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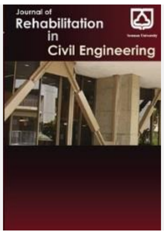

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A Comprehensive Experimental Investigation on Flexural Behavior of Alccofine-based Engineered Concrete Infused with Steel Fibers

A Muralidhar [1,2,*]; Sunil Kumar Tengli [3]

1. Ph.D. Research Scholar, School of Civil Engineering, REVA University, Bengaluru, Karnataka, India
2. Associate Professor, Department of Civil Engineering, APS College of Engineering, Bangalore, Karnataka, India
3. Professor, School of Civil Engineering, REVA University, Bengaluru, Karnataka, India

* Corresponding author: *Muralidhar.civ@gmail.com*

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ABSTRACT

Alccofine is an ultrafine supplementary cementitious material with an inherent tendency for pore refinement. This has substantially enhanced the strength and durability properties of concrete. The studies so far have exhibited limited investigations on the flexural properties of Alccofine-based concrete. This study addresses the feasibility of Alccofine-based concrete as a structural material with enhanced flexural properties by infusing 0.5% steel fibers. The steel fibers impart tensile strength to the concrete at the micro level and improve the flexural strength of the RC beams. The combinations framed in this study were for M30 grade concrete with the replacement of Alccofine by 5 to 15% and fly ash by 30% by weight of cement. The steel fibers with 0.5% of the weight of cement were added to the mix. The % of steel fibers and fly ash was kept constant in all the design mix combinations to examine the contribution of Alccofine individually on the performance of concrete. By considering four sets of combinations with under-reinforced and over-reinforced conditions each for the RC beams, the optimum combination among the defined mixes was explored through experimentation. The results on Young's modulus, relative stiffness, and ductility index of these mixes, emphasize the role of steel fibers in upgrading the deficiency of concrete to resist flexural loads. This engineered concrete matrix with reinforcement exhibits remarkable performance for the combination of 15% Alccofine with 0.5% steel fibers, among the defined combinations. The addition of 0.5% steel fibers in combination with 10% Alccofine replacement to cement has facilitated the effective transfer of tensile stresses generated at the cracked surfaces by bridging the cracks, thereby the flexural strength of the RC beams has an improvement. The mechanism has appreciable outputs in enhancing the tensile behavior of concrete at the micro level.

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1. Introduction

The research on sustainable engineered concrete using cement replaced with supplementary cementitious material is a revolutionary trend in construction materials. The dependency on traditional ingredients of the concrete over the decades has posed severe environmental issues with the degradation of natural sources of raw materials. On the other dimension, industrial effluents, slags, and sludges have imposed dreadful disposal issues. Both of these critical issues have converged the focus on inventive and effective utilization of these effluents in concrete as an SCM. Numerous novel materials that can efficiently replace cement with an appreciable percentage such as fly ash, GGBS, silica fume, etc were explored through sufficient investigations and are added to standard codal provisions. Similarly, Alccofine has been explored from GGBS origin, which possesses ultrafine particle size and has been an innovative material to examine its feasibility as a supplementary cementitious material [1]. The GGBS is well known for its binding property with calcium content in its chemical composition. When GGBS is subjected to a controlled granulation process, the Alccofine with 12000m2/kg fineness is obtained. The particles of Alccofine are uniform. The standard grade of particles in the Alccofine sample has been a super advantage in enhancing the maximum structural properties of concrete [2]. The fineness of the Alccofine can densify the microstructure of concrete, thereby upgrading the durability of concrete to a greater extent. The Alccofine introduced into the market are of two types Alccofine 1203 and Alccofine 1101. Alccofine 1203 has low calcium silicate content hence used in high-performance concretes whereas Alccofine 1101 has high calcium silicate content and is adopted in grouting concrete. In contrast, the studies in the literature have a major finding on its limitation to tensile and flexural strength. Hence the infusion of steel fibers in combination was an attempt to rectify this limitation [3,4]. The introduced fibers will technically hinder the flow of concrete. hence the addition of steel fibers has to be considered into account to counteract the flowability of concrete. Fly ash, a pozzolanic material with a spherical particle shape can also cope with this flowability. Hence a trial proportion of fly ash by 30% by weight of cement along with Master Glenium Sky 8233 superplasticizer was explored to achieve self-compacting concrete [5]. Steel fibers of 0.5% by weight of cement are chosen as a trial proportion. Generally, the steel fiber content is limited to 1% for self-compacting concretes to resist the hindrance to the flowability of concrete by fibers. Hence the combination of fly ash and Alccofine particles holds good with its structural performance as a cement replacement material [2]. The contribution of these steel fibers in upgrading the toughness, impact resistance, energy absorption capacity, ductility index, and abrasion resistance is remarkable.

The literature on Alccofine-based investigations has mainly focused on compressive strength and durability properties by varying the proportion of Alccofine replacements to arrive at an optimum replacement percentage [6,7]. These researchers have found a positive impact of Alccofine in enhancing strength and durability properties [8]. There are other attempts towards the combinations of Alccofine with SCMs such as fly ash [9], microfibers [10], and geo polymer concrete mixes by researchers. The flexural behavior of Alccofine-based engineered concrete is a prominent feature to be explored to assess the suitability of Alccofine as a structural material. The study is also needed to connect the behavior of Alccofine-based concrete at the micro level through microstructure analysis. This can prove this material's influence on concrete's structural behavior. Alccofine with low heat of hydration helps in remediating issues of surface cracking especially in mass concreting. A detailed study concentrating on all the structural properties supporting microstructure analysis is needed to expand the versatility of its industrial applications. The Alccofine-based mixes were noticed with the shortcomings of lowered flexural and tensile properties. Hence the present study is one such genuine attempt towards incorporating steel fibers and fly ash to expand its structural performance. Here the mixes were opted for the proportion of Alccofine replacements as 5%, 10%, and 15% along with the control mix without any Alccofine replacement.

Ultrafine Alccofine plays a vital role in densifying the microstructure, and the study's finding gives insight into its application in mass concretes and durable concretes. This study also helps to arrive at the Alccofine-based mixes by incorporating steel fibers.

2. Materials and methods

Traditional concrete ingredients such as OPC of grade 53, fine aggregates, and coarse aggregates were used in this study. It is added with Class F Fly ash, Alccofine-1203 with 0.5% steel fibers in the engineered mixes. 10mm and 12.5mm coarse aggregates and fine aggregates conforming to Zone II were adopted for the mix. The physical and chemical characterization of cement, fly ash, and Alccofine 1203 is conducted according to standard codal provisions in Table 1. The specific gravity test for coarse and fine aggregates was performed as per IS 2386. The particle size of the fine aggregate was examined as per the sieve analysis procedure in IS 383 2016. The results of the specific gravity and gradation analysis are given in Table 3. Master Glenium 8233 superplasticizer with a nominal dosage of 1% was implemented to achieve feasible workability and the detailed characteristics were tabulated in Table 4. Crimped-type steel fibers conforming to ASTM A 820 type-I were adopted in the mix. These steel fibers are 35mm long and 0.5mm thick, possessing an aspect ratio of 70. The crimped steel fibres have a corrugated profile with the hooked end which can increase its bonding and anchoring effect with concrete and help more effectively to transfer tensile stresses.

It is observed from the results of the characterization that, the specific gravity of Alccofine lies between cement and fly ash. The bulk density of Alccofine is lighter compared to cement and fly ash. The particle sizes of cement, fly ash, and Alccofine coincide with the well-graded sample with ascending fineness that can contribute to an excellent combination to densify the pore structure. The fineness of the Alccofine particles not only participates in the pre-packing but also in achieving self-compacting concrete [11] thereby, the Alccofine particles enhance the durability properties of hardened concrete [12]. Meanwhile, the fineness of Alccofine is attributed to the accelerated pozzolanic reactions. This can even be more evident from the chemical characterization results depicted in Table 2. The quantum of required bogue's compounds in an ideal cementitious material nearly matches with the Alccofine as per the compounds of the chemical characterization. The results of the chemical composition will fetch an idea to work out the percentage replacements of Alccofine with cement. The basic requirements of mix design were obtained based on these characterizations.

Table 1. Physical properties of Cement, Fly ash, Alccofine-1203.

Physical properties	Specific gravity	Bulk density (gm/cc)	Fineness (cm^2/g)
Cement	3.12	1.11	2252
Fly Ash	2.23	1.6	3600
Alccofine	2.88	0.68	12000

Note: Cement - IS 12269: 1987, Fly ash [class F] - ASTM C 618.

Table 2. Chemical properties of Cement, Fly ash, Alccofine-1203.

Chemical compounds	Chemical composition by mass (%)		
	Cement	Fly ash	Alccofine
SO_3	-	1.35	0.12
SiO_2	21.3	62.63	35.60
Al_2O_3	4.5	23.34	21.40
Fe_2O_3	4.0	3.93	1.30
MgO	2.4	0.46	7.98
CaO	63.1	2.04	33.60
Na_2O	0.1	0.032	-
K_2O	1.2	0.030	-
SO_2	2.2	-	-
LOI	0.39	0.3	0.58

LOI: Loss on Ignition.

Table 3. Properties of Fine aggregates and Coarse aggregates0.

Fine aggregates		Coarse aggregates	
Gradation	Specific Gravity	Gradation	Specific Gravity
Zone II	2.6	10 mm	2.7

Table 4. Properties of master Glenium 8233 (superplasticizer).

Property	Specification
Form	Viscous liquid
Specific gravity	1.08
pH	>6
Solid content	>32%
Relative density	1.08 ± 0.02 at 25° C
Aspect	Reddish brown liquid
Dosage	250 - 750ml/ 50kg of binder
Chloride content	<0.2%
Chemical type	Modified polycarboxylic ether
air entrainment	<1% at normal dosages

2.1. Preparation of engineered concrete mix

The experimental program constitutes primarily the material characterization and mix design for achieving self-compacting concrete with high strength. The mix design was carried out as per IS 10262-2019, [13] for M30 grade of concrete and the raw materials were weighed as per the mix design. The powder content (C + F + A) for the mix is maintained between 400 to 600 kg/m^3.

In this Fly ash (30%) and steel fiber (0.5%) were maintained constant throughout the mixes. Alccofine proportion is varied with 5%, 10%, and 15% by weight of cement. The coarse and fine aggregate contents were fixed based on the powder content arrived. Super plasticizer, Master Glenium 8233 was adopted with a 1% dosage to maintain the required workability. The water content obtained for the mixes is 172 L/m^3 and the superplasticizer is 4.2 L/m^3. The mix proportioning was carried out based on these percentage replacements and the details were tabulated in Table 5.

Table 5. Mix Proportioning [Mix Design as per (IS 10262-2019)] for M30 grade Alccofine-based Self Compacting Concrete.

ALC (%)	C	ALC	FA	Fa	CA	SF
0	294	0	975	126	822	1.47
5	279.3	14.7	975	126	822	1.47
10	264.6	29.4	975	126	822	1.47
15	249.9	44.1	975	126	822	1.47

Note: All the values of weights are in kg/m^3

ALC-Alccofine, C-Cement, FA-Fine Aggregate

Fa-Fly ash, CA- Coarse Aggregate, W-Water

SP-Super Plasticizer

Fig. 1. is the graphical representation of the mix proportions of the Alccofine-based concrete mix.

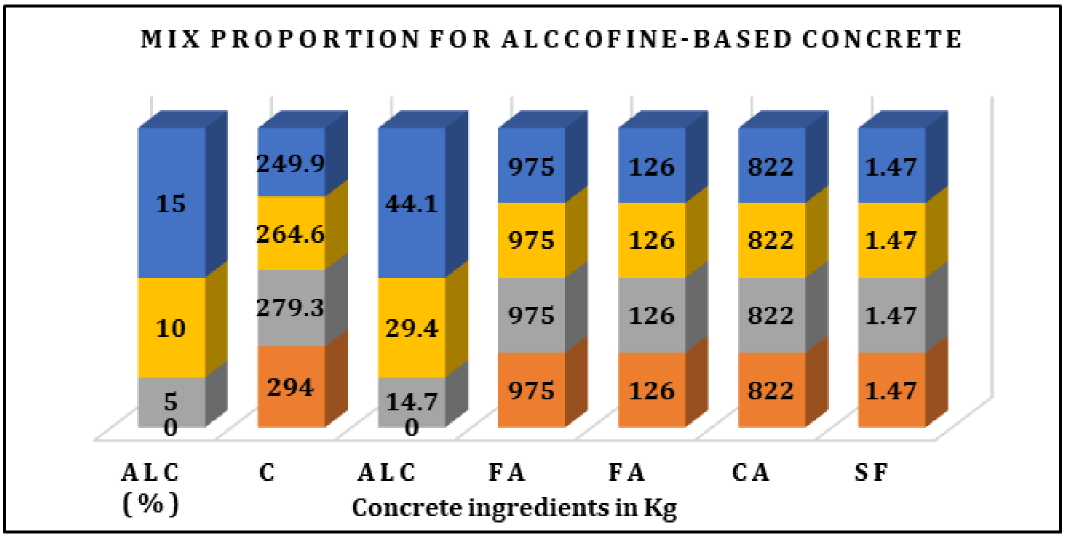


Fig. 1. Graphical representation of Mix proportions.

2.2. Preparation of reinforcement structure for RC beam

The two sets of RC beams of 100 x 200 x 2100mm size were planned each for under-reinforced and over-reinforced sections. For the former set, the main reinforcement as two bars of 10mm diameter at the compression zone (top) and the same at the tension zone (bottom) were provided. A shear reinforcement of two-legged vertical stirrups of 8mm diameter at 100 mm c/c at the support 150mm c/c spacing at the center was adopted. For the later set, the main reinforcement as two bars of 10mm diameter at the compression zone (top) and two bars of 16mm diameter at the tension zone (bottom) were provided with two-legged vertical stirrups of 8mm diameter at 100mm c/c as shear reinforcement. The effective length of the beam maintained during testing is 1800mm.

The beam was considered to be tested for simply supported conditions with a two-point loading system. The two-point loading system has the loading of the beam at l/3 distance from the support. This loading system focuses on the deflection of the RC beams in the bending zone specially to assess the role of steel fibers in the flexural property. The effective length of the beam was divided and marked for L/3 (600mm). An offset of 150mm from each end to support was maintained to get an effective length of 1800mm as shown in Figure 2. Total eight beams each set with four beams for under-reinforced and four for over-reinforced sections. One control beam and the other three with 5%, 10%, and 15% Alccofine composition were planned and prepared.

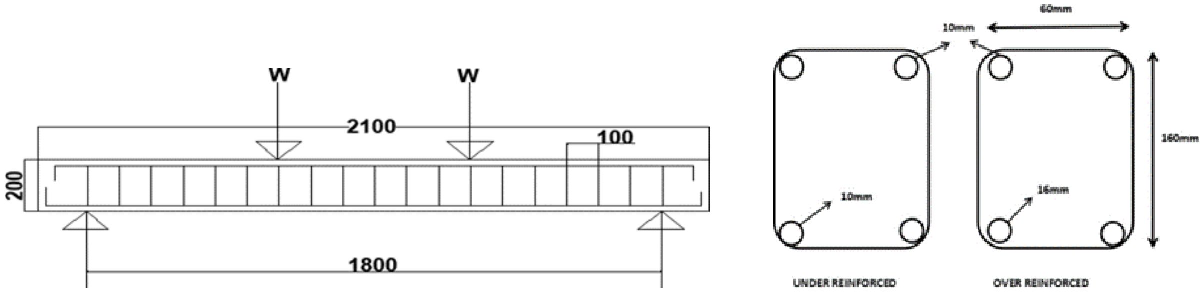


Fig. 2. Reinforcement Detailing for RC Beam.

2.3. Mixing and casting methodology

The raw materials prepared and weighed according to the characterization and mix design were dry mixed initially using a concrete drum mixer in the ascending order of their fineness (coarse aggregates, fine aggregates, cement, fly ash, and Alccofine). The steel fibers were added at the end of the dry mix to avoid distortion in the fibers. Once achieving a uniform distribution of dry ingredients, the water content mixed with a measured dosage of superplasticizer was added gradually in iterations to avoid lumped masses in the mix. Meanwhile, the variations in the workability of concrete during the mixing of water content are also crucial to examine the dosage contribution. The mixing process is maintained to a maximum of 3 minutes and the fresh property tests of the engineered mix were performed immediately.

A trial W/C ratio was maintained at 0.45 and obtained the required workability by this ratio. The prisms of 100(b) x 100(d) x 500(h) mm and cylinders of 100(d) x 300 (h) mm dimensions were cast to examine the flexural and split tensile strength of the engineered concrete [14]. The RC beams of 100 x 200 x 2100mm size were prepared with the reinforcement mentioned in the previous section. The concrete was maintained to achieve flowability to pass through the reinforcement cage as given in Figures 3 a) and b). The cast beams were demoulded after 24 hours and kept for water bath curing for 28 days.

a) arranged reinforcement in the RC beam mould.

b) pouring of engineered mix into the mould.

c) Curing of RC beams in a water bath.

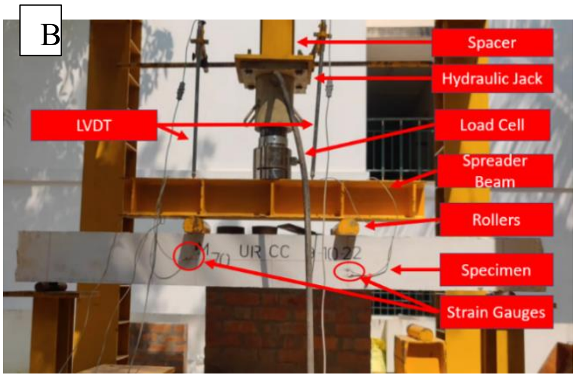
Fig. 3. Casting and curing method.

2.4. Testing methodology

The fresh properties of concrete were examined based on EFNARC guidelines. Slump flow, V-funnel, U-Box, and L-Box tests were conducted per the standard procedures. The V funnel and U-Box test assess the filling ability, the L-Box test investigates the passing ability, and the slump flow test explores the free horizontal flowability of the engineered mixes. These tests investigate the role of Alccofine and fly ash in enhancing flow properties and in contrast the hindrance caused by steel fibers.

The flexural strength and split tensile strength tests were conducted as per IS516 on prisms of 100(b) x 100(d) x 500(h) mm and cylinders of 100(d) x 300 (h) mm dimensions respectively. The flexural strength of the RC beams was examined by a two-point loading system in the flexural testing machine. The flexural failure with bending is observed in beams. The addition of steel fibers in the concrete mixes is basically to induce ductile behavior in the concrete which is the major limitation of concrete. The RC beams were subjected to a flexural test using a loading frame. The evaluation of the flexural behavior of the RC beams is intended to analyze the load-deflection and stress-strain behavior of concrete. It also focuses on ductility and stiffness parameters. The beams were painted white and marked with specifications of mixes for effective visualization of the post-cracking patterns on beams as shown in Figure 4 a). The loading frame set up for testing of Alccofine-based RC beam testing is shown in Figure 4 b).

a) The painted and marked RC beams.



b) The testing arrangement of the RC beam under the loading frame.

Fig. 4. Devising of RC beam for testing.

3. Results and discussion

3.1. Flow properties

The flow properties of Alccofine-based concrete mixes were tabulated in Table 6. Alccofine being an ultrafine material is expected to contribute significantly to enhancing the flow property of concrete. Especially when the closely spaced reinforcement cages make the concrete challenging to flow through [9,14]. The results in Table 6 depict that the increment in percentage replacement of Alccofine has enhanced the flow property of concrete mixes. The tests on flowability, that is, the slump flow test show ascending results in line with the replacement increments. The 15% replacement of Alccofine indicates an 80mm (approx. 12%) enhancement in slump flow diameter compared to the control mix. The filling ability through the V-Funnel test was examined and the results indicate reduced time taken for the flow of Alccofine-based concrete mixes through V-Funnel. This interprets the contribution of Alccofine in carrying the concrete mix through a narrow path. The passing ability was examined based on the U-Box and L-Box test as per EFNARC guidelines where the U and L-Box arrangement have rebars in the moulds. The concrete mixes subjected to flow through these two arrangements were expected to enhance the passing ability of the mixes and were assured by the Alccofine-based concrete mix compared to the control concrete mix.

The addition of steel fibers hindering the flow properties of concrete was also a major concern to investigate these mixes. Despite adding steel fibers, the engineered mixes indicate the achievement of flow properties. The reason may be the minimal quantity of steel fibers adopted in the mixes. The U-Box test indicates the decrement of the difference in height of fresh concrete mixes with the addition of Alccofine compared to the control concrete mix. The mix with 15% Alccofine replacement shows a 22.5% decrement in the height difference in the U-Box test compared to the control mix which is a remarkable passing ability. This is assured by the Alccofine with ultrafine particle size in the concrete matrix. Similarly, the L-Box test results indicate the passing ability enhancement from 0.8 (control mix) to 0.98 (15% Alccofine replaced mix). That is a 22.5% increase in the passing ability of the mix.

Table 6. Test results on Flow properties on M30 Grade SCC.

Flow properties tests	Alccofine replacement (%)				Standard values
	0	5	10	15	
V Funnel (secs)	10	10	9	8	6 to 12
U Box (mm)	28.4	26.1	24.3	22	0 – 30
L Box	0.8	0.84	0.92	0.98	0 .8– 1
Slump flow (mm)	680	710	740	760	650-800

Note: The standard values are as per EFNARC guidelines.

3.2. Flexural and split tensile strength properties

Further to examine the improvement in ductile nature of concrete based on incorporating steel fibers in combination with Alccofine, split tensile and flexural strength tests were performed on engineered mixes compared to control mixes. The results are plotted in Figure 5. The split tensile strength and flexural strength results were co-related in the same graph to analyze the trend of results related to the ductility of concrete mixes.

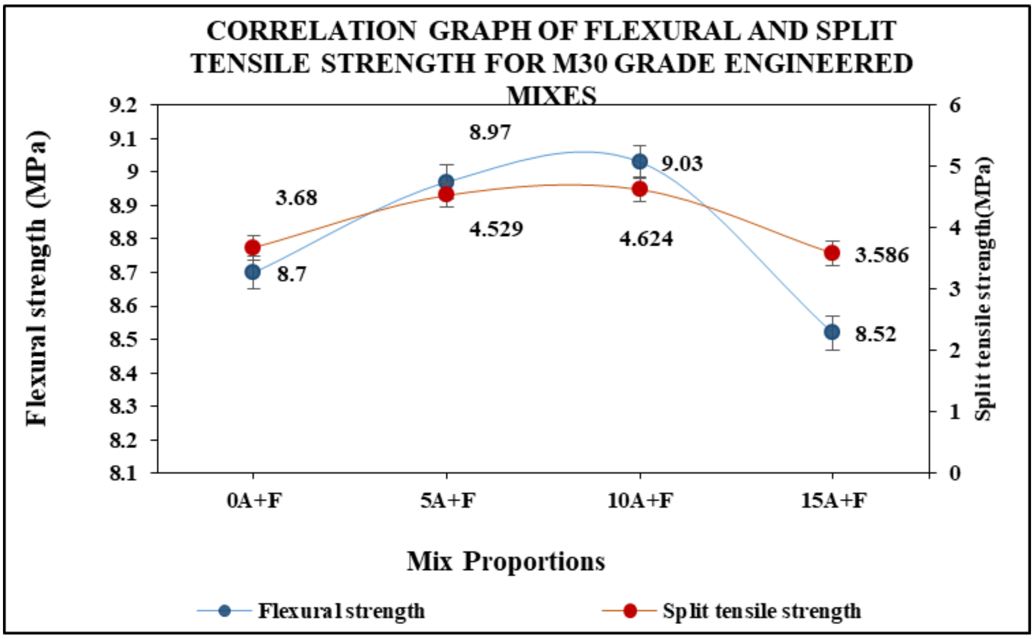


Fig. 5. Flexural and split tensile strength of M30 Grade Alccofine-based SCC.

The graph plotted in Figure 5 shows that there is a marginal improvement in these two parameters in comparison with control mix up to 10% Alccofine replacement, whereas, further increment in replacement of Alccofine has decrement in the split tensile strength and flexural strength values of the engineered mix. This behavior might be due to the compatibility of Alccofine and steel fibers holds good up to 10%, beyond which at 15% Alccofine replacement it would not contribute to further enhancement of tensile strength due to the filler effect. The steel fibers in the tension zone of concrete will take the tensile stresses on concrete to pass through it. These fibers can transfer the stresses through the concrete effectively without failing concrete.

3.3. Load deflection analysis

The RC beams tested through the loading frame exhibit substantial behavior through deflection. The results were appreciable in differentiating the effect of each variable parameter of observation. The

Figures from 6a) to d) for cracked under-reinforced sections and 7 e) to h) for over-reinforced sections after testing expresses the significant observations concerning the number of cracks, the width of the cracks, length, and depth of the cracks. There are multiple dimensions in which these results and readings are analyzed to assess the flexural behavior of these RC beams such as based on Young's modulus based on the stress-strain relationship, ductility, and stiffness. The following section of discussions elaborates on individual parameters of analysis in detail. Superficial observation of the deflection in both cases of RC beams indicates that the over-reinforced sections had failed by crushing the concrete without any warning. Whereas, the under-reinforced sections were observed to fail with sufficient warning in terms of deflection. The fundamental reason for this behavior is, that the rebars in under-reinforced sections reach the ultimate strain first and then transfer the load-carrying task to concrete soon which will be expressed by the concrete through deflection. This deflection of RC beams before the complete collapse state will permit to rectify the deterioration and address it on time. Whereas, the over-reinforced sections with excess steel than required will take the load-carrying task on themselves without transferring it to concrete until its failure. Hence not leaving any clue of deterioration until complete failure without any warning. Henceforth generally the under-reinforced sections were preferred in practice.

Fig. 6. The crack pattern of Alccofine-based M30 grade RCC beams for Under-reinforced case.

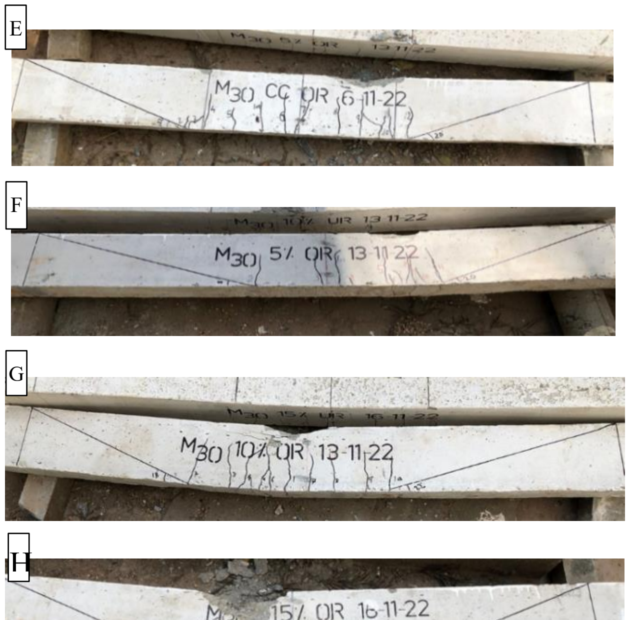


Fig. 7. The crack pattern of Alccofine-based M30 grade RCC beams for over-reinforced case.

Figures 6 and 7 represent the crack pattern of the RC beams with different percentages of Alccofine replacements for under-reinforced and over-reinforced conditions. The crack pattern follows the flexural failure of the beams. The cracks were observed to be initiated at the tension zone of the central soffit of the beam and propagate towards the compression zone shear-cracks are slightly tangential at the initial level and then propagate vertically upwards. An ideal crack pattern was observed in all the mixes and crushing failure at the compression zone was observed in over-reinforced sections.

Table 7. Crack details of RC beams subjected to flexural test.

Alc %	UL (KN)	D (mm)	MCW (mm)	MCL (cm)	NC	Alc %	UL (KN)	D (mm)	MCW (mm)	MCL (cm)	NC
Under Reinforced						**Over Reinforced**					
CC	220	25.7	7	17	11	CC	560	21.2	1	14.5	12
5	240	42.05	6	13	10	5	590	28.5	1	16.5	11
10	260	63.47	6	16.5	15	10	610	42.2	4	15	10
15	210	36.3	6	17	10	15	540	20.8	5	13	10

Note: Alc-Alccofine, UL-Ultimate Load, D-Deflection.

MCW-Maximum Crack Width, MCL-Maximum Crack Length, NC-number of Cracks.

Table 7 consolidates the details of cracks in under-reinforced and over-reinforced sections with varying Alccofine contents. The ultimate load carried by the mix combination of M30 with 10% Alccofine replacement has indicated the maximum load bearing compared to the control mix and other replacements for under-reinforced and over-reinforced conditions. A similar trend has been followed even in deflection readings with the highest deflection for 10% Alccofine replacement. A critical observation on dimension and number of cracks for these mixes says that for under-reinforced sections with 0.5% steel fibers, the number of cracks was high for 10% replacement compared to other mixes. The maximum length and width of the cracks have marginal variations compared to the control mix.

This indicates that the failure pattern of 10% Alccofine-based under-reinforced RC beams gives sufficient warning through increase in number of cracks with similar dimensions to control mixes. Here the significant role of steel fibers is in altering the flexural behavior of the beam and in varying the crack properties [15]. On the other hand, the over-reinforced sections indicate an increase in the width of cracks and a decrease in the number of cracks with the increment in Alccofine replacement whereas, the length of the crack propagation shoots up to 16.5mm for 5% Alccofine mix and thereafter gradually decreases to 13mm for 15% Alccofine replacement. The overall observation depicts that an over-reinforced section indicates insufficient warning of failure through cracks and deflection compared to under-reinforced sections.

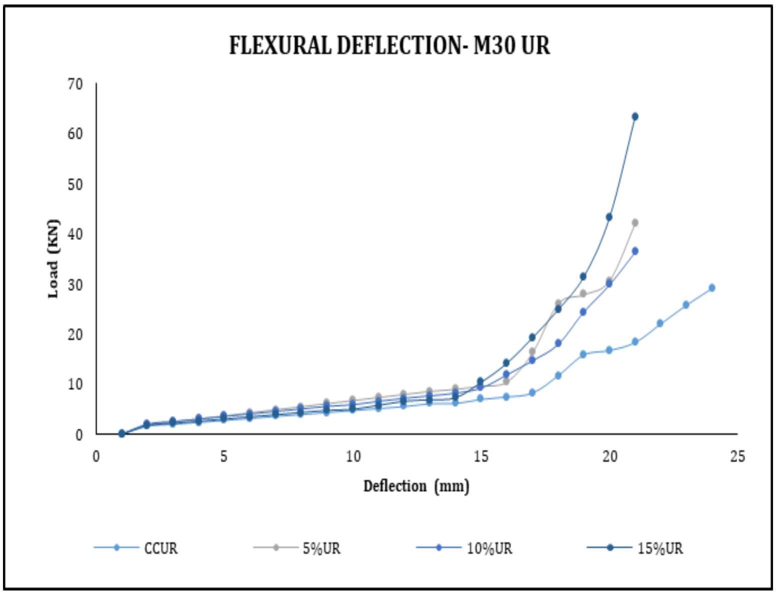


Fig. 8. Flexural deflection of M30 grade under-reinforced RC beams of Alccofine-based concrete.

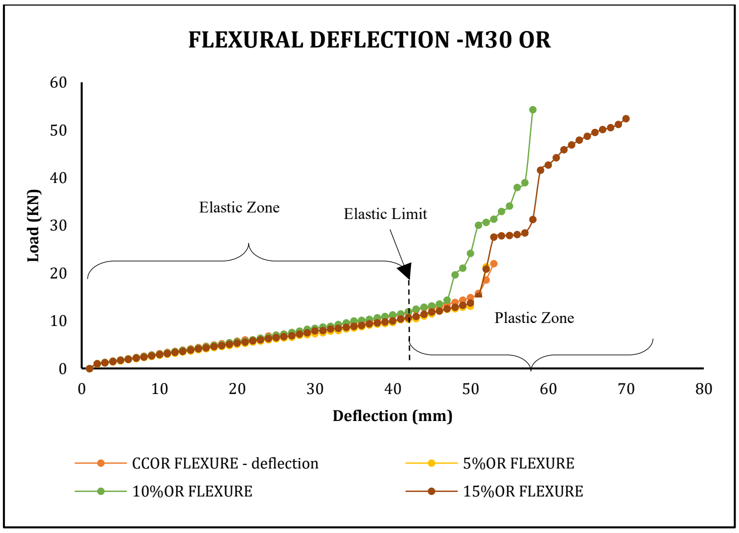


Fig. 9. Flexural deflection of M30 grade over-reinforced RC beams of Alccofine-based concrete.

Fundamentally, the flexural behavior of RC beams in terms of load versus deflection and stress versus strain follows a similar trend. To explore these behaviors in other dimensions these graphs were plotted and analyzed. Figures 8 and 9 were plotted for load versus flexural deflection of RC beams with varying Alccofine replacements. The graphs indicate that under-reinforced sections have higher load-carrying capacity with an appreciable reduction in deflection corresponding to an increment in Alccofine replacement. All the defined combinations indicate 15mm deflection approximately at the applied load of 10KN. Further application of load beyond 10KN has changed the trends of graphs for individual combinations with 15% replacement exhibiting remarkable resistance to the applied load. In over-reinforced sections, at 10KN applied load the deflection was approximately 40mm. The RC beams with control mix and 5% Alccofine replaced mix fails within 20KN with a deflection range of 45 to 55mm. whereas, the under-reinforced sections pushed the failure load above 30KN with a maximum of 23mm deflection for the engineered mixes. This flexural behavior indicates that the Alccofine in combination with 0.5% steel fibers contributes remarkably to the flexural strength enhancement of the RC beam mixes [15].

3.4. Stress-strain analysis

The result of the flexural strength test through the loading frame was tabulated and plotted in the relative graph of stress and strain as shown in Figure 10. All eight combinations, four for under-reinforced sections and four for over-reinforced sections indicate a two-band of results as depicted in the graph. It is observed that, in under-reinforced sections, the increase in the Alccofine replacement up to 15% has pushed the tendency of the beams to bear the strain significantly higher than the control mix beam. It is also observed that the elasticity zone freezes approximately the same for all the mixes and varying strain is observed in the plastic zone.

In over-reinforced sections, after the elastic limit, the sections no longer bear the stresses and indicate a sudden drop in strain before failure. The over-reinforcement has extended the elastic limit of the sections compared to under-reinforced sections as shown in Figure 9. The Over-reinforced section for the engineered mixes of 10 and 15% replacements indicates prolonged strain compared to the control mix. It is also observed that the ultimate stress resisted in these sections indicates lesser strain in comparison to under-reinforced sections.

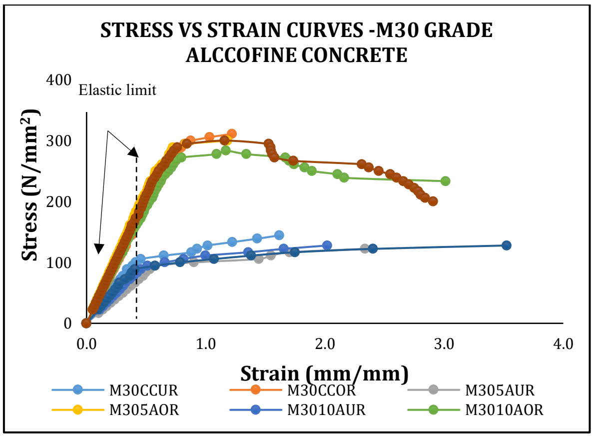


Fig. 10. The stress-strain curves of M30 grade Alccofine-based engineered mixes.

Note: UR-Under-reinforced, OR-Over-reinforced, A – Alccofine, CC - Control Concrete.

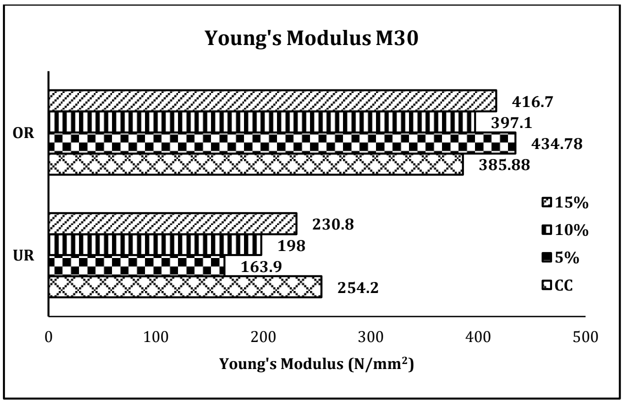


Fig. 11. Young's modulus of M30 grade Alccofine-based engineered mixes.

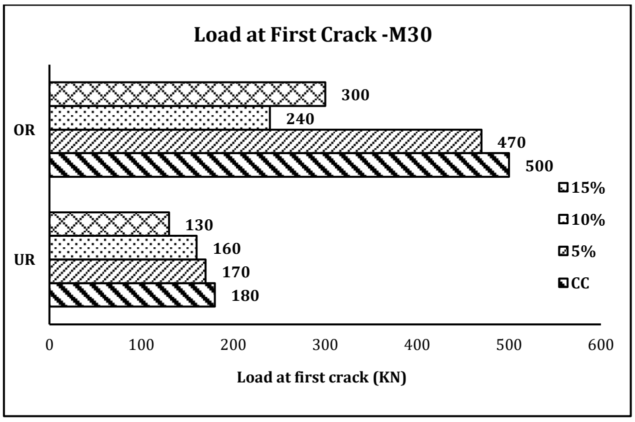


Fig. 12. Load at the first crack for M30 grade Alccofine-based engineered mixes.

It is also important to ensure that the Alccofine replacement in combination with steel fiber should improve the young's modulus of the mixes to promise flexural strength enhancement. Figure 11 graphically represents the Young's modulus of the mixes. Gradual increment in Young's modulus is observed for increment in Alccofine dosages with constant steel fiber replacement. This indicates the role of Alccofine in densifying the microstructure to improve the flexural behavior of the mixes. In Figure 12, the load at the first crack was plotted for all the combinations. There is a marginal decrement in the load at the first crack with the increase in Alccofine replacement compared to the control mix. This observation suggests increasing the steel fiber dosage further to enhance the flexural load-resisting tendency of the combinations.

3.5. Ductility index of RC beams

Generally, the major limitation of concrete in resistance to tensile stresses is counteracted by the infusion of rebars. Here rebars in combination with concrete will deal with the tensile requirement of a beam under flexure. At the micro level, the concrete is strengthened to handle these flexural cracks by infusing steel fibers. Thereby, the ductile nature of the concrete matrix is also upgraded. The Alccofine particles being irregular and angular in shape will ensure the interlocking between the particles and promise the bond between the matrix, steel fibers, and the aggregates. This fundamental mechanism at the micro level justifies the significance of Alccofine in combination with steel fiber in enhancing the tensile properties of concrete [16]. The load-deflection data of these beams under the flexure test through the loading frame is used to find the ductility factor (DF) of mix combinations. The ratio of deflection at the final load to the deflection at the first diagonal crack is considered the ductility factor (DF). Table 8 indicates the ductility factor and ductility index of the engineered mixes compared to the control concrete.

Table 8. Ductility features of RC beams.

Under Reinforced				Over Reinforced			
ALC %	Deflection at 1st crack load (mm)	Deflection at ultimate load (mm)	DF	ALC %	Deflection at 1st crack load (mm)	Deflection at ultimate load (mm)	DF
CC	7.4	25.7	3.5	CC	11.4	21.2	1.9
5	7.82	42.05	5.4	5	12.8	28.5	2.2
10	8.19	63.47	7.7	10	13.4	42.2	3.1
15	7.77	36.3	4.7	15	10.1	20.8	2.1
ALC %	The energy at the ultimate load	Energy at 75% load	DI	ALC %	The energy at the ultimate load	Energy at 75% load	DI
CC	6157.5	788.0	7.81	CC	7168.0	1656.2	4.33
5	7075.8	1174.9	6.02	5	7212.8	2048.5	3.52
10	10112.3	1410.3	7.17	10	7529.1	2219.8	3.39
15	1978.9	861.3	2.29	15	6287.8	1813.0	3.46

The ductility factors drawn from deflection readings of the RC beams with Alccofine-based concrete indicate in Table 8 infers that the RC beams with M30 grade concrete infusing 10% Alccofine substantially show higher ductility than control beams. The percentage replacement beyond 10% indicates diminishing ductility factors. This might be due to the Alccofine being beyond 10% and acting as a filler material without any further contribution towards ductility. A similar trend is observed in both under-reinforced and over-reinforced conditions. When the over-reinforced condition is compared with under-reinforced sections, under-reinforced sections possess a higher ductility factor of 2.48 times the over-reinforced sections. This can be attributed to the significance of under-reinforced sections in deflection criteria.

The ductility index also called the energy absorption factor is calculated based on the area below the deflection curve indicates that the 10% Alccofine replacement with cement in case of under-reinforced condition competes with control mix beams whereas, only 5% replacement of Alccofine in the over-reinforced condition is at the peak in comparison to other replacements. It is slightly lower to control the mix ductility index. Beyond 5% replacement has noticed diminishing readings on the energy absorption index. The concept of energy absorption infers that the Alccofine particles with steel fibers in the matrix have absorbed substantially more energy resisting the cracks. The energy absorption indicates the quantum of stresses the member can hold before failure with sufficient warning. Ductile the material the energy absorption increases. The brittle the material the energy absorption decreases thereby the specimen indicates sudden failure without warning. The infusion of steel fibers will enhance the ductility of concrete thereby the energy absorption before failure is enhanced with sufficient warning through cracks and deflection.

3.6. Stiffness

The term stiffness is coined as the tendency of the material to resist elastic deformation due to an applied force. The stiffness of RC beams for different Alccofine-based mixes for under-reinforced and over-reinforced conditions is obtained based on the readings on the load at the first crack and the corresponding deflection. The readings at the first crack indicate the initiation of elastic deformation. The calculated stiffness values are given in Table 9 below.

The overview of these readings infers that the stiffness in RC beams against the applied load is enhanced up to 10% Alccofine replaced combination for both under-reinforced and over-reinforced conditions. Beyond 10% the replacement has reduced the stiffness of the sections. The reason may be due to the packing of ITZ with Alccofine and fly ash particles along with the hydration products up to 10% replacement. The particles of Alccofine beyond 10% will merely act as a filler material. Thereby, acting as a weaker phase to crack propagation. The ultrafine particles of Alccofine can significantly densify the pore structure. This will reduce the permeability of concrete and can clog the entry of external harmful agencies. Thereby, the long-term durability and performance of concrete is assured.

Table 9. Stiffness Details.

ALC %	Load at 1st crack (KN)	Deflection at 1st crack Load (mm)	Stiffness (KN/mm)	ALC %	Load at 1st crack (KN)	Deflection at 1st crack Load (mm)	Stiffness (KN/mm)
Under Reinforced				**Ove Reinforced**			
CC	120	7.4	16.2	CC	300	11.4	26.3
5	140	7.82	17.9	5	470	12.8	36.7
10	180	8.19	22.0	10	500	13.4	37.3
15	150	7.77	19.3	15	280	10.1	27.7

4. Concluding remarks

The Alccofine-based Engineered concrete through this study has highlighted the possible modifications and admixtures adopted to overcome the limitations stated in the literature. The significance of the study is to investigate the role of steel fibers with Alccofine in improving the flexural properties of the mixes. The contribution of fly ash to counteract the hindrance caused by the steel fibers on the flow properties is one of the achieved objectives. Alccofine has proved its superiority in arriving at the pozzolanic activity because of its chemical composition including a good calcium source compared to fly ash. This article is a genuine attempt to bring the following outputs based on the investigation conducted.

The ultrafine particle size of the Alccofine particles and the calcium content depicted in the chemical composition majorly contribute towards the enhanced binding property. The flow properties to index the workability also stood superior to the control mix with the increase in percentage replacement of Alccofine with cement. The elevated flow property might be due to the uniform particle size under controlled grinding. Incorporating 0.5% of steel fibers in the mix has hindered the flow properties but is negligible compared to the control mix which has been counteracted by 30% fly ash replacement with cement.

The flexural and split tensile strength properties of Alccofine concrete were taken care of by the 0.5% steel fibers. The results indicate increases in the flexural strength at 10% (by 3.79% compared to control concrete), whereas at 15% replacement, the strength has reduced to 5.98%. The split tensile strength results at 10% indicate an appropriate value (increase by 25.65% compared to control concrete), whereas at 15% replacement, the strength is reduced by 28.94%. This behavior is due to the filler effect of the ultrafine particles of Alccofine, which needs to be optimized to 10%. The influence of Alccofine with steel fibers on the flexural strength of RC beams exhibits ascending results with replacement percentages [17,18].

The prime objective of this study is to investigate the flexural behavior of the Alccofine-based engineered mixes with 0.5% steel fiber addition. This objective explored through load deflection studies, stress-strain analysis, stiffness, Young's modulus, and also the crack details obtained indicates that the 0.5% steel fiber addition has played a crucial role in uplifting the flexural properties of concrete by arresting the crack propagation at the micro level itself. The concrete which is weak in tensile properties has been strengthened by these steel fibers which is observed from the experimental results of this study. It is necessary to check the feasibility of all these materials as a heterogenous mix in focusing on performance enhancement of the mixes without major deviations and drawbacks. The studies have revealed the role of fibers in obtaining high-performance concrete with enhanced tensile and flexural strength properties [19]. Hence it is necessary to have an intense study on various percentage replacements of steel fibers and their effect on altering the flexural properties of concrete. The ultrafine particles that pack the transition zone at the micro level might be the reason behind the strengthening of the microstructure of concrete. The overall concluding remarks of the study declare that the infusion of Alccofine as a Supplementary Cementitious Material exhibits phenomenal upgradation of the fresh and hardened properties of concrete with the optimum replacement of 10% in combination with 0.5% steel fibers. Considering the flexural behavior of the RC beams even up to 15% replacement the Alccofine and steel fiber combination holds good. The industrial application of Alccofine is more as it contributes to enhancing workability, decreasing segregation, lowering the heat of hydration, and most importantly decreasing the permeability by clogging the micro pores of the concrete. Thereby, a superior degree of durability is achieved. The Alccofine-based concrete upgrades the concrete mix design by its influence on the ITZ phase of micro structure [20]. The particles of Alccofine can pack the ITZ more effectively and strengthen the bond between the aggregate phase and the mortar phase.

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A Muralidhar: Data collection, experimental investigation of the study, methodology, and writing of the original draft.

Sunil Kumar Tengli: validation and critical analysis.

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