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International
Journal
Of Modern Engineering Research (IJMER)

An Experimental Investigation on Strength Characteristics of Concrete with Partial Replacement of Silica Fume and Metakaolin with Cement on M-30 Grade of Concrete

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Abstract: *One of the approaches in improving the durability of concrete is to use blended cement materials such as fly ash, silica fume, slag and more recently, metakaolin.. This study presents the results of different mechanical properties of concrete such as compressive strength, split tensile strength and flexural concrete by partially replacing cement with metakaolin and silica fume. The replacement of metakaolin is varied from 10%, 15%, 20% and 25% and silica fume from 6%, 8% and 10%. The property of concrete in fresh state, that is the workability is also studied during the present investigation.The optimum doses of silica fume and metakaolin in combination were found to be 6% and 15% (by weight) respectively, when used as part replacement of ordinary Portland cement.*

Keywords: *Silica fume, metakaolin, OPC, Compressive strength, Flexural strength, Split Tensile Strength, Load Deflection RC Beam*

I. INTRODUCTION

Recent societal shift toward sustainable consumption and growth applied to civil infrastructure systems requires the construction materials to be designed and used with utmost attention to their durability and long term response. A majority of design codes and specifications use the compressive strength of concrete as the main criterion for design of concrete structures. Mechanically properties which are functions of porosity could to some extent provide indications of the transport properties of concrete , however they are not valid criteria for overall durability performances. Major transport properties of concrete are permeation, diffusion and absorption through which the aggressive media penetrate into the bulk of concrete and may cause gradual degradation. Pozzolanic materials including silica fume, fly ash, slag, and metakaolin have been used in recent decades for developing high performance concrete with improved workability, strength and durability. The use of supplementary cementitous materials (SCMs) is fundamental in developing low cost construction materials for use in developing countries. Concrete is the most widely used and versatile building material which is generally used to resist compressive forces. By addition of some pozzolanic materials, the various properties of concrete viz, workability, durability, strength, resistance to cracks and permeability can be improved. Many modern concrete mixes are modified with addition of admixtures, which improve the microstructure as well as decrease the calcium hydroxide concentration by consuming it through a pozzolanic reaction. The subsequent modification of the microstructure of cement composites improves the mechanical properties, durability and increases the service-life properties. When fine pozzolana particles are dissipated in the paste, they generate a large number of nucleation sites for the precipitation of the hydration products. Therefore, this mechanism makes paste more homogeneous. This is due to the reaction between the amorphous silica of the pozzolanic and calcium hydroxide, produced during the cement hydration reactions (Sabir et al. 2001, Rojas and Cabrea 2002, Antonovich and Goberis 2003). In addition, the physical effect of the fine grains allows dense packing within the cement and reduces the wall effect in the transition zone between the paste and aggregate. This weaker zone is strengthened due to the higher bond development between these two phases, improving the concrete microstructure and properties. In general, the pozzolanic effect depends not only on the pozzolanic reaction, but also on the physical or filler effect of the smaller particles in the mixture. Therefore, the addition of pozzolanas to ordinary portland cement (OPC) increases its mechanical strength and durability as compared to the referral paste, because of the interface reinforcement. The physical action of the pozzolanas provides a denser, more homogeneous and uniform paste. Silica fume is a by product resulting from the reduction of high purity quartz with coal or coke and wood chips in an electric arc furnace during the production of silicon metal or silicon alloys. Silica fume is known to improve both the mechanical characteristics and durability of concrete. The principle physical effect of silica fume in concrete is that of filler, which because of its fineness can fit into space between cement grains in the same way that sand fills the space between particles of coarse aggregates and cement grains fill the space between sand grains. As for chemical reaction of silica fume, because of high surface area and high content of amorphous silica in silica fume, this highly active pozzolan reacts more quickly than ordinary pozzolans. The use of silica fume in concrete has engineering potential and economic advantage.Metakaolin is another pozzolanic materials which is manufactured from selected kaolins, after refinement and calcination under specific conditions. It is a highly efficient pozzolana and reacts rapidly with the excess calcium hydroxide resulting from OPC hydration, via a pozzolanic reaction, to produce calcium silicate hydrates and calcium aluminosilicate hydrates. It is quite useful for improving concrete quality, by enhancing strength and reducing setting time, and may thus prove to be a promising material for manufacturing high performance concrete.Both the Silica fume and Metakaolin are useful pozzolanic materials. In the present work, the results of a study carried out to investigate the effects of combination of these two materials on strength and workability of concrete are presented. The referral concrete M_{30} was made using 53 grade OPC and the other mixes were prepared by replacing part of OPC with Silica Fume and Metakaolin. The replacement levels were 0%, 6%. 8% and 10% (by weight) for Silca Fume and 0%, 15%, 20% and 25% (by weight) for Metakaolin.

II. MATERIALS AND THEIR PROPERTIES

1 .Materials:

1.1. Cement: Cement in general can be defined as a material which posses very good adhesive and cohesive properties which make it possible to bond with other material to form compact mass. As Shown in table 1.

Table 1

Physical properties of OPC.		Chemical Properties of OPC	
Properties	Chart Result	Properties	Chart Result
Fineness (Sp.Surface)	348 m^2 / Kg	% Soluble Silica	21.3
Specific gravity	3.15	% Alumina	5.2
Comp. Strength -7 days	16.25 MPa	% Iron Oxide	3.7
Comp. Strength – 28 days	25.0 MPa	% Lime	63.9
Initial setting Time	40 min	% Magnesia	0.7
Final Setting Time	205 min	% Insoluble Residue	0.9
Soundness (Le-Chatlier Exp.)*	1.0mm	% So_3	2.2

1.2. Fine Aggregate (FA):- The aggregate which is passing through 4.75 mm sieve is known as fine aggregate. Locally available river sand which is free from organic impurities is used. Sand passing through 4.75 mm sieve and retained on 150 micron IS sieve is used in this investigation. For the casting, locally available river-sand, free from silt and organic matters was procured and used. The particle size of fine aggregate used in this study was such a way that it passed through 4.75 mm sieve conforming to zone II of IS:383-1970.

Table 2

The Physical Properties of Fine Aggregate	
Property	Value
Specific Gravity	2.65
Fineness Modulus	3.75
Bulk Density	15.90 kN/m^3
Grading	Zone-II

1.3. Coarse Aggregate (CA):- The coarse aggregate used in the investigation is 20mm down size crushed aggregate and angular in shape.

Table 3

Physical Properties of Coarse Aggregate	
Property	Value
Specific Gravity	2.7
Bulk Density	16.05 kN/m^3
Water absorption	0.66%
Flakiness index	13.88
Elongation index	21.24
Crushing value	2.42
Impact value	16.1

1.4. Water (IS 456-2000):- Water used for both mixing and curing should be free from injurious amount of deleterious materials. Potable water is generally considered satisfactory for mixing and curing concrete. In the present work potable tap water was used.

1.5. Silica Fume:- Silica fume is also referred to as micro silica or condensed silica fume, but the term 'silica fume' has become generally accepted. It is a by-product of the manufacture of silicon and ferrosilicon alloys from high-purity quartz and coal in a submerged-arc electric furnace. The escaping gaseous SiO oxidizes and condenses in the form of extremely fine spherical form of amorphous silica (SiO2); hence, the name silica fume. Physical & chemical properties as shown in table 4 and 5.

Table 4

Physical Properties of Silica Fume	
Colour	Varies from white or pale-grey to a dark grey.
Specific gravity	2.2
Specific surface Area	About 20000/kg approx. 10 times more than Portland cement
Particle size	Mostly fine spheres with a mean dia of 0.1 micron
Bulk loose density	230 – 300 kg/m^3

Table 5

Chemical composition of Silica Fume	
Constituents	Percent
Sio_2	90 – 96
Al_2o_3	0.5 – 0.8
Mgo	0.5 – 1.5
Fe_2o_3	0.2 - 0.8
Cao	0.1 – 0.5
Na_2o_2	0.2 – 0.7
K_2o	0.4 – 1.0
C	0.5 – 1.4
S	0.1 - 0.4

1.6. Metakaolin: Metakaolin is another pozzolanic materials which is manufactured from selected kaolins, after refinement and calcination under specific conditions. The Metakaolin was sieved and the fraction passing 100µ IS sieve was used in the experiments.The physical and chemical properties of metakaolin shown in Table 6 and 7.

Table 6

Physical properties of Metakaolin	
Appearance	Off white powder
Specific gravity	2.4 – 2.6
Density	2640 kg/m^3
Brightness	76%
Particle size	12µm
Residue on 375 mesh	Max 0.5%
fineness	15000 – 30000 m^2/kg

Table 7

Typical Chemical Composition of Metakaolin	
Item	% by weight
SiO_2(%)	51.52
Al_2O_3	40.18
Fe_2O_3	1.23
Cao	2.0
Mgo	0.12
Na_2O	0.08
K_2O	0.53
Loss on ignition	0.91

2. Casting & Curing:

For each mix the standard size of (150mm x 150mm x 150mm) cube moulds, standard size of (100mm dia x 200mm height) cylinder moulds, standard size (100mm x 100mm x 500mm) prisms, modal RC beams of size (700mm x 150mm x 150mm) are casted. Cube, cylinder, prism and beam moulds are made up of cast iron for casting. Before pouring the fresh concrete into these moulds, an engine oil is applied in thin layers to the inner surfaces of moulds in order to prevent the sticking of concrete to mould. These specimens are allowed to set in the mould for 24 hours, after 24 hours these specimens are de-moulded and were kept under wet conditions by immersing them in water continuously for 7 and 28 days for cubes & Cylinders, 28 days for prisms, beams.

III. RESULTS & DISCUSSIONS

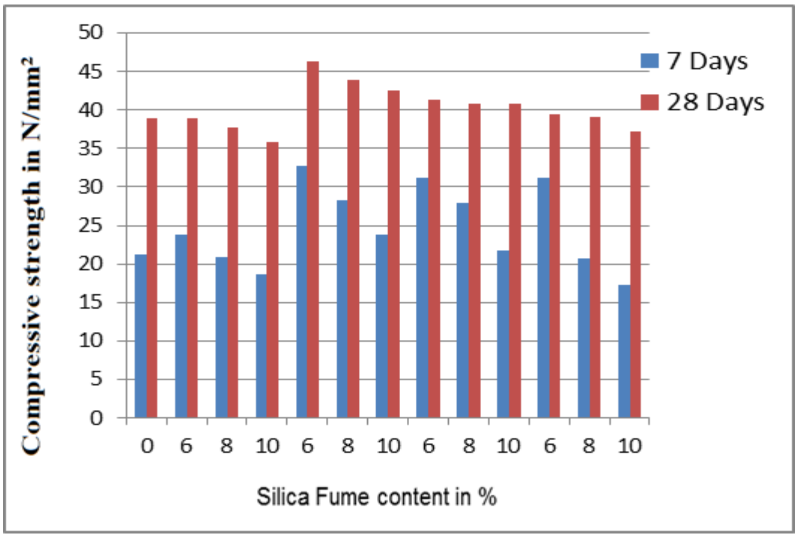
The compressive strength of the cubes, the split tensile strength of the cylinders, the flexural strength of the prisms, at different ages and different silica fume and metakaolin combination are presented in Table. The slump values and compaction factor of the different mixes are also included.

Table 8

Replacement level (%)		Slump in mm	Compaction Factor
Silica fume replacement (%)	Metakaolin replacement (%)		
0	0	58	0.80
6	10	61	0.82
8	10	66	0.84
10	10	63	0.83
6	15	59	0.91
8	15	61	0.87
10	15	62	0.90
6	20	54	0.81
8	20	57	0.82
10	20	57	0.82
6	25	52	0.80
8	25	51	0.81
10	25	53	0.81

Table 9

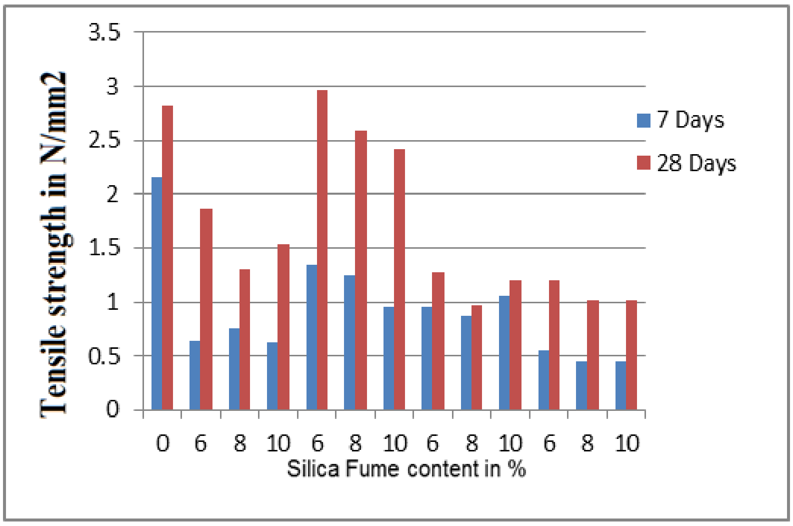
Replacement level (%)		Compressive Strength N/mm^2	
Silica fume	Metakaolin	7 Days	28 Days
0	0	21.25	38.85
6	10	23.86	39.0
8	10	20.86	37.75
10	10	18.66	35.75
6	15	32.77	46.29
8	15	28.23	43.96
10	15	23.82	42.58
6	20	31.11	41.34
8	20	27.88	40.80
10	20	21.71	40.75
6	25	31.27	39.44
8	25	20.70	39.05
10	25	17.28	37.13



Graph 1: Compressive strength at 7 and 28 Days of age at 0%, 6%, 8%, 10% and 0%, 10%, 15%, 20%, 25% of Silica Fume and Metakaolin

Table 10

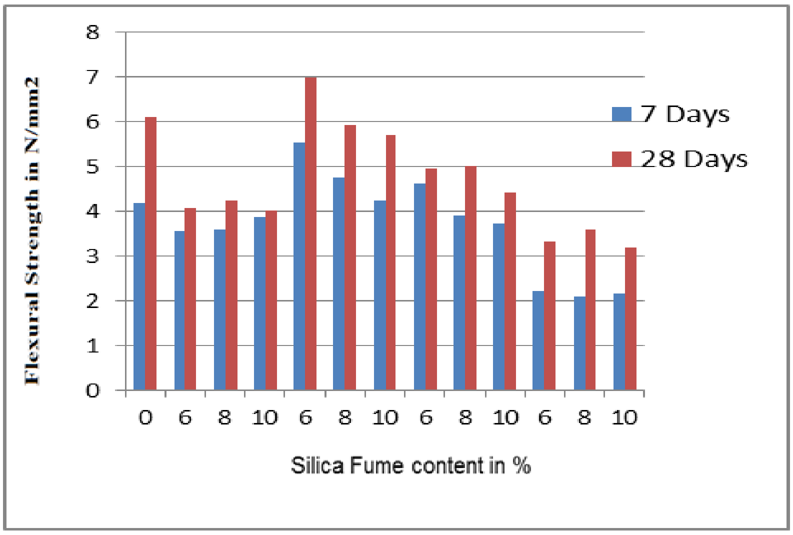
Replacement level (%)		Split tensile Strength N/mm^2	
Silica fume	Metakaolin	7 Days	28 Days
0	0	2.16	2.82
6	10	0.64	1.87
8	10	0.76	1.31
10	10	0.63	1.53
6	15	1.35	2.97
8	15	1.25	2.59
10	15	0.96	2.41
6	20	0.96	1.27
8	20	0.87	0.98
10	20	1.06	1.20
6	25	0.55	1.21
8	25	0.46	1.01
10	25	0.45	1.02



Graph 2: Split Tensile strength at 7 and 28 Days of age at 0%, 6%, 8%, 10% and 0%, 10%, 15%, 20%, 25% of Silica Fume and Metakaolin

Table 11

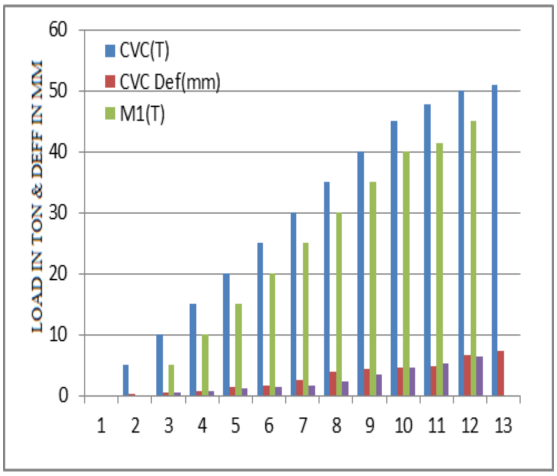
Replacement level (%)		Flexural Strength N/mm^2	
Silica fume	Metakaolin	7 Days	28 Days
0	0	4.2	6.11
6	10	3.56	4.09
8	10	3.58	4.25
10	10	3.89	4.02
6	15	5.55	7.0
8	15	4.77	5.95
10	15	4.25	5.71
6	20	4.61	4.96
8	20	3.91	5.03
10	20	3.73	4.43
6	25	2.21	3.34
8	25	2.12	3.60
10	25	2.16	3.20



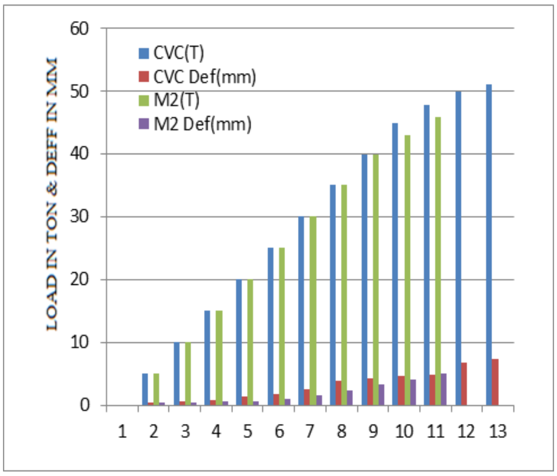
Graph 3: Flexural strength at 7 and 28 Days of age at 0%, 6%, 8%, 10% and 0%, 10%, 15%, 20%, 25% of Silica Fume and Metakaolin

The various mixes OF M30 grade with silica fume and metakaolin partially replaced with cement are designated as follows for beams;

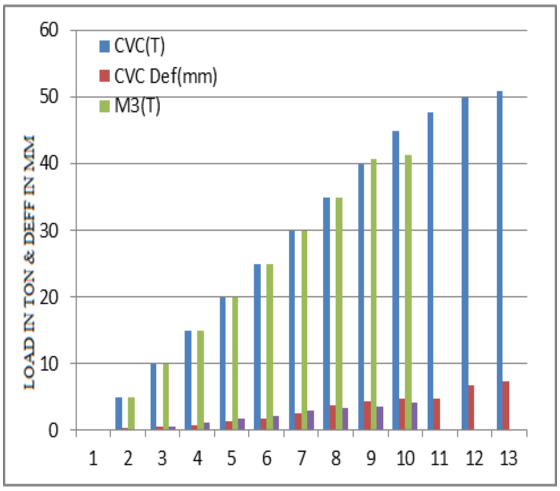
CVC	Conventional Concrete
M1	S.F. 6% & M.K. 10%
M2	S.F. 8% & M.K. 10%
M3	S.F. 10% & M.K. 10%
M4	S.F. 6% & M.K. 15%
M5	S.F. 8% & M.K. 15%
M6	S.F. 10% & M.K. 15%
M7	S.F. 6% & M.K. 20%
M8	S.F. 8% & M.K. 20%
M9	S.F. 10% & M.K. 20%
M10	S.F. 6% & M.K. 25%
M11	S.F. 8% & M.K. 25%
M12	S.F. 10% & M.K. 25%



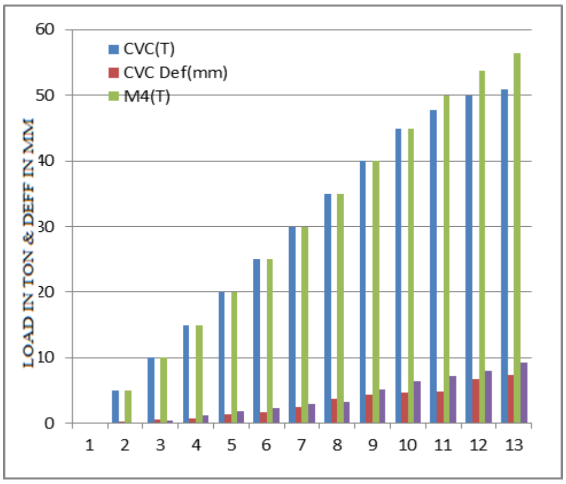
Graph 4 : Load Vs Deflection for CVC RCC beam and M1 beam



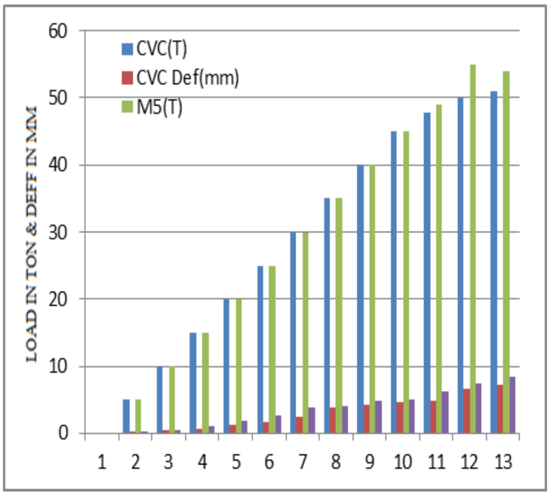
Graph 5 : Load Vs Deflection for CVC RCC beam and M2 beam



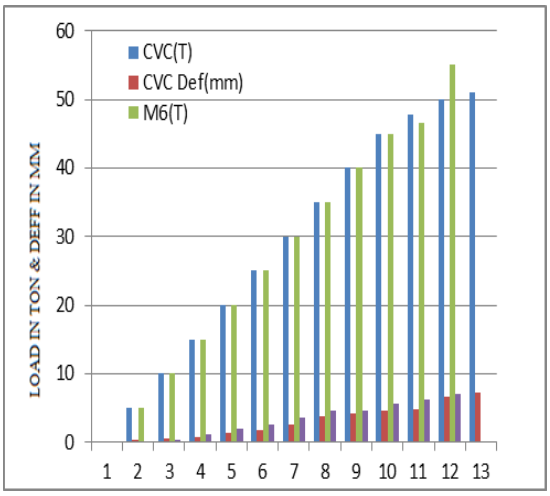
Graph 6 : Load Vs Deflection for CVC RCC beam and M3 beam



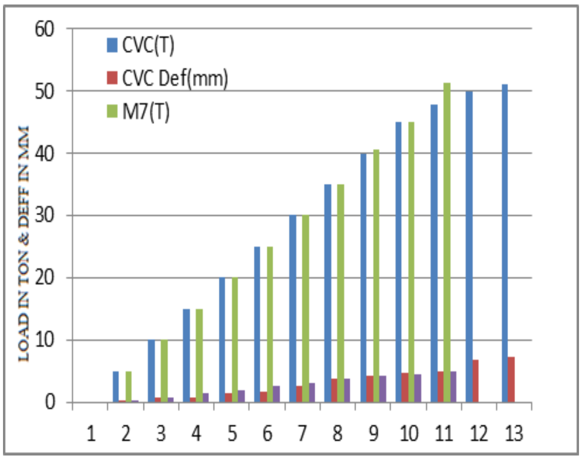
Graph 7 : Load Vs Deflection for CVC RCC beam and M4 beam



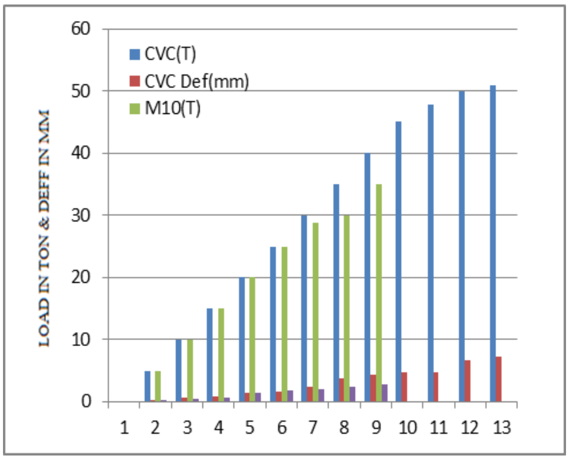
Graph 8: Load Vs Deflection for CVC RCC beam and M5 beam



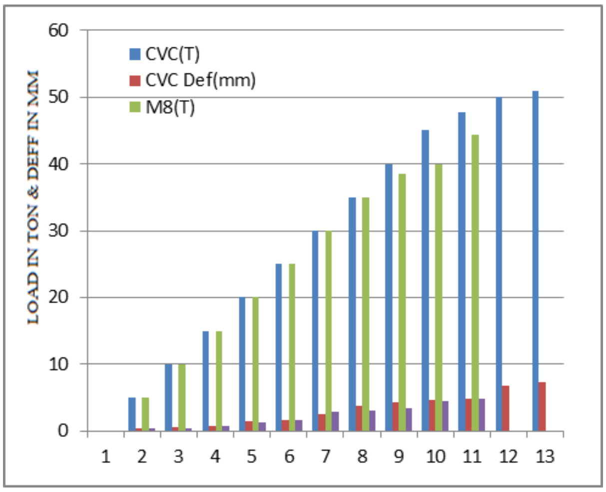
Graph 9: Load Vs Deflection for CVC RCC beam and M6 beam



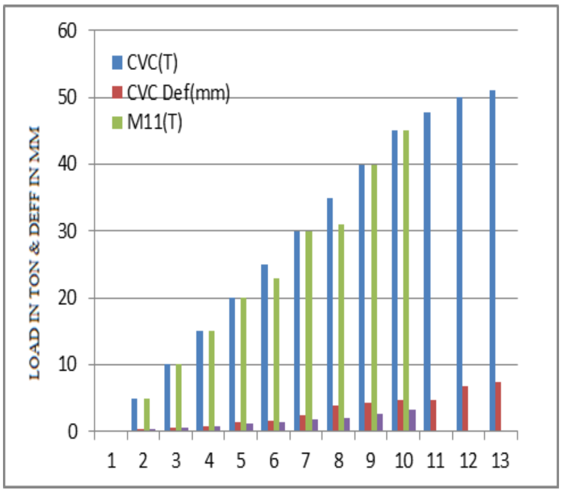
Graph 10: Load Vs Deflection for CVC RCC beam and M7 beam



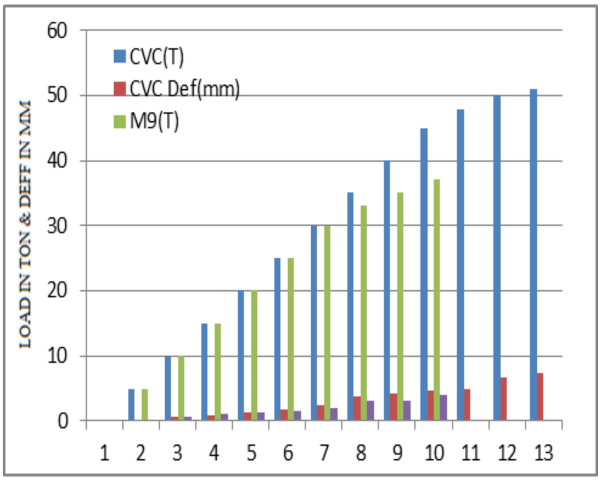
Graph 13: Load Vs Deflection for CVC RCC beam and M10 beam



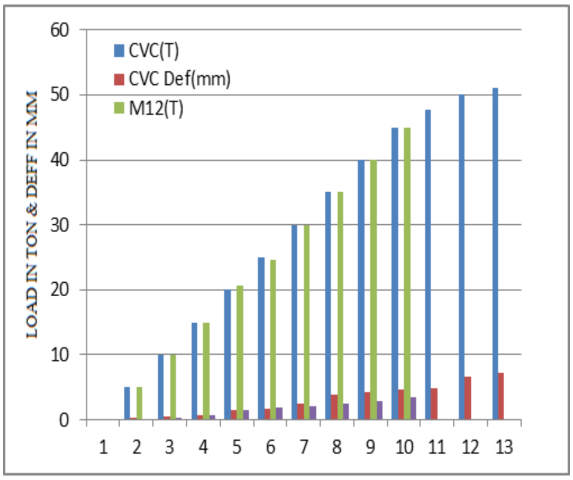
Graph 11: Load Vs Deflection for CVC RCC beam and M8 beam



Graph 14: Load Vs Deflection for CVC RCC beam and M11 beam



Graph 12: Load Vs Deflection for CVC RCC beam and M9 beam



Graph 15: Load Vs Deflection for CVC RCC beam and M12 beam

VI. CONCLUSIONS

Following observations have been made from the study of using silica fume and metakaolin in concrete:

- The 28 day Compressive strength increases with increase in percentage of metakaolin while in case of slica fume strength increases upto 15% replacement level and then starts decreasing. And the 7 day compressive strength of concrete generally decreases with the increasing Metakaolin content at all the Silica fume contents.
- Split tensile strength in Silica fume (6, 8, 10) and 10 % Metakaolin content is found to be 0.64, 0.76, 0.63. In this case after days curing the strength has increased more than 7 days curing.
- Similarly in case of Split Tensile strength of Silica fume (6, 8, 10) and 15%, 20%, 25% Metakaolin contents.
- In Split Tensile Strength, the difference between 7 days strength and 28 days strength is large.
- The concrete mixes developed flexural strength of 3.89, 5.55 and 4.61, 2.21 N/mm^2 in 7 days with the metakaolin replacement of 10%, 15%, 20% and 25% respectively. While it achieves strength of 4.25, 7.00 and 5.03, 3.60 N/mm^2 at the age of 28 days.
- The slump is found to decreases with increase in Metakaolin content at all the Silica fume contents considerably.
- In case of RS Mix S.F (6%) M.K (10%) beams the deflection is high compared to the CVC RCC beam of M-30. And the load carrying capacity is low in case of RS Mix S.F (6%) M.K (10%) beams when compared to CVC RCC beams.
- In case of RS Mix S.F (8%) M.K (10%) beams the deflection is low compared to the CVC RCC beam of M-30. And the load carrying capacity is low in case of RS Mix S.F. (8%) M.K (10%) beams when compared to CVC RCC beams.
- In case of RS Mix S.F (10%) M.K (10%) beams the deflection is low compared to the CVC RCC beam of M-30. And the load carrying capacity is low in case of RS Mix S.F. (10%) M.K (10%) beams when compared to CVC RCC beams.
- In case of RS Mix S.F (6%, 8%) M.K (15%) beams the deflection is high compared to the CVC RCC beam of M-30. And the load carrying capacity is high in case of RS Mix S.F. (6%, 8%) M.K (15%) beams when compared to CVC RCC beams.
- In case of RS Mix S.F (10%) M.K (15%) beams the deflection is high compared to the CVC RCC beam of M-30. And the load carrying capacity is low in case of RS Mix S.F. (10%) M.K (15%) beams when compared to CVC RCC beams. In case of RS Mix S.F (6%, 8%, 10%) M.K (20%, 25%) beams the deflection is low compared to the CVC RCC beam of M-30. And the load carrying capacity is low in case of RS Mix S.F. (6%, 8%, 10%) M.K (20%, 25%) beams when compared to CVC RCC beams.

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