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# Flexural Fatigue Strenght of Corrugated Steel Fibre Reinforced Concrete Containing Blends of Metakaolin and Silica Fume as Cement Additive

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***Abstract* - Large Volumes of By-Product Materials Are Generally Disposed In Landfills. Due To Stricter Environmental Regulations, The Disposal Costs For By-Products Are Rapidly Escalating. Recycling And Creating Sustainable Construction Designs Not Only Contributes To Reduced Disposal Costs, But Also Aids In The Conservation Of Natural Resources. By Combined Application Of Cement Additives/Mineral Admixtures In Concrete, The Effects Of Concrete Production Are Shown As A Way Of Participation In Sustainable Development Through Improvement Of Mechanical Characteristics Of Composite, Conservation Of Natural Resources And Reduction Of Atmospheric Pollution. The Possibility Of Enhancing Flexural Fatigue Performance Of Concrete Containing Cement Additives Has Not Been Extensively Investigated. It Is Well Known That A Material Subjected To Fatigue Loads Fails Well Below Its Static Strength. Therefore, It Is Of Paramount Interest To Investigate The Fatigue Performance Of Structural Materials.**

**The Thesis Reports Results Of An Investigation Conducted To Study The Flexural Fatigue Performance Of Steel Fibre Reinforced Concrete (SFRC) Containing Cement Additives Such As Silica Fume (SF) And Metakaolin (MK) As Partial Replacement Of Portland Cement (PC) In Binary And Ternary Blends. The Experimental Work Involved Preparing Four Mix Types I.E. Control Concrete (100% PC); Binary Blended Mixes (70% PC + 30% SF) Designated As CF And (70% PC + 30% MK) Designated As CK; Ternary Blended Mixes (70% PC + 20% MK + 10% SF) Designated As CKF, (70% PC + 20% SF + 10% MK) Designated As CFK, Cement Additives In Terms Of Two Million Cycles Endurance Limits Was Either Comparable Or Higher Than That Of Control Concrete Containing 100% PC And Addition Of Corrugated Steel Fibers In Volume Fraction of 0.8%.**

***Keywords: Fatigue Stresses, Binaryand Ternary Blends of Silica Fume and Metakaolin.***

## 1. INTRODUCTION

The primary objective of this study is to examine the effect of cement additives in binary and ternary blends on the flexural fatigue performance of steel fibre reinforced concrete (SFRC). Concrete mixes were prepared using binary and ternary blends of cement and cement additives. Silica fume (SF) and Metakaolin (MK) have been used as cement additives.

Sustainability has become an increasingly important characteristic for concrete infrastructure, as the production of Portland cement (the most common binder in concrete) is an energy-intensive process that accounts for a significant portion of global carbon dioxide emissions and other greenhouse gases. As such, even slight improvements in the design, production, and construction, maintenance of plants and equipment and materials performance of concrete can have enormous social, economic and environmental impacts.

## 2. ADDITION OF MINERAL ADDITIVES

Large quantities of industrial and agricultural by-products are generated from manufacturing processes and service industries, resulting in major environmental concerns. With the increasing awareness about the environment, scarcity of land-fill space and due to its ever increasing cost, the utilization of waste materials and by-products in concrete technology / construction has become an attractive alternative to disposal. The use of cement additives as a raw material in cement, concrete, and other construction materials is to be expected because of their voluminous availability; economical manufacture of concrete due to lower cement content; minimizing the environmental impact due to green house gases, which would otherwise have been produced in the process of cement production.

### *2.1 Silica Fume*

Silica fume is typically a by-product of manufacturing silicon and ferrosilicon alloys, i.e., a finely segregated residue captured from the oxidized vapor on top of the electric arc furnaces. Silica fume is also known as micro silica (MS), condensed silica fume (CSF) or silica dust. Silica fume is commercially available in various forms; undensified, densified (compacted), micro-pelletized and slurry form. The American concrete institute (ACI) defines SF as a ‘‘very fine non-crystalline silica produced in electric arc furnaces as a by-product of production of elemental silicon or alloys containing silicon’’. Most SF particles are amorphous and ultra-fine in size, averaging from 0.1 to 0.5 microns, or approximately one hundredth the size of the average cement particle. It is usually a grey colored powder, somewhat similar to Portland cement or some fly ashes. It can exhibit both pozzalanic and cementitious properties. It has been known that around each cement particle there are approximately 100,000 grains of SF. Clearly, this number depends on the size of the cement and SF particles, and the percentage of SF in the mixture. Because of its extreme fineness (200000 $cm^2/gm$ Blaine) and very high amorphous silicon dioxide content, SF is a very reactive pozzalanic material. Silica fume enhances the properties of concrete by providing nucleation sites for the CH crystals, reducing the thickness of the weaker transition zone.

### *2.2. Metakaolin*

Metakaolin is a highly reactive alumino-silicate pozzolan and its use in cementitious systems has been specified by ASTM C 618. It is manufactured by heating kaolin (natural clay) to a temperature of 650-900ºC to break down its structure and create an amorphous material with pozzalanic and latent hydraulic reactivity, suitable for use in cementing applications. The particle size of MK lies between FA and SF, with an average range between 1.5 to 2.5 µm. The high fineness of MK is expected to yield denser concretes and paste matrices, due to filling of the space between the cement particles. Unlike SF, which contains more than 85% $SiO_2$, highly reactive MK contains equal proportions of $SiO_2$ and $Al_2O_3$ by mass. It reacts with CH produced by hydration of Portland cement to form calcium silicate hydrate (C-S-H), which are the primary strength giving phase in concrete.

### *2.3. Binary Blended Concrete*

Deterioration of concrete depends on the penetration of aggressive substances into concrete via micro cracks and the interconnected pore system. Calcium hydroxide in the ITZ and elsewhere in the paste is water-soluble and is susceptible to deterioration in aggressive chemical environments. Sulfate attack, chloride permeability, alkali silica reaction and water penetration are the aggressive environmental agents that affect the long-term durability of concrete structures. The positive effect of cement additives can be attributed to an increase in the density and reduction in the capillary porosity caused by reaction products such as calcium silicates and calcium aluminates, which change the microstructure of the material. Thus, passages of aggressive agents through the material are controlled.

### *2.3.1. Portland cement-silica fume concrete (PC-SF)*

The effect of steel fibre volume fraction, amount of SF and their composite action on fatigue performance of SFRC was investigated fatigue performance of high strength concrete by considering the synergistic effect of SF and steel fibres which restrain the initiation and propagation of cracks during the failure. The SF improves the interfacial characteristics by filler, crystallization and pozzalanic effect. When SF and steel fibres are both incorporated into the high strength concrete (HSC) matrix, the impact and fatigue resistance performance of HSC can be enhanced considerably. It has been reported that the composite effects of SF and steel fibre are greater than the sum of the individual effects of SF or steel fibres suggested that the fatigue strength of mixes containing SF was slightly higher than that of PC high strength fibre reinforced concrete.

Silica fume has an important impact on the aggregate-cement paste interface. As a result of strengthening the interfacial zone, mechanical properties of concrete are affected substantially.

### *2.3.2 Portland cement-metakaolin concrete (PC-MK)*

The experimental results obtained show that the replacement of PC by 30% of MK leads in most cases either to improvements or at least does not significantly impair substantial properties of the analyzed high performance concrete. It was reported the slump and setting times of concretes containing 0, 5, 10 and 15% MK. It has been observed that slump decreased and setting times increased with the increase in MK content. The results of water demand and setting times of cements containing five metakaolin. It has been concluded that blended cements demanded significantly more water than the relatively pure cement. The increase in water demand could be attributed to the high fineness of metakaolin as well as to their narrow particle size distribution.

### *2.4. Ternary Blended Concrete*

### *2.4.1 Portland cement-silica fume-metakaolin concrete (PC-SF-MK)*

The neural networks to predict workability of concrete incorporating MK and SF, the results showed that the models are reliable and accurate and illustrate how neural networks can be used to beneficially predict the workability parameters of slump, compaction factor and Vebe time across a wide range of PC-SF-MK compositions.

It was reported the influence of the composition of Portland cement-pulverized fuel ash-metakaolin binders on strength development of PC-SF-MK concrete with various MK/SF proportions. The change in relative strength with curing time and MK content was analyzed in relation to the filler effect, acceleration in hydration of OPC and the pozzolanic reaction. There are three elementary factors which influence the contribution that MK makes to concrete strength when it partially replaces cement in concrete.

It was reported that the influence of PC-SF-MK concrete binders on the sorptivity and carbonation of concrete cured both in air and in water. Based on the test results, it has been concluded that increasing the MK content of water-cured PC-SF-MK concrete reduced the sorptivity values below that of control. There was a strong correlation between carbonation depth and sorptivity as the binder composition of PC-SF-MK varied

### *2.5. Fatigue Phenomenon*

Fatigue loading is of concern in the design of concrete bridges, offshore structures and concrete pavements for roads and airfields. Fatigue is a process of progressive, permanent structural change occurring in a material which is subjected to conditions which produce time fluctuating stresses and strains. The structural changes may culminate in cracks or complete fracture after a sufficient number of fluctuations and as a result the structural member may fail at a load well below its strength under statically applied loads. Parameters such as loading conditions, load frequency, boundary conditions, stress level, number of cycles, matrix composition and environmental conditions will influence the fatigue performance of concrete. The fatigue behavior of concrete during its service life is an important characteristic for assessing its useful life. The degree of damage and the sustaining time in the cycles depend on the character and structure of components, and the characteristic and effect of the interface, the dimension of original crack and resistance to crack extension and propagation under repeated load. Although the effect of steel fibres on fatigue performance is remarkable, it is difficult for the steel fibres to play their full role in strengthening concrete, if there are weaknesses in the interface between the fibre and the matrix.

### *2.6 Fatigue Studies*

A relationship between the applied fatigue stress level (S) and fatigue life (N) to predict the fatigue strength of plain concrete was proposed which was summarized the important work done in the area of statistical analysis of fatigue test data. A study revealed that the susceptibility of concrete to fatigue when subjected to tensile stresses can be described by means of the same equation as used for compressive stresses. And the included no difference in susceptibility to fatigue has been found between plain and lightweight concrete subjected to compressive stress and proposed a fatigue relationship common for both types of concrete.

### *3.1 Outline of the Research Programme*

The outline of the test programme planned for the research work is presented in fig. To achieve the objectives listed in the introduction chapter, the following phases of the planned program were executed:

(i) Tests on the basic concrete constituents i.e. Portland cement (PC), fine aggregate, coarse aggregate, silica fume (SF) and metakaolin (MK) to determine the physical properties and chemical composition of constituents.

(ii) Workability test on all freshly prepared concrete mixes.

(iii) Compressive and flexural strength tests on concrete specimens.

(iv) Flexural fatigue tests on concrete specimens at different stress levels.

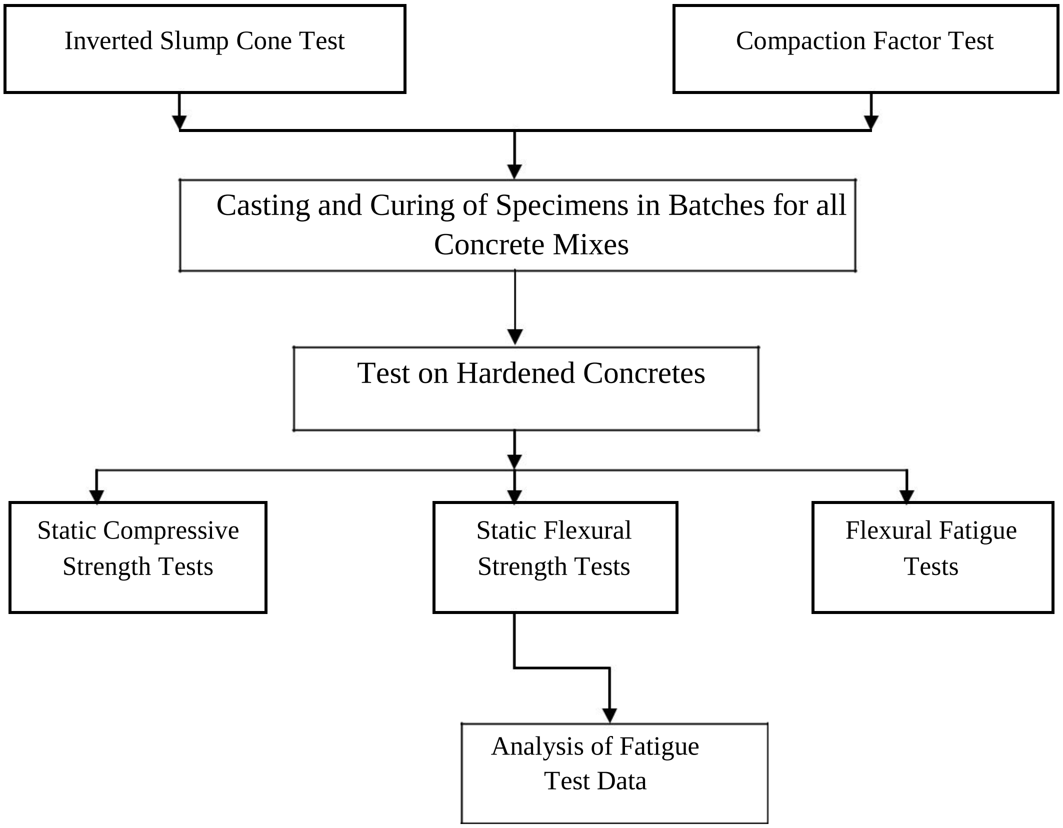

Fig: Outline of the test programme.

### *3.2 Corrogated Steel Fibre*

Corrugated rectangular shaped steel fibres (35 mm long, 2.0 mm wide and 0.6 mm thick), supplied by M/s Stewols Pvt. Ltd., Nagpur (India) were employed at a constant volume fraction of 0.8% in all the mixes. The tensile strength of the fibres was 500 MPa. Plate shows the steel fibres used in this investigation.

It has been seen that in many structural applications (like pavements, industrial floors, hydraulic structures, bridge deck overlays, crane beams, and offshore structures) where fatigue loads are important, SFRCs are of more relevance because of the greatest advantage of adding steel fibres to concrete is the improvement in fatigue resistance as compared to concrete without fibres.

Plate: Steel fibres used in the present investigation.

### 3.3 *Workability Tests on Fresh Fibrous Concrete*

Workability is defined as "that property of freshly mixed concrete or mortar which determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition." The Japanese Association of Concrete Engineers defines workability as "that property of freshly mixed concrete or mortar that determines the ease and homogeneity with which it can be mixed, placed, and compacted due to its consistency, the homogeneity with which it can be made into concrete, and the degree with which it can resist separation of materials". The inverted slump cone test was developed as a simple and inexpensive field test to measure the workability of fiber-reinforced concrete. The compaction factor test measures the degree of compaction resulting from the application of a standard amount of work. The compaction factor test and inverted slump cone test apparatus respectively. The results of the inverted cone tests along with the compaction factor tests for all mixture combinations are listed.

### 3.4 *Mix Combinations and Casting*

The present investigation on the flexural fatigue performance of SFRC mixes containing MK and SF as cement additives in different proportions, involved preparing seven mixes - control concrete (100% PC); binary blended mix combinations (70% PC + 30% SF) designated as 'CF' and (70% PC + 30% MK) designated as 'CK'; ternary blended mix combinations (70% PC + 20% MK + 10% SF) designated as 'CKF'; (70% PC + 20% SF + 10% MK) designated as 'CFK' respectively. The mix combinations incorporating cement additives were prepared by replacing 30% of PC by weight with these additives in binary and ternary mode. The reference concrete mix proportion used was 1: 1.53: 1.89 (PC: fine aggregate: coarse aggregate) with water/binder ratio of 0.46.

Table: Mix combinations considered in the study.

| Mix | Water/ binder ratio | Sand/ binder ratio | Aggregate/ binder ratio | MK/PC ratio | SF/PC ratio |
|---|---|---|---|---|---|
| Control: (100%PC) | 0.46 | 1.53 | 1.89 | - | - |
| CF: (70%PC+30%SF) | 0.46 | 1.53 | 1.89 | - | - |
| CKF: (70%PC+20%MK+ 10%SF) | 0.46 | 1.53 | 1.89 | 0.29 | 0.14 |
| CFK: (70%PC+20%SF+ 10%MK) | 0.46 | 1.53 | 1.89 | 0.14 | 0.29 |
| CF: (70%PC+30%mk) | 0.46 | 1.53 | 1.89 | - | |

### 3.5 *Tests on Hardened Concrete*

To achieve the objectives of the investigation, approximately 20 flexural fatigue tests were conducted on specimens of different concrete mixes in addition to approximately 12 flexural tests strength, which were conducted to facilitate fatigue testing. To have check on the quality of different batches of concrete mixes which were cast, approximately 8 static compressive strength tests were conducted.

#### *3.5.1 Compressive Strength Tests*

Standard 150x150x150 mm cubes were tested for 28-days compressive strength in accordance with I.S. 516-1959 using a 200 T capacity universal testing machine. The load was applied at the rate of 14 N/mm$^2$/minute approximately. The bearing surface of the machine was cleaned and the specimens were placed in the machine such that the load was applied to the specimen on the smoother face. The maximum compressive load on the specimen was recorded as that load at which the specimen failed to take any further increase in load. The compressive strength was calculated by dividing the maximum compressive load obtained by the area of the face of the concrete cube on which the load was applied. The average of three specimens was taken as the representative value of compressive strength of each batch of concrete.

The static compressive strength results of cube specimens of each batch of different concretes measured at 28 days of curing are presented in Table.

Table: Static compressive strength test results of control, SF and MK based concretes.

| Batch No. | Average compressive strength at 28 days$^*$ (MPa) | | | | |
|---|---|---|---|---|---|
| | Control concrete | CF | CKF | CFK | CK |
| 1 | 38.90 | 35.24 | 49.09 | 48.35 | 37.78 |
| 2 | 42.95 | 39.57 | 49.45 | 47.93$^{**}$ | 40.72 |
| 3 | 41.46 | 38.39 | 48.85 | 46.91 | 37.44 |
| 4 | 37.83 | 40.04 | 47.34 | 45.57 | 39.60 |
| 5 | 37.57 | 34.35 | 48.64 | 46.97 | 37.21 |
| 6 | 42.53 | 38.35 | 49.73 | 44.11 | 38.53 |
| 7 | 40.17 | 37.68 | 47.81 | 45.08 | 38.46 |
| 8 | 40.02 | 32.09$^{**}$ | 48.26 | 48.68 | 37.81 |
| Average | 40.18 | 36.96 | 48.65 | 46.70 | 38.44 |

The average 28 days static compressive strength values for CL, CLM and CLS are 36.96, 48.65 and 46.70 MPa respectively, whereas, the average 28 days static compressive strength values for CF, CFM and CFS are 38.44, 45.84 and 44.78 MPa respectively. The average static compressive strength for control concrete was observed to be 40.18 MPa.

### *3.5.2 Flexural Strength Tests*

Static flexural strength tests were carried out to determine the static flexural strength of all mix combinations, prior to the testing in fatigue, because once a specimen fails under fatigue loading it is impossible to determine the static flexural strength. To obtain the maximum ($\sigma_{max}$) and the minimum load ($\sigma_{min}$) limits for the fatigue tests, it was obligatory to estimate the static flexural strength ($f_r$) of the concrete mixes. Standard 100x100x500 mm beam specimens, simply supported on an effective span of 450 mm and loaded at the third points were tested for static flexural strength after 90 days of curing, using a 100 Kn. MTS digital closed-loop Servo-Controlled Actuator system. The components of the MTS testing machine include MTS Flex Test$^{TM}$ SE Controller, Transducers, Actuator, Servo Valve, Hydraulic Power Unit (HPU) and frame for the flexural tests. The controller provides the electronics for the closed loop control, controls and indicators for the system operation such as digital display to monitor the system and test conditions, hydraulic pressure control, program run/stop, servo loop adjustments etc. In the automated mode, the controller is connected to a PC equipped with MTS Series 793 software. When the controller is used with the PC-supervision, the station manger application was run in tandem with the controller. The station manger application is included with the model 793.00 system suite that comes with the PC-supervised controllers. The station manager provides another interface with which test activities can be performed. It is a good practice to warm up the station hydraulics before testing, by exercising the actuator without a specimen for at least 30 minutes. The actuator area was cleared of all operating personnel before applying the hydraulic pressure, because applying station hydraulic pressure puts the actuator in motion which can injure anyone in its path. The specimens were placed in such a manner that the plain and smooth surfaces were in contact with the supporting as well as loading rollers. The load was applied at a rate of 0.5 mm/minute with the machine running in the displacement control mode. Three or four specimens from a particular batch of concrete were tested and the maximum load was noted from the load-deflection curve. Figure-3.6 shows the schematic diagram for the static flexural and flexural fatigue tests. The static flexural strength ($f_r$) of the specimen was calculated from the following expression, when the fracture is initiated on the tension surface within the middle third of the span length:

Plate: shows the set up for static flexural and flexural fatigue tests.

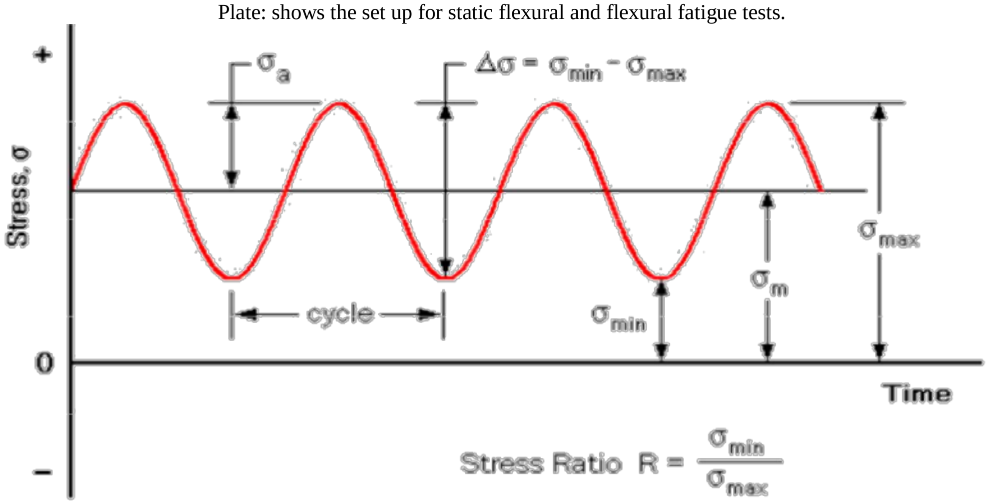

Fig: Schematic of Static Flexural and Flexural Fatigue Tests

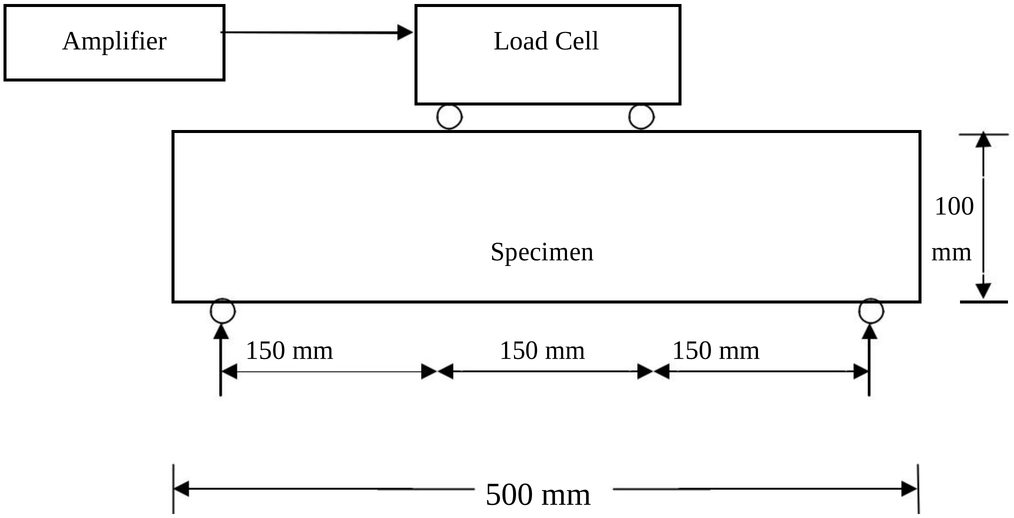

Table: Flexural strength test results of control, MK and SF based concretes.

| Batch | Average flexural strength* (MPa) | | | | |
|---|---|---|---|---|---|
| | Control concrete | CF | CKF | CFK | CK |
| 1 | 7.56 | 6.68 | 9.24 | 9.79 | 8.19 |
| 2 | 7.11 | 6.85 | 12.14 | 8.89 | 8.43 |
| 3 | 7.45 | 6.31 | 10.34 | 9.65 | 8.15 |
| 4 | 7.02 | 6.61 | 8.63 | 9.75 | 7.83 |
| 5 | 9.02 | 7.01 | 9.65 | 8.96 | 8.46 |
| 6 | 9.88 | 6.74 | 9.53 | $9.76^{**}$ | 8.56 |
| 7 | 8.53 | $6.75^{**}$ | 9.56 | 8.97 | 8.67 |
| 8 | 8.1 | 6.95 | 9.24 | $9.82^{**}$ | 8.44 |
| Average | 8.08 | 6.74 | 9.79 | 9.45 | 8.34 |

The average flexural strength values for CK, CKF and CFK are 6.74, 9.79 and 9.45 MPa respectively. The average flexural strength for control concrete was observed to be 8.08 MPa.

### 3.5.3 *Flexural Fatigue Tests*

The main thrust of the present investigation was on the flexural fatigue testing of beam specimens. After the static flexural strength testing of a particular batch was over, the remaining specimens from the same batch were tested in flexural fatigue. The flexural fatigue tests were conducted on the same machine as the static flexural strength test. In the fatigue tests also, the specimens were simply supported over an effective span of 450 mm and loaded at the third points. As the fatigue tests are concerned with stress/load levels, the load control mode was used for all the fatigue tests. A sine waveform (also called sinusoidal or haversine) loading was applied. The load applied to the specimen was sensed by the load cell attached to the cross head of the machine, and the load cell output was used as a feedback signal to control the load applied by the actuator.

The fatigue parameters include static flexural strength ($f_r$), stress level (S), stress ratio (R) and the loading frequency. The load cycle characteristic value or stress ratio 'R' is expressed as R= $\sigma_{min}/\sigma_{max}$, where $\sigma_{min}$ and $\sigma_{max}$ refer to the minimum and maximum fatigue stress respectively. The stress level 'S' is expressed as $\sigma_{max}/f_r$, where $f_r$ is the static flexural strength. Beam specimens of all mix combinations were tested at different stress levels ranging from 0.95 to 0.70. Depending upon the fatigue performance (in terms of number of cycles to failure) of different specimens with and without cement additives, stress level in the range of 0.90 to 0.75 was selected, at a constant stress ratio value of 0.1. The tests were carried out in load or force control mode using a constant amplitude non-reversed sinusoidal waveform with a loading frequency of 10 Hz

To conduct the fatigue test at a particular stress level ( $S = \sigma_{max}$ ), the maximum value of $f_r$ fatigue stress ($\sigma_{max}$) to be applied to the specimen in a fatigue test was first calculated. This was obtained from static flexural strength ($f_r$), as obtained in the static flexural tests. From this maximum fatigue stress ($\sigma_{max}$), the minimum fatigue stress ($\sigma_{min}$) to be applied is calculated for a particular value of stress ratio using expression ( $R = \sigma_{min}$ ). The maximum$^{\sigma}$ max ($P_{max}$) and minimum ($P_{min}$) fatigue loads to be applied to the specimens were calculated from the maximum and minimum fatigue stress, using the cross sectional dimensions and loading span of the specimen. These loads are programmed in the Controller.

The number of cycles to failure of the specimens went on increasing with a decrease in the stress level. Since fatigue testing is a very expensive and time consuming procedure and a large number of specimens were proposed to be tested, an upper limit of two-million cycles was selected. The machine was set so that it terminates the test as and when the specimen failed or the upper limit was reached. However, most of the specimens failed below this limit.

Table: Sample calculation for maximum and minimum fatigue loads for CKF mix.

| Static flexural stress, $f_r$ (MPa) | Stress level, $S=\sigma_{max}/f_r$ | Max. fatigue stress, $\sigma_{max}$ = (S)x($f_r$) (MPa) | Stress Ratio R=σmin/σmax | Min fatigue stress, $\sigma_{min}=(R)x(\sigma_{max})$ (MPa) | Max. fatigue load, $P_{max}$ (KN) | Min. fatigue load, $P_{min}$ (KN) |
|---|---|---|---|---|---|---|
| 9.64 | 0.90 | 8.68 | 0.10 | 0.868 | 19.29 | 1.93 |
| 9.64 | 0.85 | 8.19 | 0.10 | 0.819 | 18.20 | 1.82 |
| 9.64 | 0.80 | 7.71 | 0.10 | 0.771 | 17.13 | 1.71 |
| 9.64 | 0.75 | 7.23 | 0.10 | 0.723 | 16.07 | 1.61 |

Fig: Sinusoidal wave type applied fatigue load.

### *4.1 Probabilistic Analysis of Fatigue Life Data of Concretes*

The analysis of fatigue life data requires techniques from statistics, especially probabilistic analysis and linear regression. The fatigue design is clouded with uncertainties arising from the assumptions made in analysis as well as the inherent material variability*)*. So, the probabilistic reliability theory is an efficient way to adequately account for the uncertainties. It becomes vital to introduce probabilistic concepts to analyze the probability distributions of concrete subjected to flexural fatigue loads and to draw meaningful conclusions. Various mathematical models like the logarithmic-normal (log-normal) distribution and the Weibull distribution have been suggested for the statistical description of fatigue life data. It was suggested in the American Society for Testing and Material *(ASTM 1963)* publication, titled "A guide for fatigue testing and statistical analysis of fatigue data", that the fatigue life N can be assumed to be normally distributed..

The hazard function of the Weibull distribution increases with time, which is compatible with the expected fatigue behavior of engineering materials. Fatigue life of a group of specimens tested under a given set of conditions may be represented by the probability distribution function f(n) and the cumulative distribution function $P_f(n)$ of the Weibull probability law, which may be expressed in the following forms.

### *4.2 Establishing Fatigue Life Distributions*

The fatigue life data obtained for the tested beam specimens for all concretes corresponding to four different stress levels (0.90, 0.85, 0.80 and 0.75) and at a constant stress ratio (0.1) have been arranged in an ascending order at all stress levels. present the fatigue life data in terms of number of cycles to failure for the control concrete (100%PC), CF (70% PC + 30% SF), CFK (70% PC + 20% SF + 10% MK), CKF (70% PC + 20% MK + 10% SF) concretes respectively. The graphical method has been employed to establish two-parameter Weibull distribution for fatigue life data of concretes at a particular stress level. Three methods namely: the graphical method, the method of moments and the maximum likelihood estimate are presented to estimate the distribution parameters. The probability distributions for the fatigue life data of all concretes at different stress levels has been established in the following sections.

### *4.3 Analysis of Fatigue Life Data by the Graphical Method*

The graphical method has been employed to show that the statistical distribution of fatigue life of a concrete at a certain stress level, follows the two-parameter Weibull distribution.

### *4.4 Analysis of Fatigue Life Data by the Graphical Method*

The graphical method has been employed to show that the statistical distribution of fatigue life of a concrete at a certain stress level, follows the two-parameter Weibull distribution.

### *4.5 Analysis of Fatigue Life Data by the Method of Moments*

To obtain the parameters of the Weibull distribution by this method, an estimation of appropriate sample moments, such as sample mean and sample variance are required.

### *4.6 Analysis of Fatigue Life Data by Method of Maximum-likelihood Estimate*

The distribution parameters of the Weibull distribution can also be obtained using the method of maximum likelihood estimate. The probability density function of Weibull

### *4.7 ANOVA Study*

The fatigue results obtained in terms of number of cycles to failure (N) were characterized by the scatter. The amount of scatter in the fatigue studies was significant even for materials more homogeneous that concrete such as. To verify statistically the influence of the mix type and stress level, as well as their interaction on the fatigue life data, an analysis of variance (ANOVA) was performed.

The following dependent and independent variables were considered in ANOVA:

Number of cycles to failure (N): The logarithm to the base ten, log N was chosen as the dependent variable since it causes the results to be more normally distributed.

Type of mix: as a fixed factor, included seven mix combinations. Stress level (S): as a fixed factor, included four stress levels.

ANOVA summary reveals the significant differences between the select mix types in terms of number of cycles to failure (Fischer distribution i.e. F value =52.135; significance level i.e. $p<0.0001$). Thus the concrete composition significantly affects the number of cycles to failure. It was further inferred from the results that number of cycles to failure also vary with the stress level (F value =313.082; $p<0.0001$). However, the differences among the different concrete types vary with a change in the stress level as revealed by the significant interaction between the mix type and the stress level (F value =6.027; $p<0.0001$).

### *4.8 Estimation of Design Fatigue Lives*

This part of the study deals with the design fatigue lives, estimated at different failure probabilities for all the mixtures. The design fatigue life should be selected such that there is only a small probability that a fatigue failure will occur *(Oh 1986)*. Using the average values of Weibull parameters i.e. shape parameter ‘α’ and characteristic life ‘u’ corresponding to each stress level ‘S’, of all the mix combinations corresponding to selected acceptable probabilities of failure ($P_f$) i.e. 0.01, 0.05, 0.10, 0.15 and 0.25. The smaller probabilities of failure or higher reliabilities require the design fatigue lives to be small. A design fatigue life should be selected such that there is only a small probability that a fatigue failure will occur.

The calculated design fatigue lives for control, MK and SF based mix combinations corresponding to different failure probabilities are presented in Table-4.17. The design fatigue lives may be used to generate ‘the design fatigue life curves’ which are used by the design engineers. Figures-4.23 to 4.29 shows the design fatigue curves for control, MK based and SF based concretes. The influence of the cement additives on the design fatigue lives has been isolated with the help of design fatigue life curves for different mix combinations as shown in Fig.-4.30, where the design fatigue lives have been plotted for 10% probability of failure. Table-4.18 presents the enhanced extent of design fatigue lives of all concrete mixes with respect to control concrete at 10% failure probability. The enhancement in design fatigue life for CK, CKF and CFK mixes as compared to the control concrete mix at S=0.90 was 1829.28%, 2605.92% and 4564.64%; 306.96%, 799.05% and 917.59% at S=0.85; 212.94%, 375.86% and 462.61% at S=0.80; 55.07%, 96.51% and 185.67% at S=0.75 respectively. Clearly, the CKF mix had higher design fatigue lives as compared to other SF based concretes.

### *4.9 Development of Family of S-N-$P_f$ Curves*

The fatigue life data of the specimens of all the concrete mixtures indicate a large variability or scatter, even at the same stress level, under carefully controlled test procedures. The variability in the fatigue life of fibre reinforced concrete is more as compared to that of plain concrete due to addition of fibres and their random orientation in the concrete matrix *(Singh and Kaushik 2000)*. Hence, the incorporation of probability of failure $P_f$ into the fatigue test data is an important aspect. In the following Section, the probability of failure has been incorporated in S-N relationships to obtain, analytically and graphically, families of S-N-$P_f$ relationships for all the concrete mixes tested in this investigation.

### *4.10 Graphical Analysis for S-N-$P_f$ Relationship*

The data were analyzed by ranking the specimens in the order of the number of cycles to failure and the probability of failure $P_f$ is calculated by dividing the rank of each specimen i by (k+1), where k equals the total number of specimens tested at each stress level. The calculated values of probability of failure $P_f$ for data of control, CF,CK, CKF and CFK concrete mixes. The reason for dividing by (k+1), rather than k is to avoid obtaining a probability of failure equal to 1.0 for the specimen having greatest fatigue life. The ratio i/(k+1) can be taken as to give best estimate of probability of failure. Since this analysis requires equal number of data points at different stress levels for a particular mix used in the investigation, therefore, in some cases few data points have been left out. As a criterion, the first data points at each stress level were left out.

### *4.11 Two Million Cycles Endurance Limit/Flexural Fatigue Strength*

In recent years, considerable interest has developed in the flexural fatigue strength of concrete members. The widespread adoption of ultimate strength design, and use of higher strength materials require that structural concrete members perform satisfactorily under high stress levels subjected to a large number of load cycles. In many structural applications (like pavements, bridge deck overlays, crane beams, and offshore structures) the flexural fatigue and endurance limit are important design parameters because these structures are designed on the basis of fatigue load cycles.

In the present case, the endurance limit was defined as the maximum flexural fatigue stress at which the beam specimen could withstand two-million cycles of non-reversed fatigue loading, expressed as a percentage of the corresponding static flexural strength or modulus of rupture. The two-million cycle limit was chosen to approximate the life span of a structure that may typically be subjected to fatigue loading. It has been reported that if the specimen could withstand two-million cycles without failure, it could last for all practical purposes forever.

The fatigue behavior of concrete is generally expressed in terms of the S-N curves. The S-N curves have been plotted to determine the two-million cycles fatigue strength/endurance limit of the concrete mixes. The fatigue test data have been presented as S-N relationships, with the maximum fatigue stress expressed as a percentage of the strength under static flexural loading, and as relationships between the actually applied fatigue stress and number of loading cycles to failure.

The two-million cycles fatigue strength/endurance limit obtained for the control concrete from the present investigation had been compared with that of the concretes from the previous investigations. A comparison of the performance of concrete containing cement additives and control concrete based on S-N relationships was also obtained. The S-N curves have been used to obtain the two-million cycle fatigue strength/endurance limit for all concrete mixes.

The S-N curves for CF based ternary concrete mixes plotted in Fig.-4.49 show that the best fatigue performance in terms of the two-million cycles is given by the CKF mix, when comparison is made based on applied maximum fatigue stress expressed as a percentage of corresponding static flexural strength. It has been clearly indicated that the slopes of the S-N curves for the ternary concrete mixes were different to a certain degree from that of control concrete. The predicted two-million cycles endurance limit for the CKF and CFK concrete mixes were 75% and 76% of its static flexural strength respectively.

*4.12 Failure Mode of Specimens*

The failure of almost all the specimens of concretes containing cement additives, under all stress levels was due to the initiation of a single crack in the middle third span of a specimen. With an increase in the number of cycles, the crack propagated and widened leading to the complete failure of the specimens. The mode of failure was observed to be influenced by both, fibre pull-out and breaking of fibres.

Furthermore, it was also observed that at higher stress levels, the failure was almost immediate after the initiation of the first crack, while on the contrary at lower stress levels, specimens went on to sustain more number of cycles, even after the initiation of first crack. This indicated the crack arrest property of concrete along with good bondage between fibres and matrix.

No distinct failure pattern under fatigue loading was observed in SF and MK based concrete specimens. A typical failure pattern in some of the specimens for SF and MK based concretes.

Plate-: The typical failure pattern in control and SF based concrete specimens under fatigue loading.

### *4.13 Estimation of Theoretical Fatigue Lives*

Road surfaces, parking lots, bridge decks and industrial floors often endure repetitive cyclic loads during their service lives; the fatigue characteristics of concrete in these structures are important performance and design parameters. So, it is necessary to predict the fatigue life and parameters for structures that have been endured repeated loading.

The theoretical fatigue lives of all the mix combinations at the four applied stress levels, calculated using single fatigue equations and their enhanced extent with respect to the control concrete at 10% failure probability are presented.

It can be seen that the increased theoretical fatigue life extent for CF, CKF and CFK mixes as compared to control concrete at S=0.90 was 1380.61%, 2251.39% and 3942.49%; at S=0.85 was 523.35%, 850.29 % and 1373.53%; 162.57%, 284.25% and 437.41% at S=0.80 and 10.59%, 55.35% , 95.98% at S=0.75 respectively. The enhanced extent of fatigue life of the CF mix is lowest.

Among MK based concretes, the theoretic fatigue life extent for CK, CFK and CFK mix at S=0.90 was 2351.26%, 4164.54% and 7786.59%; 854.31%, 1462.39% and 2358.29 % at S=0.85; 271.72 %, 472.72% and 666.67% at S=0.80; 44.78%, 109.92% and 139.08% at S=0.75 respectively. Apparently, the CFK mix showed higher fatigue lives as compared to the other mixes at all stress levels.

Table: Theoretical fatigue lives of concretes calculated by single-logarithm fatigue equation at 10% probability of failure.

| Mix | S=0.90 | | S=0.85 | | S=0.80 | | S=0.75 | |
|---|---|---|---|---|---|---|---|---|
| | Theoretical fatigue number | Enhancement extent (%) | Theoretical fatigue number | Enhancement extent (%) | Theoretical fatigue number | Enhancement extent (%) | Theoretical fatigue number | Enhancement extent (%) |
| Control | 753 | 0 | 4428 | 0 | 26025 | 0 | 152973 | 0 |
| CF | 18458 | 2351 | 42257 | 854 | 96741 | 272 | 221475 | 45 |
| CKF | 32112 | 4165 | 69183 | 1462 | 149050 | 473 | 321120 | 110 |
| CFK | 59386 | 7787 | 108853 | 2358 | 199526 | 667 | 365728 | 139 |
| CK | 11149 | 1 381 | 27602 | 523 | 68335 | 163 | 169179 | 11 |

## *5.1 CONCLUSIONS*

Within the limited scope of this investigation, following conclusions are drawn:

1. The probabilistic distributions for the fatigue life of concrete containing binary and ternary blends of cement additives and control concrete have been established. With the higher values of correlation coefficients (greater than 0.92) at all stress levels, the successful modeling of fatigue life data by the two-parameter Weibull distribution has been confirmed. The distribution parameters i.e. ‘shape parameter’ and ‘characteristic life’ used to define the fatigue life distributions have been estimated by the different methods of analysis, which have been found to yield almost similar results.
2. There has been reduction in variability in the distribution of fatigue life of concretes containing cement additives as compared to control concrete. This can be interpreted from the fact that higher values of the shape parameters indicate lower variability in the distribution of fatigue life. The maximum increase in the values of the shape parameters for CF, CKF and CFK mixes with respect to the control concrete was found to be 18.12%, 33.70% and 38.82% respectively whereas, maximum decrease of about 18.36%, 28.55% and 30.79.
3. Amongst all the MK and FK based concretes tested in this investigation, the CKF concrete has shown maximum decrease in the variability in the distribution of fatigue life data to the extent of 35.75% compared to control concrete.

4. The design fatigue lives for all the concrete mixes have been determined corresponding to selected probabilities of failure ($P_f$) i.e. 0.01, 0.05, 0.10, 0.15 and 0.25. It has been observed that at a particular stress level, design fatigue lives for concrete containing cement additives are higher than those of control concrete. Amongst different blended concretes, the highest design fatigue lives were obtained for the CKF mix with an enhanced percentage as 8468.16% at S=0.90; 1967.47% at S=0.85; 817.89% at S=0.80 and 229.23% at S=0.75 as compared to the control concrete.

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