Research Article

Flexural Behavior of High Strength RC Beams Incorporating Nano-Silica and Macro-Polypropylene Fiber

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Abstract
This paper investigates the flexural behavior of high-strength RC beams experimentally to assess the effect of Nano-silica (NS) and Macro-Synthetic High Strength Polypropylene Fiber (MPF). Ordinary Portland cement was partially replaced by the NS and MPF with different proportions to produce four concrete mixtures. Tests were conducted on the full-scale high-strength RC beams, including first crack load, failure load, deflection, concrete strain, steel strain, and mode failure, which were examined and compared. In addition, the tests on the mechanical properties of high-strength concrete mixtures were also conducted at the ages of 28 and 56 days. The test results concluded that the addition of NS and MPF significantly improved the first-cracking and failure loads and decreased deflection at levels of cracking and failure loads. Additionally, an increase in NS content resulted in a minor increase in the ultimate strain related to the failure loads. Furthermore, the mix of 3% NS with 0.5% MPF was found to lead to the highest mechanical characteristics of concrete. The improvements were the concrete compressive strength by 33.6%, split tensile strength by up to 54.1%, and flexural strength by up to 28.3% compared with control specimens.

Keywords: RC Beams, Flexural Strength, Mechanical Properties, Nano-Silica, Polypropylene Fiber.

1. Introduction

One of the most famous construction materials in use today is concrete. It is used in a variety of applications because it provides significant strength at a relatively low cost (Altun et al., 2007; Ehab & Manar, 2017; Rashmi & Padmapriya, 2021). Concrete is a composite material that has two major disadvantages specifically, which are its brittleness and weakness under stress. When concrete has faced stress, it cracks quickly and the cracks generally develop with time and under stress (Ahmed et al., 2006). To solve the aforementioned disadvantages of the concrete, the strengthening method has been proposed to incorporate mixing the concrete with random discrete fibers. For example, carbon, glass, steel, and polypropylene contribute to the addition of fibers to concrete to improve energy absorption and tensile resistance to cracking (Lee et al., 2016; RAS, 2006).

Generally, an attractive alternative for conventional steel bar reinforced concrete constructions is fiber reinforced concrete (FRC) (Aidarov et al., 2022). The fiber is used as internal reinforcement in concrete constructions and leads the concrete to have less cracking, so the fibers are used to enhance its tensile and ductile behaviour. The kind, size, and proportions of the fibers have a major effect on how much the behaviour has improved (Fallah & Nematzadeh, 2017). Similarly, the mechanical properties of fresh and hardened concrete can be considerably improved by adding fibers to the concrete mix (Mashrei et al., 2018). Steel fibers can enhance the mechanical characteristics of concrete because of their high energy absorption and ability to stop cracks from spreading. However, steel fibers will still corrode, which eventually causes concrete buildings to deteriorate quickly. Nevertheless, glass fibers are extremely strong but have a low alkali resistance, particularly when added to concrete. Recently, synthetic fibers are attracting focus from researchers due to their greater environmental sustainability than other types of fibers (Abousnina et al., 2021).

In comparison to other reinforcing fibers, the advantages of MPF include chemical resistance and low specific weights. It is primarily used in concrete structures to strengthen them and minimize shrinkage cracking to a limited extent (Lee et al., 2016; Yazdanbakhsh et al., 2015). As a consequence, many research studies have been carried out on fiber (Abousnina et al., 2021; Ahmed et al., 2006; Bagherzadeh et al., 2012; Fallah & Nematzadeh, 2017; Lee et al., 2016; Mashrei et al., 2018; Mtasher et al., 2011; RAS, 2006). However, very few studies have been focused on the Nano-materials and MPF together. In particular, the effect of NS that will get higher strength (Amin & Abu el-Hassan, 2015; Mustafa et al., 2020; Rahmani et al., 2019; Rashmi & Padmapriya, 2021; Shi et al., 2021; Sridhar et al., 2019; Zhang, Sha, et al., 2021). It may be used in a variety of ways to strengthen structural elements under static and dynamic stress and to minimize cracking and crushing (Rahmani et al., 2019). The most effective way to improve the mechanical properties of concrete is using NS, which changes the Interfacial Transition Zone (ITZ) between cement paste and aggregate, reduces porosity, increases penetration resistance, and increases the strength of the hardened cement matrix (Akbarpour et al., 2018).

There are fewer than several works published regarding the model of reinforced concrete beams with aforementioned materials separately such as the effect of NS on mechanical properties, flexural behaviour, initial crack load and failure load of RC beams (Fallah & Nematzadeh, 2017; Sridhar et al., 2019). Moreover, using NS with two kinds of polypropylene fibers in concrete to improve mechanical properties such as compressive strength, split tensile strength, and elastic modulus in comparison with plain concrete (Fallah & Nematzadeh, 2017). Furthermore, the effect of NS on the flexural performance of concrete beams was investigated by Shi et al. (2021) with three volume fractions of steel fiber; they concluded that using different volume fractions in the concrete increased concrete strength, cracking load and failure load of beams; and so on spacing and number of cracks were reduced. Specifically, there are no works observed on the flexural strength of high-strength RC beams including NS and MPF simultaneously.

However, for some reason, in some structures, it is needed to use NS and MPF to increase strength and reduce cracks. Therefore, experimental investigations were conducted to examine the deflection, modes of failure, and failure loads of reinforced concrete beams and the mechanical properties incorporating NS and MPF. The outline of this study is as follows: The introduction of the study is presented in Section 1. The experimental work is presented in Section 2. Section 3 is about the results and discussion of the study. Finally, Section 4 presents the drawn conclusion of the study.

2. Experimental Work

The experimental work, which includes materials, mix proportions, specimen details, and test techniques, is presented and discussed in this section. Accordingly, mixing materials to produce high-strength concrete beam specimens and casting and testing the specimens are explained.

2.1. Materials

Cement type I (CEM-1, 42.5 R), from Tasluja, Al-Sulaymaniyah, Iraq, was used in all of the mixes in this investigation. Cement conforms with ASTM-C150 (2016) requirements in terms of its chemical and physical properties as shown in Table (1). The fine aggregate used in this study was natural sand, which has a maximum size of 9.5 mm, a specific gravity of 2.69, a fineness modulus of 2.7, and a water absorption of 1.63%. The coarse aggregate used was crushed stone, which had the following specifications: a maximum nominal size of 12.5 mm, 2.68 specific gravity, and 0.89% water absorption. Figure 5) shows the grading curves for fine and coarse aggregates that conform to ASTM-C33 (2013).

Table 1. Properties of the cement in chemical and physical composition.

Test category	Type of test	Test results	ASTM-C150 (2016)
Chemical tests	SiO_2	19.2	-
	Al_2O_3	4.65	-
	Fe_2O_3	3.22	-
	CaO	63.55	-
	MgO	1.87	≤ 6
	SO_3	2.48	≤ 6
	Loss On Ignition (L.O.I)	3.48	≤ 6

	Lime Saturation Factor	1.01	0.66 – 1.02
	Insoluble residue (I.R)	0.71	≤ 0.75
	C_3S	70.12	-
	C_2S	0.09	-
	C_3A	6.88	-
	C_4AF	9.79	-
Physical tests	Color	Grey	-
	Initial setting time; Vicat test	149	Not less than 45 minutes
	Final setting time; Vicat test	187	Not more than 375 minutes
	3 days Compressive strength	26.5	12 MPa Lower limit
	7 days Compressive strength	46.8	19 MPa Lower limit
	Standard consistency	26.34	-
	Fineness, specific surface	336	260 m²/kg Lower limit
	Autoclave expansion	0.0	0.8%, max.

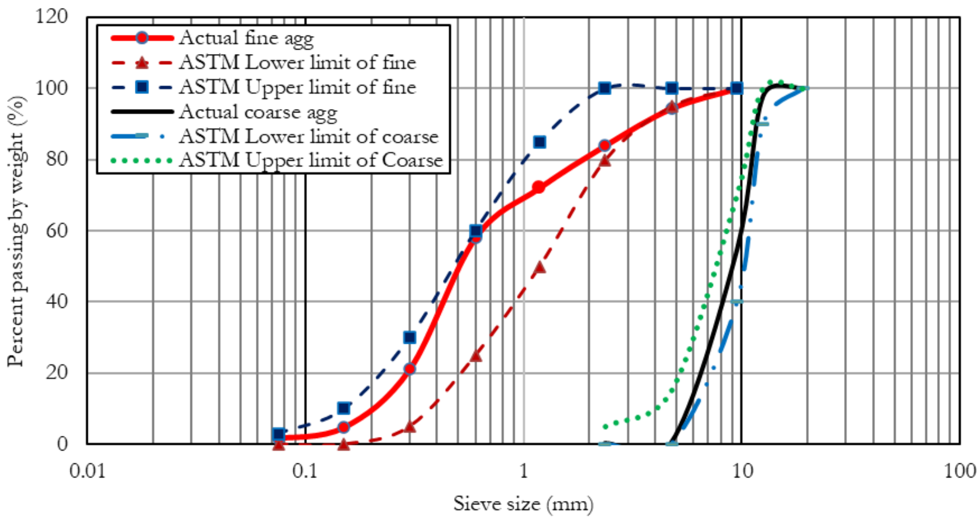


Figure 5. Aggregate gradation curve with ASTM C33 standard limits for fine and coarse aggregates.

In this study, the MPF with a length of 60 mm and an aspect ratio of 35.7 was used. The fibers' characteristics and shape are listed in Table (2) and Figure 6) respectively. The amorphous silica powder used as NS in this study has an average particle size of 30 nm and a specific surface area of 200 m²/g. The features and form of NS are given in Table (2) and Figure 7) respectively. In this investigation, Hyperplast PC260 F0, as a superplasticizer (S.P), was added as a weight percentage of the total binder to all concrete mixes. Hyperplast PC260 F0 is a modified polycarboxylic-based polymer designed to enable the distribution of MPF and NS all over the concrete mixture for improved concrete workability. Technical properties at 25º C are 1.102 specific gravity, -7º C freezing point, and a yellowish to brownish liquid color.

The water to cement ratio (w/c) was 0.27 for each of the concrete mixtures. The concrete specimens were also mixed and cured by fresh drinking water. All the test beam specimens were reinforced with steel bar reinforcement, with 10 mm for longitudinal bottom reinforcement and 8 mm for longitudinal top reinforcement and vertical stirrups. Steel bars satisfy ASTM-A615 (2020) requirements for yield strength, ultimate strengths, and elongation.

Table 2. Properties of Macro-type high strength polypropylene fiber and Nano-silica.

Macro-type high strength polypropylene fiber		Nano-silica	
Properties	**Test Results**	**Properties**	**Test Results**
Shape of fiber	Embossed	Appearance form	Powder
Color	White	Color	White
Type	Macro-type High strength	SiO_2	99.5%
Fiber length (mm)	60	Particle size (nm)	30
Fiber diameter (µm)	0.84	Specific surface area (m²/g)	185±20

Aspect ratio	35.71	Bulk density (g/cm^3)	0.18
Density (kg/m^3)	910	PH	5 -7
Elastic Modulus (GPa)	6.0	-	-
Tensile strength (MPa)	430	-	-
Elongation (%)	20 - 25	-	-
Melting point	≥ 160 °C	-	-

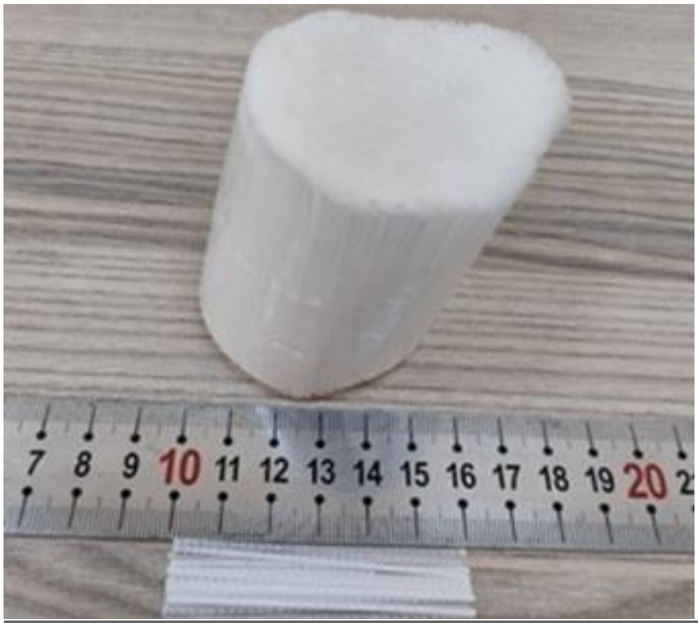


Figure 6. Shape of Macro-type polypropylene fiber.

Figure 7. Appearance of powdery Nano-silica.

2.2. Mix proportions

The target compressive strength of more than 55 MPa was fixed. The final mix proportions used to produce high strength concrete are illustrated in Table (3). The replacement levels of cement with NS by weight (0%, 1%, 2%, 3%, and 4%) and adding MPF by volume fraction (0%, 0.25%, 0.50%, 1.0%, and 1.25%), were used to determine the optimal percentage of 3% of NS and 0.5% of MPF on the flexural behaviour of reinforced concrete beams and concrete properties. The selection was made based on the most obvious improvement in the parameters of the strength of the samples of cylinders and prisms.

Table 3. Proportions of the concrete mixture.

No.	Concrete mix	NS (kg/m^3)	MPF (kg/m^3)	w/b	Cement (kg/m^3)	Fine agg, (kg/m^3)	Coarse agg, (kg/m^3)	Water (kg/m^3)	S.P (%)
1	B1-NS0%-MPF0% Control mix	0.0	0.0	0.27	450.0	750	900	121.5	1.5
2	B2-NS3%-MPF0%	13.5	0.0	0.27	436.5	750	900	121.5	1.5
3	B3-NS0%-MPF0.5%	0.0	4.55	0.27	450.0	750	900	121.5	1.5
4	B4-NS3%-MPF0.5%	13.5	4.55	0.27	436.5	750	900	121.5	1.5

In order to produce plain concrete, in a conventional rotary concrete mixer with a capacity of 0.20 m^3, the saturated surface dry (SSD) aggregates (sand and gravel) were mixed., after which the cement was added, and the mixture was mixed for 1 minute. Subsequently, a liquid mixture consisting of water and a S.P. (Hyperplast PC260 F0) was gradually added to the mixture, which was also mixed for 5 minutes to provide the necessary workability for concrete. For preparing the concrete mixes containing NS and MPF. After properly combining the cement and aggregates, NS was mixed for 5 minutes in a container with some water. Then, the remaining portion of water with superplasticizer and the NS mixture was slowly added to the mixture for 5 minutes. Finally, the fibers are dispersed manually in small bits to ensure even distribution.

2.3. Specimen detail

Four rectangular RC beams with simple supports were cast and tested. Figure 8) illustrates details of the beams and loading configuration. The reinforced concrete beams were cast in the iron formworks with dimensions of 150×200×2000 mm and tested under two equally concentrated loads. Stirrups with an 8 mm diameter and a 100 mm spacing were utilized to prevent the beams from failing under shear. The bottom steel bar, which was made up of two 10 mm-diameter steel bars, was designed to be a flexural failure. The concrete was placed into the formwork, cylinders 100×200 mm and prisms 100×100×400 mm with two layers and vibrated as shown in Figure 9). After 24 hours the specimens were demolded and moist-cured for 28 and 56 days.

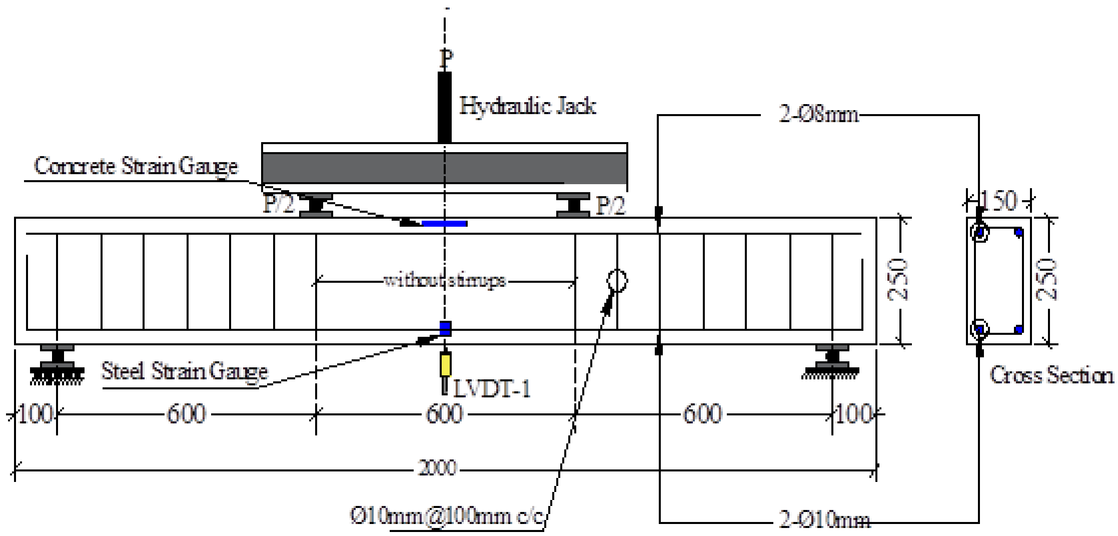


Figure 8. Details of test beams.

(a) (b) (c)

Figure 9. a) Formwork molds, b) Casting of beam specimens, and c) Vibration table of cylinders and prisms.

2.4. Test techniques

In this section, the details of specimens, instrumentation, measurements, and testing procedures are explained in accordance with the requirements of the standards.

2.4.1. Compressive strength

Cylinder specimens were tested for compressive strengths from the average of 3 cylinders for each mix at 28 and 56 days of age using a 2000 kN universal testing machine (UTM) at a loading rate of 0.2-0.3 MPa/sec according to ASTM-C39

(2014). To provide a uniform, equal distribution of stress, a sulfur-sand mixture is applied to the top of each cylinder as capping.

2.4.2. Split tensile strength

The indirect tensile strength or called split tensile strength is determined from the average of three cylinders for each mix at 28 and 56 days of age for the indirect measurement of the concrete's tensile strength by using a 2000 kN universal testing machine with a capacity of at a loading rate of 0.7-1.4 MPa/minute., which was carried out according to ASTM-C496 (2017) standards.

2.4.3. Modulus of elasticity

According to ASTM-C469 (2014) to determine the modulus of elasticity for each mixture cylinder specimen after 56 days of curing using load cell was used to measure the applied load and an electrical strain gauge was applied on the middle height of the specimen to measure the strain of the specimens. In addition, a universal testing machine with a capacity of 2000 kN was used to test each cylinder. The stress-strain data have been utilized to determine the modulus of elasticity by Equation (1).

$$E_c = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - 0.00005} \quad (1)$$

Where E_c is the modulus of elasticity of concrete in MPa, σ_2 is the stress corresponding to 40% of failure load in MPa, σ_1 is the stress corresponding to a longitudinal strain of 0.00005 in MPa, ε_2 is the longitudinal strain produced by σ_2.

2.4.4. Modulus of rapture

The flexural strength (modulus of rapture) is determined from the average of three prisms for each mix at age 28 and 56 days that conforms to ASTM-C78 (2010) requirements utilizing a 300 kN capacity universal testing instrument and tested under two-point loading to determine the modulus of rapture of plain concrete by Equation (2).

$$f_r = \frac{P * L}{b * d^2} \quad (2)$$

Where f_r is the modulus of rapture in MPa, P is the applied load in kN, L is the span length of prism in mm, b is the average width of the prism in mm, d is the average depth in mm.

2.4.5. Flexural behaviour of RC beams

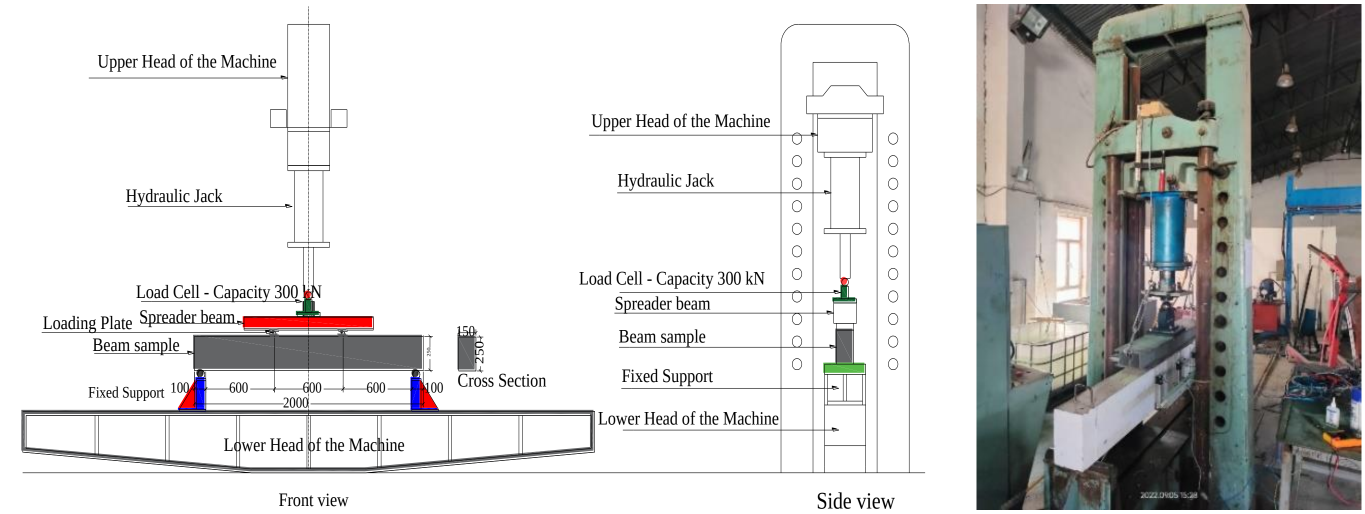
All of the beam specimens were simply supported and tested with a vertical hydraulic jack under two-point loads. The applied load was calculated using a load cell with a 300 kN capacity. On the top of the beam, a concrete strain gauge was mounted. Additionally, before casting the beam, steel strain gauges were installed on the longitudinal steel bar and stirrups. A 150 mm LVDT was placed on the beam side (at the bottom portion) using a metal angle to measure the deflection in the middle of the beams. In the process of testing, crack formation and propagation on both sides of the beam were marked, including the first initiated crack and maximum failure load of the tested beams. During the test, measurements of the applied load, deflection, and strain on the reinforcement and concrete were recorded using a data acquisition system (data logger) connected to a personal computer. The schematic presentation of the loading frame and beam test loading frame instrument are illustrated in Figure 10).

3. Results and discussion

The results and discussion, including the test results of the properties of concrete and the flexural behavior of concrete beam specimens, are presented and discussed in this section. Accordingly, the effect of NS and MPF on the mechanical properties and the flexural behavior of the beam specimens is explained.

3.1. Properties of concrete

In this section, the test results of the mechanical properties of specimens were evaluated and discussed, and the effects of NS and MPF on their parameters were presented.



(a) (b)

Figure 10. a) Schematic presentation of loading frame, and b) Beam test loading frame instrument.

3.1.1. Density

Saturated surface dry density was measured for all specimens. Table (4) shows that the concrete specimen's density increased as a result of the NS and MPF content in the concrete mix, while using NS and MPF together reduces the concrete density, due to the reduction of workability compared to the other concrete mixes led to the more porosity in the concrete mixture.

Table 4. Density of concrete mixes test results.

Concrete mix	Density (kg/m³)
B1-NS0%-MPF0%	2,483.5
B2-NS3%-MPF0%	2,487.9
B3-NS0%-MPF0.5%	2,491.7
B4-NS3%-MPF0.5%	2,482.8

3.1.2. Compressive strength

Compressive strength is the main parameter in structural design, and it is one of the most important mechanical properties. With respect to Table (5) and Figure 11), adding 3% of NS for concrete mixes B2-NS3%-MPF0% and B4-NS3%-MPF0.5% increased the compressive strength of concrete relative to the control mix (B1-NS0%-MPF0%) by 28.7% and 20.3% respectively at age of 28 days, while at ages of 56 days the compressive strength was increased to 40.4% and 33.6%, respectively. Increased compressive strength results from a stronger bond between the aggregates and hydrated cement paste. As a result, there was also an indication of decreased porosity and increased compactness at the same time (Fallah & Nematzadeh, 2017). Furthermore, the concrete mixes (B3-NS0%-MPF0.5% and B4-NS3%-MPF0.5%) with 0.5% of MPF improved compressive strength over the control mix by 12.6% and 20.3% respectively at age 28 days, and it becomes 20.7% and 33.6% respectively at age 56 days. Generally, the ability of fibers to stop and delay crack propagation as well as minimize the amount of stress concentration at the crack tip is attributed to the increase in compressive strength of fiber-reinforced concrete (Mashrei et al., 2018; Mtasher et al., 2011). In this study, the failure mechanism of the concrete cylinders is very brittle for the specimens containing NS, while the presence of fiber in concrete mixes leads to brittleness compared to the cylinders of the control mix. Furthermore, from Figure (7), it can be observed that the compressive strength of concrete containing NS and MPF increases gradually with the increase in the curing period.

Table 5. Changes in compressive strength of concrete mixes test results.

Concrete mix	Compressive strength changes at 28 days	Compressive strength changes at 56 days
B1-NS0%-MPF0% (as control mix)	0%	+2.6%

B2-NS3%-MPF0%	+28.7%	+40.4%
B3-NS0%-MPF0.5%	+12.6%	+20.7%
B4-NS3%-MPF0.5%	+20.3%	+33.6%

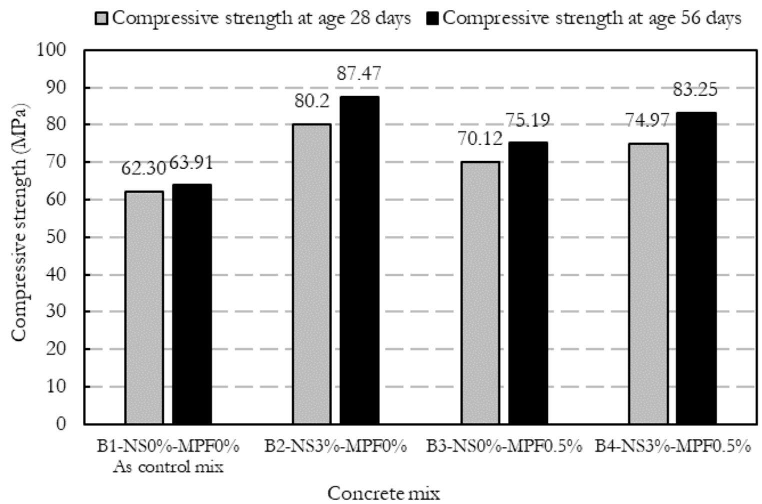


Figure 11. Compressive strength of concrete mix at age 28 and 56 days.

3.1.3. Split tensile strength

The indirect tensile strength or split tensile strength test results of all concrete mixes containing NS and MPF are shown in Figure 12) and the percentages of increased split tensile strength tests are shown in Table (6) at 28 and 56 days after curing. The tensile strength of the concrete specimen (B2-NS3%-MPF0%) containing 3% of NS exhibited an increase of 13.5% for age 28 days, and 22.7% for age 56 days. Because NS particles are very reactive at an early age, the rapid consumption of $Ca(OH)_2$, which was formed during Portland cement hydration, is what causes the increased split tensile strength in concrete containing NS (Amin & Abu el-Hassan, 2015). Moreover, the addition of MPF for concrete mix (B3-NS 0%-MPF 0.5%) increased tensile strength as compared to control mix concrete is up to 35.2% for age 28 days and 36.4% for age 56 days. Fibers improved splitting tensile strength because they could act as the stitching between two cracked portions, transferring stresses and increasing tensile capacity (Zhang, Zhang, et al., 2021). Finally, it can be concluded that the greater influence of the combination of NS with MPF compared to the control mix in increasing the concrete tensile strength reached the highest values. For instance, the concrete mix (B4-NS3%-MPF0.5%) showed the highest effect, with a 47.2% and 54.1% growth in tensile strength for ages 28 and 56 days, respectively.

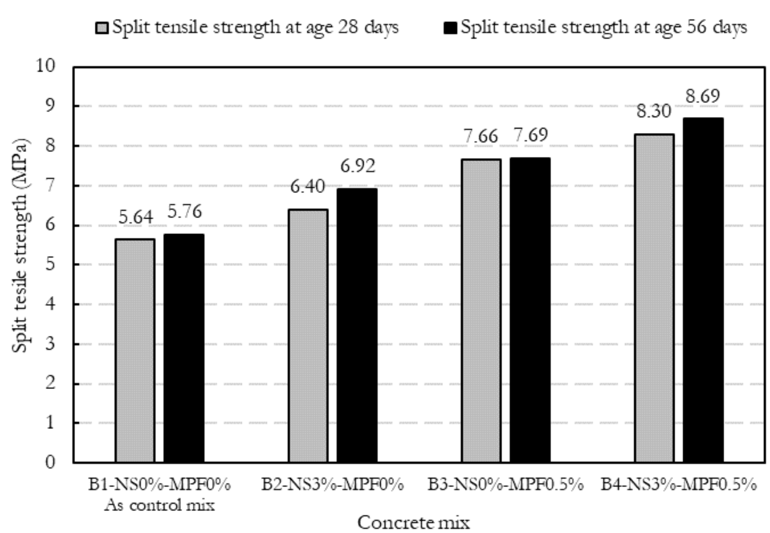


Figure 12. Indirect tensile strength of concrete mix at age 28 and 56 days.

Table 6. Changes in indirect tensile strength of concrete mixes test results.

Concrete mix	Splitting tensile strength changes at 28 days	Splitting tensile strength changes at 56 days
B1-NS0%-MPF0% (as control mix)	0%	2.1%
B2-NS3%-MPF0%	+13.5%	+22.7%
B3-NS0%-MPF0.5%	+35.2%	+36.4%
B4-NS3%-MPF0.5%	+47.2%	+54.1%

3.1.4. Flexural strength

For all concrete mixes incorporating NS and MPF, the flexural strength and Percentage increase data are shown in Figure 13) and Table (7) respectively for both ages of 28 and 56 days. The maximum flexural strength obtained among mixes was 7.91 MPa at age 28 days and 7.94 MPa at age 56 days for that mix containing the combination of 3% of NS and 0.5% of MPF (B4-NS 3%-MPF 0.5%) compared to the control mix increased by 27.8% and 28.3%, respectively. It is obvious that the fibers significantly affect flexural strength and prevent quick cracking in plain concrete (Abousnina et al., 2021). Flexural strength in the concrete mix increased slightly when NS was used alone when compared to the control mix; this may be due to an increase in compressive strength. However, when the fiber was used more improved flexural strength was noticed, this is a result of more fiber contributed during the tensile load before the samples fractured (Bagherzadeh et al., 2012). After the final failure, concrete mixtures containing fibers continued to fracture gradually without separating. This was produced by the existence of the MPF, which reduced the spread of the crack by resisting and distributing the tensile stresses produced by bending.

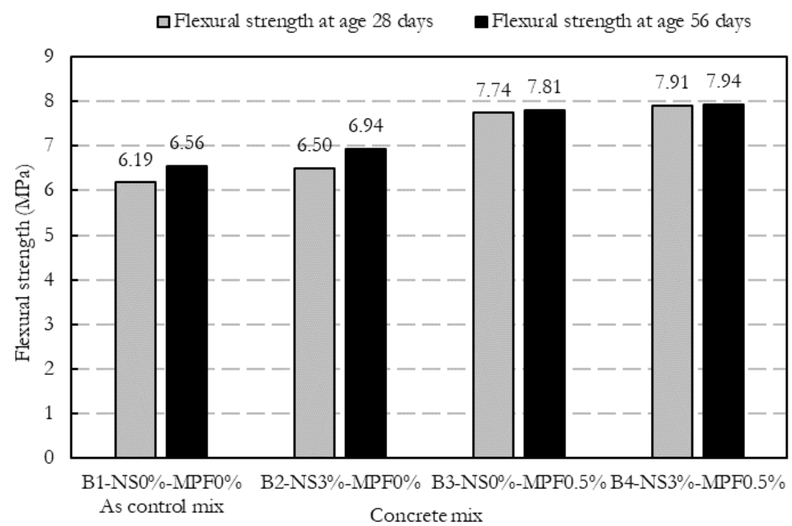


Figure 13. Flexural strength of concrete mix at age 28 and 56 days.

Table 7. Changes in flexural strength of concrete prism test results.

Concrete mix	Flexural strength changes at 28 days	Flexural strength changes at 56 days
B1-NS0%-MPF0% (as control mix)	0%	+6.0%
B2-NS3%-MPF0%	+5.0%	+12.1%
B2-NS0%-MPF0.5%	+25.0%	+26.2%
B2-NS3%-MPF0.5%	+27.8%	+28.3%

3.1.5. Modulus of elasticity

The modulus of elasticity test results of all concrete mixes containing NS and MPF are presented in Table (8) at the age of 56 days of curing. The results indicate that by addition of 3% NS improves the elastic modulus of specimens by 9.7% relative to the control mix It is caused by pore minimization, an improvement in concrete compactness, and an increase in the bond between cement paste and aggregate (Amin & Abu el-Hassan, 2015). In a similar manner, the elastic modulus associated with the MPF improved when compared to the control mix by 15.8%, the micro cracks are filled by the fibers, which increases the stiffness of the concrete (Fallah & Nematzadeh, 2017).

Table 8. Modulus of elasticity of concrete mix test results.

Concrete mix	Modulus of elasticity at 56 days (GPa)
B1-NS0%-MPF0% Control mix	44.71
B2-NS3%-MPF0%	49.05
B3-NS0%-MPF0.5%	51.12
B4-NS3%-MPF0.5%	51.78

3.2. Flexural behaviour of reinforced concrete beams

The data results of parameters of the flexural behavior beam specimens such as, cracking and ultimate load, deflection, strain in concrete and longitudinal steel reinforcement, and mode failure were evaluated and discussed, and the effects of NS and MPF on their parameters were presented.

3.2.1. Load-mid span deflection

According to test observation, measured load-deflection curves at the mid-span of the beam specimens containing NS and MPF compared to the control mix were shown in Figure 14). Results of bottom steel strain, concrete compressive strain, mid-span deflection at ultimate load and first crack loads, initial crack load ultimate load and experimental moment are summarized in Table (9). Regarding the deflection at peak load, the beam specimen containing NS (B2-NS3%-MPF0.5%) only showed a slight increment in the first crack load and ultimate load capacity by 3.3% and 4.2%, respectively. And decrement by 19.4% in mid-span deflection as relative to the control beam specimen. However, the maximum first crack load and ultimate load obtained were 33 and 88.8 kN for that beam specimen containing 0.5% of MPF (B3-NS0%-MPF0.5%) relative to the control mix increased by 10.0% and 17.3%, respectively. While the reduction in the corresponding deflection by 8.5%. In a similar manner, for beam specimen (B4-NS3%-MPF0.5%) containing NS and MPF improved by 6.7% and 10.6% at the first crack load and ultimate load respectively, and reduction by 38.7% at mid-span deflection. As can be observed, the first cracks were observed in each beam specimen on average between 30 and 35 kN, which is close to the mid-span. It can be observed that the Load-deflection curve of the pre-ultimate load of beam B4F-NS3%-MPF0.5% is more than the other beams. However, NS was added to the concrete mix, which increased the stiffness and brittleness.

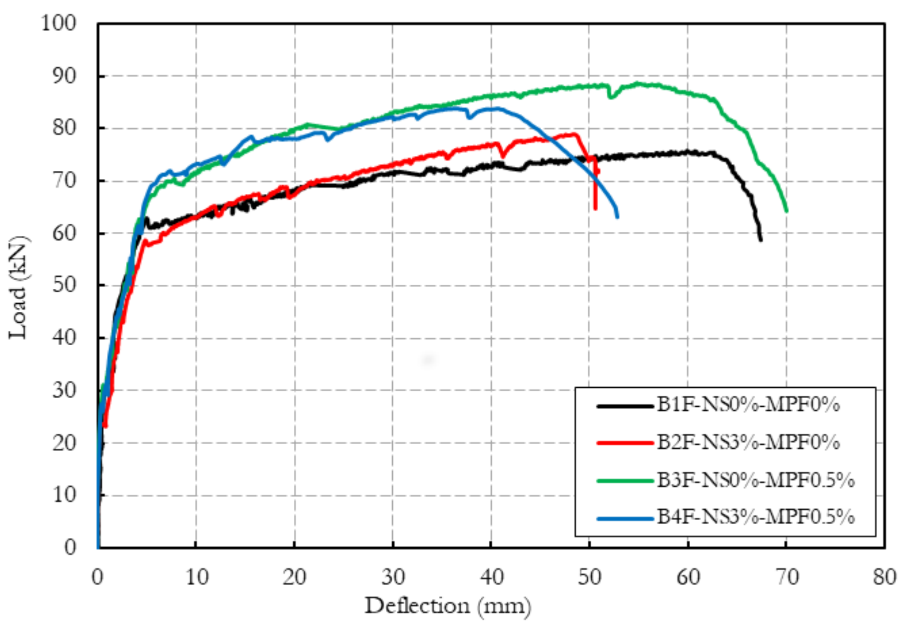


Figure 14. Load-mid span deflection relationship for all mixes.

Table 9. Test results of the reinforced concrete beam.

Beam designation	Bottom Steel strain (1×10^{-3})	Concrete compressive strain (1×10^{-3})	First crack deflection (mm)	Maximum deflection at mid-span (mm)	First crack load (kN)	Failure load (kN)	Experimental moment (kN-m)	Types of failure
B1-NS0%-MPF0% Control mix	7.089	2.814	0.77	59.9	30	75.7	22.71	Flexural
B2-NS3%-MPF0%	7.661	1.771	1.47	48.3	31	78.9	23.67	Flexural
B3-NS0%-MPF0.5%	6.064	2.889	1.00	54.8	33	88.8	26.64	Flexural
B4-NS3%-MPF0.5%	5.365	1.836	0.85	36.7	32	83.7	25.11	Flexural

3.2.2. Concrete compressive strain

Concrete compressive strain was measured by fixing one concrete strain gauge in the middle of the top surface of the beams at the compression zone. The results in Table (9) and Figure 15) indicate the concrete compressive strains at ultimate load for all beam specimens. The maximum concrete compressive strain was obtained from the beam specimen (B3-NS0%-MPF0.5%) containing only MPF as relative to the control specimen. On the other hand, concrete compressive strain decreased for the other beam specimen. in a way, that beam specimen included NS only decreased up to 37%.

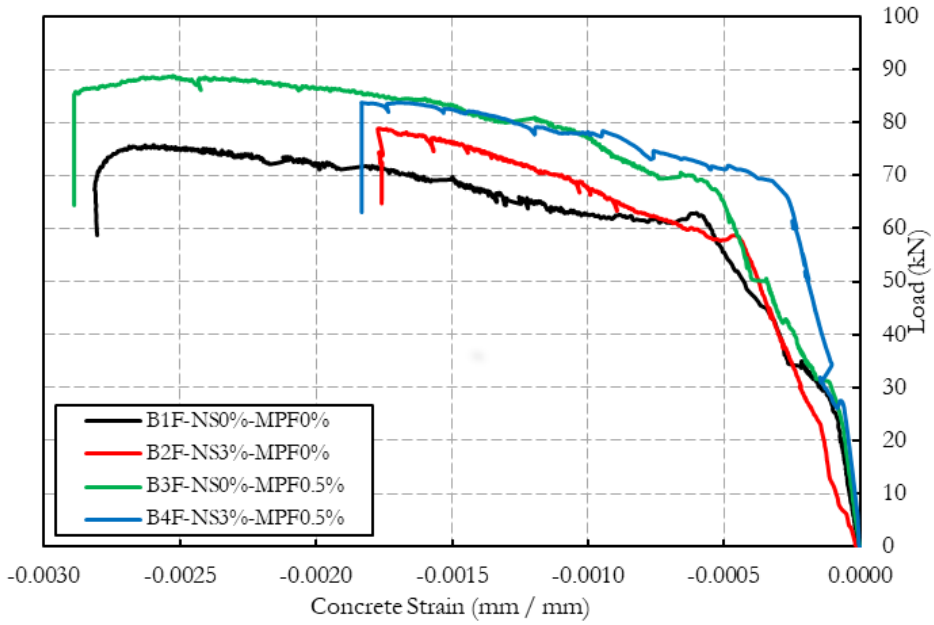


Figure 15. Load – Concrete compressive strain.

3.2.3. Steel tensile strain

The test beam specimens' steel tensile strain curves were used to investigate the effects of NS and MPF. The tested load-steel strain curves of the bottom steel bar for beam specimens are displayed in Table (9) and Figure 16). As can be observed, the addition of NS and MPF in the beam specimen (B4-NS3%-MPF0.5%) showed a higher ultimate load. The results indicate that NS and MPF in the concrete mix led to an improvement in steel strain related to the failure load. A small increase in the ultimate strain related to the failure load results from adding NS to concrete mixtures. due to the section designed to allow for flexural failure, The bottom reinforcement in each beam, which had a significant amount of strain ductility, had reached the yield load level.

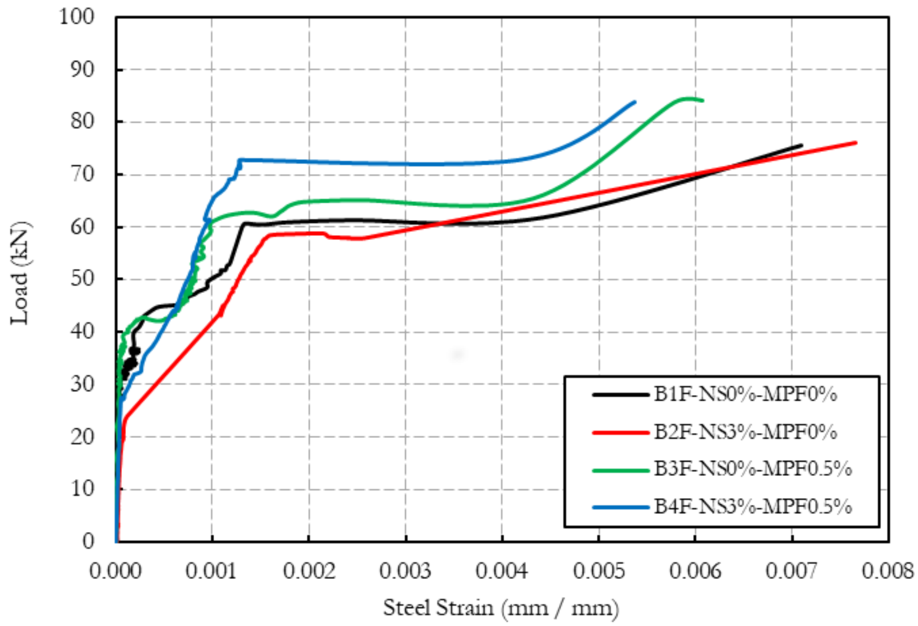


Figure 16. Load – Bottom steel strain.

3.2.4. Crack pattern and mode of failure

All of the tested beam specimens had the typical flexural failure, in which the steel bar yielded, and the concrete was crushed by the failure loads, as is shown in Figure 17), which illustrates the crack pattern and mode of failure of the each specimen. First crack moved from tension zone to compression zone from the flexural zone. Relative to the control beam specimen (B1-NS0%-MPF0%), specimens containing NS content only (B2-NS3%-MPF0%) The addition of NS particles to the concrete mixture produced a filling effect that improved crack spacing while reducing the number of cracks. All the cracks that appeared between the point loads were flexural cracks near the mid-span of the beam. Due to the relatively low ratio of the longitudinal tensile reinforcement, all of the tensile steel bars in these specimens failed, and all of the specimens displayed flexural failure. Some Shear-bending cracks occurred and extended diagonally toward the point load as the failure load level reached.

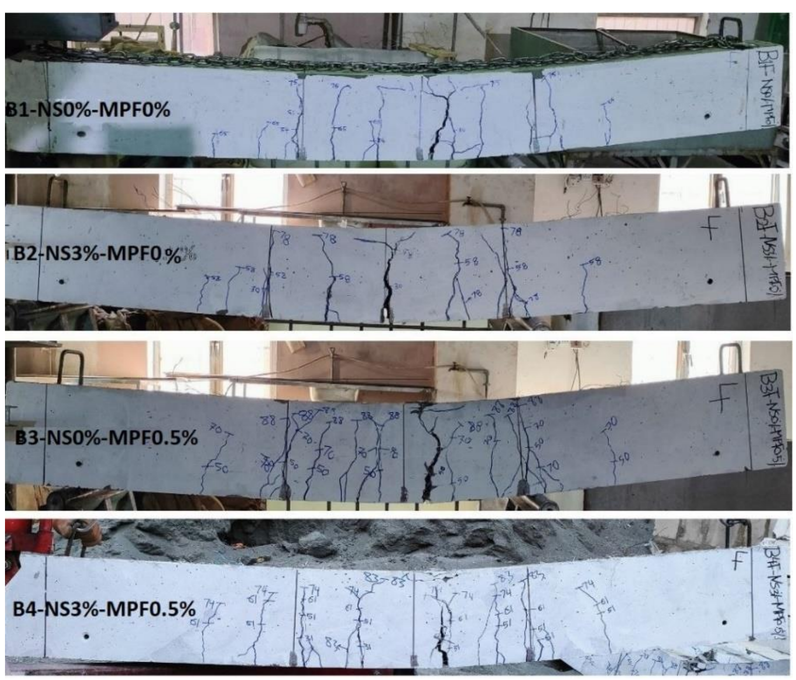


Figure 17. Crack patterns of tested beams.

4. Conclusions

The flexural behaviour of RC beams containing NS and MPF was studied and compared with the result of the control mix. The experimental structural responses were investigated using load deflection, concrete compressive strain, steel strain, and crack patterns. In addition, the mechanical properties studied, such as compressive strength, indirect tensile strength, flexural strength, and modulus of elasticity. The following conclusions were drawn in consideration of the experiment results:

- The mixture of NS and MPF greatly enhances the majority of the mechanical properties of the concrete. when relative to plain concrete and concrete containing NS and fibers individually.
- The addition of 3% of NS and 0.5% of MPF in the concrete mix, either individually or together, improved the mechanical properties, such as compressive strength by 33.6%, split tensile strength by up to 54.1% and flexural strength by up to 28.3%, compared with control specimens.
- It was found that partial replacement of cement with 3% of NS and MPF has an improvement on the elastic modulus of concrete by 15.8%.
- The Addition of 3% of NS content to mix (B2-NS3%-MPF0%), and 0.5% of MPF to mix (B3-NS0%-MPF0.5%), and combined of 3% NS with 0.5% MPF to mix (B4-NS3%-MPF0.5%) caused the failure load increased by 4.2%, 17.3%, and 10.6%, respectively, and a decrease in the ultimate deflection by 19.4%, 8.5% and 38.7% in comparison with control mix (B1-NS0%-MPF0%). Besides, the first cracking load was increased by 3.3%, 10%, and 6.7% for the above concrete mixes respectively.
- The concrete mixture containing 3% of NS has a slight effect on the enhancement of the ultimate maximum load (4.2% increase).
- The failure mode of high-strength beam specimens changed from brittle to ductile mode due to the addition of fibers. The results revealed that the MPF improved the concrete compressive strain.

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