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Research Article

Behavior of Reinforced Composite Foamed-Normal Concrete Beams

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A study has been undertaken to investigate the production and behavior of beams made with foamed, normal, and composite concrete and reinforced with different steel percentages (under, balanced, and over). Nine reinforcement beams, including three normal-weight concrete, three lightweight foamed concrete, and three composite concrete, were made with similar rectangular cross sections of dimensions (150 × 250 mm) and length of 1500 mm. A 28-day compressive strength of 29 MPa (suitable for structural purposes) was achieved for all investigated concrete mixes. Ultimate load, crack mode, ductility, deflection, and stiffness as flexural parameters were investigated. The results showed that in terms of loading, the load of composite concrete beams was equal to that of normal concrete beams, and a slight increase in the lightweight foamed concrete beams was noticed. The ductility of foamed concrete beams with balanced reinforcement and under reinforcing was lower than that of normal concrete. In the case of the over-reinforcement beams, the ductility of foamed concrete beam increased by about 19.5% compared to that of normal reinforced concrete. In addition, the ductility and stiffness of composite concrete beams increased by about 91.7% and 5.6% compared to normal beams and 61% and 15.1% compared to foamed concrete beams, respectively.

1. Introduction

The Romans were the first to discover that agitating a mixture of small gravels, coarse sand, heated limestone, water, and animal blood resulted in the formation of tiny gas bubbles, which enhanced the mixture. This discovery was made during the first century of the Common Era [1, 2]. Several nations, including the United Kingdom, Germany, the Philippines, Turkey, and Thailand, use foamed concrete (FC) in construction [3]. Foamed concrete is distinguished by its low density (400–1850 kg/m^3) and its intermittent air holes, which result from adding a foam agent combination to the mortar [1]. For structural applications, the density should be between 1350 and 1900 kg/m^3, and the compressive strength should be greater than 17 MPa [4].

In the study by J. H. Tan et al. [5], flexure behavior of two reinforced foamed concrete beams with cement-sand ratios W1 and W2 was compared to conventional concrete beams with densities of 1,750 kg/m^3 and compressive strengths of 25 MPa. It was determined that foamed concrete beams carry 22% to 24% less final load than standard-weight concrete beams and can perform 54% for W1 and 49% for W2 over their design capacity. In addition, lightweight reinforced concrete beams typically deflect 13 to 20% more than normal-weight reinforced concrete beams. However, the reinforced foamed concrete beams exhibited less displacement ductility than the normal-weight reinforced concrete beams.

Lee et al. [6] investigated the flexural characteristics of reinforced normal concrete beams and slabs composed of foamed concrete at densities from 1700 to 1800 kg/m^3. The investigators recorded their observational findings. Four foamed concrete beams and three conventional-weight concrete beams were investigated. In order to achieve the prescribed compressive strength of 20 MPa intended for structural applications within 28 days, the four lightweight foamed concrete mixes were generated by utilizing varying cement-sand and water-cement ratios. From the findings, the reinforced foamed concrete beams demonstrated a diminished ability to endure the ultimate load, which varied from 8% to 34%, in contrast to the reinforced normal-weight concrete beams with identical reinforcement configurations.

An investigation conducted by Abd and Ghalib [7] focused on analyzing four reinforced concrete beams comprising two foamed concrete beams and two normal-weight concrete beams with dimensions of $200 \times 250 \times 1500$ mm. The density aimed for the lightweight foamed concrete beams was 1800 kg/m^3. After conducting a comparative analysis between conventional concrete beams and lightweight foamed concrete reinforced with GFRP bars, it was observed that the load capacity of the latter was increased by 3.6% in comparison to the load capacity of the former. The results suggested that using glass fiber reinforced polymer (GFRP) bars as reinforcement for foamed concrete beams led to an increment of 11.54% in the load-bearing capacity compared to beams reinforced with steel.

Syahrul et al. [8] analyzed the flexural behavior of typical reinforced concrete using 28 mm steel bars in the compressed cross section, 216 mm and 8 mm shear steel bars in the tensile section, and foamed concrete at both ends with normal-weight concrete anchors consisting of two lightweight foamed concrete composite beams and two control normal-weight concrete beams, all of which have the same reinforcing structure and measurements of 1600 mm in length, 200 mm in height, and 150 mm in width. The flexural test findings for a composite foamed concrete beam showed diagonal crack patterns, ductile deflection behavior, and a limited flexural capacity for the beam.

Al-Farttoosi et al. [9] examined twelve concrete columns comprising two distinct concrete layers. The beams comprised two kinds of concrete layers: lightweight aggregate concrete (LWAC) and normal-weight concrete (NWC). Compared to typical concrete beams, the preponderance of two-layer beams exhibited minimal variations. Still, there have been notable improvements that completely replaced LWAC beams. Using ACI 318-19, experimental results were compared to predicted values after a few changes were made to suit the equations to two-layer beams. Analyses were made regarding service load-induced deflection, moment capacity, and fracture moment.

Composite beams with foamed concrete reduce the structure's overall mass. Due to harsh surroundings and excessive mechanical loading, structures made of lightweight concrete are susceptible to variable degrees of damage [10, 11]. Damages include cover spalling, severe cracking, excessive deflections, corrosion of steel reinforcement, and concrete durability deterioration [11, 12]. This study adopted the layered system, i.e., separating the beam into two layers and casting the lower layer with lightweight foam concrete and the upper layer with regular concrete to reduce these damages.

This study investigates the behavior of beams made with various concrete types and steel reinforcement percentages. The flexural behavior of nine cast beams made of three normal concrete (NC), three foamed concrete (FC), and three composites (CC) consisting of one layer of foamed concrete and another of normal concrete was investigated. Each group (foamed, normal, and composite) was additionally reinforced as under-reinforced, balance-reinforced, or over-reinforced.

2. Experimental Program

2.1. Mixtures and Material Proportions. In this investigation, normal concrete and foamed concrete both were evaluated. The foamed concrete mix was intended to have a target density of 1700 kg/m^3. Sand that complies with ASTM C33-13 [13], gravel, water, and ordinary Portland cement that meets ASTMC150M-15 [14] make up normal concrete. The ingredients of foamed concrete included ordinary Portland cement, fine sand with a maximum size of 2.36 mm [15], fly ash that complied with ASTM C618 [16], silica fume that complied with ASTM C1240 [17], superplasticizer, water, polypropylene fiber at 0.5% of the mix volume, and foam. In order to make the preformed foam, a foaming agent liquid was diluted with water in the foam generator at a volume ratio 1 : 40 [18]. The mix proportions are provided in Table 1.

2.2. Steel Reinforcement. For the bottom longitudinal reinforcement of the beams, deformed steel bars of 12 mm and 8 mm diameter were utilized. In comparison, bars of 6 mm diameter were used for the top reinforcement, and bars of 8 mm diameter were used for the stirrups. Steel bars and stirrups yield tensile strengths of 600 MPa, 667 MPa, and 420 MPa, respectively.

2.3. Section Configuration. As indicated in Table 2, nine concrete beams having the measurements such as 1500 mm in length, 250 mm in height, 150 mm in width, and 1350 mm clear span between supports were strengthened. Figure 1 shows the details of the reinforcement of the beam. The beams comprised three normal-weight concrete beams, three foamed concrete beams, and three composite beams. The concrete cover thickness was 25 mm.

2.4. Casting and Curing. There were nine reinforced concrete beams: three foamed concrete beams, three normal-weight concrete beams, and three composite beams. The vibrator was employed when the samples were cast while casting the beam sample with the standard mixture. In the case of foamed concrete, we did not use the vibrator because the mixture does not need compaction, as it is self-compacting. When pouring the layers, a layer of foamed concrete was poured and left for 40 minutes until it hardened and the normal concrete layer was poured. The reinforcing steel determined the size of the layer, as shown in Figure 2. There were two different forms of treatment. In the first, samples of normal concrete were submerged in water for 28 days. The second type was wrapping foamed and composite layer concrete samples with nylon and leaving them for 28 days.

2.5. Setup of Testing. A hydraulic machine with a 500 kN capacity was used to perform four-point bending tests on specimens with a total length of 1500 mm, a clear span of

Table 1: Mix proportion of investigated normal concrete and lightweight foamed concrete mixes.

Mixes	Material								
	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)	Fly ash (kg/m^3)	Silica fume (kg/m^3)	Superplasticizer (kg/m^3)	Foam (l/m^3)	Polypropylene fiber (%)
NC	425	700	1100	210	—	—	—	—	—
FC	500	882.5	—	160	100	50	7.5	270	0.5

Table 2: Details of reinforcement.

Beams code	Concrete type	Reinforcement percentage
-Nρ1	Normal concrete	2 × 8 mm steel bar (under reinforcement)
-Nρ2	Normal concrete	2 × 12 mm steel bar (balance reinforcement)
-Nρ3	Normal concrete	3 × 12 mm steel bar (over reinforcement)
-Fρ1	Foamed concrete	2 × 8 mm steel bar (under reinforcement)
-Fρ2	Foamed concrete	2 × 12 mm steel bar (balance reinforcement)
-Fρ3	Foamed concrete	3 × 12 mm steel bar (over reinforcement)
-Cρ1	Foamed + normal concrete	2 × 8 mm steel bar (under reinforcement)
-Cρ2	Foamed + normal concrete	2 × 12 mm steel bar (balance reinforcement)
-Cρ3	Foamed + normal concrete	3 × 12 mm steel bar (over reinforcement)

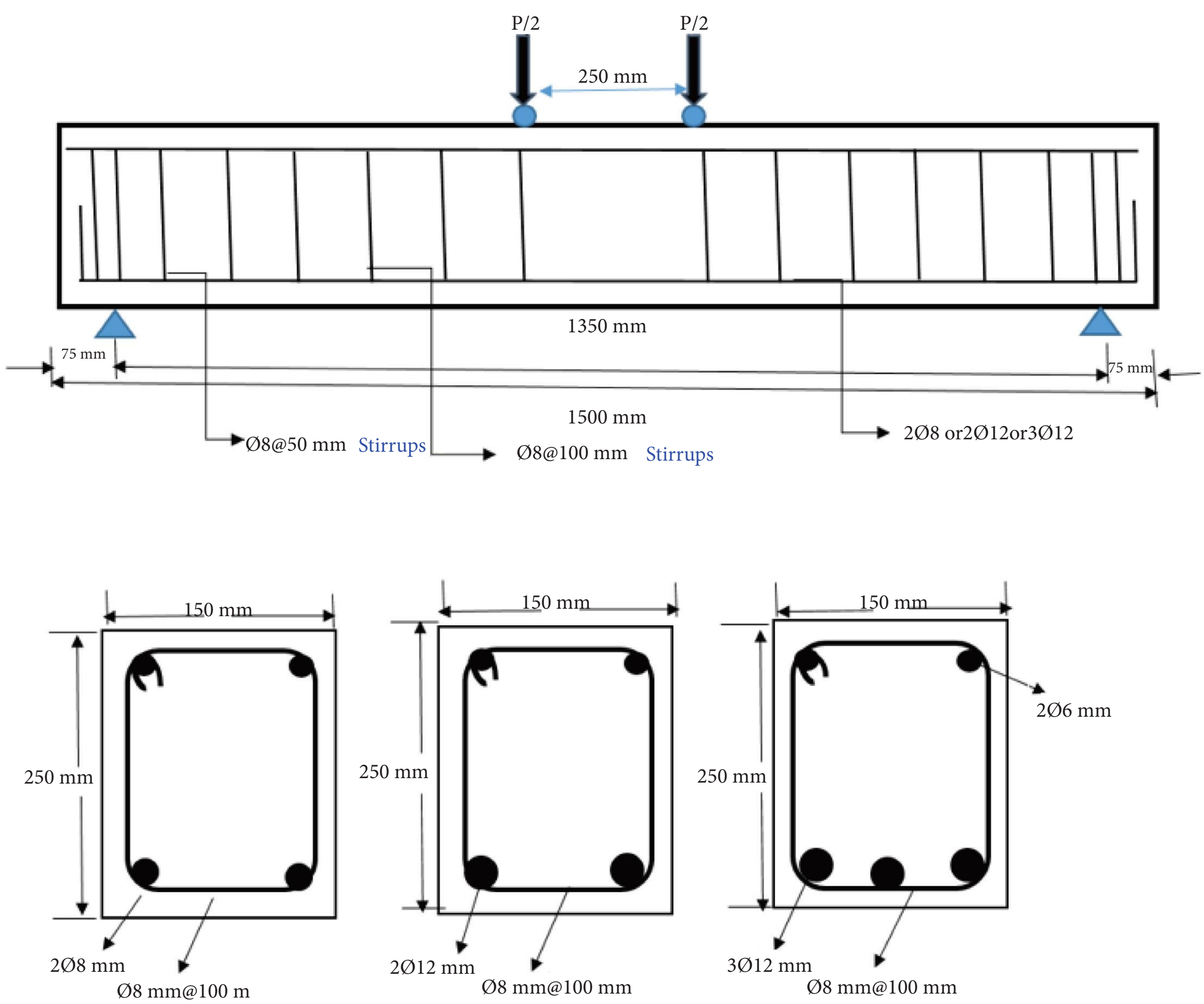

Figure 1: Beam reinforcement details.

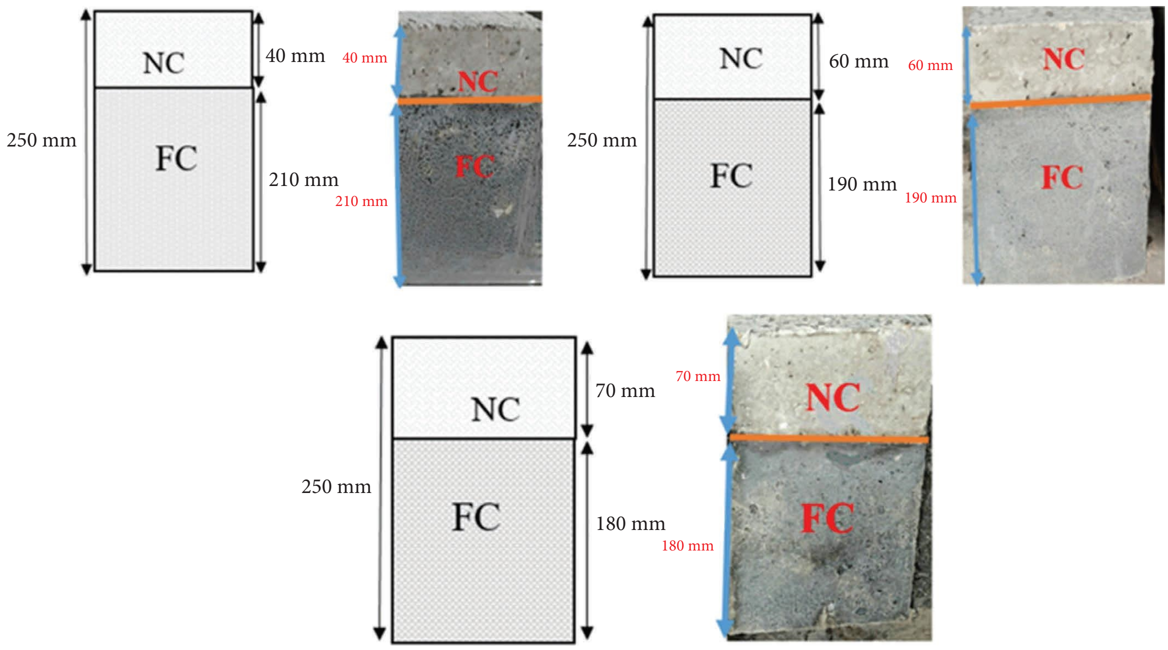

Figure 2: Cross sections of composite beams.

1350 mm, and a shear span of 550 mm, as shown in Figure 3. The cross sections in the beams were 150 mm wide and 250 mm deep. All test specimens were supported by roller supports placed 75 mm from the supports right and left ends.

During the test, the load is applied to a rigid steel plate through a hydraulic jack, coupled to two rigid steel cylinders fixed at the loading locations. Between the hydraulic jack and the steel plate, load cells are located. The load application rate was 5 kN/second. Four linear variable differential transducers (LVDTs) with a capacity of 120 mm were used to measure the deflection, one fixed at mid-span, another on the same height as the support beam, and the other two fixed under the two-point of loading. Two strain gauges were attached to steel reinforcements to measure the object strain before casting. During the loading test, the crack patterns were observed and mapped.

3. The Results and Observations

3.1. Weights of Reinforced Concrete Beams. Table 3 shows the weights of concrete beams for all reinforced concrete beams. A decrease was observed in the weight of the lightweight foamed-reinforced concrete beams by a rate ranging between 24.6 and 25.4, and this explains the increase in the deflection in the foamed beams compared to what is in the normal concrete. As for the composite reinforced concrete beams, the reduction percentage by weight ranged between 19.4 and 21.4.

3.2. First Crack Load. The appearance of the first crack on the bottom side of the tested samples was adopted to determine this load. Figure 4 demonstrates that foamed concrete beams have a lower first cracking load than conventional concrete beams. The reason is that the foamed concrete beams have a lower modulus of elasticity, so the stress according to the same deformation level is lower [19]. A careful analysis of these values shows that concrete strength and the amount of tensile reinforcement have the greatest influence on the formation of flexural cracking, increasing or delaying the formation.

3.3. Behavior of Load Deflection. A graph of the load-deflection curves was created to illustrate the influence of the applied load on the mid-span deflection. These graphs illustrate the beam deformations that were caused by the application of a bending moment to the specimens that were tested. Figure 5 illustrates the usual load-deflection profiles for the studied beam specimens. That load-deflection response of the experimentally tested reinforcement concrete beams can be divided into phases as follows: linear elastic up to first cracking, postcracking stage with multiple crack growth, yielding of tension reinforcement stage, and deformation due to plasticity phase with gradual loss of load carrying capacity until failure [20].

Table 4 presents the crack, yield, and ultimate load and deflection results. The load-deflection response of all nine beams put through the test was, on average, close to being identical. The curves representing each tested beam began with a linear slope at the beginning of the test and stayed relatively steady until the first cracks emerged in the beams. After the cracks appeared, the slope of the curve continued to get steeper until the tensile reinforcement finally broke away. The curve appears to be nearly horizontal before the end of the test, and then the curve starts to go down at the point of failure, and failure occurs. The deflections were measured in the middle of the sample period. In general, it was discovered that all samples showed almost the same behavior for the load-deflection relationship. However, it

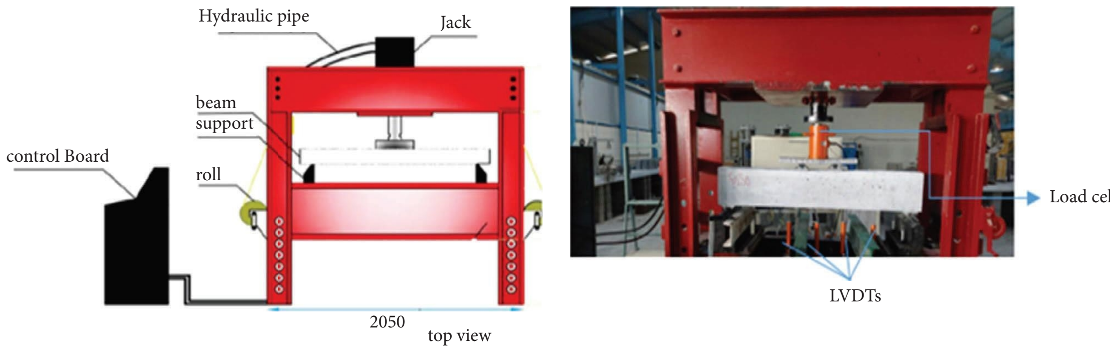

Figure 3: Setup of testing (a) machine testing schematic and (b) actual beam models under the test device.

Table 3: Weights of reinforced concrete beams.

Beam symbol	Weight (kg)	Reduction (%)
Nρ1	140	—
Fρ1	105	25
Cρ1	110	21.4
Nρ2	142	—
Fρ2	106	25.4
Cρ2	114.5	19.4
Nρ3	143.2	—
Fρ3	108	24.6
Cρ3	115.5	19.4

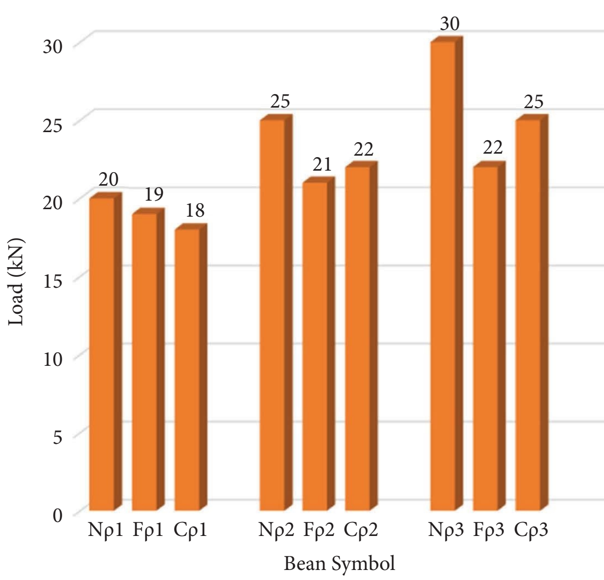

Figure 4: First crack results.

differed in the foamed concrete beams, where it was more deflected than the rest of the normal and composite beams. Figures 5(a) and 5(b) show the beam mid-span deflections at the ultimate experimental moment. The most reinforced composite concrete beams had mid-span deflections that were less than those of reinforced normal-weight concrete beams and foamed concrete beams, where the presence of a normal concrete layer helped to restrain the movement of foamed concrete and lessen the deflection of the composite beam. As for Figure 5(c), in the case of high reinforcement, it was found that foamed concrete (Fρ3) is less deflected than normal concrete (Nρ3) and composite concrete (Cρ3).

3.4. Reinforcement Strain at the Mid-Span. Figure 6 shows the reinforcement strain behavior investigated beams. The steel reinforcement at both the top and bottom of the structure had its strain measured. These strain gauges were utilized to analyze the behavior of the strain. The general pattern revealed that the top portion of the samples for all beams was subject to compression, as shown by the strain gauge's recording of negative values; conversely, the lower portion of the samples was subject to tension, as indicated by the strain gauge's recording of positive values. We can see from all the numbers that the strain grows as the weight on the beam grows. It begins linearly, and when cracking occurs, it gradually increases until it reaches its peak at failure. We also noticed that the strain reaches its maximum in the case of over-reinforcement beams. Table 5 presents the maximum tension and compression strains.

3.5. Ductility. The ability of an element to behave inelastically and absorb energy is measured by its ductility. Based on the beam's inelastic deformation state, flexural ductility denotes that the structural member can endure significant deflections before failing [9]. There are numerous varieties of ductility, such as curvature ductility, rotational ductility, and displacement ductility. Within the scope of this study is an investigation into displacement ductility. When referring to tensile steel, the term "displacement ductility" refers to the deflection ratio that occurs at the ultimate load to the amount of deflection that occurs at the point where the steel first yields. The ultimate load is the highest possible load that may be placed on a beam while being tested [21]. Table 6 demonstrates that the ductility of foamed concrete beams with balanced reinforcement and under reinforcement is significantly lower than that of normal concrete. This demonstrates that raising the reinforcement ratio results in decreased ductility and deflection. Also, according to Shafigh

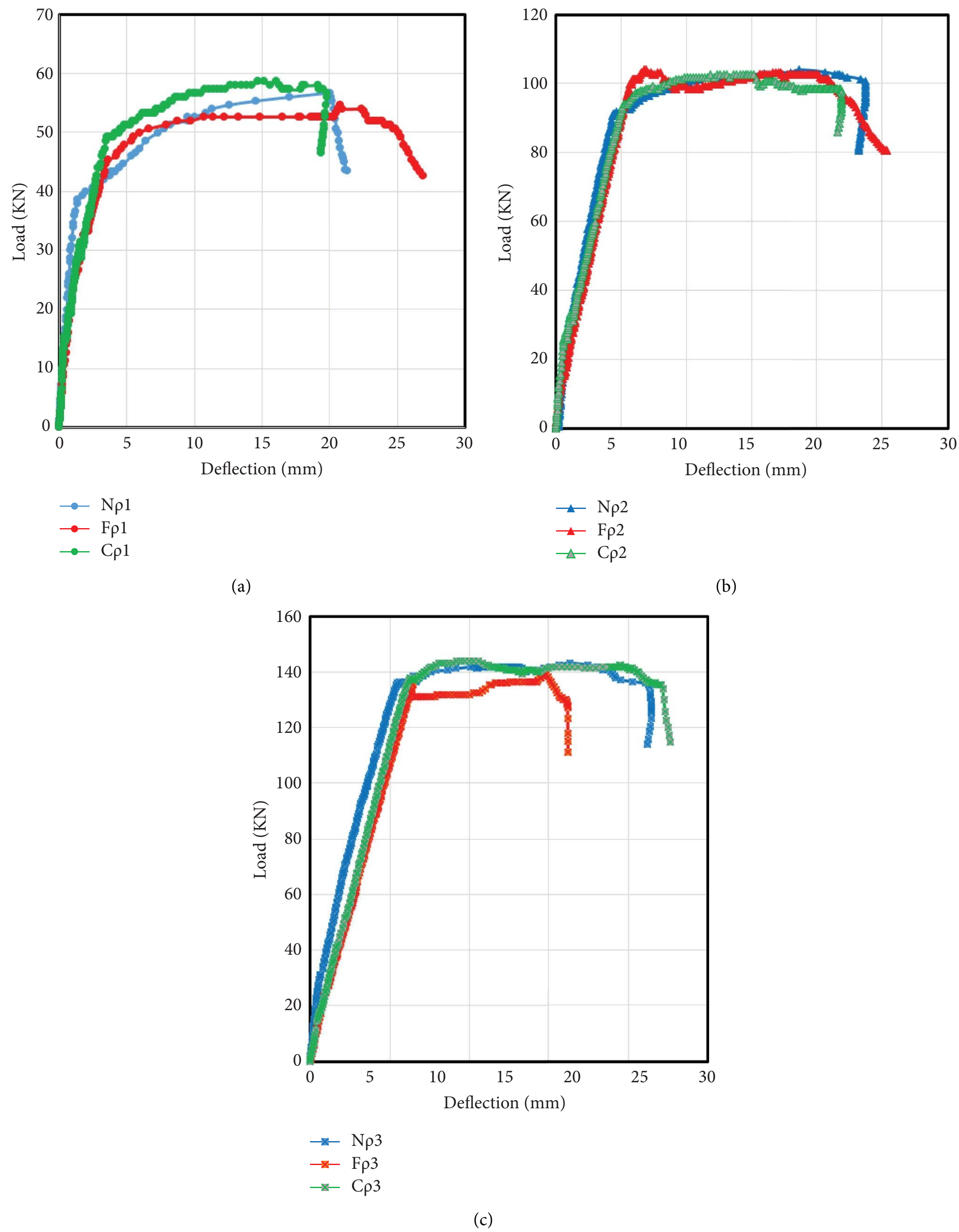

Figure 5: Load-deflection of investigated beams.

et al. [22], increasing the amount of tension reinforcement in reinforced lightweight concrete beams reduces ductility. In the case of the over-reinforcement beam, the ductility of the foamed concrete model (Fρ3) increased by 19.5% compared to the normal reinforced concrete (Nρ3), and the ductility of the composite concrete (Cρ3) increased by 91.7 compared to (Nρ3) and 61% compared to (Fρ3).

3.6. Stiffness. One of the most essential characteristics of a structural member is its flexural stiffness. It is measured by the degree to which a body resists deformation when subjected to a load. Initial stiffness is the slope of the linear part of the load-deflection curve before the onset of the first flexural fracture. Service stiffness is defined as the slope of the values representing fifty percent and eighty

Table 4: Results of loads and deflection for the examined beams.

Beam symbol	Cracking load (P_{crack}) (kN)	Cracking deflection (Δ_{crack}) (mm)	Yielding load (P_y) (kN)	Yielding deflection (Δ_y) (mm)	Ultimate load (P_u) (kN)	Ultimate deflection (Δ_u) (mm)
Nρ1	20	0.74	41.96	3.35	56.4	20.01
Fρ1	19	0.83	43.96	3.55	54.61	22.39
Cρ1	18	0.67	47	3.3	58.61	18.67
Nρ2	25	0.82	86.2	4.12	103.9	18.69
Fρ2	20	0.94	80	5.1	103.9	19.25
Cρ2	20	0.5	82.58	4.35	102.56	16.85
Nρ3	30	0.62	129	5	142.52	10.24
Fρ3	22	0.8	121.88	6.09	139.19	14.88
Cρ3	25	0.78	130.54	5.8	143.86	22.77

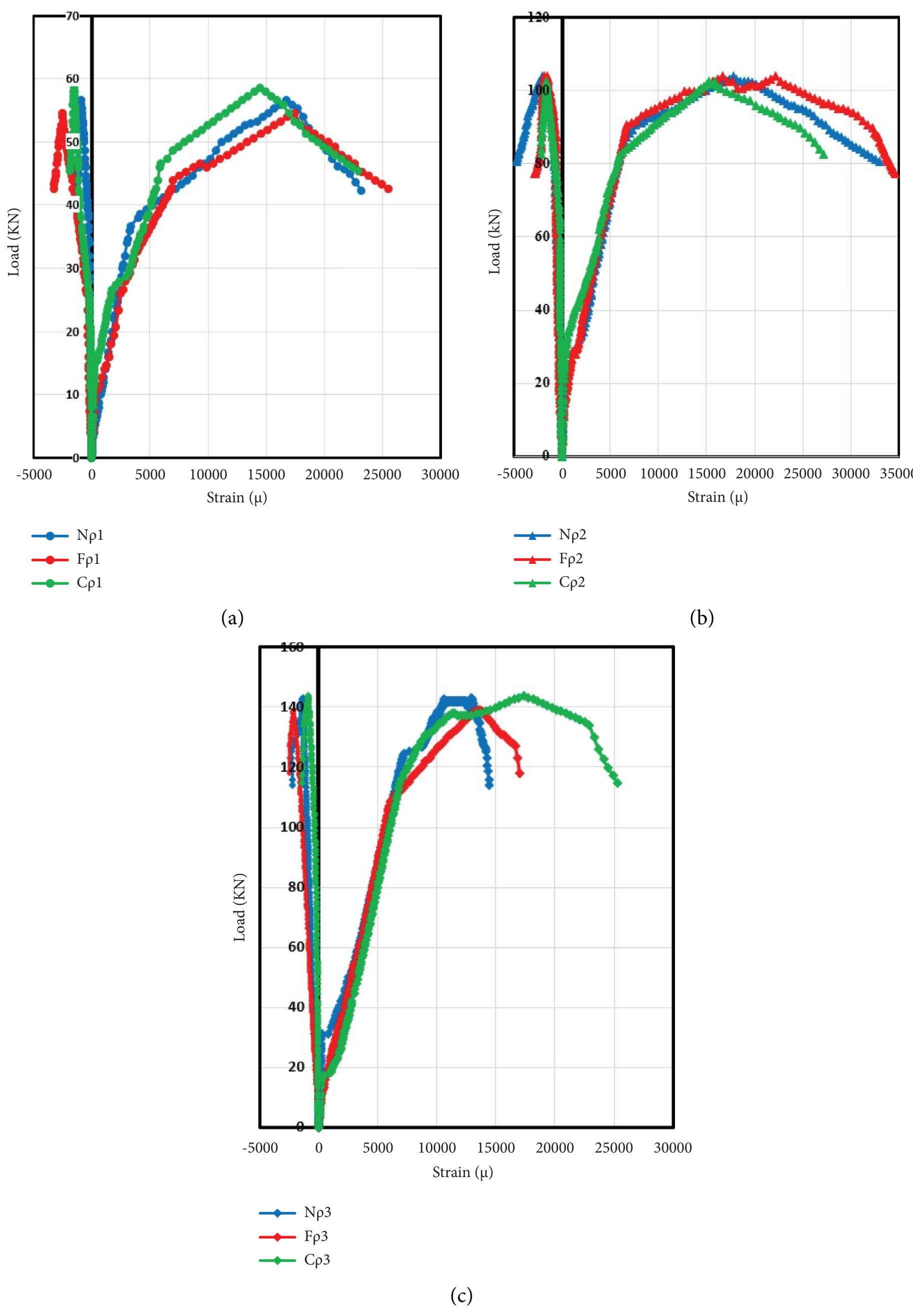

Figure 6: Reinforcement behavior for investigated beam.

Table 5: Maximum strain results.

Beam symbol	Ultimate load (kN)	Max. tension strain (μ)	Max. compression strain (μ)
Nρ1	56.4	23197.9	−1250.8
Fρ1	54.61	25547.4	−3269.1
Cρ1	58.61	22962.5	−1875
Nρ2	103.9	32953.3	−4713.4
Fρ2	103.9	34614.4	−2850.4
Cρ2	102.56	27209	−2190.8
Nρ3	142.52	14442.5	−2219.7
Fρ3	139.19	17041.7	−2517.7
Cρ3	142.52	25337	−1403.32

Table 6: Ductility values of investigated beams.

Beam symbol	Δu (mm)	Δy (mm)	Ductility	Increase (%)	Decrease (%)
Nρ1	20.01	3.35	5.97	—	—
Fρ1	22.39	3.55	5.86	—	1.84
Cρ1	18.67	3.3	5.65	—	0.167
Nρ2	18.69	4.12	4.54	—	—
Fρ2	19.25	5.1	3.77	—	31.9
Cρ2	16.85	4.35	3.87	—	14.7
Nρ3	10.24	5	2.05	—	—
Fρ3	14.88	6.09	2.44	19.5	—
Cρ3	22.77	5.8	3.93	91.7	—

Table 7: Stiffness value of investigated beams.

Beam symbol	P_{crack} (kN)	Δ_{crack} (mm)	Initial stiffness (kN/mm)	Increase (%)	Decrease (%)	Service stiffness (kN/mm)	Increase (%)	Decrease (%)
Nρ1	20	0.74	27	—	—	16.83	—	—
Fρ1	19	0.83	23.2	—	14	15.38	—	9.2
Cρ1	18	0.67	26.8	—	0.7	17.7	5.16	—
Nρ2	25	0.82	30.48	—	—	25.2	—	—
Fρ2	20	0.94	21.27	—	29	20.3	—	19.4
Cρ2	20	0.5	40	31.2	—	23.57	—	6.46
Nρ3	30	0.62	48	—	—	28.5	—	—
Fρ3	22	0.8	27.5	—	42	22.5	—	21
Cρ3	25	0.78	32	—	33	24.57	—	13.78

percent of the ultimate load capacity on the upper section of the load-deflection curve [19]. Table 7 shows that stiffness has been found to increase the amount of tension reinforcement. The initial compressive stiffness of the specimen might be improved by increasing the reinforcement ratio, which would also cut down on the number of folds [23].

3.7. Cracking Pattern and Mode of Failure. Figure 7 illustrates many ways in which each of the investigated beams failed. The beams failed similarly, which was a flexural failure at the middle of their spans, as was seen. When the load was first applied, every specimen exhibited elastic behavior. The first transverse crack appeared close to the center of the span as the load reached the strain tensile limitation of concrete. Cracking then progressed in the direction of the loading sites. At the maximum load, cracks began to spread to the top surface and were controlled by the reinforcement.

It is clear from Figure 7 that concrete has a lower total number of cracks, whereas composite concrete has a higher total number of cracks. Cracks become smaller, narrower, closer, and more widespread in layered concrete samples. Over-reinforcement beams of lightweight foamed concrete did not suffer from the damaging effects of concrete spalling or crushing. Beams with over reinforcement are strengthened so that the concrete cracks before the steel reinforcement give way, yet this condition does not occur when the ultimate load is applied. One possible explanation for this is that lightweight foamed concrete possesses less flexibility. The more the tortuosity of cracks, the higher the strength of the beam [24]. It should be noted here that all investigated beams were failed in the flexural mode.

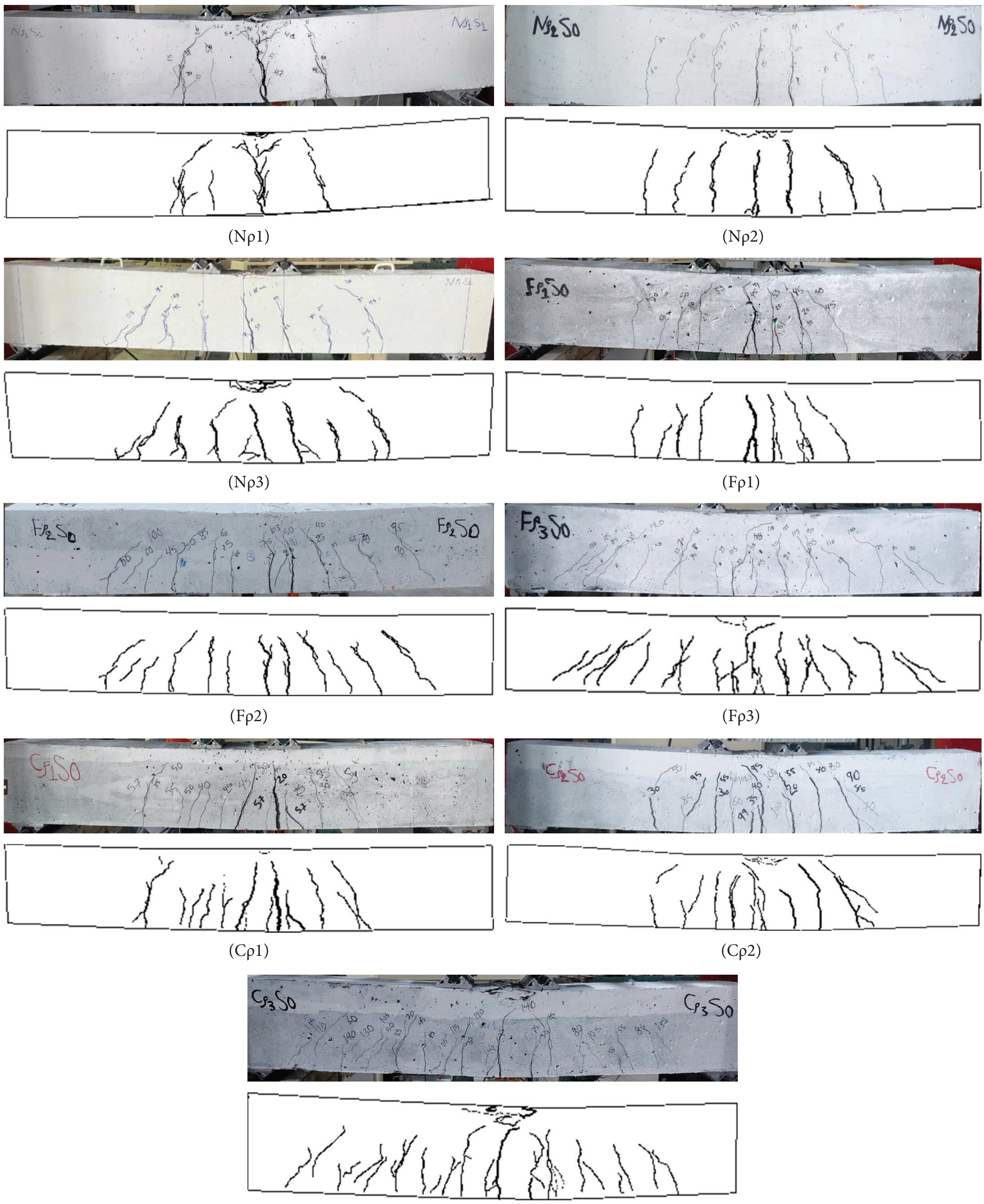

Figure 7: Failure modes and cracking pattern for investigated beams.

4. Conclusions

The flexural behavior of nine beams made with normal, foamed, and composite concretes reinforced with three different configurations was studied. The following conclusions can be drawn from the obtained results:

(1) Compared to the normal beams, about 25% beam weight reduction was achieved with using foamed concrete and this reduction was about 20% in the composite beams.

(2) The composite concrete beams exhibited a higher carrying capacity than the normal and foamed concrete beams.

(3) The deflections at the mid-span of the over-reinforced lightweight foamed concrete beams were greater than those of the reinforced normal-weight concrete and composite beams. It was determined that composite concrete had a lower deflection than foamed concrete and normal concrete. Foamed concrete (Fρ3) has a lower amount of deflection than both normal concrete (Nρ3) and composite concrete (Cρ3) when the reinforcing level is increased.

(4) The ductility of foamed concrete beams with balanced reinforcement and under reinforcement was lower than that of conventional concrete. The ductility of the foamed concrete (Fρ3) increased by 19.5% compared to the normal reinforced concrete (Nρ3) in the case of the over-reinforcement beam. Also, the ductility of the composite concrete (Cρ3) increased by 91.7 compared to Nρ3 and 61% compared to Fρ3.

(5) It was noticed that the stiffness increased in the composite concrete beam (Cρ1) by 5.6% and 15.1% compared to that of the normal concrete beam (Nρ1) and foamed concrete beam (Fρ1), respectively. This indicates that composite concrete beams are more rigid than ordinary and foamed concrete beams.

(6) It was discovered that increasing the quantity of tension reinforcement led to increasing stiffness. The initial compressive stiffness of the specimen may be improved by increasing the reinforcement ratio, which also has the potential to lower the number of folds.

In general, it was noticed that all investigated beams failed in flexural modes. In addition, the composite section (normal and foamed concrete) can be recommended to increase ductility and stiffness. With regard to the reinforcement percentage, it was found that the over-reinforced type was the best with the composite concrete beam.

Data Availability

No underlying data were collected or produced in this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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