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Comparative study on structural behavior of RC beam under static load using fly ash from micro to nano scale

Manickam Harihanandh[1], Murugesan Saravanan[2], Veerappan Prabhu[3], Ammapalayam Ramasamy Krishnaraja[4]

[1]Adithya Institute of Technology, Department of Civil Engineering. Coimbatore, Tamil Nadu, India.

[2]Marri Laxman Reddy Institute of Technology and Management, Department of Civil Engineering. Hyderabad, Telangana, India.

[3]Hindustan Institute of Technology and Science, Department of Civil Engineering. Chennai, Tamil Nadu, India.

[4]Kongu Engineering College, Department of Civil Engineering. Perundurai, Tamil Nadu, India.

e-mail: harivmk@gmail.com, bitsaravanan.murugesan@gmail.com, drprabhu.mat@gmail.com, krajacivil@gmail.com

ABSTRACT

Researchers are working towards achieving the good strength, finding sustainable material, high performance; improve the structural & durability behaviour etc., of the concrete. This study focuses on the analysis and benefits of addition of raw (RFAC), ultra fine (UFFAC) and nano fly ash (NFAC) on its optimum level in the concrete. The optimum content of raw, ultra fine and nano fly ash is 19%, 22% & 23% are obtained through mechanical properties tests. To find the flexural performance of reinforced concrete beam, the specimen of 2000 mm*100 mm*150 mm has been designed to with stand the load of 35kN. Under the static load, the parameters of load vs. mid span deflection, moment vs. rotation, ductility, energy absorption are calculated and all the results were compared with conventional (CC) specimen. Among all the specimens, NFAC specimens have performed well and the minor cracks are developed due to its high bond between the ingredients. The load carrying capacity of the NFAC specimen has been improved about 9.23%, 8.64% and 5.20%, the deflection has been reduced by 12.32%, 9.70% and 1.63%, also the moment carrying capacity of the NFAC specimen has been improved by 19.66%, 12.90% and 5.26% with respect to CC, RFAC and UFFAC specimens.

Keywords: Raw flay ash; Ultra fine fly ash; Nano fly ash; Scanning Electron Microscope (SEM); Static load; ductility; Energy absorption.

1. INTRODUCTION

This paper focuses on the investigation of combined effect of Nano $CaCO_3$ and fly ash in mechanical and durability properties of concrete with different water binder ratio through orthogonal analysis. In that, the 0.4 water binder ratio, 20% fly ash and 1% Nano $CaCO_3$ has been determined as optimal mix proportion [1]. In this investigation, Nano silica was utilized to increase the impermeability of the cement fly ash system, and used as surface protection materials [2–4]. Here the Nano silica helps to accelerate the hydration process, refined the pores, increases the complexity of the pre structure, improves the micro structures, it causes the significant improvement in the cement fly ash system [5–7]. There by 70% of cement, 30% of fly ash and Nano silica of 0-4% of binder ratio were used [8, 9]. Ball mill is used to derive the Nano fly ash, which is used as partial replacement for cement by its weight between 0.25 to 1%. The reference mortar mix was made and their mechanical properties, particles size distribution through scanning electron microscope and XED have been made [10]. This research work is to investigate the effect of using silica fume and Nano silica as individual and also in hybrid combination with certain accelerators and hydrated lime up to 80% replacement of OPC to study the performance of high volume ultra-fine fly ash (HV-UFFA) based cement composites. To investigate the effect of these mineral admixtures, compressive strength, X-ray diffraction, thermo gravimetric analysis and SEM analysis were performed. From the results obtained, it was noted that the 7 days and 28 days strength of this HV-UFFA based cement composites improved for about 273% and 413% respectively [11]. While studying the strength of high volume fly ash Nano silica (HVFANS) concrete, it was found that the strength of concrete was lower than conventional concrete in ambient temperature, whereas the strength increases at increase in temperature [12]. Using boron wastes and various quantity of CuO Nano particles are used to study the compressive, flexural, thermal

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properties and pore structure of mortars. The addition of Nano-CuO ranges between 2% to 2.5% decreases the setting time and increases the mechanical properties on water absorption resistance [13]. This research paper focuses the performance of nano fly ash (NFA) on self compacting concrete (SCC) at normal and elevated temperatures. It contains two stages. At first, the preparations of Nano fly ash through ball milling and its characterization. At second stage, the parameters for workability of SCC, elastic modulus, ultrasonic pulse velocity (UPV), compressive and flexural strength were performed at normal temperature and 700°C also. From the test results, it was concluded that presence of FA and NFA reduces the flowability of SCC mixtures but in the case of hardened state, their performs are remarkable [14]. This research work deals with the workability, compressive strength and durability properties of a concrete with Nano TiO_2, Nano $CaCO_3$ and combination of both with different ranges from 0.5% to 3.0% by the weight of cement. The 3% replacement produces improved strength, workability and low RCPT values and high pH values offered proves concrete have good adoptability [15, 16]. This work uses different Nano materials such as carbon Nano filaments, Nano silica and Nano clays in cement paste, mortar and cement concrete. The tests on workability, morphology and mechanical properties on concrete were conducted by three, seven, twenty eight and fifty six days duration of tests. From the test results, the carbon Nano tubes and fibers should increases the flexural strength up to 40% and Nano silica enhances the pozzolanic activity up to 40% [17]. This research work was concentrated on the study of Nano silica utilization to make the special and normal concrete. And the test results prove the Nano silica is better replacement for cement to enhance the pozzolanic properties through mechanical, durability properties [18]. This paper investigates the possibility of nano fly ash to substitute with cemen in the mortar. Here the mortar compressive strength was improved by 14.81% [19]. The ingredients used for this research work were cement, Nano silica, quartz powder, fine sand, coarse aggregate and super plasticizers. This paper deals with the mechanisms of assimilation of Nano materials in concrete, and to enhance durability. Application of Nanotechnology is one of the effective way to reduce pollution also to increase the durability of concrete [20]. This paper focuses to find the effects of adding silica nanoparticles in to the cementitious composites concrete. Three different amounts of nanosilica 0.5%, 0.75%, and 1.0% will be applied in proportion to the mass of cement [21]. The cementitious composites were subjected to an analysis that included water absorption, acid etching, and compressive strength testing at 3, 7, and 28 days of curing. According to the findings, densification improves compressive strength and decreases acid attack and water absorption [22]. This research compares the structural performance of laced reinforced concrete beams (LRC-45) with conventional beams (RC-90) under reverse cyclic loading. LRC-45 showed superior crack resistance, higher displacement capacity, increased ductility by 56.39%, and 143.43% more cumulative energy dissipation. Additionally, LRC-45 exhibited significantly higher stiffness. The study highlights LRC-45's potential for enhancing structural resilience, crucial for seismic events [23]. This study evaluates composite CST with lightweight concrete (M20 to M40) using quarry waste as a sand replacement. Lightweight concrete mixes were analyzed for mechanical properties using machine learning, with materials cured for 7 and 28 days. A Modified Krill Herd Optimization model trained a Neural Network, achieving an optimal model accuracy of 98.78% and minimal error values [24]. Concrete's strength and durability are being enhanced using Fibre Reinforced Polymer (FRP) composites. This study tested manufactured sand as a fine aggregate replacement and used response surface methodology to predict concrete strength. Evaluating five reinforced concrete beams with GFRP and CSM laminates showed a 107% increase in ultimate load and a load-carrying capability of 115 kN [25]. The adhesive fracture resistance of structural joints in mode II is evaluated using two models without measuring crack length during three-point bending tests. Load vs. transversal displacement results are analyzed with a damage model for unstable cracks and a cohesive zone model for stable cracks. Initial findings show both models' viability and the significant impact of initial crack length and load rate on evaluation [26]. This paper evaluates hybrid fiber-reinforced concrete-filled steel tubular sections, focusing on fiber volume fraction and hybridation ratio. Optimal fiber dosages from tests on mono fiber mixes were used in hybrid mixes. Results show significant improvement in the flexural performance of the fiber-reinforced concrete-filled steel beams and columns [27].

2. MATERIALS AND METHODS

2.1. Materials

Ordinary Portland Cement of the 53 Grade, which complies with IS 8112-2013 [28], is what is used here. The natural sand that was dredged up from the Cauvery River and used to make fine aggregate was sourced from that river. According to the results, it would seem that the sand falls under Zone III of the IS: 383–1970 [29]. The method described in IS 2386, Part I, 1963 [30], were used in order to conduct an investigation into the properties of sand. Crushed granite stones from nearby quarries make up the coarse aggregate for the project, which has already been bought. The maximum permissible particle size for the coarse aggregate that can be used is twenty millimeters. The investigation of the aggregate's qualities is done using the testing methods for coarse aggregate that are outlined in the standard IS: 2386 (Part III)-1963 [31]. Potable water devoid of salt was used during the concrete casting and curing process in accordance with IS: 456–2000 [32] requirements.

This experiment made use of fly ash that was acquired from the Mettur Thermal Power Station in order to carry it out. The properties are displayed in Table 1.

In compliance with the requirements of the IS 10262–2009 [33], a mix has been developed and their values are displayed in Table 2 for the grade of M20.

The designation of concrete mix has been displayed in Table 3.

2.1.1. Preparation of nano fly ash and particle size confirmation

The raw fly ash which collected from Mettur Thermal Power plant, classified under Class F, was used in this research, the fly ash size has been reduced from micro to nano size using ball milling process of eight hours running [34, 35]. Also the fly ash size has been reduced in to ultra fine is after 6hrs of ball milling. The size of fly ash particles after ball milling was confirmed by scanning electron microscope [36]. Figures 1, 2 shows the morphology of raw and nano fly ash.

Table 1: Properties of fly ash.

PROPERTIES	OBTAINED VALUE
Classification	Class F
Minerals	Calcium based
Specific gravity	2.2
Fineness	5.50%

Table 2: Design mix for the grade of M20.

CEMENT	F.A	C.A	WATER
352	739.2	1108	158.4
1	2.1	3.15	0.45

Table 3: Abbreviations used for the concrete.

SPECIMEN ID	ABBREVIATION
RFAC-19	Concrete with 19% of raw fly ash added with cement
UFFAC-22	Concrete with 22% of ultra fine fly ash added with cement
NFAC-23	Concrete with 23% of nano fly ash added with cement

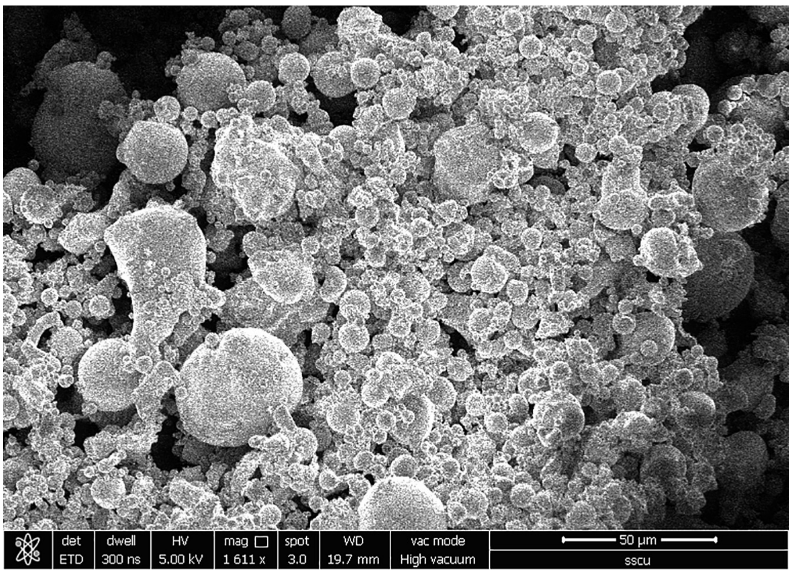

Figure 1: Morphology of raw fly ash.

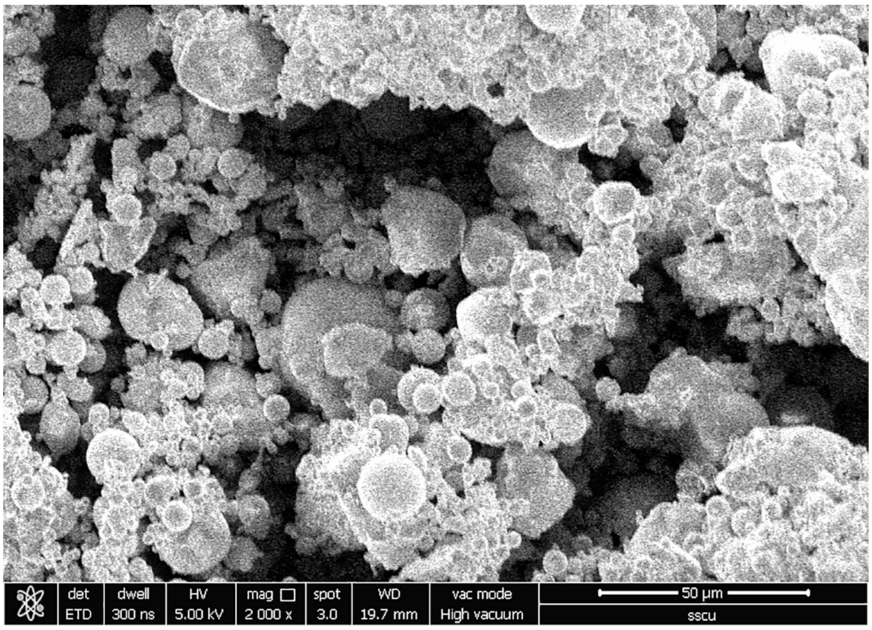

Figure 2: Morphology of ultra fine fly ash.

The impact and wear principle is used in ball milling, a process that reduces mineral size to a level that is easier to handle. The particles will be torn to pieces by the force of the ball's collision. In addition to the cold-welding procedure, ball mills are often utilized in mechanical alloying procedures [37]. Steel balls are used to convert the flyash from micro to nano. A small number of studies have been done on the quantity of fly ash that, when substituted with cement, increases the strength of the concrete [38].

The optimum content of raw fly ash and nano fly ash has been found using mechanical properties test. Here the raw fly ash of 19%, ultra fine fly ash of 22% and the nano fly ash of 23% possess good responses in mechanical properties. The conventional concrete specimen are denoted as CC, raw fly ash with 19% addition in cement are designated as RFAC-19, ultra fine fly ash of 22% addition in cement are designated as UFFAC-22% and the nano fly ash with 23% addition in cement are designated as NFAC-23. Figures 1, 2 & 3 represents the SEM image of raw, ultra and nano fly ash morphology.

2.2. Methodology

Conducting the structural behaviour on the beam specimen and salient features of static load test parameters such as displacement and rotational ductility, system and section energy absorption are discussed.

2.2.1. Mechanical properties tests

The mechanical properties tests such as compression strength, split tensile strength, modulus of rupture strength, and modulus of elasticity strength tests have been conducted on the standard specimen.

2.2.2. Specimen and loading details

This experimental study consists of casting and testing of 2.0 m long reinforced concrete beams of conventional, raw fly ash and Nano fly ash of its optimum dosage as 19% and 23%. The optimum dosage of fly ash with respect to its category has been finalized based on its compressive strength test. The tested beams are taken as simply supported for the span of 1.8 m. All the beams were designed as under reinforced section to withstand an ultimate load of 35 kN. The section, reinforcement details and loading setup are displayed in the Figure 4. The Load is applied on the beam specimens by a hydraulic jack of 100 kN capacity and every 3.0 kN interval, the deflection and strain at mid span and strain have been measured. Meanwhile, the cracking on the faces of the beam also observed. The first cracking, the corresponding load, deflection and strain values also noted.

2.2.3. Displacement & rotational ductility

Displacement ductility (μ) is the ratio between the ultimate deflection (δ_u) and the first yield deflection (δ_y). Rotational ductility is the ratio between the rotations at ultimate and yield point.

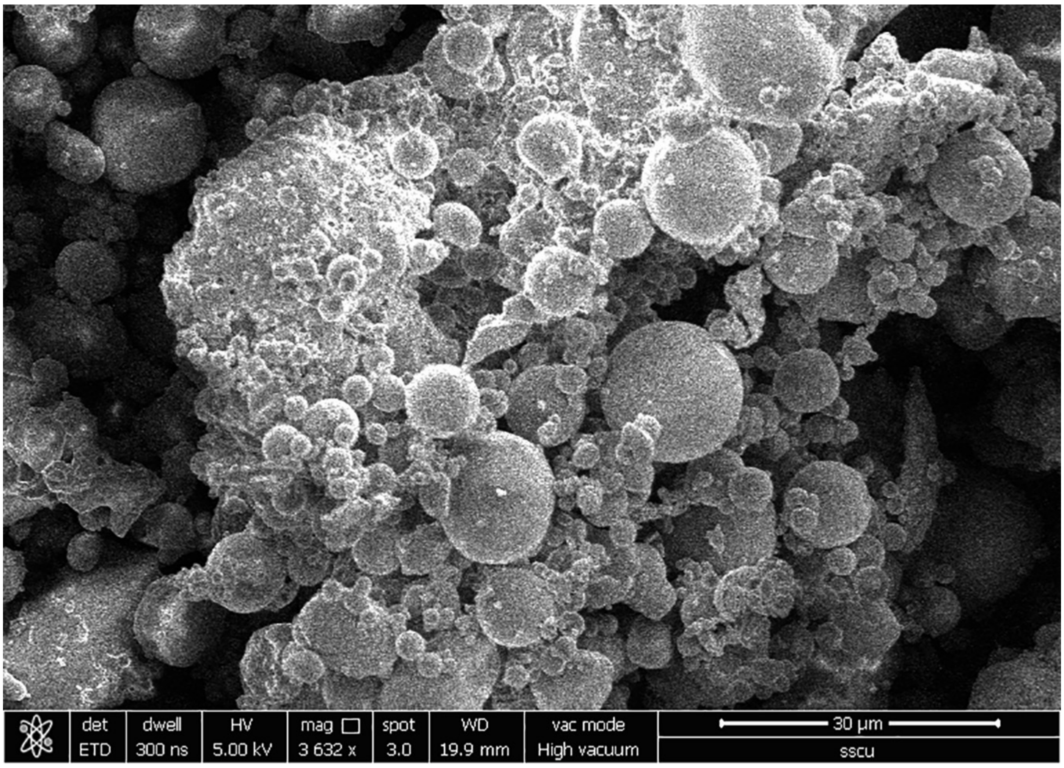

Figure 3: Morphology of nano fly ash.

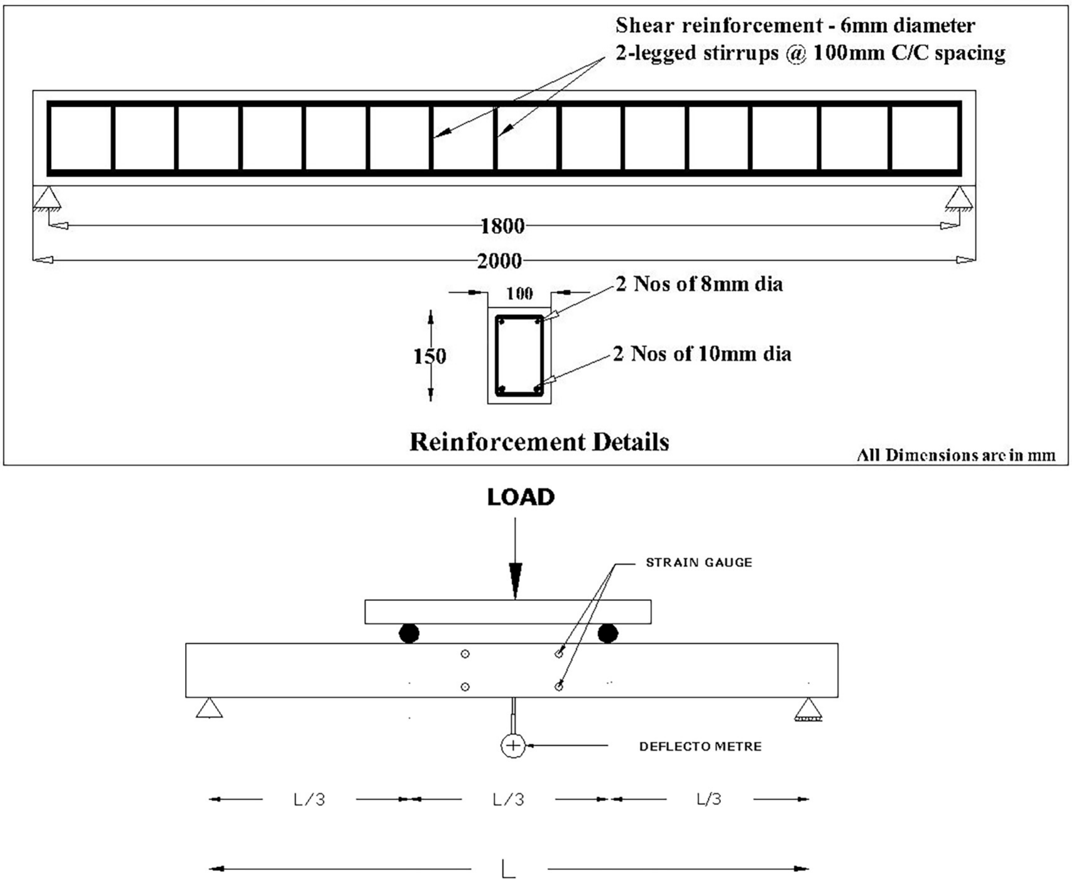

Figure 4: Reinforcement and load set up of beam specimen.

$$\text{Displacement ductility } (\mu) = \text{Ultimate deflection } (\delta_u) \,/\, \text{Yield deflection } (\delta_y) \quad (1)$$

$$\text{Rotational ductility} = \text{Ultimate rotation} \,/\, \text{Ultimate rotation} \quad (2)$$

2.2.4. System & section energy absorption

System energy absorption is the area between yield and ultimate points under the curve of load vs. deflection. Similarly, Section energy absorption is the area between yield and ultimate points under the curve of moment vs. rotation.

3. RESULTS AND DISCUSSION

The flexural behavior of beam has been carried out under static load condition for CC, RFAC-19, UFFAC-22 and NFAC-23. The experimental work has been done to obtain the results and discussion on load vs. deflection, energy absorption, moment-curvature and stiffness degradation over the beam specimen.

3.1. Mechanical properties of concrete

The mechanical properties tests such as compression strength, split tensile strength, modulus of rupture strength, and modulus of elasticity strength tests have been conducted on the standard specimen. The test results are displayed in Table 4.

From the mechanical properties tests, the properties were improved when adding the fly ash from micron to nano scale. The compressive strength is increased from 6.29% to 33.97%. Split tensile strength is increased from 10.36% to 12.72%. The modulus of rupture strength is increased from 10.33% to 14.91% and the modulus of elasticity of concrete is increased from 14.98% to 25.55%. When adding the fly ash in nano form, the molecules bonding between the concrete and the pores inside the concrete specimens are filled at the maximum. This leads to improve the strength of the specimens.

3.2. Load vs mid span deflection under static load

Flexural testing on reinforced concrete beam have been tested under static loading condition at one-third distance from each support as two point loading system for all the specimen. The loads at first crack found over those specimens were 12 kN, 13 kN, 13 kN and 15 kN and its deflection at yield loads were 4.9 mm, 5.2 mm, 5.1 mm and 4.8 mm. Similarly the ultimate load of those beams was 39 kN, 42.8 kN, 44.2 kN and 46.5 kN and the deflection value corresponding to the ultimate load were 27.60 mm, 26.80 mm, 24.6 mm and 24.20 mm.

The NFAC-23 specimen offers the ultimate load of 46.5kN. This value is 19.23%, 8.64% and 5.20% more than the strength of CC, RFAC-19 & UFFAC-22 specimens. The ultimate deflection of NFAC-23 specimen is 24.2 mm. Corresponding to the ultimate load, the deflection values are 12.32%, 9.70% & 1.63% lower than the value of CC, RFAC-19 & UFFAC-22 specimens. The deflection values of RFAC, UFFAC and NFAC beams are compared with conventional beam specimen to know their ductile behavior. It seems that the NFAC has the good confinement, bonding between the ingredients of concrete. So that it exhibits good capability to resist the load under the static load.

Similarly, the breaking load of 26.4 kN, it is (-) 5.71%, 3.53% & (-) 1.63% higher than the CC, RFAC-19 & UFFAC-22 specimens. The breaking point deflection of NFAC-23 specimen is 49.8 mm. Corresponding to the breaking load, the deflection values are 6.41%, 11.91% & 0.40% lower than the value of CC, RFAC-19 & UFFAC-22 specimens. Here the (-) sign denotes reduction in strength. In breaking point level the RFAC has earlier breaking means that did not yields much at this level suddenly reaches its failure and the values are 2%

Table 4: Mechanical properties test results.

SPECIMEN ID	COMPRESSIVE STRENGTH IN MPA	SPLIT TENSILE STRENGTH IN MPA	MODULUS OF RUPTURE STRENGTH IN MPA	MODULUS OF ELASTICITY IN MPA
CC	25.76	3.38	5.23	21.49
RFAC-19	27.38	3.73	5.77	24.71
UFFAC-22	31.24	3.74	5.91	26.31
NFAC-23	34.51	3.81	6.01	26.98

lower than the CC. But NFAC has yields much rather than other specimen as an amount of 6.4% higher than the CC. So that the NFAC has absorbs more energy till its complete failure.

All the beams have failed in flexural mode by yielding to tension steel. Crushing and spalling of concrete takes place after yielding in tension zone for all the beams since the beam have been designed as under reinforced section. The addition of Nano fly ash makes the beam with good behaviour rather than sudden failure, lesser value of load, deflection and uneven propagation of crack etc. The NFAC beam has linearity propagation in curve under load vs. deflection. It states that the beam behavior was well and good under static loading condition.

The load vs. deflection curves of the beams (CC, RFAC-19, UFFAC-22 and NFAC-23) are shown in Figure 5. From the figure, it is observed that, all the type of specimen behavior at the salient points such as first crack, first yield and ultimate is improved due to the addition of Nano fly ash. The ultimate load over the NFAC does not made much difference, while compared with the CC and RFAC the performance of NFAC is good under static load. The failure pattern should obey stress strain linearity. The behavior post cracking and post ultimate load has been increased while adding the Nano sized fly ash. The results obtained are in similar trend with the results of Fuzail HASHMI *et al.* [39]. Figure 6 shows the crack patterns of CC, RFAC-19, UFFAC-22

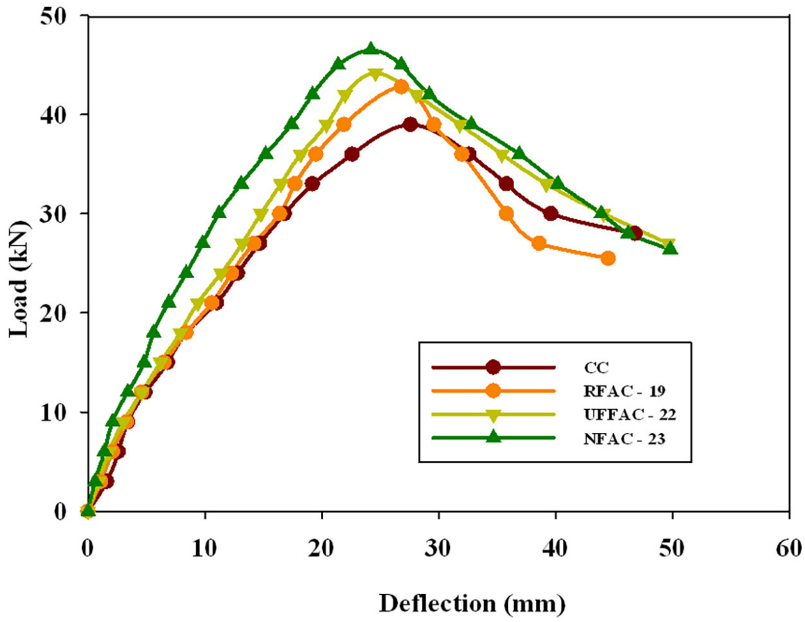

Figure 5: Load vs deflection curve of CC, RFAC-19 & NFAC-23 beam.

Figure 6: Crack & failure pattern of beam under static load test.

Table 5: Salient points of load vs deflection.

SPECIMEN ID	LOAD IN kN AT			DEFLECTION IN mm AT		
	P_y	P_u	P_b	δ_y	δ_u	δ_b
CC	12	39	28	4.9	27.6	46.8
RFAC-19	13	42.8	25.5	5.2	26.8	44.5
UFFAC-22	13	44.2	27	5.1	24.6	49.6
NFAC-23	15	46.5	26.4	4.8	24.2	49.8

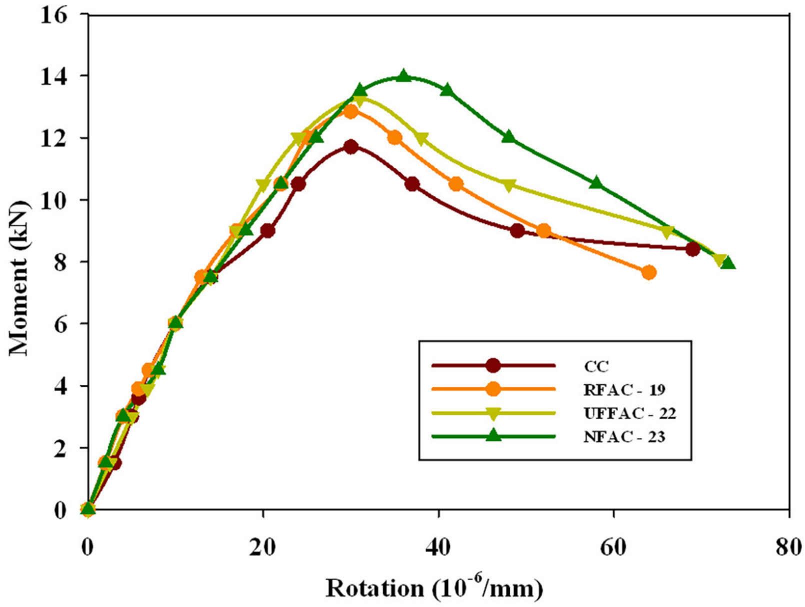

Figure 7: Moment vs rotation curve of CC, RFAC-19 & NFAC-23 beam.

Table 6: Salient points of moment vs rotation.

SPECIMEN ID	MOMENT IN kN-m AT			ROTATION IN 10^{-6}/mm AT		
	M_y	M_u	M_b	θ_y	θ_U	θ_b
CC	3.6	11.7	8.4	5.8	30	69
RFAC-19	3.9	12.4	7.7	6	30	64
UFFAC-22	3.9	13.3	8.1	6.8	31	72
NFAC-23	4.5	14	7.9	8	36	73

and NFAC-23 beams under static load. Table 5 shows the salient points of the load vs. displacement curve of the beam.

3.3. Moment vs mid span rotation under static load

The moment-rotation curve for the beams is displayed in Figure 7. The NFAC curve shows the better performance when compared with other beams. It shows that the post cracking and ultimate behavior has an improved manner when compared with other beams as similar to JOANNA *et al.* [40]. Table 6 shows the salient points of the moment vs. rotation curves.

In the aspect of moment carrying capacity for CC, RFAC and NFAC at yield, ultimate and breaking points are seems that the values of, 3.6 kN-m, 11.7 kN-m, 8.4 kN-m for CC, 3.9 kN-m, 12.4 kN-m, 7.7 kN-m for RFAC and NFAC has the values of 4.5 kN-m, 14.0 kN-m, 7.9 kN-m. The values of moment carrying capacity of RFAC & NFAC at yield level are 8.3% & 25.0% more than CC. At ultimate point, 6.0% & 19.2% more than the CC and at breaking point, 9.8% & 6.7% higher than the conventional concrete.

Table 7: Ductility and energy parameters.

SPECIMEN	μ_{dd}	μ_{rd}	EA_{sys}	EA_{sec}
CC	5.63	5.17	1250.9	558.51
RFAC-19	5.15	5	1478.9	627.45
UFFAC-22	4.82	4.56	1695.4	747.31
NFAC-23	5.04	4.5	1947.36	843.89

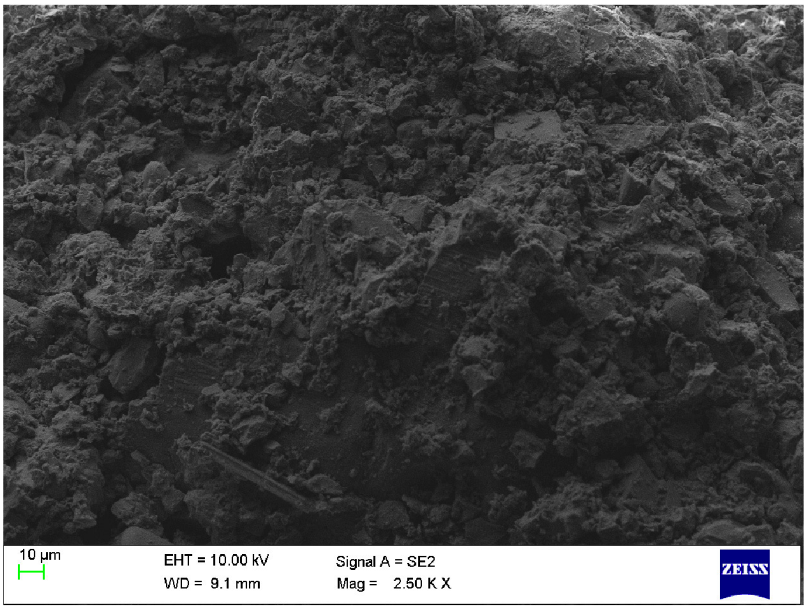

Figure 8: SEM - morphology of CC specimen.

In this observation, the NFAC has better moment carrying capacity when compared with other beam specimen and absorbs much energy while it is loaded which are in accordance with the results of ZHANG *et al.* [41]. The CC has the values of 5.8 × 10^{-6}/mm, 30 × 10^{-6}/mm & 69 × 10^{-6}/mm in the aspects of rotation at yield, ultimate & breaking points. The strength of the RFAC and NFAC at yield, ultimate and breaking points are, 3.4%, 37.9% at yield level, 0%, 20% at ultimate point higher than the CC. At breaking point, the RFAC has the value of 7.3% less than CC, NFAC has the value 5.8% more than the CC.

3.4. Displacement ductility

The following Table 7 shows the values of displacement & rotational ductility and system & section energy absorption of the various beams.

The displacement ductility values of the CC, RFAC and NFAC beam specimen are 5.63, 5.15 & 5.04. These values are 9.29% & 11.72% less than the CC beam. The rotational ductility has the values of 5.17, 5.00 & 4.50 and these values are 3.45% and 14.94% lower than CC. These values suggests that the addition of Nano fly ash causes reduction in ductility because its make concrete much denser so that the crack caused by the deflection was enlarged much [42, 43, 44].

The system energy absorption under the load vs. deflection curve has the values of 1250.90 kN.mm, 1478.90 kN.mm & 1947.36 kN.mm. These values are 18.23% and 55.68% higher than the CC beam.

The section energy absorption under moment vs. rotation curve has the value of 558.51, 627.45 and 843.89. These values are 12.34% and 51.10% higher than the CC beam. Through this result, it is found that the energy absorption of the NFAC specimen is almost 50% more than the CC and on average, 30% more than RFAC beam.

3.5. Scanned electron microscopy results on concrete specimen

Scanned electron microscopy examinations are performed to determine the morphology of the object [45]. The SEM study was performed on a concrete specimen measuring 10 mm × 10 mm × 10 mm. Figures 8, 9, 10, and 11

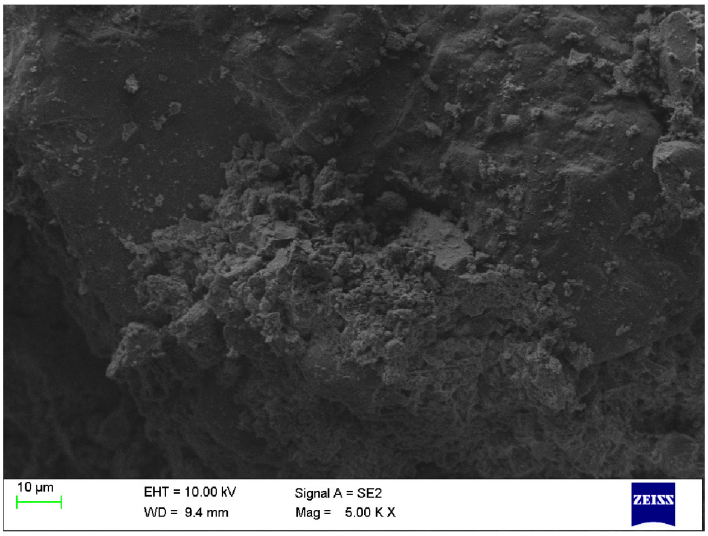

Figure 9: SEM - morphology of RFAC-19 specimen.

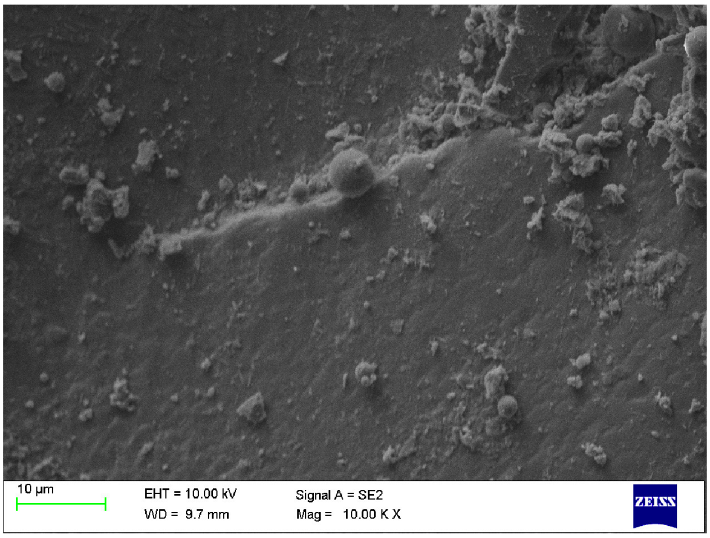

Figure 10: SEM - morphology of UFFAC-22.

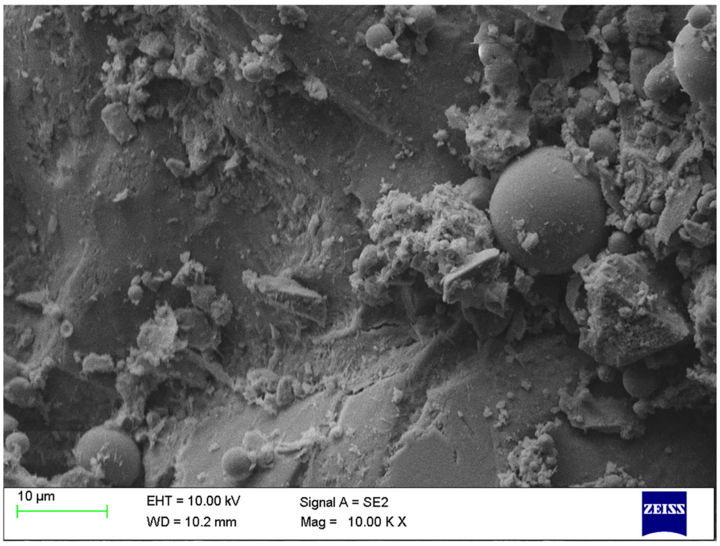

Figure 11: SEM - morphology of NFAC-23.

exhibit the findings of the SEM study. The NFAC morphology guarantees the presence of nanofly ash particles in the concrete. RFAC and CC had no change in their shape, although the surface had spreader particles of fly ash in RFAC.

4. CONCLUSIONS

From the elaborated study on structural behavior of beam for CC, RFAC-19 and NFAC-23 the following points are arrived.

- The NFAC-23 beam has resisted the ultimate load of 46.5 kN which is 19.23%, 8.64% and 5.20% more than the CC, RFAC and UFFAC beam specimen. The Ultimate deflection has the value of 24.2 mm which is 12.32%, 9.70% and 1.63% lower than the CC, RFAC-19 and UFFAC-22.
- The NFAC-23 beam has resisted the ultimate moment of 14 kN-m. This is 19.66%, 12.90% and 5.26% more than the CC, RFAC and UFFAC beam. Similarly its rotation corresponding to its ultimate point is 36.0×10^{-6}/mm. It's about 20% more than the CC and RFAC-19 beam and 16.13% more than the UFFAC-22 beam rotation capacity.
- The energy absorption of the NFAC-23 has the value of 1947.36 kN-m. This is 55.7%, 31.68% and 14.86% more than the energy of CC, RFAC-19 and UFFAC-22 beam.
- The section energy absorption has the value of 843.89 kN.mm is 51.1%, 34.5% and 12.92% more than the CC, RFAC-19 and UFFAC-22 beam.
- The NFAC-23 beam proves that, if the material density becomes high their stiffness is high but the ductility is low. The displacement ductility has the value of 5.04. This is 10.5% & 2.2% lower than the CC and RFAC specimen. Also 4.56% higher than the UFFAC-22 beam specimen.
- The NFAC-23 has the better load, moment and rotation carrying capacity when compared with other beam specimen for the less amount of deflection. It happened because of fewer pores presented in concrete or the high bonding between the concrete ingredients.
- All the beams have failed in flexural mode by yielding to tension steel.
- SEM analysis proves the Nano fly ash have good bonding with concrete ingredients, also the pores presented in the concrete are arrested drastically and improves the structural property of concrete when compared with other specimen.

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