COPPER SLAG -SILICA FUME BLENDED FIBRE CONCRETE – AN ECO-FRIENDLY HEALTHY ALTERNATIVE FOR CONVENTIONAL CEMENT CONCRETE

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This study aims at utilizing industrial wastes and hybridized fibres to improve the strength and stability of concrete to obtain an eco-friendly healthy concrete. Steel, basalt and alkali reactive glass fibres were hybridized in various ratios to obtain modified concrete mixes containing 7% silica fume as cement replacement. This study also focuses on the effective ways of utilizing copper slag as fine aggregate replacement thereby reducing the pollution as well as meets the increasing demand of river sand for concrete. This experimental investigation includes the mechanical strength characterization such as compressive strength, flexural strength and split tensile strength at various ages and durability properties such as water absorption, porosity and resistance towards acid attack. The results obtained showed that the hybridization of fibres in combination with copper slag replacement can be incorporated in concrete to improve their mechanical strength and durability.The results also show that such fibre hybridization is indeed a promising concept that can significantly enhance the strength of the industrial waste incorporated concrete.

Keywords: *silica fume, copper slag, fiber hybridization, mechanical strength, durability.*

1. Introduction

Concrete, an indispensable construction material has occupied a predominant place in the construction of worldwide infrastructural facilities. No material has been proved to be an effective alternative to concrete and seems impossible even in the future. Substantial advancements taken in the recent decades have shown improved concrete with remarkable strength and sufficient stability to aggressive environments. Despite several advancements the construction industry still faces a major problem by posing a greater threat to the environmental sustainability due to greater demand of fine aggregates. The need to focus on the innovative materials as replacements for fine aggregates is increasing day by day due to the pressure of incorporating sustainable aspects in the construction industry. Moreover, the high amount of the energy associated with the production of cement demands the use of mineral or pozzolanic admixtures to solve the technical and environmental problems. Mineral admixtures mostly obtained from the industrial by-products are rich in alumina and silica and can function as effective cement replacements. Silica fume is a highly reactive mineral admixture that possesses high pozzolanic activity and can contribute significantly towards the strength improvement of concrete [1]. Several studies have seen significant enhancement in the properties of concrete due to the incorporation of silica fume both at the hardened and the fresh state. The inclusion of the silica fume has also been found to reduce the bleeding of concrete due to their comparatively high-water demand. The strength improvement in concrete due to silica fume addition may be attributed not only to their pozzolanic activities but also to their particle size which is finer when compared to the cement [2]. Similarly, copper slag also improved the strength of the concrete due to their filler effect and particle packing capacity [3-5]. The beneficial utilization of fibres and silica fume in concrete and their combined effects has been well documented by several researches [6-8]. Despite several studies have been reported on the utilization of copper slag and silica fume in concrete [9] no studies have attempted to replace binder and fine aggregate together as well as incorporating fiber hybridization. A comprehensive understanding is necessary when replacements to cement and fine aggregate is done at the same time and this study is an effort to glean the effect of replacement of fine aggregate by copper slag [10,11] and cement by silica fume together with fiber hybridization [12,13] on the strength and stability of cement concrete.

2.Research Objective

The primary objective of the research work is to investigate the effect of cement and fine aggregate replacements on the strength of concrete. Following are the specific objectives of the study:

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- Investigate the effect of silica fume and copper slag replacement on the workability of concrete.
- Evaluate the compressive, flexural and split tensile strength of concrete as a function of fine aggregate replacement and fiber hybridization.
- Examine the durability performance of copper slag and silica fume substituted concrete through water absorption and porosity tests.
- Assessment the micro structure of produced concrete through FTIR and SEM analysis.

3.Materials and Mix proportions

Two series of concrete mixes M40 and M50 grades are produced with varying water-binder ratios as shown in Table 1. Ordinary Portland cement conforming to IS 1489-1991 was chosen as the main binder. Silica fume and copper slag were obtained from the nearby industry and the purity levels were analyzed using X-ray fluorescence test as shown in Table 2. The particle size distribution of the materials is shown in Fig 1. The fine aggregate used in this study is natural river sand which conformed to zone 2 of IS 383-1970. The mix designations and the proportion of the replacements of fine aggregate and binder are also tabulated. The fibers were chopped to a length of 5 cm using manual methods. The superplasticizer dosage was fixed as 2% to attain required workability.

The workability of the fresh concrete mixes were investigated as per the procedure stated in IS 1199-1959. The compressive strength of the concrete at various ages of 14, 28 and 90 days were done on cubic specimens of size 150 x 150 x 150 mm confirming to the standard IS 516-1959. The flexural strength of the beams of size100 x 100 x 500 mm was determined at 28 and 90 days. The split tensile strength was conducted on cylindrical specimen of size150 mm diameter x 300 mm high at the age of 28 and 90 days. All the specimens were cast in triplicates and the average forms the final result.

Table 1

Chemical composition of the cement (OPC), copper slag (CS) and silica fume (SF)

Component	OPC (%)	CS (%)	SF (%)
SiO_2	20.85	33.05	96.19
Al_2O_3	4.78	2.79	1.41
Fe_2O_3	3.51	53.45	0.47
CaO	63.06	6.06	0.01
MgO	2.32	1.56	0.75
SO_3	2.48	1.89	0.02
K_2O	0.55	0.61	0
Na_2O	0.24	0.28	0.31
TiO_2	0.25	0	0.01
Mn_2O_3	0.05	0.06	0
Cl	0.01	0.01	0

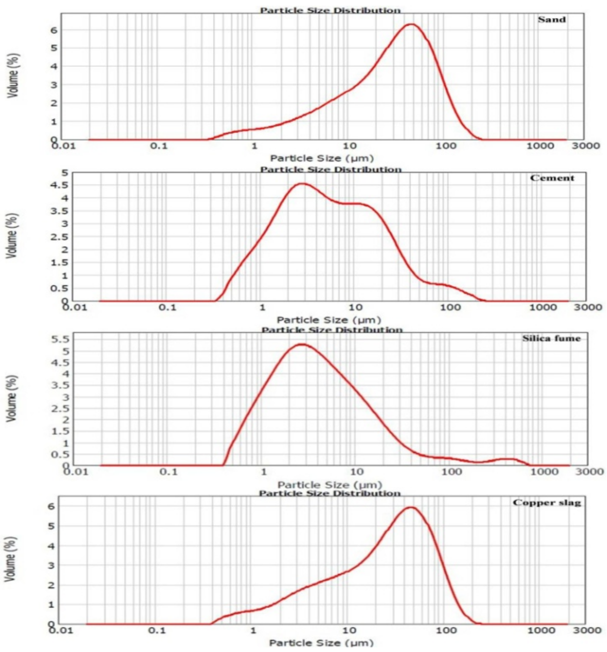

Fig 1 - Particle size distribution of the materials used.

Table 2

Mix ratio, proportions, % replacement of binder and fines, fibre addition

Mix ID	Grade of concrete	w/b	Mix Ratio	% by weight of cement	(% by weight of sand)	Steel Fiber (%)	Basalt Fiber (%)	ARGF (%)
				Silica Fume	Copper Slag			
CM1	M40	0.4	1:1.65:2.92	0	0	0	0	0
SCB1				7	10	1	0.5	1.5
SCB2				7	20	1.5	1	0.5
SCB3				7	30	0.5	1.5	1
CM2				0	0	0	0	0
SCB4	M50	0.35	1:1.47:3.04	7	10	1	0.5	1.5
SCB5				7	20	1.5	1	0.5
SCB6				7	30	0.5	1.5	1

4.Results and discussion

4.1.Workability

The effect of silica fume, copper slag replacements and fibre hybridization on the workability of the fresh concrete is obtained from the slump test as shown in Fig 2. The hybridization of fibres affects the workability of the concrete. The low water binder ratio adopted for the M50 grade concrete mixes caused the M50 concrete grade concrete mixes to exhibit relatively lower slump values when compared to M40 grade concrete mixes. A considerable improvement in the workability of the concrete was observed due to the replacement of fine aggregate by copper slag [14]. Copper slag exhibits glassy surface texture when compared to the normal sand thereby increasing the amount of free water available in the concrete. This amount of free water available in the copper slag incorporated concrete is much higher than that of the normal concrete and is the main causative agent of the workability improvement in the copper slag substituted concrete. Despite the hydrophobic nature of the copper slag the decrease in the workability for the concrete mixes may be due to the steel fibres. The interlocking network formation between the fibres and the cement matrix reduced the workability. The cement replacement by silica fume also affects the workability of the concrete due to their fineness and higher specific surface area of the silica fume that absorbs more water making the concrete cohesive. The improved workability in the concrete mixes was mainly contributed by the lower steel fibre content and higher copper slag replacement.

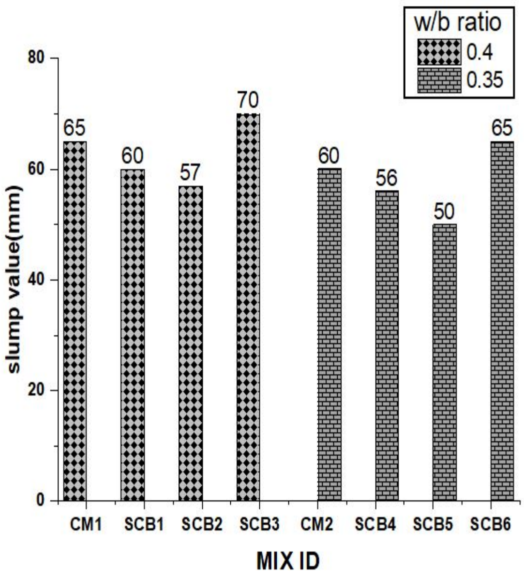

Fig 2 - Slump values of various concrete mixes.

4.2.Compressive strength

The compressive strength of the concrete mixes in M40 grade series and M50 grade series and the control concrete is shown in Fig 3. The copper slag addition improves the compressive strength of the concrete at the later ages of the concrete since the time taken for the slag alkaline reaction is higher than that required for the pozzolanic reaction to occur. The copper slag also requires higher humidity and the duration for the formation of hydration products. The higher water binder ratio also improved the compressive strength of the silica fume replaced concrete due to the higher water absorbing property of the silica fume and without required water content the formation of hydration products will be incomplete. The later age compressive strength increase of the concrete mixes improvement was only marginal due to the addition of the fibres that caused the aggregation of the fibres with one another which leads to increased number of voids. The copper slag also influenced the compressive strength and silica fume that filled the pores caused by the addition of the fibres. Some of the fibre reinforced concrete mixes also showed higher compressive strength than the control mix due to the energy absorbing property of the fibres. Moreover the use of silica fume improved the adhesive bonding between fibers and concrete and also enhances the bridging capacity of fibers during formation of micro crack. The magnitude of increase of compressive strength in fibre reinforced concrete mainly depends on the type of the aggregates used and the quality of the cement matrix rather than the type and quantity of the fibres added in the concrete.

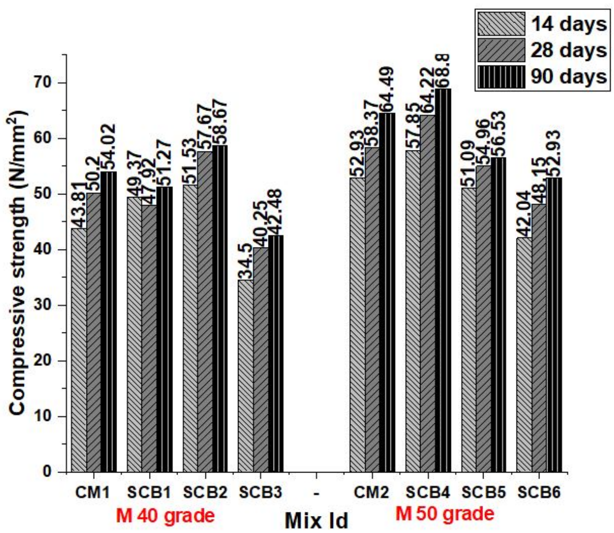

Fig. 3 - Compressive strength of various concrete mixes.

4.3. Flexural strength

The flexural strength of the M40 and M50 grade concrete series is shown in Fig. 4. This improved flexural strength of the concrete is an indication of the improvement in the ductility of the concrete. The reason behind this increase may be attributed to the higher flexibility of the basalt and glass fibres and high tensile strength of the steel

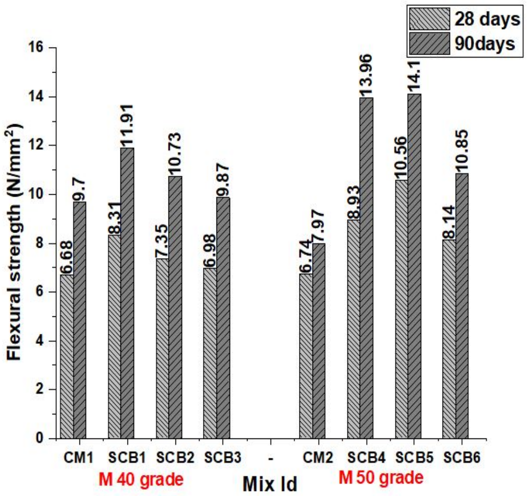

Fig 4- Flexural strength of various concrete mixes.

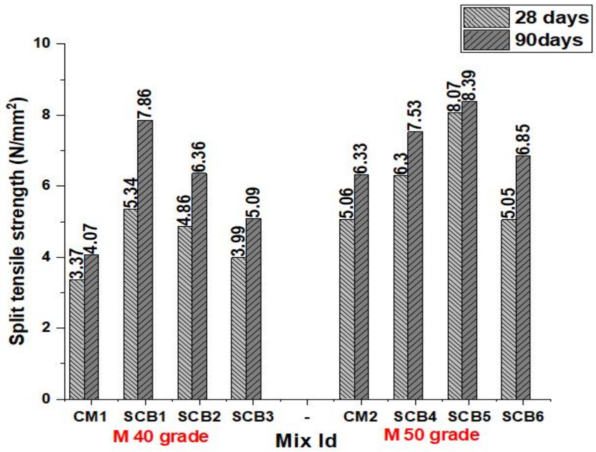

Fig 5 - Split tensile strength of various concrete mixes.

fibre. The steel fibres play a significant role in improving the ultimate flexural strength of the concrete by delaying the formation of micro cracks. The flexural strength increased linearly with increase in the concentration of steel fibres in the concrete. This insignificant improvement in the flexural strength of the concrete was mainly due to the agglomeration property of the fibres due to balling effect that created discontinuity in the cement matrix. This may be due to the angular surface texture of copper slag that increases the cohesion of the concrete and formation of the slag reaction products occurs only at the later ages of the concrete and thus increases the flexural strength of the concrete by transforming the brittle property of the concrete to more ductile material. The above stated flexural strength results supports the fact that concrete hybridized with different types of fibres has better ability to bridge the major crack formation by enhancing the micro-mechanical feature of the fibre reinforced concrete from the initial stage of crack formation to the point of ultimate loading and even beyond that point of ultimate loading.

4.4.Split tensile strength

The improvement in the splitting tensile strength may be due to formation of strong bond by the fibres with the cement matrix. The addition of steel fibres with high tensile strength also reduces the formation of micro cracks and propagation of cracks through the specimen. The basalt and glass fibres also positively influence the splitting tensile strength of the concrete but the magnitude of improvement is comparatively lesser when compared to the effect of split tensile strength. The glass fibres effectively arrest the crack formation and bridges the gaps formed in the concrete and thus significantly improve the spitting tensile strength of the concrete. The addition of steel fibres beyond 1% reduces the splitting tensile strength of the concrete due to the higher stiffness of the fibres that hinders the uniform distribution of the fibres. This insignificant improvement in the splitting tensile strength of the concrete was mainly due to the agglomeration property of the fibres due to balling effect that created discontinuity in the cement matrix. In Fig. 5, the silica fume replacement also enhances the splitting tensile strength of the concrete by forming active bonds with the cement particles and by converting the calcium hydroxide to strong CSH gel.

4.5.Water absorption and porosity

The results of water absorption and porosity expressed as a percentage for the M40 and M50 grade concrete series are shown in Fig 6.

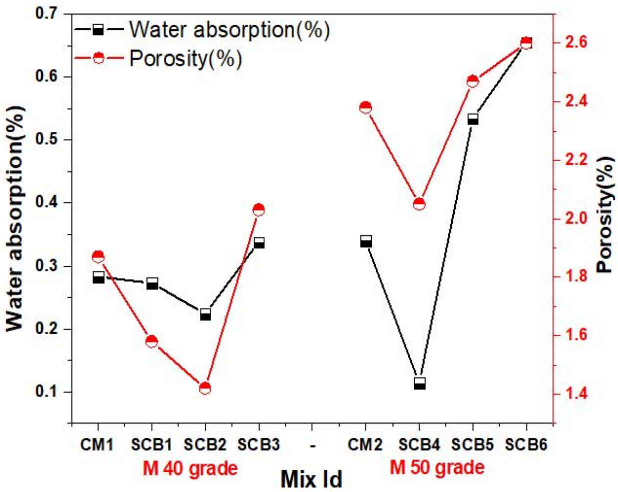

Fig 6 - Water absorption and porosity of various concrete mixes.

It clearly depicts that the water absorption was pronounced for the concrete mixes and this increase in the water absorption of the fibrous concrete mixes with higher percentage of copper slag replacement for fine aggregate may be due to the high amount of pores created by the addition of copper slag in concrete. The inclusion of copper slag in the concrete causes an increase in the amount of excessive free water content in the concrete mixes that causes the separation of the ingredients of the concrete leaving large amount of pores in the hardened concrete. These pores are easily accessible to water. However the addition of silica fume reduces the water absorption and porosity due to the filling capacity of the silica fume. Also, the replacement of cement by silica fume formed the stable non water soluble reaction product CSH gel that filled the pores of the concrete. The silica fume and copper slag addition cause reduced water absorption of the fibre reinforced concrete by making the pores discontinuous due to their pore blocking property. The greater interfacial area between the fibres and the cement binder creates micro voids and pores that allow the travel of the free water molecules through the concrete pores due to the formation of micro channels in the concrete. The hybridization of fibres also introduces heterogeneity in the homogeneous concrete mix that causes an increase in the porosity.

4.6.Attack of acids

Fig 7 and 8 shows the percentage loss in weight and percentage loss in strength of the M40 and M50 grade concrete series when subjected to acid attack. Generally higher porosity allows the dissolution of hydrogen ions freely through the concrete specimens finally resulting in higher weight loss. It can be seen that the M50 grade concrete series showed significant reduction of loss in weight and loss in strength for all the concrete mixes than the M40 grade concrete mixes. This may be due to the improvement in the dense nature of the concrete specimens with remarkable reduction the porosity that prevents the ingress of the hydrogen ions through the pore spaces in the concrete.

4.7.FTIR

FTIR spectra of the various concrete mixes are shown in Fig 9. The formation of the peak around 3400 cm-1 is due to the presence of –OH bond in the concrete. The chemically combines water and the physically bonded water appear as hydroxyl –OH bonds. The intensity of the –OH bond was significantly reduced in the silica fume added concrete mixes which showed the formation of well reacted hydration products. The –OH bond also indicated the presence of the hydration product $Ca(OH)_2$.The reduced intensity of the –OH bonds also significantly indicate that the pozzolanic reaction has taken place by the transformation of the Ca $(OH)_2$ to CSH gel. The appearance of the broad band at 3400cm-1also indicates the water crystal lattice present in the CSH gel. The band formed around 980 cm-1 belongs to the CSH gel formation. It can be seen that CSH gel band becomes broader and wider with higher intensity in all the concrete mixes when compared to the normal concrete mix. This shows that the interaction has taken place leading to more stable and complex hydration products. This further confirms the above stated results that the improvement in the strength of the fibre reinforced concrete was due to the formation of CSH gel by silica fume.

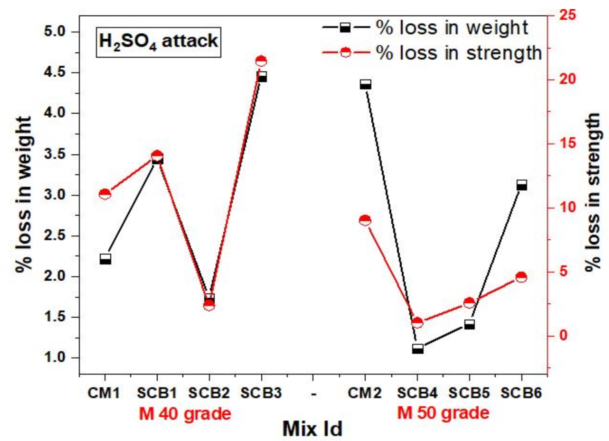

Fig 7 - Loss in weight and strength of the concrete due to H_2SO_4 attack.

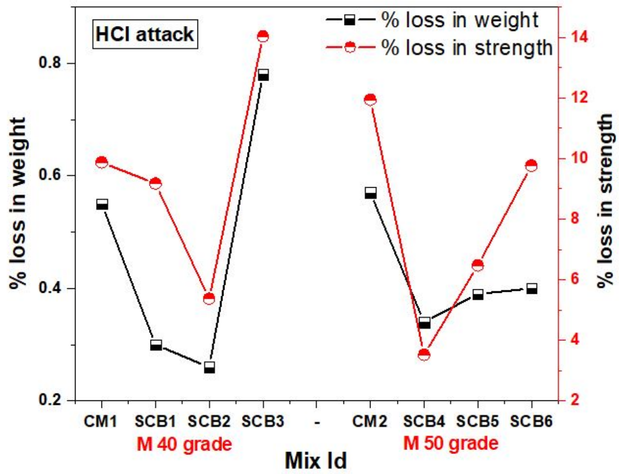

Fig 8 - Loss in weight and strength of the concrete due to HCL attack

4.8.SEM

The morphology of the concrete mixes as obtained from the SEM imaging is shown in Fig 10. The dark regions in the SEM images indicated the presence of pores or voids in the concrete. The images of the normal concrete mix showed higher amount of pores than the other concrete mixes. Moreover the volume of pores present in the control mix was much higher when compared to the other concrete mixes. The development ofpores in the concrete was much reduced in the silica fume added concrete mixes that support

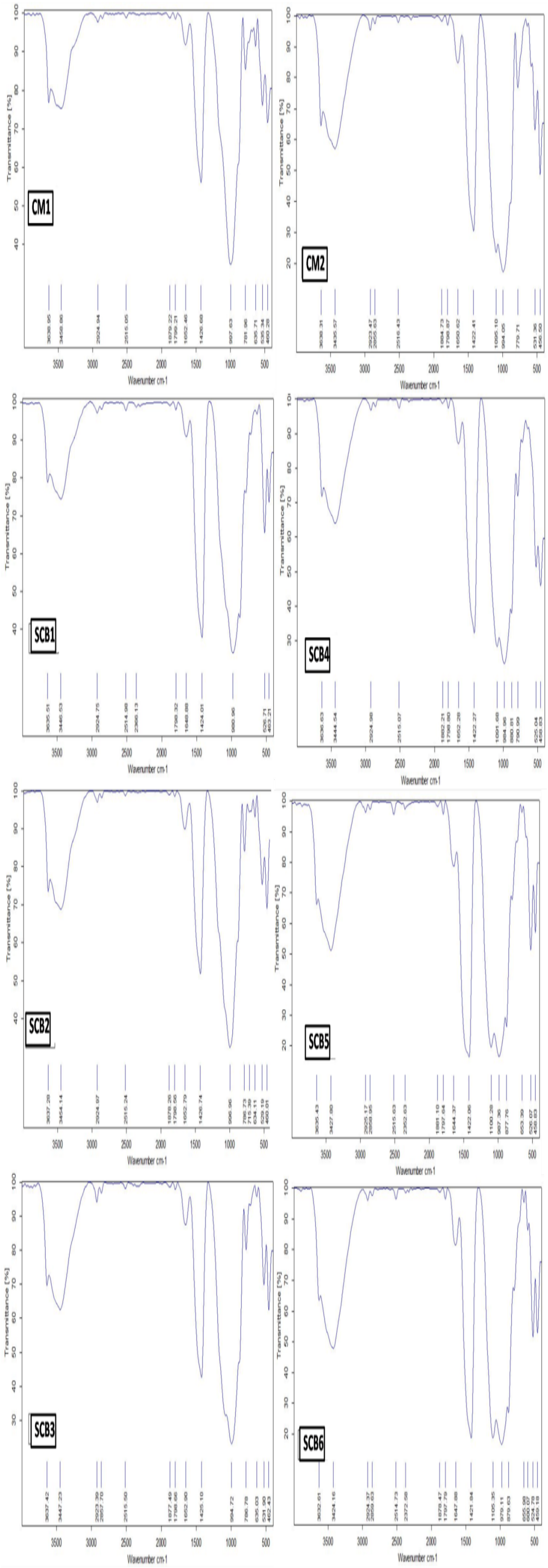

Fig 9- FTIR spectra of various concrete mixes.

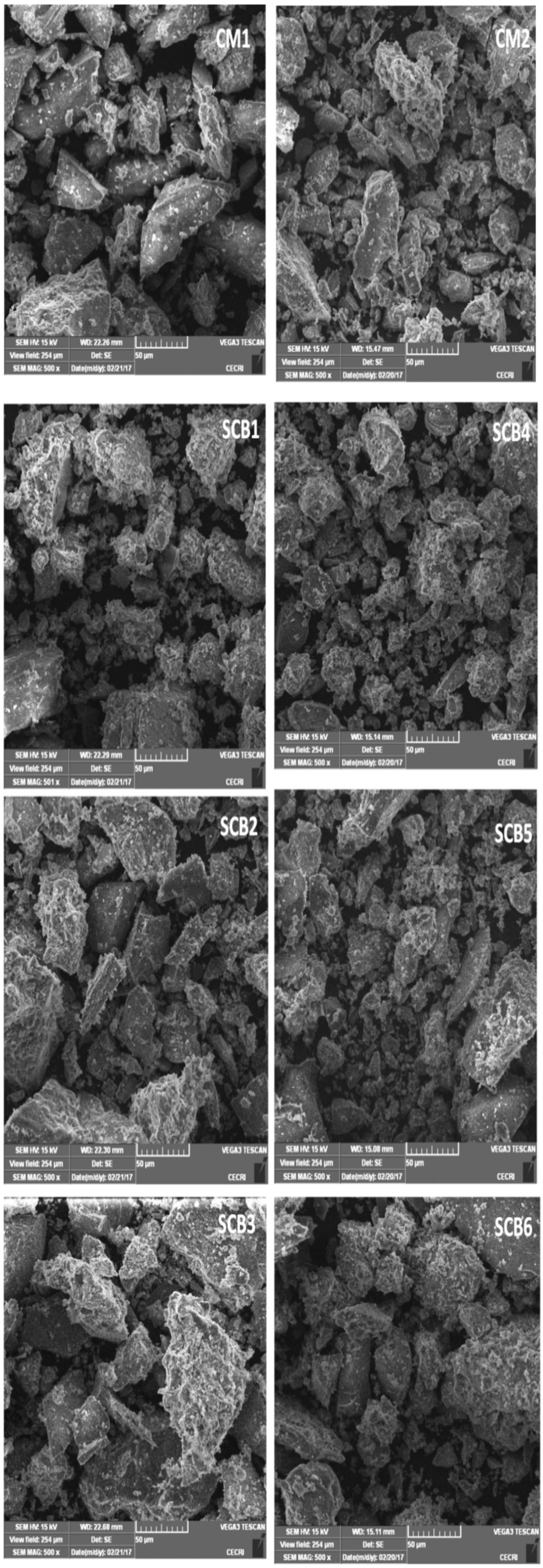

Fig 10 - SEM images of various concrete mixes.

the filling capacity of the silica fume. The presence of flaky gel like structures are present in the silica fume added concrete which indicates the formation of CSH gel. The interfacial zone between the aggregates and the cement paste also shows a well developed thick layer of the CSH gel formation that improved the strength of the concrete by reduction in the porosity. The increasing copper slag replacement also showed the well bonded aggregates with the cement paste that increases the denseness of the concrete. The denseness and compacity of the M50 grade concrete series was much higher than the M40 grade concrete series as obtained from the SEM images. The M 50 grade concrete SEM images also show the presence of some unhydrated reaction products due to the lesser available water binder content. The higher copper slag replaced specimens show relatively higher pores and voids with the less amount of binder phase surrounding the aggregate.

5. Regression analysis

From the experimental data obtained the regression analysis was performed and the best model that fits the various parameters of the concrete was found. The proposed prediction equation and the corresponding R^2 value obtained are shown in Fig. 11 and 12. The R^2 value obtained were almost higher and shows that all the strength parameters of the concrete are inter-related to each other and thus follows a linear trend.

6. Health and economical benefits

Copper slag is a waste material, produced during the smelting and refining process of copper ore. For every ton of copper produced, roughly 3 tons of copper slag gets generated. Presently, about 2500 tons of copper slag is produced per day and a total accumulation of approximately 1.5 million tons per annum. Copper slag contains highly toxic elements like arsenic, barium, cadmium, copper, lead and zinc. The disposal of copper slag is one of the major issues for environmentalist as dumping of copper slag as a waste material may cause severe environmental problems or hazards. Copper slag can release these elements into the environment causing pollution of soils, atmospheric air, surface waters and groundwater. Copper smelter also releases copper selenium. They are highly toxic if present overabundant. They contaminate the soil in the vicinity of smelters, destroying the vegetation. Copper slag possess number favourable engineering properties such as excellent soundness characteristics, good abrasion and

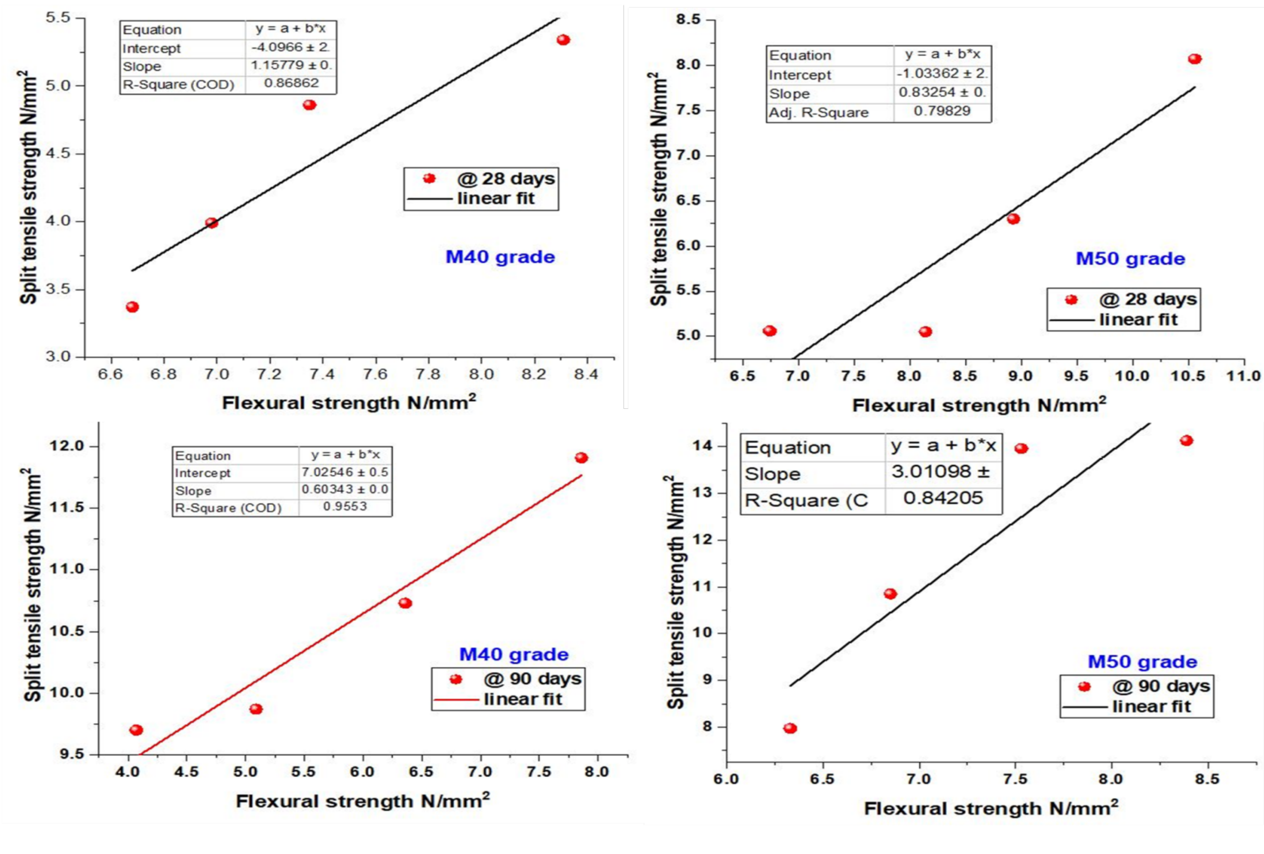

Fig 11 - Relation between flexural strength and split tensile strength of the concrete mixes at various ages.

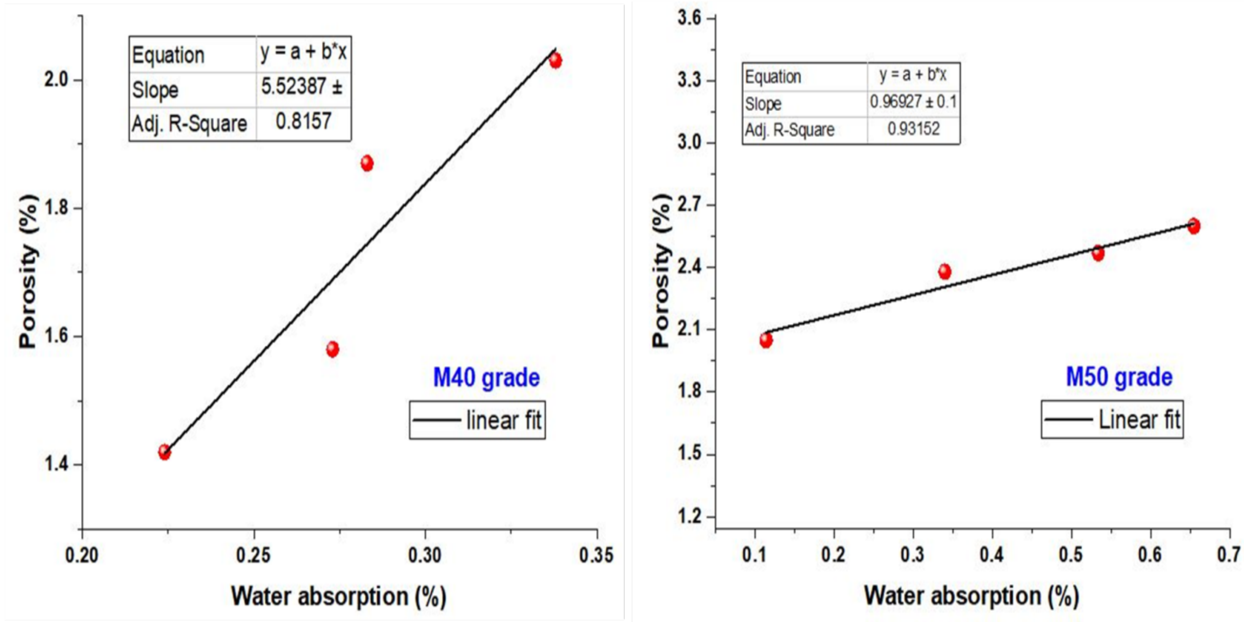

Fig 12 - Relation between water absorption and porosity of the concrete mixes at 28 days.

stability to be used as a building material. Copper slag possesses physical and chemical characteristics that qualify the material, to be used in concrete as an excellent substitute for Portland cement or as a partial replacement for aggregates reduce the cost of dumping, reducing cost of concrete and minimizing air pollution problem. Another noticeable factor is improvement towards health and safety is the substantial improvement in the reduction of waste thereby contributing to the health and safety of the environment. Thus the usage of copper slag in concrete provides sustainability of construction industry considering the use of natural materials, energy and man power, emission of carbon dioxide and durability failure in concrete structures.

7. Conclusion

From the results obtained from the experiments conducted on the M40 and M50 grade concrete series made with silica fumes as cement replacement, copper slag as fine aggregate replacement and hybridisation of the fibers in the concrete the following conclusions can be withdrawn.

1) The workability of the concrete mixes decreased with increase in the steel fibre content whereas the workability of concrete increased with increase in the basalt fibre concentration. This may be due to the higher flexibility of the basalt fibre when compared to the steel fibre. The combined use of silica fume and copper also significantly improved the workability of the concrete.

2) The addition of steel, basalt and glass fiber also improved the compressive strength of concrete when used in combination with silica fume and copper slag. The silica fume helped in attaining the strength of the concrete at the early ages of curing.

3) The flexural strength of the M40 and M50 grade concrete series also much enhanced due to the hybridization of steel fibres with the basalt and glass fibre. The formation of highly stable hydration products by silica fume addition and the flexible nature of the fibres in improving the bridging mechanism of concrete enhanced the flexural strength of the concrete at all ages.

4) The addition of the fibres in the concrete caused a substantial improvement in the flexural toughness of the concrete. The post cracking behaviour of the concrete was much improved due to the addition of the fibres. The addition of silica fume compensated for the strength and toughness loss of the concrete specimens caused due to the increase in the percentage of copper slag replacement.

5) The addition of steel fibres in combination silica fume also reduced the water absorption of the concrete mixes. The copper slag replacement upto 20% proved to be effective in reducing the water absorption of the concrete. The water resistant behaviour of the concrete mixes

was much improved in the M50 grade concrete series than the M40 grade concrete series.

(6) The remarkable reduction in the porosity values were observed for the concrete mixes containing silica fume and copper slag with various types of fibres. The addition of steel fibres improved the pore structure of the concrete due to the high degree of interlocking mechanism exhibited by the steel fibres with basalt and glass fibres. The silica fume and copper slag addition also refined the pore structure of concrete due to their filling capacity.

(7) The M40 and M50 grade concrete series showed improved resistance to acid attack accompanied by a progressive decline in the loss of weight and strength after exposure to acids. This improved resistance to aggressive acids was due to the addition of silica fume and copper slag which reduced the ingress of the hydrogen ions of the acid by disrupting the formation of continuous transport channels.

(8) The scanning electron microscopic images showed the well formed CSH gel around the aggregate which improved the denser nature of the concrete. The porosity and pore volumes in the concrete was also much reduced due to the silica fume addition. The higher pozzolanic action of the silica fume and chemical composition and metastable nature of silica fume to form active hydration products are the main reasons for the improvement in the pore structure of the concrete.

(9) The FTIR spectra of the concrete mixes showed the formation of CSH gel with subsequent reduction in the amount of Ca(OH)2 formed. This further confirms the pozzolanic activity of the silica fume that actively converted the calcium hydroxide to CSH gel. The Si-OH bands were also much altered in all the concrete mixes that indicates the effect of replacement of sand by copper slag.

(10) The regression analysis performed to study the relationship between the various strength parameters of the concrete established a well defined prediction equation and the proposed model with higher R2 values. The linear trend analysis performed on the experimental data confirmed that the obtained data best fits the proposed model with greater accuracy and conformity.

The final conclusion can be stated that the hybridization of the concrete with steel, basalt and alkali resistant glass fibre proved to be a promising concept to improve the overall performance of the concrete when used in combination with 7% silica fume as cement replacement and minimizing the sand replacement by copper slag to about 20%.

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