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# Ductility, Toughness, and Flexural Performance of Hybrid Foamed-Normal Concrete Beams

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**ABSTRACT**

A study examined the ductility and toughness properties of beams made of reinforced concrete, including foamed, normal, and hybrid beams. Nine reinforced concrete beams were produced: three foamed concrete beams, three normal concrete beams, and three hybrid concrete beams. Each beam possessed identical rectangular cross-sectional dimensions of 1500 mm × 250 mm × 150 mm. The flexural parameters (ultimate load, ductility, deflection, and durability) were assessed for each type of concrete utilized. The study's results showed that the load-bearing capacity of hybrid concrete beams was comparable to that of normal concrete beams, whereas foamed concrete beams exhibited slight improvement in their ability to carry loads. The ductility of reinforced foamed concrete beams was lesser than that of normal concrete. For over-reinforced beams, the ductility of hybrid concrete beams showed a significant improvement of 61% compared to foamed beams and an even more significant increase of 91.7% compared to normal beams. Furthermore, the hybrid concrete beam with over-reinforcement had a flexural toughness of 18.7% greater than the normal concrete beam. Suggested that a hybrid section comprising conventional and foamed concrete be utilized to decrease ductility and improve stiffness.

## 1. Introduction

Foamed concrete is a type of concrete that has a low weight, with a density ranging from 400 to 1850 kg/m3. It is made by introducing air gaps into a mortar using a mixture of foam agents (Jones & McCarthy, 2005). The density for structural applications should be within the range of 1350 to 1900 kg/m3, while the compressive strength must surpass 17 MPa, (Neville, 2006). Normal-weight concrete's dead weight raises building costs because the structural member must carry its weight and the applied load. Cost savings are greater with a lighter structural part. Deadweight reduction lowers column loads and foundation loads. The material usage savings are considerable, and the building will be easier to design and build. Reinforced lightweight foamed concrete beams have superior strength-to-weight ratios, allowing longer beam spans and fewer intermediate columns. As member sizes decrease, steel reinforcements will be used less, (Tan et al., 2005).

Abd and Ghalib (2018) investigated four reinforced concrete beams. Beams were classified into two distinct categories: foamed concrete beams and conventional concrete beams. The dimensions are 1500 mm in length, 250

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mm in height, and 200 mm in width. It has been determined that the optimal density for lightweight foamed concrete pillars is 1800 kg/m3. The load capacity of foamed concrete beams was enhanced by 3.6% when reinforced with GFRP bars, as opposed to conventional concrete beams. According to the study's findings, incorporating GFRP bars as reinforcement into lightweight foamed concrete beams increased their load capacity by 11.54 % when compared to steel reinforced with steel.

AL-Farttoosi et al. (2021) investigated a total of twelve concrete columns that were constructed using two separate layers of concrete. Two distinct types of concrete were utilized to fabricate the beams: lightweight aggregate concrete (LWAC) and normal-weight concrete (NWC). The data suggests that most two-layer beams demonstrated only marginal deviations as opposed to normal concrete beams. Despite some significant improvements, when compared to totally lightweight aggregate concrete (LWAC) beams. To establish a connection between the equations and two-layer beams, the ACI 318-19 model underwent modifications before comparing the experimental results and the projected values. The comparison was conducted based on fracture moment, moment capacity, and deflection caused by service load.

Syahrul et al. (2021) examined the flexural characteristics of lightweight foamed concrete (CB) with normal-weight concrete anchors positioned at both ends. In addition, they analyzed normal reinforced concrete that utilized 28 mm steel bars in the compression area, 2Ø16 mm steel bars in the tension area, and 8 mm shear steel bars. The structure comprises two beams of foamed concrete hybrid and two of normal-weight concrete. The latter beams are included for comparison. By employing the same way, the beams are strengthened, and their dimensions are as follows: 1600 mm in length, 200 mm in height, and 150 mm in breadth. A composite beam made from lightweight foamed concrete was subjected to flexural testing, and the results showed that the beam displayed ductile deflection behaviour, diagonal fracture patterns, and a relatively low flexural capacity.

The aim of using hybrid beams and lightweight foamed concrete together is to make the building process lighter overall. Environmental factors such as harsh and heavy mechanical loads can break down lightweight concrete structures differently (Kim et al., 2007). Problems include cover spalling, severe cracking, excessive deflections, corrosion of steel reinforcement, and loss of concrete durability (Batran et al., 2021). This study adopted a structure with layers to minimize these damages. The beam was divided into two parts, with the lower half constructed using foamed concrete and the upper part composed of normal concrete.

This study assesses the flexural performance, ductility and toughness of beams constructed using different concrete and steel reinforcing ratios. It was undertaken to enhance the flexural performance of nine cast beams. Nine concrete specimens were utilized in the fabrication of these beams. During the test, a total of three beams, each of normal concrete (NC), foamed concrete (FC), and hybrid concrete (HC), were included. The hybrid concrete (HC) beams consisted of two separate layers: one made of foamed concrete and the other made of normal concrete. In addition, all of the three groups (foamed, normal, and hybrid) received reinforcement using one of three different approaches: under-reinforced (UR), balance-reinforced (BR), or over-reinforced (OR).

## 2. Experimental program

### *2.1 Material*

- Ordinary Portland cement that adheres to the Iraqi specification (IQS No5., 2019). The chemical composition of the cement utilized is presented in Table 1.
- The fine aggregate used in this research is natural sand. Iraqi specifications determined the physical parameters of the sand and sieving (IQS No45., 1984). The fineness modulus was 2.5.
- Natural aggregate with a maximum particle size of 12.5 mm was the coarse aggregate used to produce normal concrete beams. Iraqi specifications determined the physical parameters of the sand and sieving (IQS No45., 1984).
- Fly ash is within the limits of the specification of (ASTM C618, 2023). Table 2 lists fly ash's chemical properties.
- Silica fume is within the limits of the specification (ASTM C1240, 2015). Table 3 shows the chemical properties of fly ash used.
- Superplasticizer is an additive that reduces the content of water. The study used Sika viscocrete super 5930L.
- Water
- The polypropylene fibres used were mono-filament polypropylene fibres (PPF) that were 12 mm in length.

- Steel Reinforcement: The beams were reinforced longitudinally with deformed steel rods measuring 8 mm and 12 mm in diameter. Stirrup bars of 8 mm in diameter were used for the stirrup bars, while 6 mm diameter bars were used for the upper reinforcement. The yield strength of stirrups was 667 MPa, but the yield strength of steel rods was 600 MPa. The overall strength of the stirrups was 420 MPa.
- Foaming agent: In this investigation, foamed concrete was produced using a protein foaming agent. A foaming agent solution containing 25 grams of foaming agent per litre of water produced 30 kilograms per cubic meter of froth.

**Table 1 – Chemical composition of cement.**

| Oxides | Percentage | IQS 5/2019 |
|---|---|---|
| SiO2 | 21.1 | - |
| CaO | 64.1 | - |
| Fe2O3 | 3.4 | - |
| Al2O3 | 1.81 | - |
| MgO | 2.2 | Not more than 5% |
| SO3 | 2.33 | Not more than 2.8% |
| LIO | 2.25 | No more1than 4% |

**Table 2 – Chemical composition of fly ash.**

| Oxides | Percentage | IQS 5/2019 |
|---|---|---|
| SiO2 | 46.68% | - |
| Al2O3 | 27.93% | - |
| Fe2O3 | 17.84% | - |
| CaO | 4.99% | - |
| MgO | 2.55% | Max 5 % |
| SO3 | 0.31% | Max 5 % |
| C3A | 43.64% | - |
| LSF | 0.03 | - |

**Table 3 – Chemical composition of silica fume.**

| Oxides | Percentage | IQS 5/2019 |
|---|---|---|
| SiO2 | 92.5 % | Min 85% |
| Al2O3 | 1.2% | - |
| Fe2O3 | 2.0% | - |
| CaO | 1.0 % | - |
| MgO | 0.84 % | |
| SO3 | 0.14% | Max 4% |
| LSF | 3.4% | Max 6% |

## 2.2 Mix design

This study involved the evaluation of both conventional and foamed concrete. The objective was to achieve a target density of 1700 kg/m3 for the foamed concrete mixture. Normal concrete comprises sand, gravel, water, and standard Portland cement. Foamed concrete mixes Portland cement, sand (up to a maximum size of 2.36mm), silica fume, fly ash, superplasticizer, water, 0.5% volume proportion of polypropylene fibre, and foam. The pre-formed foam was produced by diluting a liquid foaming agent with water in a foam generator, using a volume ratio of 1 part foaming agent to 40 parts water (Hilal et al., 2014); mixes proportions are shown in Table 4.

**Table 4 – Mix proportion of foamed concrete and normal concrete mixes.**

| Materials | NC | FC |
|---|---|---|
| Cement ($kg/m^3$) | 425 | 500 |
| Sand ($kg/m^3$) | 700 | 882.5 |
| Gravel ($kg/m^3$) | 1100 | - |
| Water ($kg/m^3$) | 210 | 160 |
| Superplasticizer ($kg/m^3$) | - | 7.5 |
| Fly ash ($kg/m^3$) | - | 100 |
| Silica Fume ($kg/m^3$) | - | 50 |
| Foam ($l/m^3$) | - | 270 |
| Polypropylene fibre % | - | 0.5 |

## 2.3. Casting and curing

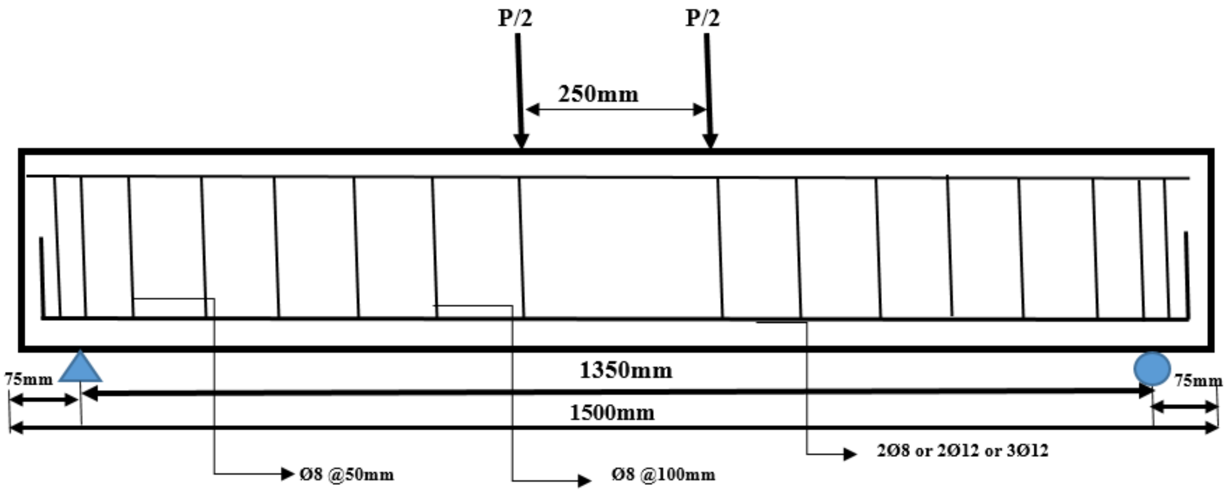
The experiment involves strengthening nine concrete beams, comprising three of normal-weight concrete, three of foamed concrete, and three of hybrid beams. The beams had the following dimensions: length of 1500 mm, height of 250 mm, width of 150 mm, and clear span between supports of 1350 mm. The concrete cover had a thickness of 25 mm. The data is presented in Table 5 and Figure 1. The vibrator was utilized during the casting process, namely when the beam sample was cast using the traditional combination. The vibrator was not utilized in the manufacturing process of foamed concrete due to its inherent self-compacting qualities, which eliminated the need for compaction. A foam concrete layer was poured and allowed to harden for forty minutes. It is then covered with a layer of regular concrete. The proportion of reinforcement steel determines the thickness of the layer. Treatment was provided using two different methods. Normal concrete samples were immersed in water for 28 days. In the second method, foam concrete and hybrid layer concrete samples were wrapped in nylon and left to dry for 28 days. Table 6 shows the values of the mechanical properties of normal and foamed concrete.

**Table 5 – Reinforcement details.**

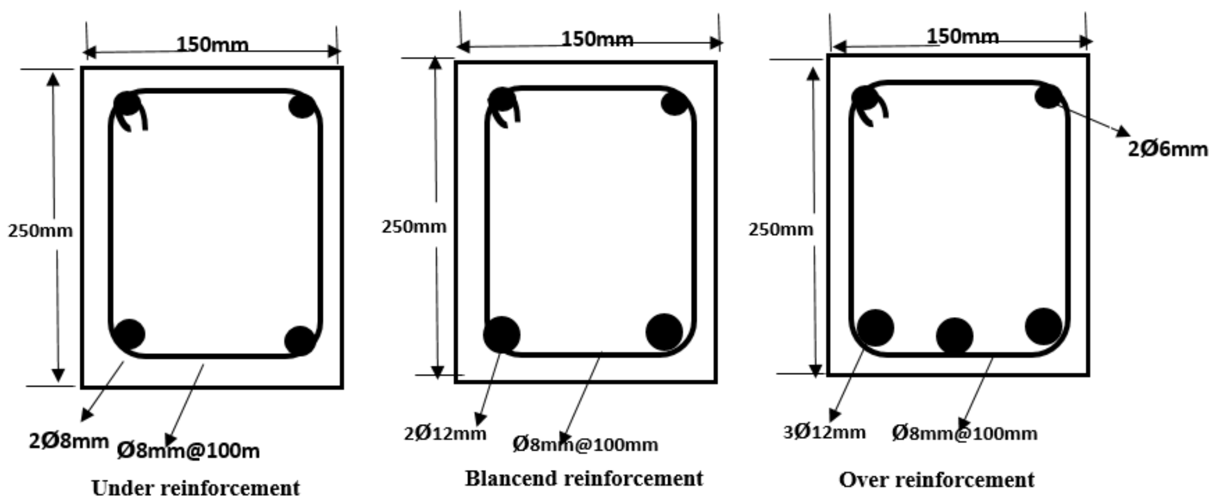
| Beams code | Concrete type | Reinforcement percentage |
|---|---|---|
| -N1 | Normal concrete | 2×8 mm steel bar (Under reinforcement) |
| -N2 | Normal concrete | 2×12 mm steel bar (balance reinforcement) |
| -N3 | Normal concrete | 3×12mm steel bar (over reinforcement) |
| -Fρ1 | Foamed concrete | 2×8 mm steel bar (Under reinforcement) |
| -Fρ2 | Foamed concrete | 2×12 mm steel bar (balance reinforcement) |
| -Fρ3 | Foamed concrete | 3×12mm steel bar (over reinforcement) |
| -H1 | Foamed + normal concrete | 2×8 mm steel bar (Under reinforcement) |
| -H2 | Foamed + normal concrete | 2×12 mm steel bar (balance reinforcement) |
| -H3 | Foamed + normal concrete | 3×12mm steel bar (over reinforcement) |

**Table 6 – The mechanical properties of normal and foamed concrete.**

| Mixes | Compressive strength ($f_{c'}$) (MPa) | Flexural strength (MPa) | Tensile strength (MPa) | Modulus of Elasticity (GPa) |
|---|---|---|---|---|
| NC | 29 | 4.5 | 3.6 | 26 |
| FC | 29 | 4.4 | 3.42 | 16.4 |




(a) Beam reinforcement




(b) Bstirrups

**Fig. 1 Beam reinforcement details.**

## *2.4. Test Setup*

The beam specimens used in the experiment were submitted to specific criteria for the four-point bending tests. The test measured 1350mm in clear span, 550mm in shear span, and 1500mm in total length. The hydraulic apparatus employed for this objective possesses a maximum capability of 500 kilonewtons. The beam had a cross-sectional height of 250mm and a width of 150mm. Roller supports supported the test specimens positioned 75mm to the right and left of the supports, as illustrated in Figure 2A, hydraulic lift puts force on a solid steel plate during the test. The hydraulic lift is linked to two steel barrels that stay in place at the loading areas. The load cells are placed between the hydraulic actuator and the steel plate. Five kN/s of stress were put on it. The displacement was determined using four linear variable differential transducers (LVDTs) with a combined capacity of 120 mm. Four Linear Variable Differential Transformers (LVDTs) were strategically positioned: one in the center, another at the same elevation as the support beam, and the remaining two at the locations where the load would be exerted.


**Fig. 2 Actual beam specimen under testing**

## 3. Test Results and Observations

### *3.1 Flexural Capabilities*

The testing results of the reinforced concrete are presented in Table 7. The experiment's findings are characterized by their utmost load-bearing capacity. It was noted that the ultimate load of all reinforced concrete beams rose proportionally with the amount of steel reinforcement. The foamed concrete beams also exhibited an ultimate load nearly identical to the normal concrete beams. Regarding the hybrid beams, there was a modest increase in the ultimate load.

**Table 7 – Load of investigated beams**

| Beam symbol | Ultimate load (kN) | Enhancement (%) |
|---|---|---|
| N1 | 56.4 | - |
| N2 | 103.9 | 84 |
| N3 | 142.52 | 152 |
| F1 | 54.61 | - |
| F2 | 103.9 | 90 |
| F3 | 139.19 | 154 |
| H1 | 58.61 | - |
| H2 | 102.56 | 75 |
| H3 | 143.86 | 145 |

### *3.2. Load–Deflection Behavior*

The load-deflection curves for the mid-span deflection are presented according to the applied load. The curves illustrate the distortions of the beams that were exposed to the applied bending moment. Figure 3 depicts the load-deflection profiles of the investigated beam specimens. The beams exhibited a linear relationship between load and deflection, with a steep increase during the cracking phase, suggesting a significant level of stiffness. After the initial application of force, the load-deflection curve maintained a linear trajectory. Over time, the slope of the curve gradually diminished as fractures formed, indicating a decline in stiffness. As the tension applied to the beams increased, the steel reinforcement deformed, substantially reducing the beams' stiffness. The load-deflection curve exhibited nonlinearity as the beams experienced significant deformation in response to a little increase in applied stress. The studied reinforced concrete beams' load-deflection response can be broken down into several stages. At first, the material behaves in a straight line until the first cracks appear. The next stage is "post-cracking," during which many cracks spread. After that, there is a phase where the tension support starts to give way. This is followed by a phase of plastic deformation where the load-bearing capacity slowly decreases until it breaks (Abtan & Jaber, 2016).

The load-deflection behaviour of all nine examined beams generally exhibited a uniform pattern. At the initial phase of the beam test, the curves showed a consistent linear incline until the first occurrence of cracks. The slope of the curve decreased as cracking occurred and continued until the tensile reinforcement hit its yield point. The curve demonstrates an almost parallel or level course as it approaches the finish of the test. The measurements were recorded in the exact centre of the object. In general, it was noticed that all specimens had the same load-deflection properties. The mid-span deflections of the beam at the measured ultimate moment are shown in Figures 3(a) and (b). The foamed concrete beams exhibited greater curvature in their midsections than the normal-weight concrete beams and the mixed beams with reinforcement. Results from real-world tests show that composite concrete bends less than normal concrete and foamed concrete. Figure (3) c shows that adding a lot of reinforcement to foamed concrete (F3) reduces deflection by increasing the material's stiffness, distributing loads more effectively, and controlling cracking.

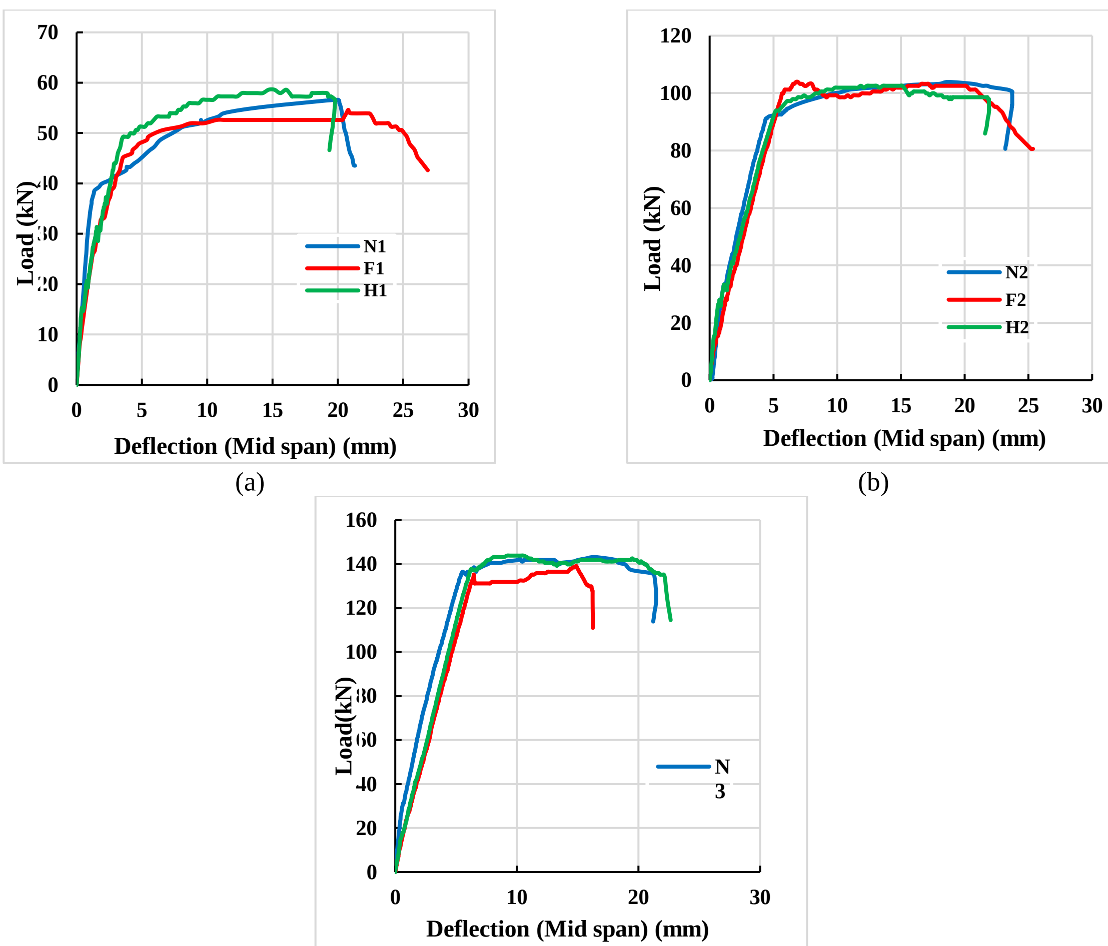



**Fig. 3 Load- Deflection of tested beams**

### *3.3 Ductility*

Ductility assesses an element's capacity to demonstrate non-elastic behaviour and assimilate energy. Flexural ductility is determined by the beam's ability to undergo significant deflections without failing, indicating its inelastic deformation condition (AL-Farttoosi et al., 2021). Ductility can be divided into different types, including displacement, rotational, and curvature ductility. This study focuses on the investigation of displacement ductility. The displacement ductility of tensile steel is characterized by the deflection ratio at initial yielding to deflection at ultimate load. During testing, the ultimate load refers to the maximum force that may be applied to a beam (Kong et al., 2006).

Table 8 shows that foamed concrete beams with symmetrical reinforcement and under-reinforcing have reduced ductility compared to conventional concrete beams. This demonstrates that when the reinforcement ratio increases, both deflection and ductility decrease. As stated by (Shafigh et al., 2011), The ductility of reinforced lightweight concrete beams decreases when the tension reinforcement increases (Jaffal et al., 2023). The foamed concrete beam (F3) exhibits a ductility that is 19.5% lower in the over-reinforced beam compared to the normal reinforced concrete (N3). Furthermore, it was noted that the hybrid concrete beam (H3) exhibited a remarkable increase in ductility with a 91.7% enhancement compared to (N3) and a 61% enhancement compared to (F3). The extraordinary increase in ductility of a hybrid concrete beam (H3) is primarily due to the combination of materials and reinforcements that provide better crack control, higher energy absorption, and delayed failure mechanisms. These enhancements allow the beam to deform before failure, improving its overall ductility and making it more resilient under load.

**Table 8 – Ductilities of tested beams**

| Beam symbol | Δu (mm) | Δy (mm) | ductility | Increase (%) | Decrease (%) |
|---|---|---|---|---|---|
| N1 | 20 | 3.34 | 5.98 | - | - |
| F1 | 20.8 | 3.55 | 5.85 | - | 1.85 |
| H1 | 19.79 | 3.32 | 5.97 | - | 0.167 |
| N2 | 18.68 | 4.10 | 4.5 | - | - |
| F2 | 19.25 | 5.1 | 3.7 | - | 31.9 |
| H2 | 16.85 | 4.35 | 3.87 | - | 14.7 |
| N3 | 15.65 | 5 | 3.13 | - | - |
| F3 | 14.88 | 6.09 | 2.44 | - | 19.5 |
| C3 | 22.76 | 5.8 | 3.93 | 91.7 | - |

### *3.4 Flexural Toughness*

The flexural toughness of concrete is defined as its ability to absorb and dissipate energy. Additionally, it is employed to assess concrete's fracture resistance and flexibility. The investigated beams' toughness values were determined by calculating the area under the curve using Excel software and AutoCAD 2022. Figure 4 displays reinforced beams for various kinds of concrete. The flexural toughness of the foamed concrete beam (F1) rose by 23.7% compared to the normal beam (N1). Conversely, the hybrid concrete beam (H1) decreased flexural toughness by 6.7% compared to the normal concrete.The foamed concrete beam F2 exhibited a decrease in flexural toughness, with a 23.6% reduction compared to the normal beam N2.

Similarly, the hybrid concrete beam (C2) had a 9.9% reduction in flexural toughness compared to the normal concrete beam. An observed decline in flexural toughness was noted in the foamed concrete beam (F3), with a decrease of 33.4% compared to the normal beam (N3). The reduced flexural toughness of foamed concrete relative to normal concrete is attributable to its increased air content, absence of coarse aggregates, weaker matrix bonding, reduced density, brittle characteristics, and diminished tensile strength. These variables diminish its efficacy in resisting bending forces and absorbing energy before failure. The hybrid concrete beam, H3, exhibited a substantial 18.7% enhancement in flexural toughness compared to the normal concrete beam.

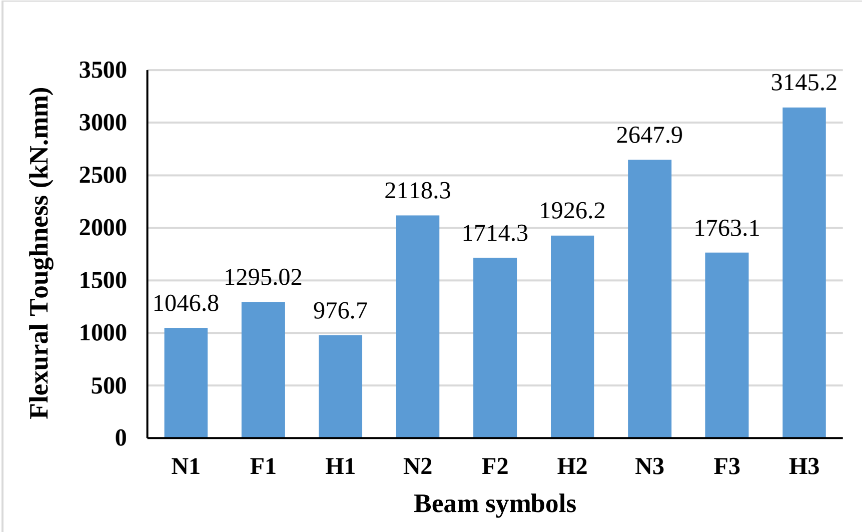



**Fig. 4 Flexural toughness of tested beams**

## 4. Conclusions

A study analyzed the ductility of nine beams constructed from foamed concrete and standard concrete, each with three distinct reinforced configurations. The obtained data yield several conclusions:

1. Hybrid concrete beams exhibit a greater load-bearing capacity than normal-weight concrete and foamed concrete beams.
2. The midpoint deflections of the reinforced foamed concrete beams revealed larger values than the reinforced normal-weight concrete and hybrid beams. When compared to foamed concrete and conventional concrete, the deflection of hybrid concrete was comparable to that of both types of concrete mixes. When comparing foamed concrete, normal concrete, and hybrid concrete, it is evident that it deflected less than the other two types.
3. The ductility of foamed concrete beams with balanced reinforcement and under-reinforcement was lower than that of normal concrete beams. Compared to normal concrete, the ductility of over-reinforced concrete, which includes hybrid materials, demonstrated a large rise of 91.7%, and when compared to foamed concrete, it exhibited a substantial increase of 61%.
4. The hybrid concrete beams demonstrate improved rigidity compared to normal and foamed concrete beams.
5. The study revealed that the hybrid concrete beam, reinforced beyond the standard amount, exhibited an 18.7% increase in flexural toughness compared to the typical concrete beam.
6. It is suggested that a hybrid section comprising conventional and foamed concrete be utilized to decrease ductility and improve stiffness. In terms of the percentage of reinforcing, the over-reinforced variety of concrete performed the best when combined with hybrid concrete, according to the study.

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