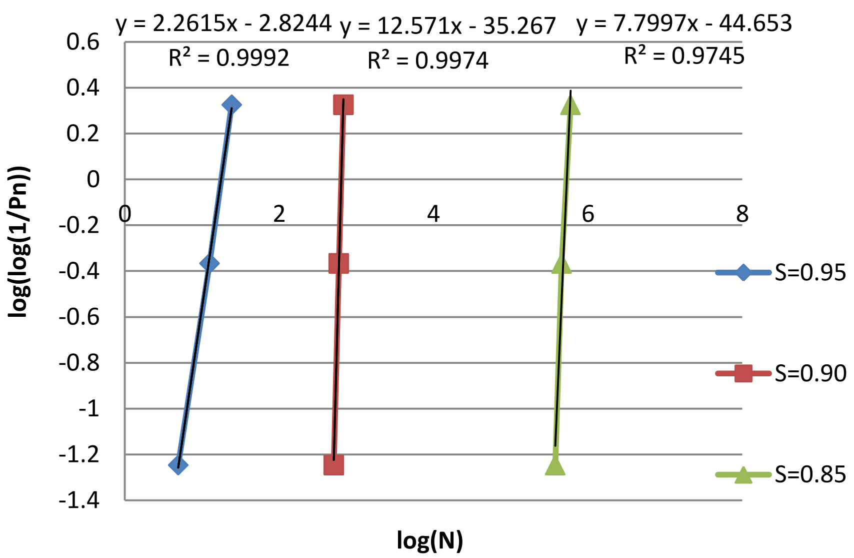

Fig. 5 Plot for graphical analysis of fatigue life data

Table 6 Weibull parameters for FRSCC

Mix Designation	G_0P_0		$G_5P_{0.1}$		$G_{10}P_{0.1}$		$G_{15}P_{0.1}$		$G_{20}P_{0.1}$	
Stress level	β	η	β	η	β	η	β	η	β	η
0.95	2.261	3.486	3.076	4.5	1.609	4.463	2.216	4.314	1.768	2.023
0.90	12.57	16.528	6.658	18.042	6.965	19.086	5.214	20.465	4.345	17.473
0.85	7.799	306.448	26.23	379.84	19.55	395.25	22.54	408.103	20.72	373.082

At each stress level an empirical survival function for fatigue life has been chosen from failure order number j = 1, 2, 3...... n and k as sample size which is the number of fatigue life data.

$$P(n) = 1 - \frac{j}{k+1} \tag{9}$$

The parameters of the above distribution can be found from plotting the values of $y = \log\left(\log\frac{1}{P(n)}\right)$ and $x = \log n$ since the fatigue lives follow Weibull distribution. The slope of such a plot is the Weibull slope β at each stress level for each mix type. And the scale parameter η is the value of fatigue life which corresponds to a failure probability of 1-P(n) =0.632.

The plot between $y = \log\left(\log\frac{1}{P(n)}\right)$ and $x = \log n$ was made for each mix type under investigation and the Weibull parameters have been found and listed in Table 6. One of the plots for control concrete without any fibre content and GSW content have been shown in Fig 5. From the results, it is seen that the coefficient correlation is always greater than 0.95 for all curves corresponding to each mix. Hence it is validated that a linear relationship exists between $y = \log\left(\log\frac{1}{P(n)}\right)$ and $x = \log n$ which proves that the survival probability of concrete mixes referred in this study follows a Weibull distribution with a correlation coefficient greater than 0.9.

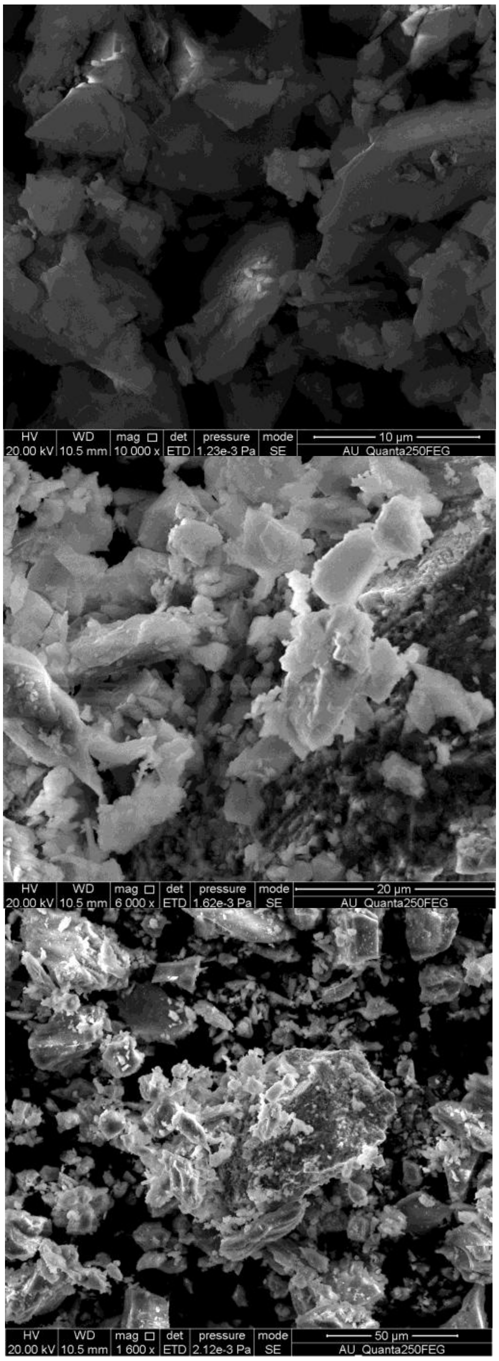

Fig. 6 Scanning Electron Micrograph results of GSW

The results of Weibull parameters show that the Weibull slope increases when the stress level is decreased. This represents that the variation of fatigue life distribution of FRSCC is not pronounced when the stress level is decreased. The self compacting concrete does not need any vibration for placing the concrete. Hence the usually observed deficiencies like segregation and bleeding are avoided. This result in homogeneity of concrete and the density also increases with increase in GSW content. Due to the above facts, the variation of fatigue life distribution of FRSCC is less at lower stress levels. But when examining the variation of Weibull slope at a particular stress level for different mixes, the increase in GSW content cause decrease in Weibull slope. Hence the variation in the fatigue life distribution is high. The scanning electron microscope results of GSW grains show that the particle size and texture are highly irregular and the grains are slightly larger, more angular, and more porous and of greater specific surface and roughness. Therefore the variability in the fatigue life distribution is more when the GSW content is increased and the objective of this work is to examine this effect. The SEM micrograph is shown in Fig. 6.

As the fatigue life data follow the double parameter Weibull distribution, the constants shown in Table 5 can be used to find the fatigue life of all the concrete types under study at different stress levels. The fatigue life at different survival probabilities for all mixes can be obtained by taking logarithm of Eq. (3) on both sides.

Table 7 Fatigue data calculated from distribution

Mix Designation	Survival Probability	0.95	0.9	0.85
G_0P_0	0.95	1	13	209
	0.9	1	14	230
	0.8	2	15	253
	0.7	2	15	269
	0.6	3	16	281
	0.5	3	16	292
$G_5P_{0.1}$	0.95	2	12	339
	0.9	2	13	349
	0.8	3	14	359
	0.7	3	15	365
	0.6	4	16	370
	0.5	4	17	375
$G_{10}P_{0.1}$	0.95	1	12	340
	0.9	1	14	352
	0.8	2	15	366
	0.7	2	16	375
	0.6	3	17	382
	0.5	4	18	388
$G_{15}P_{0.1}$	0.95	1	12	358
	0.9	2	13	369
	0.8	2	15	382
	0.7	3	17	390
	0.6	3	18	396
	0.5	4	19	402
$G_{20}P_{0.1}$	0.95	1	9	323
	0.9	1	10	335
	0.8	1	12	347
	0.7	1	14	355
	0.6	1	15	361
	0.5	2	16	367

Table 8 Constants of regression analysis

Mix Designation	G_0P_0		$G_5P_{0.1}$		$G_{10}P_{0.1}$		$G_{15}P_{0.1}$		$G_{20}P_{0.1}$	
Survival probability	C_1	C_2	C_1	C_2	C_1	C_2	C_1	C_2	C_1	C_2
0.95	0.9498	-0.021	0.9578	-0.021	0.9476	-0.019	0.9474	-0.019	0.9455	-0.019
0.9	0.9500	-0.020	0.9585	-0.021	0.9486	-0.019	0.9581	-0.021	0.9462	-0.019
0.8	0.9622	-0.023	0.966	-0.022	0.9597	-0.021	0.9594	-0.021	0.9475	-0.019
0.7	0.9618	-0.022	0.9667	-0.022	0.9602	-0.021	0.9677	-0.022	0.9486	-0.019
0.6	0.9702	-0.024	0.9728	-0.023	0.9679	-0.022	0.9683	-0.022	0.9490	-0.019

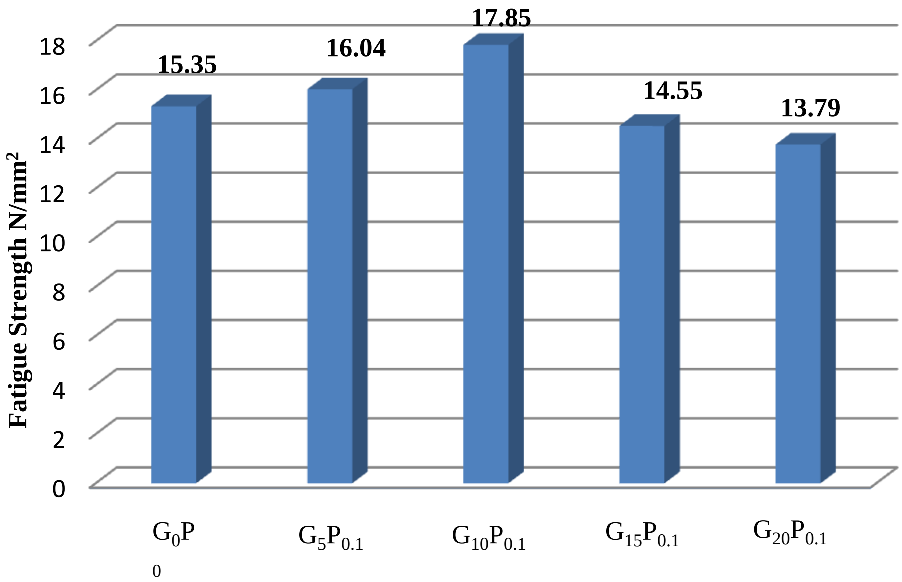

Fig. 7 Fatigue strength of FRSCC at 90% survival probability

$$N = (-\log P(n)\eta^{\beta})^{\frac{1}{\beta}} \tag{10}$$

Hence using the Weibull parameters β and η at a certain stress level S for a particular survival probability P(n) the fatigue lives have been obtained. The values of fatigue lives at survival probabilities of P(n) =0.95, 0.9, 0.8, 0.7, 0.6, 0.5 for all mixes are shown in Table 7.

Observing the values of fatigue life as given in the Table 7, it is found that the fatigue life of concrete with polypropylene fibres is greater than that of control concrete. Fibres have a tendency to inhibit crack extension during load cycles and they bridge cracks hence, the fatigue life is good for FRSCC. According to previous researchers the addition of fibres improves the fatigue life for lower frequencies. But at a particular stress level, the fatigue life or the number of repeated cyclic loads the material can sustain increases when the survival probability decreases. The increase is more pronounced in case of control concrete without any GSW. At the stress level of 0.85, the increase in fatigue life from a survival probability of 0.95 to 0.5 is 40% in case of control concrete but it varies only from 10-14% in the concrete with GSW. It is attributed to the fact that the inclusion of GSW makes the concrete less sensitive to variations.

Further the S-N relationship is expressed in terms of a power relation at different survival probabilities and regression analysis has been used to find the constants $C_1$and C_2.

$$S = C_1 \, (N)^{C_2} \tag{11}$$

The constants obtained are listed in Table 8. The constants will be useful to find the fatigue life of FRSCC with different survival probabilities and stress levels.

The fatigue strength of SCC and FRSCC have been found considering 90% survival probability and 2×10^6 cycles of loading using the regression equation. For comparing the results the same has been plotted and shown in Fig. 7. And it is found that the concrete with 10% of GSW has showed highest fatigue strength. It is 16% higher than the concrete without any GSW and fibres. But the excess use of GSW beyond 15% reduces the fatigue strength of FRSCC.

5. Conclusion

The following conclusions are drawn in this investigation

• The FRSCC with GSW and Polypropylene fibres have improved fatigue performance. The addition of GSW reduces the fatigue performance of concrete when used in excess of 15%. The main composition of GSW which are SiO_2, Al_2O_3, CaO and Fe_2O_3 based components along with their tiny particle size ensure their use as a partial replacement material for cement in concrete. But when it is used in more than 15% the fatigue performance is affected.

• The fatigue life distribution data shows high variation when the GSW content increases. For a particular type of FRSCC when the stress level is decreased the variation is not much. The particle size and texture of GSW influences much on the variation of data.

• At a particular stress level, the life of FRSCC decreases when the survival probability increases. But the variation in data is much pronounced only in control concrete not in GSW concrete.

• The fatigue strength at 10% of failure probability calculated with 2×10^6 cycles of fatigue loading is high at 10% of GSW and this value is 16% higher than the control concrete without any GSW.

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