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Flexural Behaviour of Reinforced Concrete Beam Containing Steel Slag as Coarse Aggregate

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Abstract. Results of an investigation conducted to study the flexural strength of steel slag reinforced concrete (SSRC) containing steel slags of mixed aspect ratio are presented. Approximately ten beam specimens of size 150 mm x 150 mm x 900 mm were tested under four-point static flexural loading in order to obtain the flexural performace lives of SSRC at different stress levels. The specimens incorporated 0.1, 0.2 and 0.3% volume fraction of steel slag fibres. From the experimental investigation it has been observed that the moment capacity of SSRC beams was higher than NWC beams. Thus, the SSRC beams showed a ductile failure, giving amble warning before failure happened. SSRC beams also exhibited a lot of cracking thus the crack width and crack spacing was small. The other advantage for SSRC beams was deflection. The SSRC beams exhibited higher deflection under constant load until failure, compared to NWC beams that failed in brittle manner without warning.

Keywords: Steel slag reinforced concrete (SSRC), Structural Behavior, Failure Mode, Ductile Behavior, strain characteristics, crack study.

1 Introduction

Steel Fiber Reinforced Concrete (SFRC) has gained increased popularity in construction industries in the recent years. Slag is a byproduct of metal smelting and hundreds of tons of it are produced every year all over the world in the process of refining metals and making alloys. Like other industrial by products, slag actually has many uses, and rarely goes to waste. Use of more and more environment-friendly materials and industrial wastes in any industry in general and construction industry in particular, is of paramount importance Slag appears in concrete, aggregate road materials, as ballast, and is sometimes used as a component of phosphate fertilizer. In appearance, slag looks like a loose collection of aggregate, with lumps of varying sizes. Slag is also sometimes referred to as cinder, in a reference to its sometimes dark and crumbly appearance. Slag works very well as a loose aggregate and can be ground to produce a more even grain. Slag is also mixed with materials for making roadways, used as ballast on trains and large trucks, and is also applied as phosphate fertilizer. When used as fertilizer, the slag is ground very fine before being spread and it slowly time releases nutrients because it takes a long time to break down. It also utilizes the waste products of industries like fly ash and steel slag which otherwise would pose problem for their safe disposal and sometimes degrades the environment. Concrete with steel fibers is known as Steel Fiber Reinforced Concrete (SFRC).

Hisham Qasraui et al.(2009) studied the effect of waste material of steel plant in concrete. In their investigation local unprocessed steel slag was used in concrete as fine aggregate replacing the sand partly or totally. The compressive strength of concrete was reported to be improved when steel slag is used for low sand replacement ratio (up to 30%). Johnson Alengaram et al,(2008) conducted experiemtns on palm kernel shell concrete and its comparison with normal weight concrete (NWC).From their work they concluded that the PKSC beams showed a ductile failure, giving amble warning before failure. PKSC beams also exhibited a lot of cracking thus the crack width and crack spacing was small. The other advantage for PKSC beams was deflection. The PKSC beams exhibited higher deflection under constant load until failure, compared to NWC beams that failed in brittle manner without warning. Khidhair et al. (2009) has used the steel slag as replacement of aggregate in the concrete. The results showed that the density of concrete, compressive strength, flexural strength after 7 days and 28 days were increased by increasing slag content while water absorption was decreased by increasing slag content. Mansur et al(1982) investigated on addition of steel fibers in concrete improves the torsional strength of the rectangular beams in pure torsion. Narayanan and Darwish (1988) studies show that addition of SFRC offers a multidirectional reinforcement, simple detailing without congestion, and higher post-cracking residual stress and ductility. Also shown that including discrete fibers in concrete enhance the strength and the deformation capacities of deep beams in addition to better cracking control. Ramakrishnan et al.(1987) studied the flexural fatigue performance of concrete reinforced with collated hooked-end steel fibres of size 50 mm×0.50 mm and 60 mm×0.80 mm. Two different fibre volume fractions of 0.50% and 0.75% were tested. After addition of these fibres to the concrete, the ductility and post-crack energy absorption capacity were greatly increased.

2 Material Properties

2.1 Steel slag-Physical Properties

Steel slag aggregates are highly angular in shape and have rough surface texture. They have high bulk specific gravity and moderate water absorption (less than 3 percent) The physical properties of steel slag are shown in Table 1.

a) Steel slag left on the steel mill area

b) Selected steel slag for concrete mix

Figure 1: Steel slag used for concrete mix

Table 1.Typical physical properties of steel slag

Property	Value
Specific Gravity >	3.2 - 3.6
Unit Weight, kg/m^3	1600-1820
Absorption	up to 3%
Maximum size of aggregate,mm	16.00
Aggregate impact value (%)	8.00
Aggregate crushing value(%)	9.00

Table 2. Typical steel slag chemical composition.

Constituent	Composition (%)
CaO	40 - 52
SiO_2	10 - 19
FeO	10 - 40 (70 - 80% FeO, 20 - 30% Fe2O3)
MnO	5 - 8
MgO	5 - 10
Al_2O_3	1 - 3
P_2O_5	0.5 - 1
S	< 0.1
Metallic Fe	0.5 - 10

2.2 Steel slag-Chemical Properties

The chemical composition of slag is usually expressed in terms of simple oxides calculated from elemental analysis determined by x-ray fluorescence. Table 2 lists the range of compounds present in steel slag from a typical base oxygen furnace. Virtually all steel slags fall within these chemical ranges but not all steel slags are suitable as aggregates. Of more importance is the mineralogical form of the slag, which is highly dependent on the rate of slag cooling in the steel-making process. The cooling rate of steel slag is sufficiently low so that crystalline compounds are generally formed. Free calcium and magnesium oxides are not completely consumed in the steel slag, and there is general agreement that the hydration of unslaked lime and magnesia in contact with moisture is largely responsible for the expansive nature of most steel slags. Steel slag is mildly alkaline, with a solution pH generally in the range of 8 to 10. However, the pH of leachate from steel slag can exceed 11, a level that can be corrosive to aluminum or galvanized steel pipes placed in direct contact with the slag.

2.3 Concrete Properties

The concrete mix was made with ordinary Portland cement, river sand and coarse aggregate of maximum size 20mm. Cement, sand and coarse aggregates was 1:1.5:3 in proportion by weight. Steel slag of 0.5 mm diameter and 30 mm length was used for the entire concrete mix. Steel slags are obtained from north Chennai steel plant. First dry mix was prepared from ordinary Portland cement, river sand and coarse aggregates maximum 20mm), and steel fibers were added to the dry mix of the materials. Water was then added to the mix to prepare the concrete. The W/C ratio for the mix was 0.50. After through mixing, beam specimens were cast along with companion cube moulds to measure the compressive strength of concrete. All the beams and companion cubes were compacted properly. The beam specimens were stripped from their moulds after 24 hours and submerged in water tank for 28 days for curing after casting. Before testing, the beams were coated with whitewash to facilitate the observation of cracking pattern.

3 Experimental Program

In the present investigation, tests were conducted on ten beam specimens of 150mmX150mm X 900mm cast in moulds. Specimens labels were shown min Table 3 according to the volume of steel slag added in to the concrete. The steel slag is added in to 10%-50%, the beams referred as 10% of steel slag as SSRC1 respectively. The reinforcement used are 2 Nos. of 12mm diameter bar for all the beams. All the nine beams were tested in a Universal Testing Machine (U.T.M) of capacity 40 Tones available in the structural Engineering Laboratory. The tensile and compressive strains of both reinforcement and concrete were measured through electrical resistance gauges. During testing, the beams were preloaded with a minimal force of 0.5kN to allow initiation of the diagauges and strain gauges. The developments of cracks were observed and crack width was measured at the level of tensile reinforcement using a handle-held microscope with sensitivity of 0.02mm.All strain, crack width and deflection measurements were measured at every load increment. The first crack load was noted immediately after the formation and all the cracks were marked as and when they propagated in the beam.

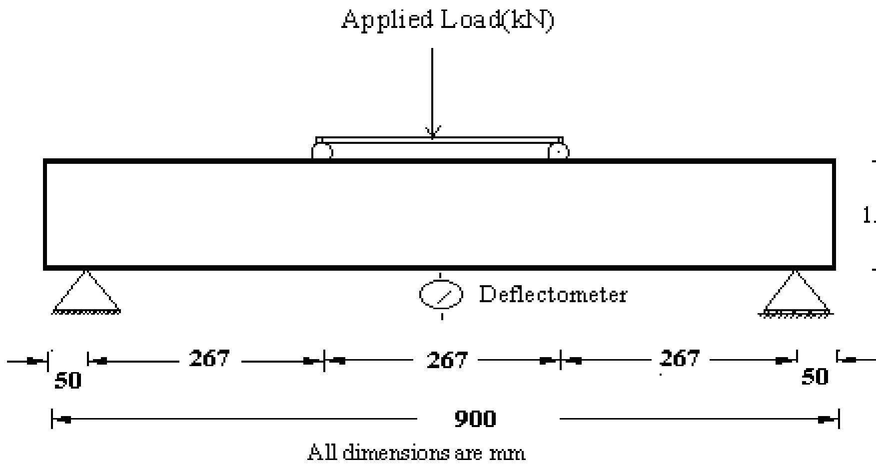

Figure 2: Details of test

4 Test result and Discussion

4.1 Bending moments

A comparison between the experimental ultimate moments (M_{ult}) and the theoretical design moments are shown in Table 3. The theoretical design moments (M_{des}) of the beams was predicted using the rectangular stress block analysis are recommended by IS 456-2000. For slag beams, the ultimate moment obtained from the experiments was approximately 2% to 32% higher compared to predicted values. From the performed tests, it was observed that for steel slag concrete beams, IS 456 can be used to obtain a conservative estimate of the ultimate moment capacity and also adequate load factor against failure.

Table: 3 Comparison between experimental and theoretical ultimate moments

Beam No.	Experimental Ultimate moment(kN m)	Theoretical design moment (kN m)	Capacity ratio of Steel slag concrete beams
SSRC1	6.81	5.24	1.30
SSRC2	6.68	5.24	1.27
SSRC3	6.41	5.24	1.22
SSRC4	5.87	5.24	1.12
SSRC5	5.61	5.24	1.07
NWC	6.94	5.24	1.32
PSCB1	5.34	5.24	1.02
PSCB2	4.67	5.24	0.90
PSCB3	2.54	5.24	0.50
PCCB	5.34	5.24	1.02

4.2 Deflection behaviour

Figures 3 show the typical experiment load-deflection curves for steel slag concrete beams. In all beams, before cracking occurred, the slope of the load-deflection curved was steep and closely linear. Once flexural cracks formed, a change of slope of the load-deflection curve was observed and this slope remained fairly linear until yielding of the steel reinforcement took place.
Table 4 compares the predicted midspan deflection under service moments with the experimental values. The predicted deflection is calculated from load values according to the strength of materials equation, using the formula

$$\Delta = \frac{5wl^3}{163EI} \quad \text{---------------- (1)}$$

Where,
Δ = Midspan deflection in mm,
W = Load acting on the beam in Kn,
l = Effective span of the beam in mm and
EI = Flexural rigidity in N/mm^2.

It was observed that the deflection obtained from the experiment at the service moments compares reasonably well to the predicted deflection. The modulus of elasticity of concrete very much governed by the stiffness of the coarse aggregate. From the properties in Table 1, it can be seen that steel slag is porous in nature also equal density compacted to granite, which directly influence the stiffness of the aggregate. Due to the equal modulus of elasticity of the steel slag beam when compared to R.C.C beam, the deflection under the service loads is acceptable as the span –deflection ratios ranged between 167 to 291 and are within the allowable limit provided by IS 456. IS 456 recommends an upper limit of span/250 for the deflection in order to satisfy the appearance and safety criteria of a structure. From the load deflection graph is also observed that the beams are conventional R.C.C and 10% to 50% steel slag concrete shows leaves behavior at the yield point and have further yielded with loads. Particularly the beam specimens filled with normal concrete have no ductile failure the failing in compression remaining all specimens are failure in shear failure. Hence it is also absorbed the grade of concrete and reinforcement ratio and spacing of stirrups have certain effects on the flexural behavior of reinforced concrete beam.

Table 4 : Deflection of concrete beams at service moments

Beam No.	Theoretical design service moment (kN m)	Deflection form experiment Δexp (mm)	Theoretical deflection Δthe (mm)	Δexp / Δthe	Span/Δexp	Mode of failure
SSRC1	5.24	5.50	1.63	3.37	167	Flexure
SSRC2	5.24	4.53	1.41	3.21	173	Flexure
SSRC3	5.24	5.72	1.76	3.23	151	Flexure
SSRC4	5.24	4.00	1.35	2.96	291	Flexure
SSRC5	5.24	4.20	1.30	3.23	229	Flexure
NWC	5.24	4.50	1.51	2.98	174	Flexure
PSCB1	5.24	5.50	1.50	3.67	276	Shear
PSCB2	5.24	5.30	1.40	3.78	320	Shear
PSCB3	5.24	4.95	1.25	3.96	267	Shear
PCCB	5.24	4.50	1.20	3.75	162	Shear

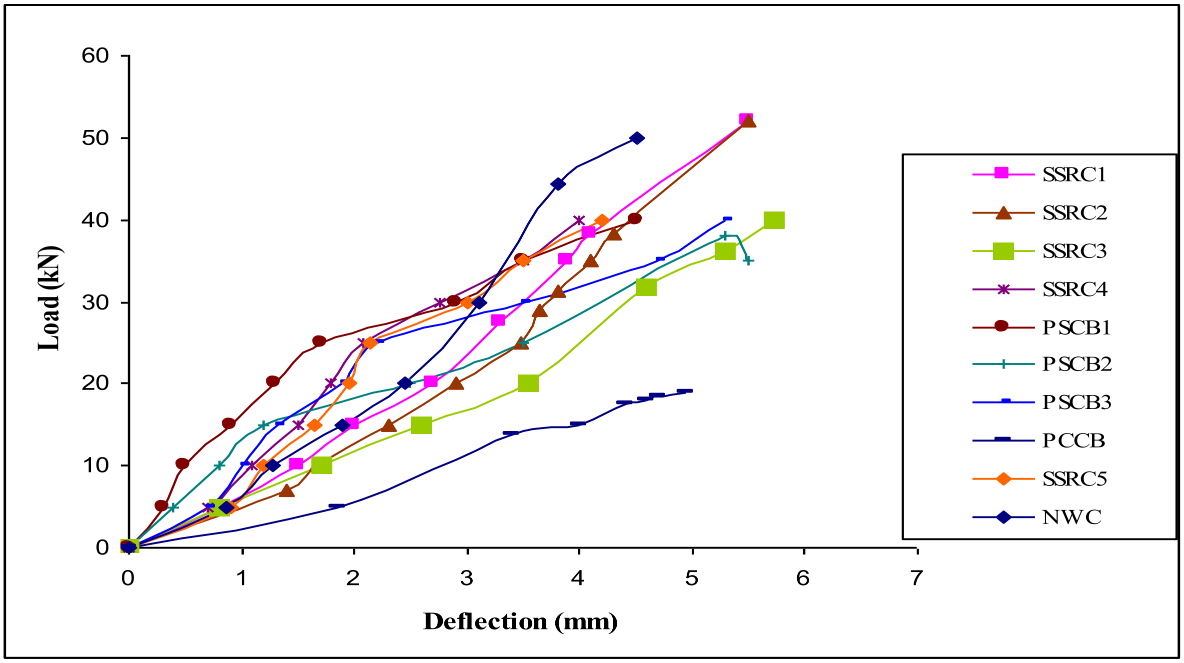

Figure 3 : Load Vs Deflection of tested beams

4.3 Ductility behaviour

The ductility of reinforced concrete structures is also of paramount importance because any member should be capable of undergoing large deflection at near maximum load carrying capacity , providing ample warning to the imminence of failure. In this study , the displacement ductility was investigated. Table 5 shows the ductility of the tested steel slag concrete beams. The displacement ductility ratio is taken in terms of $\mu = \Delta_u/\Delta_y$, which is the ratio of ultimate to firest yield deflection, where Δ_u is the deflection at ultimate moment and Δ_y is the deflection when steel yields. In general, a high ductility ratio indicates that a structural member is capable of undergoing large deflections prior to failure. In this investigation it was observed that the steel slag beams have ductility ratio of more than 3 it shows relatively good ductility. One of the important factors contributing to the good ductility behaviour of the steel slag beam was toughness and good shock absorbance nature of steel slag aggregate as indicated by the aggregate crushing value and aggregate impact value from Table 1. Ashour (2000) mentioned that the members with a displacement ductility in the range of 3 to 5 has adequate ductility and can be considered for structural member subjected large displacements, such as sudden force caused by earth quake.

Table 5 : Displacement ductility of concrete beams obtained from experiment

Beam No.	Yield stage		Ultimate stage		Displacement Ductility ratio $\Delta u/\Delta_y$
	Moment kNm	Deflection,(Δ_y),mm	Moment kN m	Deflection (Δu),mm	
SSRC1	3.33	1.50	6.81	5.50	3.67
SSRC2	3.20	1.55	6.68	4.83	3.11
SSRC3	3.07	1.60	6.41	4.80	3.00
SSRC4	3.20	1.65	5.87	4.95	3.00
SSRC5	3.74	1.75	5.61	4.90	2.80
NWC	2.68	1.30	6.94	4.50	3.46
PSCB1	3.20	2.60	5.34	5.50	2.11
PSCB2	3.33	2.65	4.67	5.30	2.00
PSCB3	2.94	2.80	2.54	4.95	1.76

PCCB	2.68	2.40	5.34	4.50	1.88

4.4 Cracking Behaviour

Crack widths were measured at every load interval at the tension steel level and the crack formations were marked on the beam. The initial cracks were occurred at about 15% to 30% of the ultimate load. It was noticed that first crack was always appears close to the midspan of the beam. The cracks forming on the surface of the beams were mostly vertical, suggesting failure in flexure. The cracking characteristic of the steel slag concrete beams are illustrated in Table 6.

The theoretical cracking moment , $Mcr_{(the)}$ of the beam is determined using the formula as recommended by ACI 318,

$$M_{cr} = \frac{f_{cr}\, I_g}{y} \qquad \text{-----------------}(2)$$

Where:

f_{cr}= flexural tensile concrete strength (taken as 0.7 $\sqrt{fcu}$ M_{Pa}) , I_g = gross moment of uncracked section = depth from the bottom fiber to the neutral axis.

It was observed that the experimental cracking moments were about 20% to 37% of the theoretical moments. The first crack moment was taken as the point where a sudden deviation from the initial slope of the load-deflection curve occurs. The use of modulus of rupture greatly over estimates the experimental cracking moments. Therefore it is recommended that a reduced value of about 70% of f_{cr} , should be used to predict the cracking moment with better accuracy. In most codes of practice, the maximum allowable crack width lie in the range of 0.10 mm to 0.40 mm, depending upon the exposure condition. The average measured for crack widths levels of 0.4 mm to 0.6mm.For members protected against weather, ACI 318 permits crack widths up to 0.41 mm. It was observed that for steel slag concrete, the crack width at service load were below the maximum allowable value as stipulated by BS 8110 for durability requirements.

Table 6: Cracking behaviour of Steel slag concrete beam

Beam No.	Experimental cracking moment Ms (kN m)	Experimental cracking moment at ultimate load stage Mcr(exp) (kN m)	Theoretical cracking moment Mcr(the) (kN m)	Theoretical design service moment Ms (kN m)	Experimental crack width at Ms (mm)	Experimental crack width at failure (mm)
SSRC1	2.25	6.80	1.21	5.24	0.22	2.20
SSRC2	2.00	7.20	1.21	5.24	0.35	2.50
SSRC3	1.75	7.70	1.20	5.24	0.50	2.90
SSRC4	1.60	7.80	1.10	5.24	0.70	3.10
SSRC5	1.50	7.00	1.08	5.24	0.90	3.30
NWC	2.50	6.70	1.23	5.24	0.20	2.00
PSCB1	1.00	3.20	0.95	5.24	1.10	3.60
PSCB2	0.85	3.50	0.90	5.24	1.50	3.70
PSCB3	0.75	3.70	0.80	5.24	1.70	4.00
PCCB	1.10	3.00	1.00	5.24	1.00	3.50

Figure 5(a): Shear failure pattern of R.C.C beam

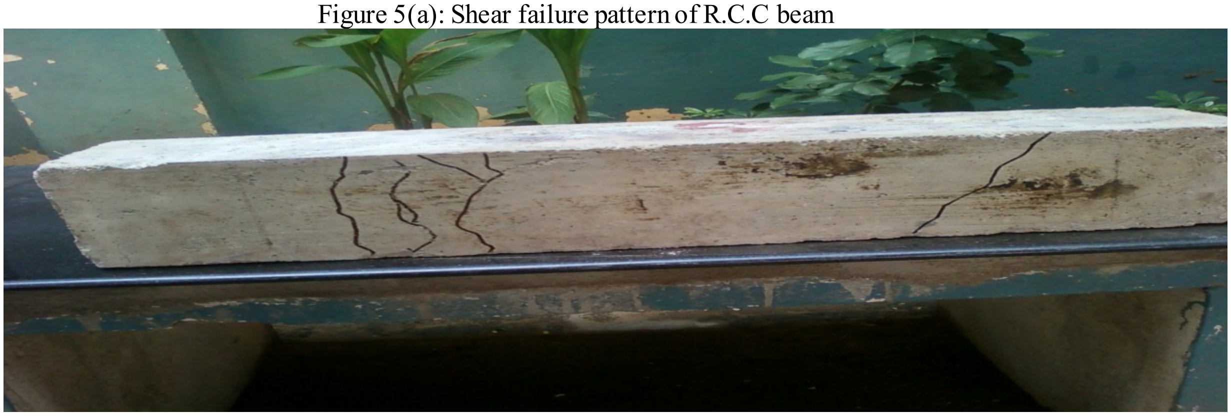

Figure 5(b): Flexure cum Shear failure pattern of S.S.R.C beam

Figure 5(c): Failure pattern of P.C.C beam

Figure 5 : Failure pattern of concrete beams

4.5 Concrete and Steel Strains characteristics

The tensile and compressive strains of reinforcement and concrete respectively were measured at every load increment. The strain measurements against the loads for both NWC, SSRC, PCCB and PSCB beams are shown in Figure 6. While the, Compressive strains in the concrete are shown in positive values while the negative values show the tensile strains in the reinforcement. The highest tensile and compressive strain in SSRC beams reached 5500 x 10^{-6} m/m and 6800 x 10^{-6} m/m in SSRC before failure. The maximum strains in the NWC beams recorded were 5500 x 10^{-6} m/m and 6000 x 10^{-6} m/m in concrete and steel respectively.

The higher strains in SSRC beams may be attributed to higher deflection due to low modulus of elasticity of the SSRC. The strains were linear in both NWC and SSRC beams until yielding of steel and then rapidly increased before failure. The increasing strain shows that good bond between steel and concrete existed till the yielding of steel. From these results it is understand that SSRC beam is able to achieve its full strain capacity under flexural loading. The increasing strains in PSCB concrete beams also shows. The strains, before final failure may have been higher than the strains reported here.

The compressive strains in concrete at service moments varied between 500 x 10^{-6} to 1170 x 10^{-6} m/m in NWC beams, however the SSRC beams recorded slightly higher strains between 1000 x 10^{-6} to 1425 x10^{-6} m/m.

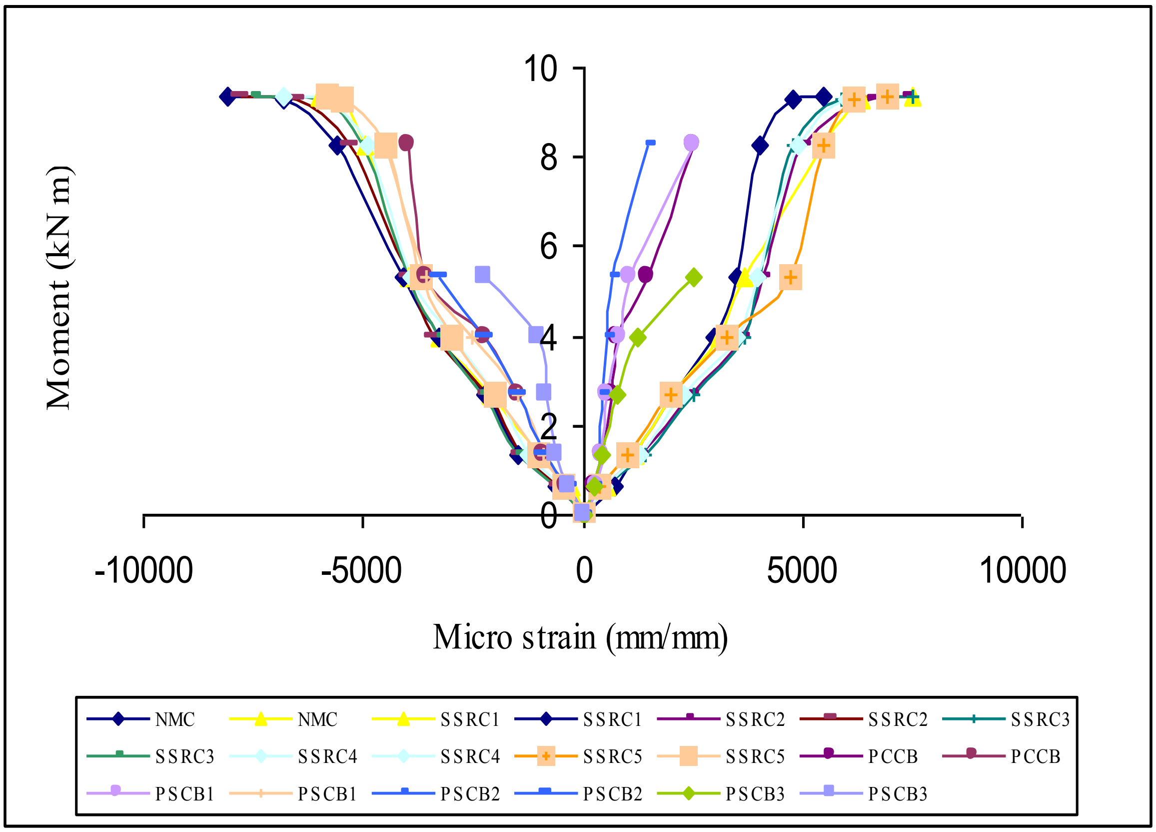

Figure 6 : Compressive and tensile strains of concrete and steel

5 Conclusion

From the experimental conducted, it was generally observed that the investigation of flexural behaviour of steel slag concrete beam gives encouraging results for steel slag to be used as coarse aggregate especially protection of natural resources, prevention of environmental pollution and contribution to the economy by using the waste material. The following observations and conclusions can be made on the basis of the current experimental results.

1) The overall flexural behavior of SSRC beams used in this study closely resembles that of equivalent beam made with NWC.

2) The experimental ultimate moment gives a conservative estimate for steel slag concrete beams for 7% to 32% of a theoretical ultimate moment.

3) Steel slag beams showed good ductility behaivour. All the beams exhibited considerable amount of deflection, which gives enough warning to get start of failure.

4) The crack widths at service loads varies from 0.20 mm to 0.45 mm and this was within the maximum allowable limits.

5) Higher tensile steel strains of the SSRC beams show the existence of the stronger bond between the concrete and the steel

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Abbreviations

NWC : Normal weight cement concrete beam
SSRC : Steel slag Reinforced cement concrete beam
PCCB : Plain cement concrete beam
PSCB : Plain steel slag concrete beam

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