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Analysis of Flexural Fatigue of Concrete containing Coarse Recycled Concrete Aggregates (RCA)

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***Abstract:*— The paper presents results of an investigation to study the flexural fatigue performance of concrete beams made with 100% Coarse Recycled Concrete Aggregates (RCA). Experimental investigation has been carried out to obtain the flexural fatigue lives of concrete beam specimens of size 100 × 100 × 500 mm at various stress levels under four points flexural fatigue loading. The test data is used to plot the S-N curves and a simple regression analysis is used to propose an equation to estimate the flexural fatigue strength of concrete made with 100% RCA. The flexural fatigue performance of concrete made with 100% RCA has been assessed in terms of its mean fatigue life. Two million cycles fatigue strength/endurance limit has also been estimated and compared with the previous studies available on Coarse Natural Aggregates (NA).**

Keywords: Recycled concrete aggregates, Mean and design fatigue life, Endurance limit.

I. INTRODUCTION

Concrete is the most widely used construction material. Aggregates, the building blocks of the concrete globally, makes up to three - quarters of total concrete volume. However, increasing demand of coarse natural aggregates (NA) has set up an alarm to find substitutes to meet up the needs of construction industry. Simultaneously, a lot of waste aggregates produced from demolition of old civil infrastructures (C & D waste), buildings or highways are accumulating rapidly worldwide. Out of 48 million tons of solid waste generated in India, annual C & D waste makes up 25% [1]. The total quantum of C & D waste generated in India is estimated to be 11.4 to 14.69 million tons per annum, out of which seven to eight million tons consists concrete and brick waste [2]. Over last few decades, the use of coarse recycled concrete aggregates (RCA) is being explored as coarse aggregates in order to achieve sustainable construction [3]. Investigations have been carried out by researchers on the mechanical properties of concrete using 100% RCA as coarse aggregate, with same water–cement ratio, volume of aggregate same amount of cement and water as used in concrete made with NA. A large number of experiments are usually required to decide a suitable mix for obtaining the desired requirements of concrete made with recycled concrete coarse/fine aggregates. This is because of wide range of variability of engineering properties of RCA [4]. In this research the mechanical performance of concrete made with RCA under static loadings has been studied, by replacing NA partially and fully with RCA [5]. It is widely recognized that compressive strength of concrete containing recycled aggregate is generally lower than normal concrete with the same water/cement ratio because fracture process in concrete of recycled aggregate is not identical to normal concrete [6]. It is reported with the help of SEM observations that the normal strength RCA-cement interfacial zone consisted mainly of loose and porous hydrates whereas high performance RCA-cement interfacial zone consisted of dense hydrates [7]. To improve the strength of concrete made with RCA, a method has been investigated i.e. by applying acoustic emission technique for detecting micro-cracking in concrete under compression [8]. The compressive strength and stress–strain curves of recycled aggregate concrete (RAC) with different replacement percentages of RCA by experiments and proposed analytical expressions for the peak strain and the stress–strain relationship are obtained [9]. Similarly concrete made with RCA gives lower strengths (1-15%), lower modulus of elasticity (13-18%) and reduction in the fracture energy (27-45%) when compared with concrete made with NA [10]. The applications of concrete made with RCA can be in bridge decks & piers, precast structural elements, pavements and high rise buildings. Since most of these structures are subjected to dynamic loading thus there is a call for investigating the performance of concrete made with RCA under fatigue loading. In the past five decades, considerable research has been dedicated to investigate the fatigue behavior of concrete made with NA. For example, the fatigue behavior of plain concrete has been investigated by testing 462 cylindrical specimens under static and dynamic compression [11, 12]. Empirical expressions between the stress level (S), number of cycles (N) and probability of failure (P_f), S-N-P_f relationships, were derived on the basis of fatigue strength results [11]. The effect of variable stress levels on the fatigue behavior of concrete containing NA was investigated under flexure loading and it was reported that the Palmgren-Miner hypothesis might give conservative or unsafe predictions of the fatigue strength, depending on the loading schemes [12, 13].

Many researchers adopted a relationship between stress level S (S= f_{max}/f_r; f_{max} = *maximum fatigue stress*, f_r = *static flexural stress*) and the number of cycles to failure *N* [14, 15, 16]. The relationship established, known as the Wholer's equation, is as follows:-

$$S = \frac{f_{\max}}{f_r} = A + B\log_{10}(N)$$

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where A & B are the experimental coefficients. The values of the coefficients *A* & *B* the Eq. (1) have been obtained as 1.1339 & -0.0889 for respectively in for concrete made with NA [15].

However, very few studies have been carried out on the fatigue performance of concrete made with RCA. These studies have shown that the fatigue life decreases as the percentage of RCA is increased in replacement with NA [3]. Thomas concluded that, quality of recycled concrete aggregates as well as new concrete made with RCA, both are observed to be influential on the fatigue response of concrete.

II. EXPERIMENTAL PROCEDURE

In present study the NA were fully replaced with RCA. The mix containing RCA was cast in several batches and each batch consisted of seven beam specimens of size 100mm × 100mm × 500mm and 3 cube specimens of size 150mm × 150mm × 150mm. Out of seven beam specimens four were tested for flexural fatigue and three complementary static flexural tests were conducted under four point loading. Compressive strength tests were carried out on the three cube specimens under compressive testing machine.

A. Material Used

In the present investigation, well graded RCA with maximum size of 12.5 mm, specific gravity value as 2.47 and aggregate crushing value around 25% were used as coarse aggregates, after processing in the Concrete Laboratory of the authors Institute. The gradation of RCA was intentionally made equivalent to the NA used in previous studies. Comparison between the grading curves of RCA and NA is shown in Figure-1

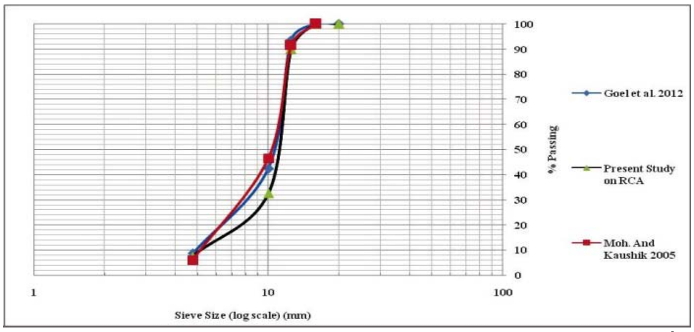

Fig. 1 Comparison of grading curve of RCA with grading of ***NA in previous studies.***

It is observed that the gradation of RCA is similar to that of NA used in previous studies. Locally available coarse sand was used as fine aggregates in this study. Ordinary Portland cement (OPC) of grade 43 was used with value of specific gravity as 3.15 and Blain's surface area as 234 m^2/Kg.Cement was partially replaced with Class F fly ash upto 30% by weight. To obtain required workability of fresh concrete, polycarboxylic ether based superplasticizer was used as chemical admixture. Different mix proportions of concrete made with RCA are shown in Table-1

B. Casting of Specimens

In the present study, workability of fresh concrete was tested using slump test. Slump values of mixes were observed to be in the range of 70 - 100mm. The specimens were cast in batches. Each batch constituted 7 beam specimens of size 100mm × 100mm × 500mm to investigate flexural properties and 3 cube specimens of size 150mm × 150mm × 150mm to test the compressive strength of concrete made with RCA. Mixing of concrete was done using drum mixer. Table vibrator was used for compaction of concrete specimens and vibrations were given at the rate of 3600rpm. Specimens were demoulded 24 hours after casting and then cured in laboratory conditions for more than 90 days in order to avoid any possible increase in the strength during the fatigue tests. The value/quality of each batch of concrete made with RCA was controlled by acquiring its 28- day compressive strength. Compressive strength of various batches of concrete made with RCA is shown in Table-2. Average of 28- day compressive strength values of all batches was obtained as 31.7 MPa.

Table 1- Mix proportions of Concrete made with RCA

Cement	**Fly Ash**	**Fine Aggregates**	**Coarse Aggregates**	**Water**	**SP**
343 Kg	148 Kg	762 Kg	935 Kg	206 lts	0.25 %

Table 2- Compressive strength and static flexural strength test results of Concrete made with RCA

Batch No.	***28 days Compressive Strength (N/mm^2)***	***Static Flexural Strength (N/mm^2)***
1	*30.24*	*4.59*
2	*32.09*	*4.84*
3	*34.52*	*4.17*
4	*32.87*	*4.89*
5	*31.66*	*4.66*
6	*31.10*	*4.29*
7	*30.56*	*3.98*
8	*30.47*	*4.79*
Average	***31.7***	***4.53***

C. Static flexural and flexural fatigue testing

The estimation of static flexural strength was required prior to the selection of minimum and maximum stress limits for calculating fatigue tests. The static flexural strength tests on a particular batch of concrete made with RCA were conducted prior to the fatigue testing. Three specimens from each batch were tested under four point static flexural loads and the mean flexural strength was obtained as 4.53MPa for concrete beam specimens made with RCA and the same is tabulated batch-wise in Table-2. The left over beam specimens from each batch were tested for flexural fatigue. Servo controlled actuator (100kN) was used to conduct static flexural and flexural fatigue tests. The loading points were the same as for the static tests (i.e. four points loading) and the span was 450 mm. Flexural fatigue tests were conducted at different stress levels, S (S = f_{max}/f_r; f_{max} = *maximum fatigue stress*, f_r = *static flexural stress*), ranging from 0.85 to 0.55. The fatigue stress ratio, R (R = f_{max}/f_{min}), was kept constant at 0.10 throughout the investigation. All the tests were conducted at constant amplitude with sinusoidal loads applied at a frequency of 10 Hz. The number of cycle to failure of each beam specimen under fatigue loading was displayed on the cycle counter of MTS machine. The test was terminated as and when the specimen suffered the failure or an upper bound of 2×10^6 cycles was attained. The maximum limit of 2 million cycles was so chosen that if the specimen can sustain this much of cycles then it can be applicable for all the practical applications of concrete structures. The other factor was the testing of large number of specimens, so to make the testing less time consuming as well as economical, an upper limit of 2×10^6 cycles was chosen.

III. RESULTS AND DISCUSSION

Fatigue test results

The detailed representation of number of cycles to failure for each beam specimen under different stress levels is tabulated in Table-3. Some data points which gave drastically heterogeneous values were considered as outlier. Chauvenet□s Criterion was applied to all the data points at different stress levels and the identified data points were then excluded from further analysis. The same criterion has been applied for the rejection of outliers in various studies on fatigue behaviour of conventional and self compacting concrete. The equation used for this relationship is given by Eq. (1). Figure-2 summarizes the test results in the form of *S-N* curves obtained from this study for concrete made with 100% RCA. Least square method based linear regression was used to calculate the values of coefficients A & B. The material coefficients calculated for concrete made with 100% RCA by using Eq. (1), are A = 1.152, B = -0.098.

Fatigue life distributions of concrete made with RCA

A number of mathematical models have been used till date by various researchers to statistically depict the fatigue data. Weibull distribution is most commonly used for the statistical description of fatigue data of concrete due to its physically valid assumptions and sound experimental verification. Thereafter, two-parameter Weibull distribution has been used persistently to determine the fatigue life distribution of plain as well as fibrous concrete mixes. In the present study, the two-parameter Weibull distribution has been verified for the fatigue life distribution of concrete made with RCA and then distribution parameters were obtained by using S-N relationships. This paper only used the results of Graphical method for verification of two parameter Weibull distribution for fatigue life of concrete made with RCA at various stress levels *(S)*.The mean fatigue life of concrete made with 100% RCA obtained in the present investigation has been plotted and compared with that of concrete made with NA [16] in Figure-5. It can be seen that the mean fatigue life of concrete made with 100% RCA lies in a comparable range with that of concrete made with NA [16].

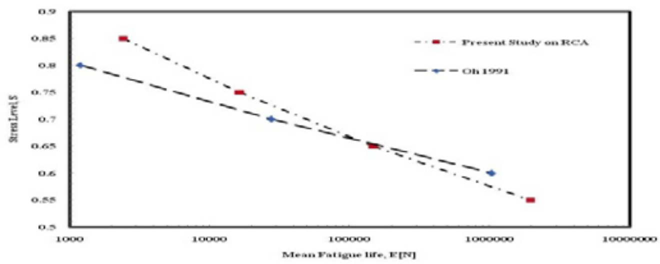

Fig. 2 □ Mean fatigue life of concrete containing 100% RCA 3.6. Two million cycles fatigue strength/endurance limit

Fatigue limit/endurance limit and flexural fatigue strength are necessary design parameters in almost all the important concrete structures like bridge decks, harbors, docks, multi-storey buildings, highways or airfield pavements etc. The design of these structures is based on the fatigue phenomenon i.e. the number of fatigue load cycles a concrete structure can withstand without failure.

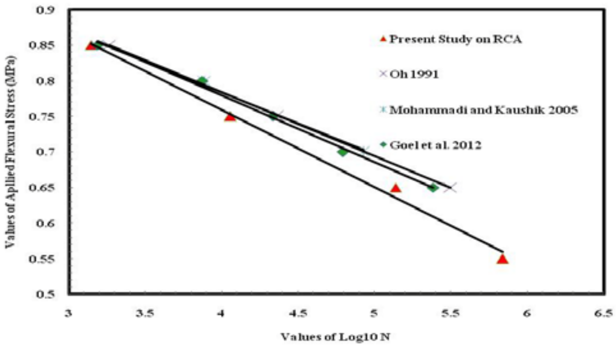

Fig. 3 □ Comparison of fatigue strength/endurence limit based on percentage of average static flexual strength of plain concrete containing 100% RCA with concrete containing 100% NA

IV. CONCLUSION

Fatigue behavior is becoming very important design parameter while designing multi storey buildings, bridges, decks, harbor and pavements etc. This is due to the fact that the flexural stresses induced in these structures are very critical in nature.

The present experimental investigation has been carried out to study the fatigue behavior of concrete made with 100% RCA. The flexural fatigue life of concrete made with 100% RCA is obtained for various stress levels. The mean fatigue life of concrete made with 100% RCA has also been calculated. The two million cycles fatigue strength/endurance limit was also estimated for concrete containing 100% RCA and compared with the previous studies on NA[16,17,18]. The endurance limit obtained in the present study is 50% of the average flexural strength.

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