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Study on prestressed concrete beams and poles with cement replaced by steel dust

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Abstract. Cement acts as the most important component of concrete as it binds and holds the concrete together. But it is one of the major CO_2 emitters all over the world, during manufacturing (900 kg of CO_2 per 1000 kg). Some of the modern construction methods aim at reducing the amount of usage of cement and came out with numerous solutions for replacement of the same. One such supplement in current trend is the Steel dust or the Electric Arc Furnace Dust (EAFD), which is a waste product from the electric arc furnace when the scrap metal is melted. When the concrete containing steel dust is exposed to atmosphere, the environmental oxygen and moisture play role to form rust and ultimately the member becomes harder. As Cement is the binder of conventional concrete, only certain percentage of the same could be replaced by the new material, steel dust. Tests were conducted for the 28 days cube strength of M45 grade (suitable for prestressing) concrete which has 0%, 10%, 20%, 30%, 40% and 50% steel dust instead cement. From the test, the optimum percentage replacement of steel dust was obtained, for which the beams and overhead poles were cast, prestressed and tested for the failure load and deflections. A conventional concrete beam and overhead pole were also cast, prestressed and tested to compare the results with those of the beam and pole that contained steel dust. The load vs. deflection plot and other results from the test is also discussed.

Keywords: concrete; pre tesntioend prestressed concrete; overhead pole and steel dust

1. Introduction

Concrete, a versatile mouldable material used in the field of construction for a number of decades. The materials used in conventional concrete (Cement, sand/fine aggregate, coarse aggregate and water) are proven to be the most suitable materials. Due to the increased pollution nowadays, the whole construction industry is in a situation to move towards a similar alternative for the material in concrete which pollutes the atmosphere more. Cement tops in CO_2 emission as its manufacturing is responsible for 900 kg of CO_2 per 1000 kg. A single industry accounts for around 5% of global carbon dioxide (CO_2) emissions. Cement production is growing by 2.5% annually, and is expected to rise from 2.55 billion tons in 2006 to 3.7-4.4 billion tons by 2050.

The production of cement releases greenhouse gases in two ways:

• Directly: When the limestone s heated up CO_2 is emitted.

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Fig. 1 Steel dust and liquid zinc

Table 1 Losses in pre-tensioned prestressing

Sl. No.	Pre-tensioning losses
1	Elastic deformation of concrete
2	Relaxation of stress in steel
3	Shrinkage of concrete
4	Creep of concrete

• Indirectly: Kiln heats up only when the fossil fuels are burnt which in turn emits CO_2.

A chemical process called "Calcination" emits cement directly. Limestone contains calcium carbonate. When it is heated up, calcium oxide and CO_2 is produced. This process is responsible for almost 50% of emissions during production of cement.

When fossil fuels are burnt to heat kiln up, indirect emissions take place. Kilns are usually heated by coal, natural gas, or oil, and the combustion of these fuels produces additional CO_2 emissions, just as they would in producing electricity. This accounts around 40% of emissions from cement. Also, the electricity for plants and transportation causes indirect emissions. They are about 5-10% of the industry's emissions.

It is inevitable to completely kick out cement from concrete as it takes care of binding. But it is possible to reduce the quantity of cement by the usage of several eco-friendly materials as a partial replacement. Steel dust, a waste material available from the steel industries is considered as the replacement for cement (Galal *et al*. 2016).

Steel dust (KO61), also known as Electric Arc Furnace dust is the by-product from the electric arc furnace (Alexandre *et al*. 2006). On the process of manufacture of steel, the waste product called steel slag or scrap metal is the key source of steel dust. Steel dust is created (Fig. 1) when the scrap metal is melted in the electric arc furnaces at high temperature (around 1600℃). This material ultimately ends in landfill. Moreover, this landfill squanders thousands of tons of Zinc and Iron rich material. Much of the Zinc is stayed back in the steel plant for galvanizing new steel while the Iron materials will become an ingredient for Cement. This steel dust, when imparted into concrete, increases the compressive strength and holds the structure without collapse even after failure. Studies reveal that using optimum quantity of steel dust increases the strength of concrete by 5 times that of conventional concrete.

Prestressed concrete is a concrete in which internal stresses of a suitable magnitude and distribution are introduced so that the stresses resulting from external loads are counteracted to a

Table 2 Material test result on cement

Sl. No	Physical properties of cement	Results	Requirements as per IS 8112-1989
1	Specific gravity	3.14	3.10-3.15
2	Standard consistency (%)	29%	30-35
3	Initial setting time	33 minutes	30 minutes minimum
4	Final setting time	175 minutes	600 minutes maximum
5	Compressive strength-7days	39.44 N/mm^2	43 N/mm^2
6	Compressive strength-28 days	52.57 N/mm^2	53 N/mm^2

Table 3 chemical composition of steel dust

Metal	Presence in %	Metal	Presence in %	Metal	Presence in %	Metal	Presence in %
Fe	41	Pb	1.44	Na	0.74	Cd	0.12
Zn	14.30	Si	1.19	S	0.42	Mo	0.08
Ca	4.48	C	1.20	Cu	0.14	Al	0.28
Mn	1.70	Cr	1.15	Ni	0.29	Co	0.06
Mg	1.51	K	0.87	P	0.16	-	-

Table 4 material test results on aggregate

Property	Fine aggregate	Coarse aggregate	
		20 mm down	10 mm down
Fineness modulus	3.34	7.56	3.20
Specific gravity	2.38	2.76	2.68
Water absorption (%)	1.21	1.84	1.34
Bulk density	1753	1741	1711

desired degree. In reinforced members the prestress is commonly introduced by tensioning the steel reinforcement.

Pre tensioning system of prestressing was used in which the tendons are first tensioned between rigid anchor-blocks cast on the ground in a column or unit-mould-type pretensioning bed, prior to the casting of concrete in the moulds. There major losses are given in Table 1.

2. Materials and methods

The materials used for the experimental works and the design methods adopted for the paper work are included below.

2.1 Materials

The materials used for throughout the paper are maintained with same specifications and are given as follows.

2.1.1 Cement

Table 5 Material test results on prestressing strand

Coil Number	Diameter (mm)	Ultimate tensile strength (N/mm^2)	% elongation	Number of bends	% proof stress (N/mm^2)	Young's modulus ($X10^5$) (N/mm^2)
1	3.99	1776.47	4.5	5	1559.26	1.98
2	3.99	1809.03	4.5	5	1588.68	2.00
3	3.99	1792.17	4.5	5	1569.06	2.01
4	3.99	1800.01	4.5	5	1578.87	2.05

OPC 53 grade cement conforming to IS 8112-1989 was used. The various properties of the used cement are in Table 2.

2.1.2 Steel dust-supplement for cementitious material

A brief description of steel dust and the process involved in the production of steel dust has been dealt under the introduction and its specific gravity was found to be 3.12. The chemical composition of steel dust is in Table 3.

2.1.3 Aggregate

They are the important constituent that gives body to the concrete. They ultimately reduce the shrinkage and have a great impact on economy. Good gradation of aggregates is a sign and one of the most important factors of producing workable concrete. Gradation should be in such a way that the voids should be less which in turns reduces the concrete paste and water required to fill the voids. This also increases the durability of concrete.

The two aggregates used are specified below.

• Coarse aggregate-aggregates conforming to IS: 383 and are fractions from 20-4.75 mm are used. 15% of flakiness index and elongation index was preferred.

• Fine aggregate-aggregates conforming to IS 383 and are fraction from 4.75 mm-150 micron are used. They are the combination of crushed sand and river sand.

The properties of both the aggregates are given in Table 4.

2.1.4 Prestressing steel

It a stretchable element used in the concrete member of structure to impart prestress to the concrete. Generally, it is high-tensile steel wires, bar called or strands. The specifications of the prestressing steel used are given in Table 5.

2.1.5 Water

Usually, water plays major role due to its participation in chemical reaction with cement. Also, the new supplement material for cement, steel dust, when absorbs water and oxygen, reacts with the atmospheric moisture, forms rust and imparts strength to the concrete. Hence, both quality and quantity of water is notable.

2.2 Methods

The methods include the various designs conforming to Indian Standards which required for the paper work. They are as follows.

• Mix design

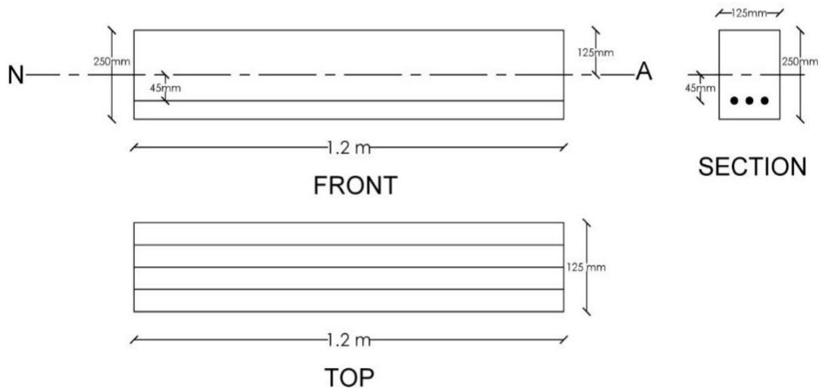

Fig. 2 Prestressing strand detailing for beams

- Design of PSC beam
- REC specifications for Overhead PSC pole

2.2.1 Mix design

The mix design procedure was followed using IS 10262-2009. The steps involved are follows.
Mix proportion:
Cement=491.5 kg/m^3
Water=197 kg/m^3
Fine aggregate=757.831 kg/m^3
Coarse aggregate=1010.873 kg/m^3
W/C ratio=0.40
Mix proportion-1: 1.54: 2.05

2.2.2 Design of beam

Since the beam is prestressed and tested for flexure, the design was adopted conforming to IS 1343-2012 and the steps involved are as follows.

(a) Design stipulations:
Cross section of the beam=125 mm×250 mm
Length of the beam=1.2 m
Live Load in the beam=110 kN
Diameter of the prestressing strand=4 mm
Loss of stress at transfer=1.4 N/mm^2
Concrete cube strength=45 N/mm^2
Tensile strength of concrete=1.7 N/mm^2
Density of concrete=25 kN/m^3
Permissible stresses:
At transfer-compressive stress, f_{ct}=15 N/mm^2; Tensile stress, f_{tt}=-1 N/mm^2
At working load-compressive stress, f_{cw}=17 N/mm^2; Tensile stress, f_{tw}=0 N/mm^2
Ultimate strength of the prestressing steel, f_{pu}=1794.42 N/mm^2

(b) Prestressing force:

Prestressing force, $\mathrm{P} = A\dfrac{[f_{inf}Z_b + f_{sup}Z_t]}{Z_b + Z_t}$

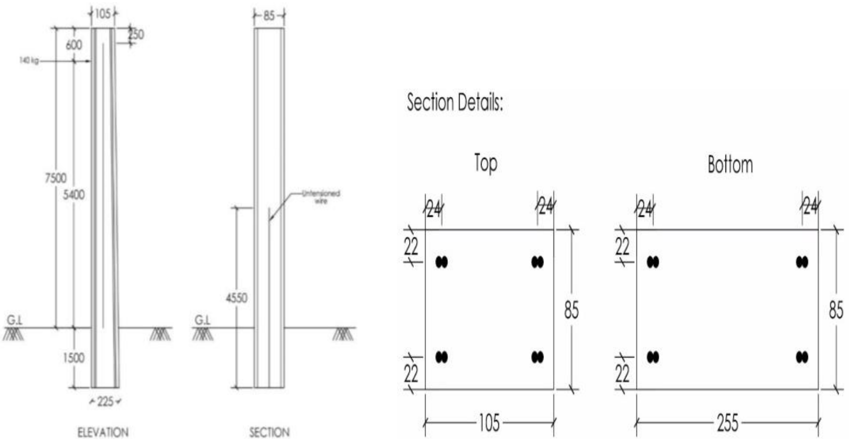

Fig. 3 Prestressing strand detailing for overhead poles

$$P = \frac{31250X1.3X10^6[1.5-0.1078]}{2X1.3X10^6} = 21753\ \text{N} = 21.75\ \text{kN} \approx 22\ \text{kN}$$

(a) Eccentricity:

Eccentricity, $e = \frac{Z_t Z_b[f_{inf}-f_{sup}]}{A[f_{sup}Z_t+f_{inf}Z_b]}$

$$= \frac{[1.3X10^6]^2[1.5+0.1078]}{31250X1.3X10^6X[-0.1078+1.5]}$$

= 48.04 mm≈50 mm

(c) Number of strands required for prestressing:

Area of 4 mm wire=$\pi^r 2/4=\pi(4)^2/4=12.57$ mm^2

Force in each wire=12.57×1794.42=22.56 kN

Number of wires required=63/22.56=2.793≈3 numbers.

The detailing of the beams are shown in Fig. 2.

2.2.3 REC specifications for prestressed concrete overhead pole

The Rural Electrification Corporation (REC) of India specifies the standards for 7.5 m long prestressed concrete pole suitable for use in overhead 11 kV without L.T. power lines. The dimensions and reinforcement detailing (see Fig. 3) are given as follows.

- Number of tensioned wires: 8
- Number of un-tensioned wires: 2
- Clear cover to wires: 20 mm
- Concrete quantity per pole: 0.115 m^3
- Steel quantity per pole: 9.61 kg
- Weight of pole: 320 kg

2.3 Specimen details

The experimental executions contain three major steps as stated below.

- Casting and testing of concrete cubes
- Casting and testing of PSC beam
- Casting and testing of overhead PSC pole

Fig. 4 Compression test on cube

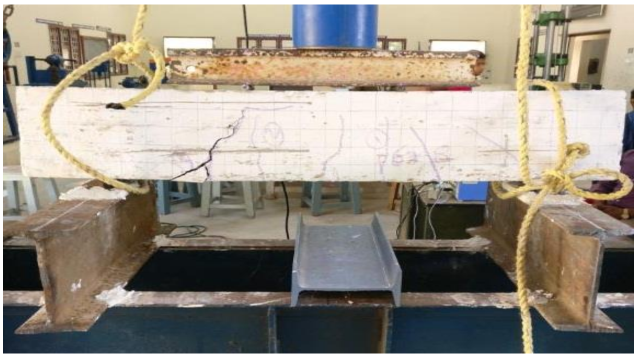

Fig. 5 Four-point-bending test on beam with final failure (due to shear cracking)

Fig. 6 Test set up for poles (with fixed bottom end and loading frame)

Though there were various specimens cast, the experimental procedure remains the same. Method of weight batching was used. Wooden moulds were used for the cubes and steel moulds

Fig. 7 Four-point-bending test on beam with final failure (due to shear cracking)

Table 6 7 days compression test on cubes

Sl. No.	% of steel dust	Compressive strength (MPa)		Average compressive strength (MPa)
		Specimen 1	Specimen 2	
1	Nominal	34.09	33.99	34.04
2	10	36.23	36.82	36.525
3	20	29.07	27.85	28.46
4	30	18.04	20.10	19.07
5	40	12.33	13.50	12.915
6	50	6.33	7.50	6.915

Table 7 28 days compression test on cubes

Sl. No.	% of steel dust	Compressive strength (MPa)		Average compressive strength (MPa)
		Specimen 1	Specimen 2	
1	0	44.10	45.01	44.56
2	10	44.30	44.60	44.45
3	20	29.50	30.74	30.17
4	30	18.63	17.97	19.30
5	40	14.62	10.41	12.51
6	50	10.42	9.51	9.97

were used for the beams and poles. Moulds were greased properly for the easy removal after the concrete is being hardened. The concrete mix was prepared according to the mix proportion mentioned previously and was poured in to the mould. Compaction was done at every one-third layer in order to avoid the honey combing. A vibrator compactor was used for the beams and poles. The concrete was allowed for 24 hours to get set and be hardened. After so, the mould was removed and the cube was exposed to atmosphere to get rid of the dampness. 28 days of water

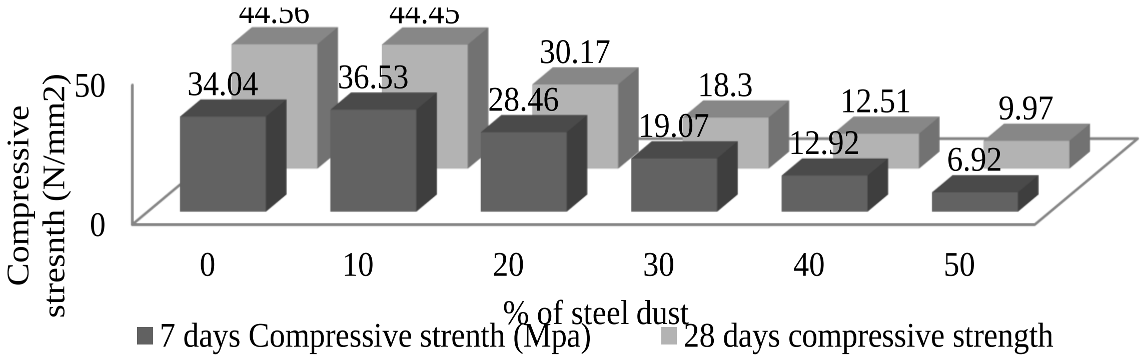

Fig. 8 Comparison between the compressive strength

curing was adopted. The cubes were immersed in water for 28 days and tested. Test for the compressive strength was carried out on the cubes using the Compression Testing Machine (CTM) (see Fig. 4). The PSC beams were subjected to four-point bending test using a 100T loading frame (see Fig. 5) and the overhead poles were tested using another loading frame specially meant to test the poles, where the bottom 1.5 m is fixed and loaded at 0.6 m from the top, which gives cantilever action to the pole (see Figs. 6 and 7).

3. Results and discussion

The compression behavior of the cubes, deflection and ultimate load, load at first crack, deflections and crack patterns of the overhead pole are discussed below.

3.1 compression test report

The strength comparison graph for the above results is given below in Fig. 8.

As far as the compression strength is concerned, a 10% of steel dust instead of cement earns more strength than others. Also, it is found that the increase in steel dust further shows a fall in compressive strength abruptly. The above results show that the reduction in 10% of cement can be compensated by steel dust, since the 28 days compressive strength of the nominal M45 cube is nearly equal to that of the cube with 10% of steel dust replaced for cement. From the 7 days test results, it is evident that the steel dust boosts the strength gaining process.

Analyzing the reason for this strength development even at the absence of 10% of cement, the broken cubes was found to show rust which was formed due the steel dust. Thus, the “Process of formation of Rust” became the key factor for the development of strength. Rust formation is an electrochemical process which involves the transfer of electrons and reactions that take place are stated as follows.

Here, the Iron (Fe) in steel dust acts as the reducing agent and atmospheric oxygen acts as the oxidizing agent. The key reaction of the process is “reduction” of oxygen.

$$O_2 + 4e^- + 2H_2O \longrightarrow 4OH^-$$

The reduced electrons from the above reaction oxidize the iron which is responsible for the rust formation.

Table 8 Deflection test report on beam

Sl. No.	Load (kN)	Deflection (mm)	
		Conventional beam	Beam with 10% steel dust instead cement
1	0	0	0
2	10	0.19	0.13
3	20	0.37	0.24
4	30	0.61	0.34
5	40	0.79	0.44
6	50	1.00	0.55
7	60	1.28	0.74
8	70	1.73	0.97
9	80	2.09	1.18
10	90	2.43	1.39
11	100	2.74	1.62
12	110	3.09	1.81
13	120	3.49	2.12
14	130	4.14	2.34
15	140	4.22	2.6
16	142.5	4.31 (max)	-
17	150	-	2.87
18	159.2	-	3.31 (max)

$$Fe \longrightarrow Fe^{2+} + 2e^-$$

When the concrete is under curing, the following "Redox reaction" takes place in the presence of water and is crucial to the formation of rust.

$$4Fe^{2+} + O_2 \longrightarrow 4Fe^{3+} + 2O^{2-}$$

Additionally, the following "Acid-base reaction" affects the course of rust formation.

$$Fe^{2+} + 2H_2O \rightleftharpoons Fe\ (OH)_2 + 2H^+$$

$$Fe^{3+} + 3H_2O \rightleftharpoons Fe\ (OH)_3 + 3H^+$$

As seen above, the reaction is reversible and the dehydration equilibria is as follows.

$$Fe\ (OH)_2 \rightleftharpoons FeO + H_2O$$

$$Fe\ (OH)_3 \rightleftharpoons FeO(OH) + H_2O$$

$$2FeO\ (OH) \rightleftharpoons Fe_2O_3 + H_2O$$

From the above equations, it is also clear that the corrosion products are dictated by the availability of water and oxygen.

Hence, from the compressive strength results, the flexural parameters and deflection were

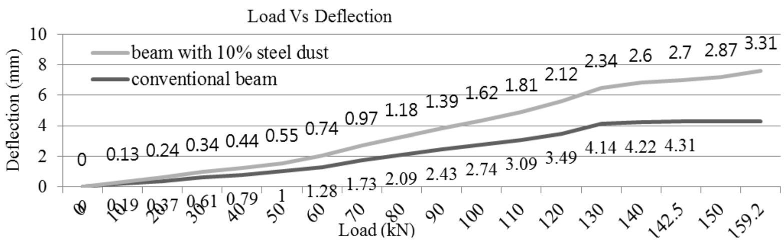

Fig. 9 Comparison between the load vs. deflection curves

compared between the conventional prestressed concrete beam (pole) and beam (pole) with 10% of steel dust in place of cement.

3.2 Deflection report on beam

An LVDT was placed under the center point of the beam and the readings were observed (see Table 8).

The Load vs Deflection is plotted in the form of a graph as in Fig. 9.

Both the conventional beam and the beam with 10% of steel dust instead of cement weren't failing by flexure which may be due to the prestressing force given to the beam. Instead, shear failure occurred during the test. Initially, the cracks were under the loads but the major crack arouse from the support. Though both the beams have failed by shear, the beam with steel dust could give more shear resistance than that given by the conventional beam.

Concerning the deflections, the conventional beam deflected more than the beam with steel dust. The steel dust holds the integrity of the structure with collapsing rapidly. But the conventional beam could tolerate more deflection than the beam with steel dust. The load carrying capacity was lesser for the conventional beam than that of the beam with steel dust.

3.2.1 Other results

Table 9 Test results on beam

Sl. No.	Description	Beam	Result
1	Load at First crack (kN)	Conventional beam	65
		Beam with 10% steel dust	64.6
2	Deflection at first crack (mm)	Conventional beam	1.52
		Beam with 10% steel dust	0.83
3	Maximum deflection (mm)	Conventional beam	4.31
		Beam with 10% steel dust	3.31
4	Crack width (mm)	Conventional beam	3
		Beam with 10% steel dust	2.5
5	Ultimate load (kN)	Conventional beam	142.5
		Beam with 10% steel dust	159.2
6	Factor of safety	Conventional beam	2.6
		Beam with 10% steel dust	2.89

Table 10 deflection test report on poles

Sl. No.	Load (kg)	Load (kN)	Conventional beam		Beam with 10% steel dust instead cement	
			Deflection (mm)	Crack propagation distance from bottom (m)	Deflection (mm)	Crack propagation distance from bottom (m)
1	0	0	0	-	0	-
2	50	0.49	5	-	10	-
3	100	0.98	10	-	15	-
4	150	1.47	20	-	20	-
5	200	1.96	40	-	40	-
6	210	2.06	45	-	50	-
7	250	2.45	80	-	70	-
8	300	2.94	120	-	90	-
9	350	3.43	210	1.9	140	-
10	360	3.53	300	2.1	160	-
11	370	3.63	340	-	180	-
12	380	3.73	370	2	200	1.85
13	390	3.83	390	2.50	220	1.95
14	400	3.92	450	2.66	260	2.25
15	410	4.02	520	2.92	310	2.45
16	420	4.12	550	3.16	370	2.65
17	430	4.22	620	3.26	400	2.77
18	440	4.32	660	3.41	480	2.90
19	450	4.42	720	3.58	520	3.06
20	460	4.51	-	-	570	3.24
21	470	4.61	-	-	600	3.50
22	480	4.71	-	-	640	-

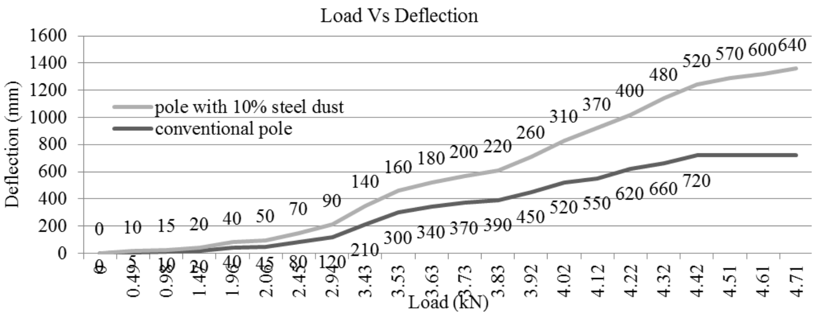

Fig. 10 Comparison between load vs. deflection curves for poles

3.3 Test report on overhead pole

The overhead pole was unlike the beam and was given cantilever action by fixing the bottom 1.5 m and the loading of 140 kg (design load) is given at 0.6 m from top.

The various results observed from the test of both the conventional pole and the pole with 10%

of cement replaced by steel dust, are in Table 10.

The Load vs Deflection is plotted in the form of a graph as in Fig. 10.

3.3.1 Other results

Table 11 test results of poles

Sl. No.	Description	Pole	Result
1	Load at First crack (kN)	Conventional pole	3.43
		Beam with 10% steel dust	3.73
2	Deflection at first crack (mm)	Conventional pole	210
		Beam with 10% steel dust	200
3	Deflection after releasing all loads (mm)	Conventional pole	170
		Beam with 10% steel dust	130
4	Crack width (mm)	Conventional pole	2
		Beam with 10% steel dust	1.5
5	Ultimate load (kN)	Conventional pole	4.42
		Beam with 10% steel dust	4.71
6	Factor of safety	Conventional pole	3.22
		Beam with 10% steel dust	3.43

The conventional PSC pole sounded good in tolerating the deflection, since the deflection value of that is higher than the pole with steel dust. Since the pole supports lateral force, the highest wind force may be experience during heavy storms. Hence, taking the Indian wind data into consideration, the pole is discussed as follows.

According to Indian Meteorological department, the Tropical Cyclone Intensity scale is categorized as in Table 12.

Table 12 Categorization of tropical cyclones in India

Cyclone category	Sustained wind (3 mins avg.) (km/h)
Super cyclonic storm	≥221
Extremely severe cyclonic storm	116-220
Very severe cyclonic storm	118-165
Severe cyclonic storm	89-117
Cyclonic storm	66-88
Deep depression	51-62
Depression	31-50

As far as the worst condition is concerned, the super cyclonic storm may hit with velocity more than 221 km/h (61.3889 m/s). To convert this wind velocity into force, the steps are adopted.

- Vp=0.6×speed
  =0.6×61.3889^2×2
- Vp=4522.32 m/s
- Pound force=1.45×10^{-4}×4522.32
  =0.6557 N/mm^2
- Total force=0.6557×Area
  =0.6557×(2102.37)
  =1378. 52 N
  =1.38 kN<4.71 kN (ultimate load of the pole with steel dust)

As stated above, the pole with steel dust can withstand more lateral loads. Converting the ultimate load of 4.71 kN into wind velocity, a wind speed of 408.5 km/h can be tolerated the PSC pole with 10% of steel dust in place of cement.

4. Conclusions

As far as the previously mentioned behaviors of the specimens are concerned, the usage of steel dust in concrete as partial replacement for cement has the following aspects.

- A 10% of cement replacements by steel dust to attained equal strength to that of the normal conventional cement concrete.
- The concrete initial and final setting time increases with the increase in steel dust added to it.
- The compressive strength was found to be meagerly higher at the beginning stage, but ultimately it was nearly equal to that of the conventional concrete.
- Though prestressing arrests the beam to fail by flexure but by shear, steel dust also adds shear resistance to the beam.
- It was also found that the incorporation of steel dust on concrete reduces the crack and crack propagation which in turns increases the durability of the structure. Also, steel dust holds the structure integrity without collapse even after the failure load is attained.
- Workability and slump retention of the concrete was found to be increasing with the addition of steel dust.

Taking in to account the above mentioned behaviors, it is finally concluded that an optimal quantity of steel dust can be added instead of cement in concrete.

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