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CORROSION EFFECTS ON THE FLEXURAL STRENGTH BEHAVIOUR OF CONCRETE CONTAINING MANUFACTURED SAND

B. Vijaya[1] and S. Senthil Selvan[2]
[1]S.R.M University, Kattankulathur, Chennai, India
[2]Department of Civil Engineering, S.R.M. University, Kattankulathur, India
E-Mail: bvijayasuresh@gmail.com

ABSTRACT

The corrosion in reinforcing steel is the most detrimental effect on endangering the structural behaviour of steel in concrete. This present study focuses on predicting the corrosion behaviour of concrete in which Manufactured Sand (M-Sand) is used as a partial replacement for natural sand. To retain the natural resource such as natural sand an attempt is made in this research by partially replacing the natural sand with M-Sand. Experimental and numerical investigation has been carried out for three different levels of corrosion 5%, 10% and 25% to define mild, medium and severe exposure condition. National Bureau of Standard (NBS) beams have been casted and analysed for thecorrosion performances of steel that is embedded in concrete by accelerated corrosion technique for concrete of grade M40 replaced with 60% manufactured sand for river sand which is found optimum. From the experimental investigation, it has been observed that there is adecline in the load carrying capacity of NBS RC beams due to reinforcement corrosion. Numerical investigation was made with concrete modelled as solid 65 element and reinforcement modelled as Link 8 elements by ANSYS software using finite element method.

Keywords: manufactured sand, accelerated corrosion, load-deflection, load-strain, numerical model.

1. INTRODUCTION

The world wide decline in the availability of construction sands along with the environmental pressures to reduce extraction of sand from rivers, the use of manufactured sand as a replacement is increasing. The use of Manufactured sand (M-sand) has been increasing due to the scarcity of good quality natural river sand. Adams Joe, M. *et al*. (2013), experimentally investigated the effect of addition of M-sand by replacing river sand in high performance concrete. By replacing 50% of M-sand, gave maximum strength and durability criteria than conventional concrete. The effect of corrosion in reinforcement has been identified as being the predominant deterioration mechanism for reinforced concrete structures, which seriously affects the serviceability and durability of RC structures. Akshatha Shetty *et al*. (2015). concluded that the load carrying capacity and the bond behaviour of NBS RC beams decreases with the increase in reinforcement corrosion. They investigated that for every percentage increase in the corrosion level, there is 1.6 and 1.8% decrease in the load carrying capacity for experimental and numerical model beam specimen, respectively. Amir Poursaee *et al*. (2008) investigated the corrosion behaviour of HPC containing 25% slag and 25% fly ash. They proved that the HPC containing 25% slag and 25% fly ash exhibits superior protection to steel than OPC. Bhaskar Sangoju *et al*. (2011) found that the rebar corrosion is lower in concrete with lower water to cement ratio. They also found that there is reduction in the weight loss of rebar for concrete with lower water to cement ratio and this is caused due to increased impermeability and lower electrical conductivity. Feng WU *et al*. (2014). Investigated the calculation of corrosion rate for reinforced concrete beams based on corrosive crack width. They concluded that there exists a linear relationship between crack width and corrosion rate. Hakan Yalciner *et al*. (2012) concluded that due to higher permeability of concrete with higher water to cement ratio, the crack width of higher strength concrete was more than that of lower strength concrete for the same corrosion level. Homayoon Sadeghi-Pouya *et al* studied the corrosion durability of high performance steel fibre reinforced concrete. They concluded that less percentage of corrosion was observed in the specimen containing steel fibres. Indrajit Ray *et al*. (2011). Investigated the effect of concrete substrate repair methods for beams aged by accelerated corrosion and strengthened with CFRP. They concluded that the large scale beams that were unrepaired and subjected to corrosion cycles I and II exhibited large reduction in the strength properties. JIN Wei-Liang and ZHAO Yu-xi (2001) studied the effect of corrosion on bond behaviour and bending strength of reinforced concrete beams. They concluded that the increasing reinforcement corrosion decreases the bending strength of corroded reinforced concrete beams. Kishore Kumar, M. *et al* (2012) investigated that the initiation time of corrosion is increased with the increase in the percentage replacement of fly ash. They also concluded that the initiation time of controlled concrete is very less when compared with fly ash blended concrete and it is maximum for 30% replacement of cement with fly ash. Leema Rose, A. *et al*. (2009). studied the strengthening of corrosion damaged reinforced concrete beams with glass fiber reinforced polymer laminates. They concluded that GFRP laminates had enhanced the ultimate strength carrying capacity of RC beams. Malumbela, G. *et al* (2009) studied the structural behaviour of beams under simultaneous load and steel corrosion. They concluded that the depth of neutral axis, the longitudinal strain and curvature depends on the loading condition and the rate of corrosion. They also studied that the moment of inertia depends only on the level of corrosion. Poornachandra Pandit *et al*. (2014) studied the experimental and numerical investigation of flexural behaviour of accelerated corroded beams. In their research they concluded that while comparing the numerical results with the experimental part, the numerical model showed 11.5 % more load carrying capacity than that of experimental prediction and 12.2% less deflection when compared to experimental values. They also concluded that the FEM modelling can be utilized satisfactorily to measure load-deflection behaviour and crack pattern of real time structures. Prabakar, J. *et al* (2010) investigated that the lower grade concrete has minimum initiation period when compared with higher grade concrete. They also concluded that the low grade OPC concrete exhibits high chloride profile and diffusion coefficient when compared with high grade concrete.

2. EXPERIMENTAL INVESTIGATION

In the experimental investigation, the mechanical properties of the conventional and M-sand concrete were determined by conducting the compressive strength test. In order to predict the corrosion resistance from the compressive strength, accelerated corrosion tests on NBS RC beams were conducted to concrete to assess the durability properties.

2.1. Material description

Ordinary Portland cement of grade 53 having specific gravity of 3.14 and fineness modulus 2.56, Coarse aggregate passing through 20mm and 12mm down having specific gravity of 2.65 and conforms to IS 383-1970 were used. M-Sand is used as partial replacement of fine aggregate which is used for preparing the concrete. The bulk density of manufactured sand is 1862 Kg/m^{3}and specific gravity is 2.50. The fineness modulus of M-sand is 2.68. The sieve analysis revealed that the M-Sand falls in Zone II as given in IS 383:1970. The properties of fine aggregate and coarse aggregate is found to confirm with IS 383: 1970.

2.2. Experimental testing procedure

In this experimental study, concrete cubes are prepared for M40 grade of concrete with 30%,40%,50%,60%,70% and 100% replacement of river sand by manufactured sand. In this experimental investigation, strength characteristic such as compressive strength, split tensile strength and flexural strength were determined experimentally for the conventional and M-Sand concrete. Durability measurements is quantified by conducting acid attack test, sulphate attack test and rapid chloride permeability test. The experimental results revealed that strength and durability properties of concrete is enhanced by partial replacement of sand with 60% of M-Sand (which found optimum) for M40 grade of concrete. To obtain the damage occurrence times on reinforced concrete specimens, accelerated corrosion tests are also performed on NBS RC beams.

2.3. Experimental program on the strength behaviour of concrete

Totally 108 cubes, 63 cylinders and 63 prisms were casted using ordinary river sand and M-sand. In order to study the mechanical behaviour of conventional and M-sand concrete, the casted cubes were cured for 28 days and tested. Cube compressive test, split tensile test and flexural strength test were conducted to illustrate the variations in the strength characteristics for M40 grade concrete for various percentage replacement of M-sand with river sand. An overview of the parameter study on the cube compressive strength, split tensile strength and flexure strength at 28 days of curing was recorded and systematically analysed and are illustrated in the Table-1.

Table-1. Compressive strength, split tensile strength and flexural strength with percentage replacement of M-sand.

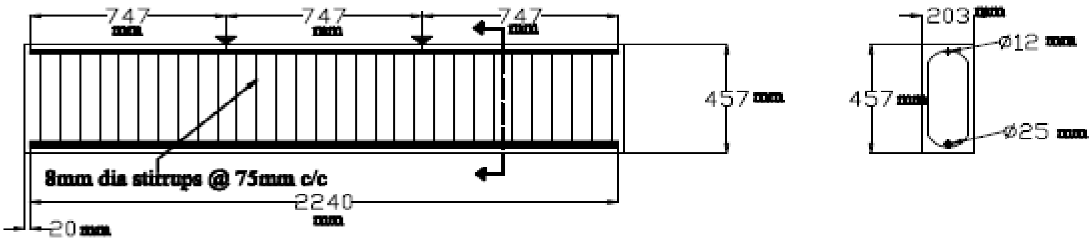
S. No.	Concrete type	M-Sand replacement percentage	Compressive strength (Mpa)	Split tensile strength (Mpa)	Flexural strength (Mpa)
1	M40	0	46.80	4.05	4.99
2	M40	30	48.51	4.20	5.20
3	M40	40	51.26	4.36	5.36
4	M40	50	53.08	4.56	5.58
5	M40	60	55.82	4.87	5.72
6	M40	70	52.24	4.74	5.48
7	M40	100	50.22	4.63	5.26

From the Table-1 the increase in percentage of M-sand increases the value of compressive strength up to 60% replacement of M-sand, beyond which there is decrease in compressive strength for the replacement of M-sand with river sand. For M40 grade concrete, the compressive strength is increased by 19% for 60% M-sand replaced concrete compared with conventional concrete. It is also found from the test results that the split tensile strength is increased by 20% for M40 grade concrete, for 60% replacement of M-sand with river sand. This improved split tensile strength is due to the manufacturing process of M-sand, which resulted in reduced surface area and better particle packing. This could have contributed to the better binding effect with the available cement paste and thereby improved the split tensile strength. From the results obtained, it is clearly illustrated that the flexural strength shows significant increasing trend of 14% for M40 grade concrete for 60% replacement of river sand with M-sand. Above 60% the flexural strength decreases. From the tabulated results it is clearly found that there is an increase in the flexural strength values for the conventional and M-sand concrete up to 60% replacement of river sand with M-sand. Further increase in replacement of M-sand results in reduction of flexural strength. Apart from the compressive and flexural strength identification, this research work focuses on simplified durability evaluation with the help of accelerated corrosion technique. To gauge the long-term corrosion performance of reinforcing steel in concrete in a relatively short period of time, it is necessary to employ accelerated corrosion technique. In this research, an electrochemical method was adopted to accelerate the corrosion of the reinforcement bars.

2.4. Accelerated corrosion test

Apart from the compressive and flexural strength identification, this research work focuses on simplified durability evaluation with the help of accelerated corrosion technique. To gauge the long-term corrosion performance of reinforcing steel in concrete in a relatively short period of time, it is necessary to employ accelerated corrosion technique.In this research, an electrochemical method was adopted to accelerate the corrosion of the reinforcement bars.

For the present study, National Bureau of Standard (NBS) beam specimens of size 2.44 m x 0.457 m x 0.203 m are used. Beams with an effective cover of 25mm were designed. Bottom reinforcement is provided with two 25mm diameter bars, at the top two bars of 12mm diameter were used as hanger bars and 8mm diameter stirrups were placed centre to centre at an spacing of 75mm.



Elevation Section

Figure-1. Reinforcement details of the beam specimen.

24 NBS beam specimens were casted and cured for 28 days, and they were subjected to accelerated corrosion process. In this process, the beam specimens were partially immersed in a 5% NaCl solution. Current required to achieve the different corrosion level can be calculated using Faraday's law.

Figure-2. Preparation of beam specimens.

Figure-3. Beam specimens under accelerated corrosion.

2.4.1. Calculation of amount of current required to obtain different corrosion level

Corrosion current density, i_{corr} is calculated by

$$i_{corr} = \frac{(W_i - W_f) \times F}{(\pi DLWT)} \quad (1)$$

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Degree of corrosion, ρ

$$\rho = \frac{(W_i - W_f) \times 100}{W_i} \quad (2)$$

The applied current, i_{app}

$$i_{app} = i_{corr} = \frac{(\rho \times W_i \times F)}{(100 \times \pi \times D \times L \times W \times T)} \quad (3)$$

Where ρ is the degree of corrosion, T is the time in seconds; W_i is the initial weight of steel (20,000g for the present study), F is the Faraday's constant (96487 amp sec), W is the equivalent weight of steel (27.925 g), $i_{app}$is the applied current (A).

Based on the calculation, the amount of current required for accelerated corrosion varied from 5A, 10A and 25A for 5%, 10% and 25% corrosion level to define mild, medium and severe exposure condition respectively.

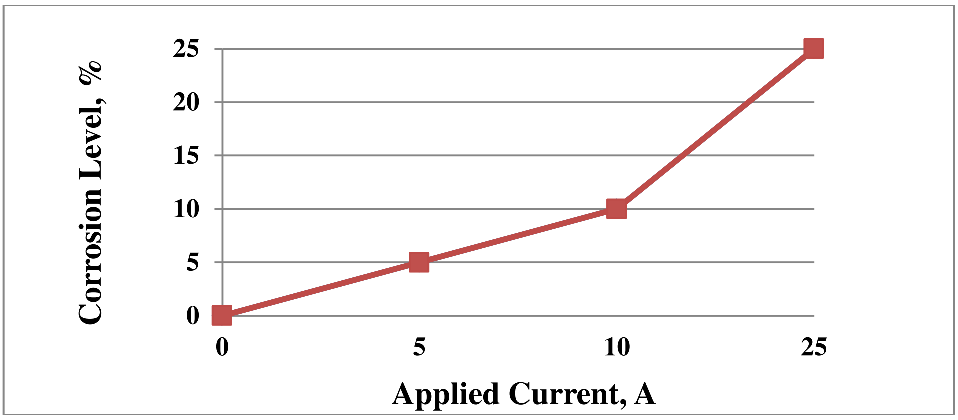

Figure-4. Variation of corrosion levels with applied current.

Obtained corrosion levels for the applied current is shown in Figure-4 It is seen from the graph that the corrosion levels increases linearly with the increase in the applied current

$Y = 0.98 X-0.26$, $R^2= 0.996$ (M40- conventional concrete) (4)

$Y = 0.96 X-0.54$, $R^2= 0.998$ (M40 - M-sand concrete) (5)

Where X= applied current, A and Y = obtained corrosion level, %.

2.5Corrosion rate measurements

Corrosion rate was measured with Applied Corrosion Monitoring (ACM) instrument based on linear polarisation resistance (LPR) after the completion of accelerated corrosion process. This linear polarisation technique is followed to achieve the desired degree of corrosion levels in beam specimens after inducing corrosion for a particular duration.

3. Test setup used for the flexural strength study

The corroded beam specimens are tested under two-point loading for a load increment of 15KN using a loading frame. The loading was continued until failure. The deflections were measured using mechanical dial gauges at the mid span and at the loading points.

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Table-2. Ultimate load, deflection and strain for different degree of corrosion.

S. No.	Concrete grade	Beam specimen with corrosion level (%)	Ultimate load (KN)		Deflection at mid span (mm)		Micro strain (μ x 10^{-6})
			Theo (Wth)	Expt (Wep)	Theo (δ_{th})	Expt (δ_{ep})	
1	M40	0%	213.37	225	5.24	6.8	1425
	M40 (Msand60%)		238.63	240	4.82	5.6	1392
2	M40	5%	205.73	210	6.43	7.4	1553
	M40 (M-sand 60%)		223.67	225	5.36	6.2	1480
3	M40	10%	186.63	195	7.84	8.6	1656
	M40 (M-sand 60%)		209.18	210	6.23	7.0	1528
4	M40	25%	156.34	150	8.38	9.8	1817
	M40 (M-sand 60%)		168.23	165	7.17	8.8	1698

Table-2 gives the ultimate load, Deflection at the mid span and the micro strain value for the different corrosion level. The ultimate load carrying capacity of the conventional beam specimen is found to be 225KN and when compared with conventional concrete beam specimen the load carrying capacity of the M-sand replaced concrete is high by 6.66 %. With the increase in the percentage of reinforcement corrosion, the failure mode of the beam specimen would change from ductile mode to brittle mode, as in the case of under reinforced beams. As the corrosion level changes from mild exposure condition to medium exposure the load carrying capacity decreases by 7.1 % for conventional beam and for M-sand replaced beam the load carrying capacity decreased by 6.6%, for the decrease in the corrosion level from 5% to 10%. There is further decrease in the load carrying capacity of 33.3% when the beam is subjected to severe exposure condition, when compared with conventional beam specimen. However when compared with conventional beam, the load carrying capacity of M-sand replaced beam decreased only by 31.25% for severe exposure condition of 25% corrosion level. When comparing the deflection at the mid span of the un-corroded beam, the deflection increased by 44.11% for conventional concrete and for M-sand replaced concrete it is only 29.41% for severe exposure condition of 25% corrosion level. For the increase in the corrosion level, from mild to severe exposure condition, the strain also decreases.

The effect of corrosion on the ultimate load carrying capacity of the beam is shown in Figure-5.

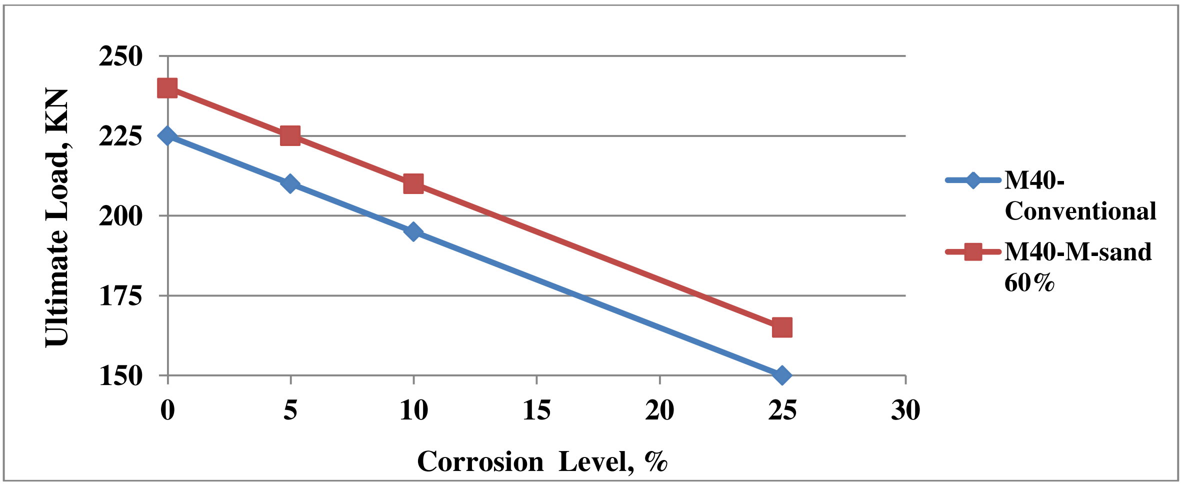

Figure-5. Effect of corrosion on the ultimate load carrying capacity of beam.

4. EFFECT OF CORROSION ON THE LOAD - DEFLECTION CHARACTERISTICS OF NBS BEAMS

Effect of corrosion on ultimate load carrying capacity is shown in Figure-5. From the figure, it is clear that, as the corrosion level increases the load carrying capacity decreases. The load carrying capacity of M40 conventional concrete is 225 KN and for M-sand replaced concrete it is 240KN. For 5% corrosion level, the load carrying capacity for M40 conventional and M-sand

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concrete are 210KN and 225KN respectively. As the corrosion level increases from 5% to 10%, the load carrying capacity decreases to 195 KN for M40 conventional and 210 KN for M-sand concrete. For further increase of corrosion level by 25%, the load carrying capacity reduced to 150KN and 165KN for M40 conventional and M-sand replaced concrete.

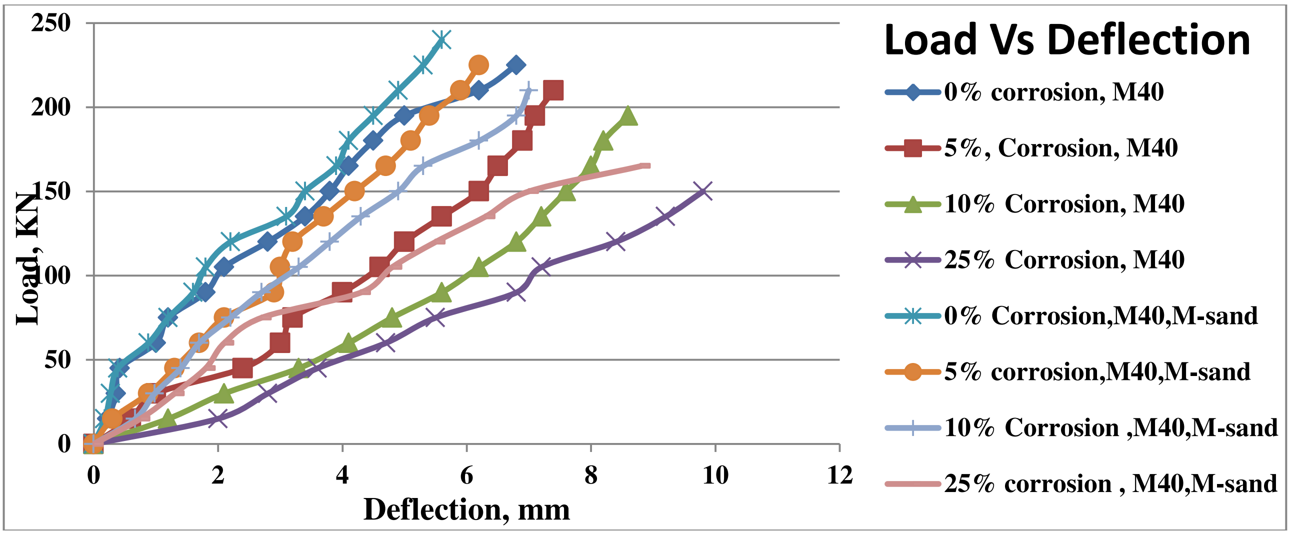

Figure-6. Effect of corrosion levels on central deflection of NBS beam.

The graph shows the effect of corrosion on ultimate load carrying capacity. It is observed that as the degree of corrosion level increases the load carrying capacity of the beam decreases. At the ultimate load level, the load carrying capacity of the 5% corroded specimen decreased by 6.67% when compared to M40 conventional specimen. However the strength decreased by 13.33 % and 33.3 % for 10% and 25% degrees corrosion damage respectively when compared with the controlled specimen. Based on the test results on M-sand replaced concrete, the reduction in the ultimate load carrying capacity was found to be 6.25%, for 5% corrosion level when compared with un-corroded specimen. The percentage reduction in the ultimate load carrying capacity for 10% and 25% corrosion level was found to be 12.5% and 31.25% respectively when compared with controlled un-corroded M-sand replaced specimen. The deflection at the ultimate stage was found to be 6.8mm, 7.4mm, 8.6 mm and 9.8mm for 0%, 5%, 10% and 25% corrosion level on M40conventional beam respectively. From Figure-6 it is clear that as the corrosion level increases the deflection also increases. But the deflection tends to reduce by 5.6mm, 6.2mm, 7mm and 8.8mm for 0%, 5%, 10% and 25% corrosion level respectively for M-sand replaced concrete. Based on the test results, it is concluded that M-sand concrete has beneficial effects even at the corrosion damaged stage.

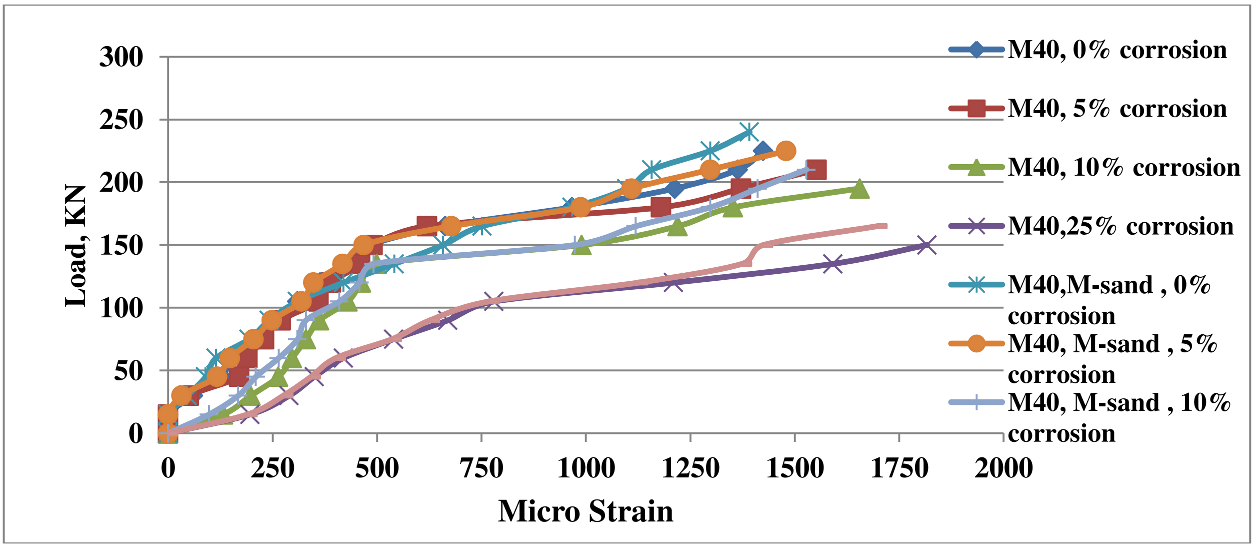

Figure-7. Effect of corrosion levels on Load strain behaviour of NBS beam.

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Figure-7 shows the variation of strain with incremental load. From the Figure-7, it is clear that as the load level increases, the strain value also increases linearly. For M40 conventional the strain is 1425 for an ultimate load of 225 KN whereas for M-sand replaced concrete the decrease in strain is only 1392 for an ultimate load of 240KN for 0% corrosion level. Similarly for 5% corrosion level, the strain is 1553 and 1480 for conventional and M-sand replaced concrete respectively for a load carrying capacity of 210 KN and 225 KN. When the corrosion level increases from 5% to 10% the increase in the strain for conventional and M-sand is 1656 and 1528 respectively for 195KN and 210KN load. Similar results were observed for higher corrosion level and it is concluded that for increasing corrosion level, the strain value increases in the initial stage. It is also concluded that at higher corrosion levels the rate of increase of strain is higher for the same incremental load and the M-sand replaced concrete has lesser strain value than conventional concrete for the same corrosion level.

5. NUMERICAL MODELING

The NBS beam specimen of size 2.44m x 0.203m x 0.457m used in this research is modelled by Finite Element Model (FEM), by using commercial software package ANSYS.

5.1 Element types

Concrete is modelled by using an eight node solid element, Solid65. This solid element consists of eight nodes with three degrees of freedom at each of this node with translations in the nodal x, y and z direction. The steel reinforcement is modelled using Link8 element. This Link8 element contains two nodes with three degrees of freedom at each of this node with translations in the nodal x, y and z direction. The steel element used for FEM modelling was assumed to be an elastic-plastic material and identical in tension and compression. A value of zero is entered for initial strain because it is assumed that there is no initial stress in the reinforcement.

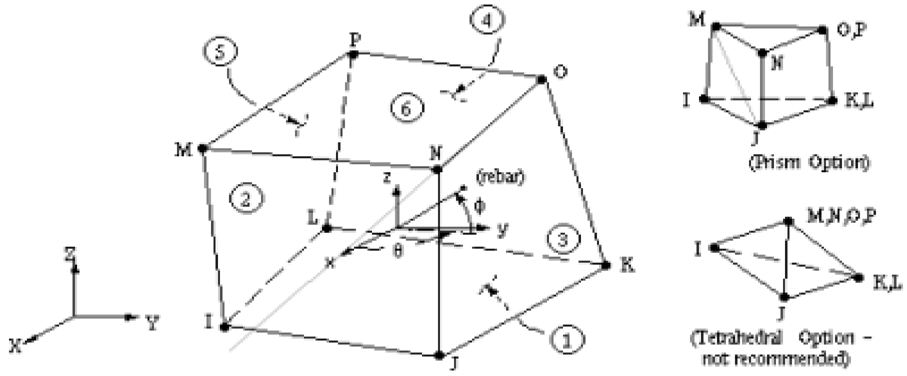

Figure-8. Solid 65 element in ANSYS.

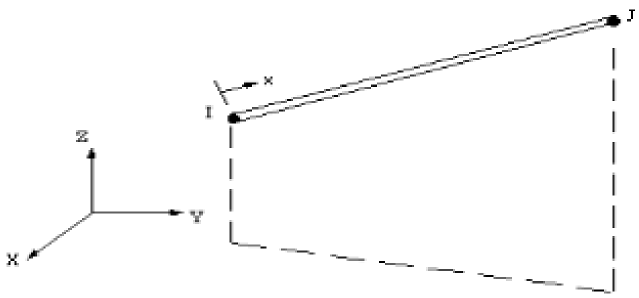

Figure-9. Link 8 element in ANSYS.

5.2 Modeling

The NBS beam is modelled with 62 nodes in the x direction, with a spacing of 40mm between successive nodes. In the y direction 10 nodes were placed at 50mm between successive nodes and in the z direction the nodes were placed at 36mm. The elastic modulus of concrete (Solid 65) is taken as 30,058.27 N/mm^{2}and Poisson ratio 0.2. Uniaxial tensile strength is 4.71 N/mm^2. The elastic modulus of Link 8 element is 2 x 10^5 N/ mm^2. The poisson ratio is taken as 0.3. The yield strength of the main bar is 480 N/ mm^2.

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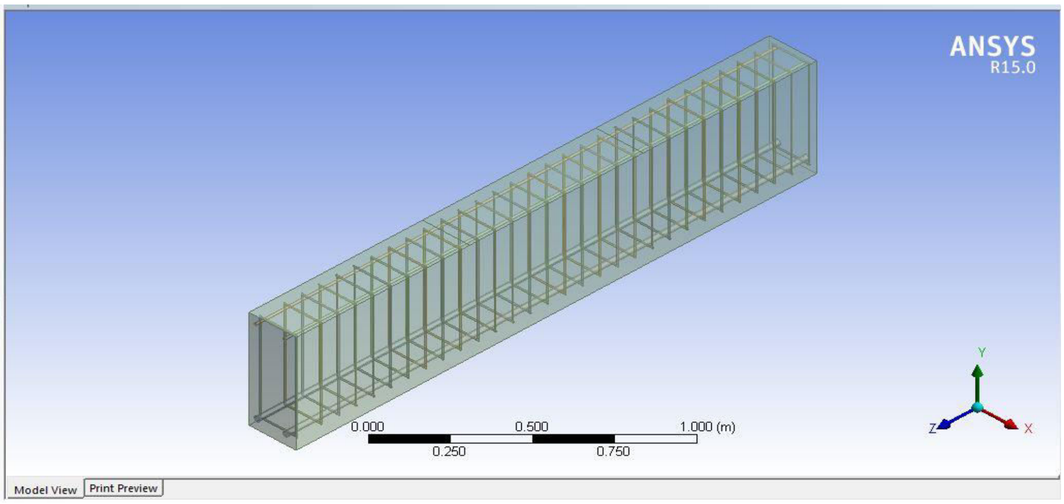

Figure-10. ANSYS- NBS beam model.

5.3 Load and boundary conditions

Boundary conditions should be imposed on the model to act in the same way as that of the experimental beam. Imposing the displacement boundary conditions to the model will result in unique solution. Two point loading is induced with support roller condition, to allow rotation at the supports.

5.4 Numerical results from ANSYS

The finite element analysis of NBS beam specimen were examined and compared with the experimental results. The NBS beam specimens were subjected to an incremental loads of15KN up to failure. Since the NBS beams were subjected to transverse loading in FEM modelling, static analysis procedure is used. A view of displacement contour of control beam specimen is shown for its ultimate loading condition.

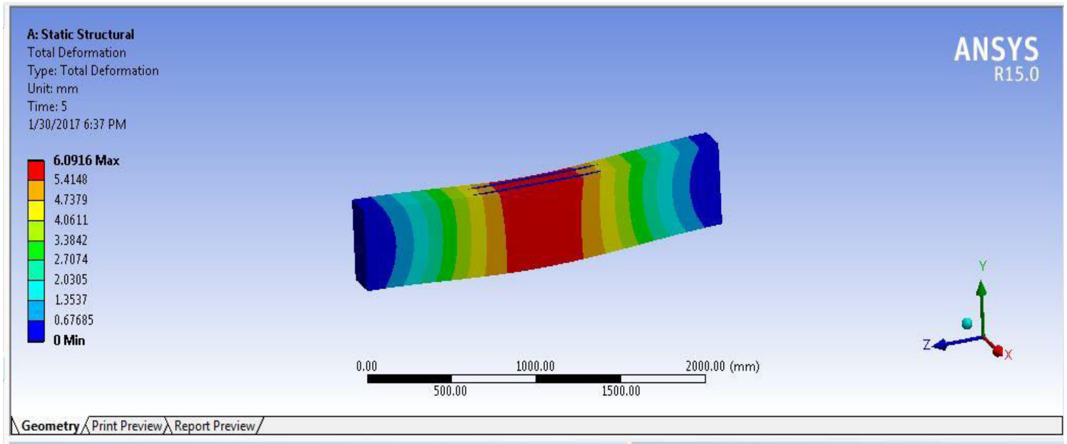

Figure-11. A view of displacement contour of control beam specimen for Ultimate load.

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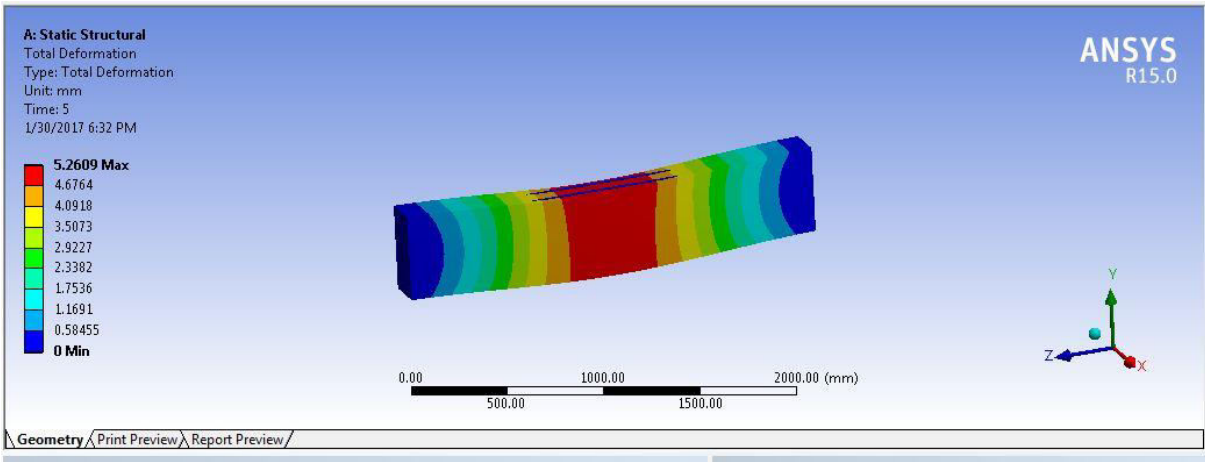

Figure-12. A view of displacement contour of M-sand replaced beam specimen for Ultimate load.

Figure-11 and Figure-12 Shows the effect of displacement for ultimate loading condition. The mid span displacement was found to be 6.09 mm for an ultimate load of 248KN for M40 conventional NBS beam specimen. In case of M-sand replaced concrete beam the mid span displacement was found to be 5.26mm for an ultimate load of 255KN.

Table-3. Experimental and numerical values for ultimate load, deflection and strain for different degree of corrosion.

S. No.	Concrete grade	Beam specimen with corrosion level (%)	Ultimate load (KN)		Deflection at mid span (mm)		Micro strain (μ x 10^{-6})	
			Expt	Ansys	Expt	Ansys	Expt	Ansys
1	M40	0%	225	248	6.8	6.09	1425	1436
	M40 (M-sand60%)		240	255	5.6	5.26	1392	1386
2	M40	5%	210	230	7.4	6.52	1553	1478
	M40 (M-sand 60%)		225	240	6.2	5.60	1480	1412
3	M40	10%	195	220	8.6	7.22	1656	1620
	M40 (M-sand 60%)		210	225	7.0	6.68	1528	1598
4	M40	25%	150	160	9.8	8.46	1817	1812
	M40 (M-sand 60%)		165	170	8.8	7.82	1698	1682

From the Table-3, the experimental and numerical results show an average variation of 0.91for conventional concrete and 0.94 for M-sand replaced concrete in load carrying capacity. Similarly the experimental and numerical deflection at the mid span varies by an average of 1.14 for conventional and 1.08 for M-sand replaced concrete. The experimental and numerical increase in the strain value

From the Table-3, the experimental and numerical results show an average variation of 0.91for conventional concrete and 0.94 for M-sand replaced concrete in load carrying capacity. Similarly the experimental and numerical deflection at the mid span varies by an average of 1.14 for conventional and 1.08 for M-sand replaced concrete. The experimental and numerical increase in the strain value for conventional concrete is 1.01 whereas for M-sand replaced concrete it is only 1. From the results it is concluded that numerical values showed a less variation with the experimental results and hence FEM numerical analysis using Ansys software is an effective tool to study the flexural behaviour of RC structure

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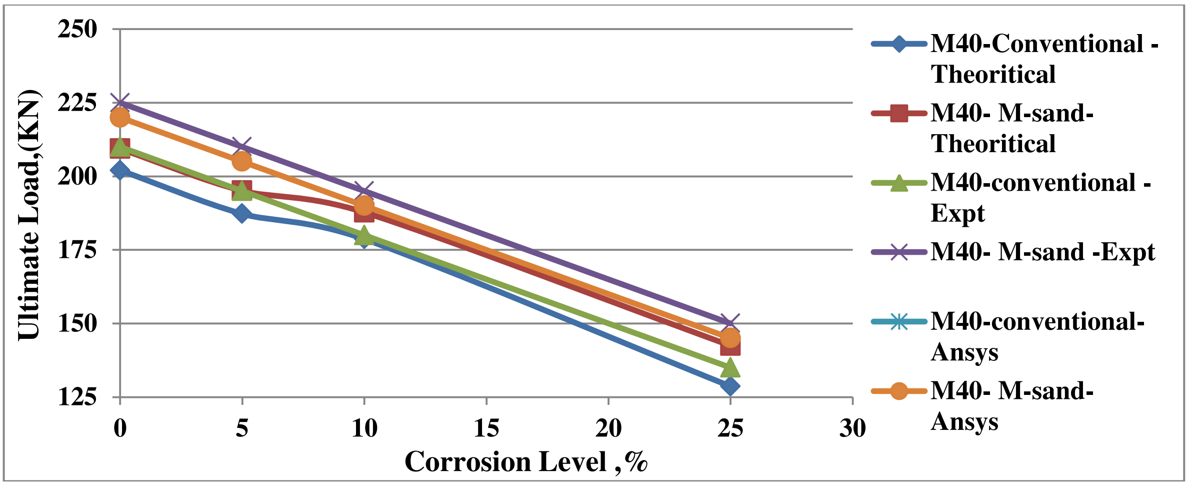

Figure-13. Effect of corrosion on ultimate load carrying capacity of NBS beam.

Figure-13 shows the effect of corrosion on the ultimate load carrying capacity of beam specimen. The load carrying capacity of M40 conventional is found to be 225KN whereas for M-sand replaced concrete the ultimate load carrying capacity is 240KN. Numerical analysis using FEM software gave 248KN as the ultimate load for M40 and 255KN for M-sand replaced concrete. For 5% corrosion level, the load carrying capacity decreases to 210KN and 225KN for conventional and M-sand concrete. FEM model gave 230KN for conventional with 5% corrosion level and 240KN for M-sand replaced concrete. As the corrosion level increases from 5% to 10% the load decreases to 195KN and 210KN for conventional and M-sand replaced concrete.whereas numerical analysis gave increased load carrying capacity of 220KN and 225KN for conventional and M-sand replaced concrete. For extreme corrosion level of 25%, the load carrying capacity was found to be 150KN and 165KN for conventional and M-sand replaced concrete. FEM analysis using ANSYS software showed an increased load carrying capacity of 160KN and 170KN respectively.

CONCLUSIONS

- The accelerated corrosion of the rebar in the NBS beam specimen tends to decrease the load carrying capacity of the beam.
- At the ultimate load level, the load carrying capacity of the 5% corroded specimen decreased by 6.67% when compared to M40 conventional specimen. However the strength decreased by 13.33 % and 33.3 % for 10% and 25% degrees corrosion damage respectively when compared with the controlled specimen.
- Based on the test results on M-sand replaced concrete, the reduction in the ultimate load carrying capacity was found to be 6.25%, for 5% corrosion level when compared with un-corroded specimen. The percentage reduction in the ultimate load carrying capacity for 10% and 25% corrosion level was found to be 12.5% and 31.25% respectively when compared with controlled un-corroded M-sand replaced specimen.
- From the experimental investigation it is observed that the load carrying capacity is high for control beams, but deflection is less for control beams with respect to corroded beams (5%, 10% and 25%).
- As the degree of corrosion increases from 0% to 25%, the mid span deflection also increases linearly.
- The tests performed in this research indicate that there is a significant increase in the load carrying capacity of M-sand replaced concrete beams when compared with conventional beams.
- FEM analysis and the experimental analysis proved that the accelerated corrosion damage reduces the cross sectional area and thereby the stiffness of the beam is reduced and ultimately the load carrying capacity of the beam is reduced.
- The FEM model results showed a good agreement with the predicted experimental results for a full scale NBS beam tests.

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