Structural Performance of Layered Concrete Beams Under Vertical loading

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Abstract

In this research, an analysis is conducted on the bending strength of composite concrete beams made up of high-strength concrete (HSC) and normal strength concrete (NSC) in various combinations. The main purpose of this study is to examine the effect of different combinations on the performance of reinforced concrete beams. There were three different kinds of composite layers that were studied. In the first arrangement, the beam was composed of 25% high-strength concrete and 75% normal-strength concrete. In the second arrangement, the beam had an equal amount of high-strength and normal-strength concrete. Lastly, the third arrangement was composed of 75% high-strength concrete and 25% normal-strength concrete.

Testing for this experiment was done by performing tests on flexure loading using a four-point loading test. Key parameters like ultimate load, formation of crack, crack propagation, and deflection at midspan were measured and evaluated. Based on the results, it can be concluded that adding more percentage of HSC in the tension zone leads to improved load-carrying capacity and minimized deflection. From this research, it is evident that the use of layered concrete is a good strategy in optimizing the performance of structures by minimizing the consumption of materials.

Keywords: Layered concrete beams, High Strength Concrete (HSC), Normal Strength Concrete (NSC), load-carrying capacity, crack propagation, deflection.

I. INTRODUCTION

Beams made out of concrete are typically made using just one grade of concrete, but the stress pattern at different depths will differ when loaded under flexural loads. The upper part is responsible for handling the compressive forces, while the lower part has tensile forces acting on it. This can result in inefficient construction techniques since only a single grade is used. A very useful way of making concrete beams would be to use layered concrete. This means that the different grades, such as High Strength Concrete (HSC) and Normal Strength Concrete (NSC), are put in layers according to stress demands.

In the current investigation, beams with varying HSC and NSC layer percentages are subjected to testing when loaded in flexure. The performance of such concrete layer systems will be assessed based on their load-carrying capacity, deflections, and crack formation behavior.

II. MATERIALS AND METHODS

2.1 Materials and Their Properties

The following materials are required for the experiment; Ordinary Portland Cement (OPC 53 grade), fine aggregates, coarse aggregates, water, and superplasticizer. Fine aggregates consist of river sand, whereas coarse aggregates were in the form of crushed stone. The high strength concrete (HSC) was manufactured by using a low water to cement ratio with admixtures, whereas normal strength concrete (NSC) was prepared by using conventional proportions.

The characteristics of the materials were determined using standardized test procedures. It was observed that the specific gravity of the cement was 2.9, coarse aggregate had a value of 2.715, and fine aggregate had a specific gravity of 2.613.

2.2 Mix Proportions and Experimental Design

Table 1: M70 Grade Concrete (HSC)

S. No	Parameter	Value (kg/m³)
1	Cement	535
2	Water	141
3	Fine Aggregate	577
4	Coarse Aggregate	1215
5	Water-Cement Ratio	0.264
6	Admixture	8.02

Mix Ratio (C: FA: CA) = 1: 1.07: 2.27

Table 2: M30 Grade Concrete (NSC)

S. No	Parameter	Value (kg/m³)
1	Cement	434
2	Water	157.7
3	Fine Aggregate	665
4	Coarse Aggregate	1179.2
5	Water-Cement Ratio	0.40
6	Admixture	6.51

Mix Ratio (C : FA : CA) = 1 : 1.53 : 2.71

Once the mixture proportioning for the concrete M70 and M30 were done, cubes were poured in order to test their compressive strength. They were kept for curing for 7 days and then subjected to compressive strength test using compression testing machine.

Table 3: Test results for M70 & M30 grade

Grade	S. No	Load (kN)	Compressive strength (N/mm^2)	Average Compressive Strength (N/mm^2)
M70	1	1376.5	61.17	
	2	1375.1	61.17	61.94
	3	1430.7	63.55	
M30	1	733.2	32.58	
	2	610.7	27.14	29.34
	3	637.0	28.31	

2.3 Casting of Cubes for Different layer Depths

After finalizing the mix proportions, concrete cubes were cast using layered combinations of M30 and M70 concrete. The moulds were prepared and cleaned properly before casting. Concrete was placed in layers based on the required proportions, such as 25%–75%, 50%–50%, and 75%–25% arrangements. Each layer was placed carefully to maintain proper bonding between layers.

Adequate compaction was provided for each layer using tamping to remove air voids and ensure uniformity. The top surface was finished smoothly, and the specimens were left

undisturbed for 24 hours. After demoulding, the

cubes were cured in water for the required period before testing.

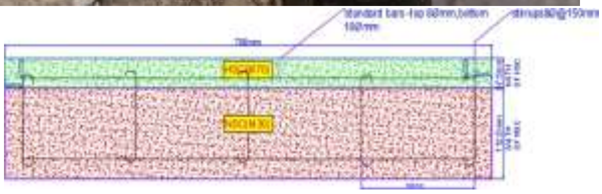
Table 4: Test results for Different layer depths

S.No	fck for 14 days(N/mm^2)	fck for 28 days(N/mm^2)
1	32 N/mm^2	39 N/mm^2
2	38 N/mm^2	43.5 N/mm^2
3	42 N/mm^2	45.6 N/mm^2

2.4 Casting of beams for Different layers for 14 Days & 28 Days

2.4.1 Stage 1: First Layer Depth

[1/4TH M70 HSC (3.75cm) + 3/4TH M30 NSC (11.25cm)]



In the first stage, reinforced concrete beams were cast with a layered arrangement consisting of 25% High Strength Concrete (HSC) and 75% Normal Strength Concrete (NSC) along the depth. The moulds were prepared and reinforcement was placed with proper cover. Initially, the NSC layer (75% depth) was placed, followed by the HSC layer (25% depth). A waiting period of 2 hours was maintained between the layers, and the surface of the previously placed layer was roughened to ensure proper bonding. Each layer was compacted adequately, and the top surface was finished smoothly. After 24 hours, the beams were demoulded and cured in water until testing.

2.4.2 Testing of beams for first layer depth for 14 Days

$$M_u=0.36 f_{ck}\, b\, x_{umax}\, (d-0.42\, x_{umax})$$

$$M_u=WL/3$$

f_{ck}=32 N/mm^2

W_t for 14 days

$$M_u=0.36 f_{ck}\, b\, x_{umax}\, (d-0.42\, x_{umax})$$

$$WL/3=0.36 f_{ck}\, b\, x_{umax}\, (d-0.42\, x_{umax})$$

W_t=93.4 kN

W_{ex} for 14 days W_{ex} =119.7 kN

$\mathbf{W_{ex} > W_t}$

2.4.3 Load Vs Deflection Curve

Initial Stiffness:

Rapid increase in load (up to ~60 kN) within 0–1.5 mm deflection, indicating strong resistance to deformation.

Elastic Transition:

Load rises from ~60 to ~110 kN between 1.5–4 mm, showing gradual stiffness reduction and internal stress redistribution.

Ultimate Behavior:

Load reaches ~120 kN and stabilizes (4–6 mm), reflecting ductile response and maximum load capacity.

2.4.4 Testing of beams for first layer depth for 28 Days

$M_u = 0.36 f_{ck}\, b\, x_{umax}\, (d - 0.42\, x_{umax})$

M_u=WL/3

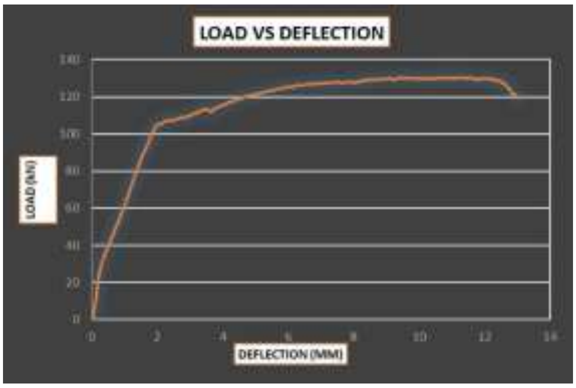
f_{ck}=39 N/mm^2 W_t
for 28 days

$M_u = 0.36 f_{ck}\, b\, x_{umax}\, (d - 0.42\, x_{umax})$
WL/3=$0.36 f_{ck}\, b\, x_{umax}\, (d - 0.42\, x_{umax})$
W_t=113.76 kN

W_{ex} for 28 days
W_{ex} =131.67 kN

$W_{ex} > W_t$

2.4.4 Load Vs Deflection Curve



Initial Stiffness:

Load increases sharply up to ~100–105 kN within about 0–2 mm deflection, indicating very high initial stiffness and strong resistance to deformation.

Elastic Transition:

From ~2 to 5 mm deflection, the load gradually rises from ~105 kN to ~120–125 kN, showing reduced stiffness and internal stress redistribution.

Ultimate Behavior:

The load continues to increase up to ~130 kN, after which it remains constant with minor fluctuations, thus signifying a ductile behavior

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and then a slight decrease in load-carrying capacity.

2.4.5 Stage 2: Second Layer Depth

[1/2TH M70 HSC (7.5cm) + 1/2TH M30 NSC (7.5cm)]

In the second stage, reinforced concrete beams were cast using a layered configuration consisting of 50% High Strength Concrete (HSC) and 50% Normal Strength Concrete (NSC) along the depth. The moulds were properly prepared, and reinforcement was placed with adequate cover. Initially, the NSC layer was cast up to half the depth, followed by the placement of the HSC layer after a time interval of 2 hours. The surface of the previously cast layer was roughened to enhance bonding between the two layers. Proper compaction was ensured for each layer, and the top surface was finished uniformly. After 24 hours, the beams were demoulded and subjected to water curing until the time of testing.

2.4.6 Testing of beams for Second layer depth for 14 Days

$M_u=0.36 f_{ck}\, b\, x_{umax}\,(d-0.42\, x_{umax})$
M_u=WL/3

W_t for 14 days f_{ck}=38 N/mm^2

$M_u=0.36 f_{ck}\, b\, x_{umax}\,(d-0.42\, x_{umax})$
WL/3=$0.36 f_{ck}\, b\, x_{umax}\,(d-0.42\, x_{umax})$
W_t=110.85 kN

W_{ex} for 14 days W_{ex} =132.3 kN

$\boldsymbol{W_{ex} > W_t}$

2.4.7 Load Vs Deflection Curve

Initial Stiffness:

Load increases rapidly up to ~60 kN within 0–1 mm deflection, indicating strong elastic response.

Elastic Transition:

Load rises from ~60 to ~115 kN between 1–2 mm, showing effective load sharing and reduced stiffness.

Ultimate Behavior:

Load reaches ~130 kN within 2–3 mm, indicating peak capacity with slight stiffness degradation.

2.4.7 Testing of beams for Second layer depth for 28 Days

$M_u=0.36\ f_{ck}\ b\ x_{umax}\ (d-0.42\ x_{umax})$ M_u=WL/3

W_t for 28 days f_{ck} =43.5 N/mm^2

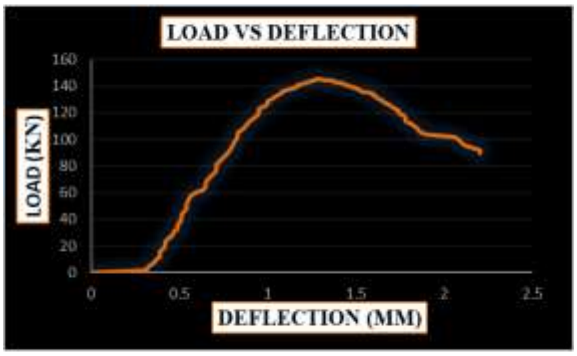
$M_u=0.36 f_{ck}\ b\ x_{umax}\ (d-0.42\ x_{umax})$

WL/3=$0.36 f_{ck}\ b\ x_{umax}\ (d-0.42\ x_{umax})$
Wt=126.89 kN

W_{ex} for 28 days W_{ex} =145.53 kN

$W_{ex} > W_t$

2.4.8 Load Vs Deflection Curve



Initial Stiffness:

The load shoots up rapidly till around 80 kN between 0 and 1 mm of deformation. This suggests the stiffness is very high.

Elastic Range:

There is an increase in load from around 80 to 140 kN in the range of 1 to 2 mm.

Ultimate Behavior:

Load reaches ~150 kN within 2–2.5 mm and then decreases slightly, indicating peak load followed by post-peak response.

2.4.9 Stage 3: Third Layer Depth

[3/4TH M70 HSC (11.25cm) + 1/4TH M30 NSC (3.75cm)]

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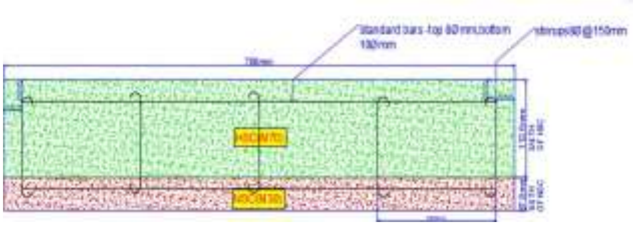


In the third stage, reinforced concrete beams were cast using a layered configuration consisting of 75% High Strength Concrete (HSC) and 25% Normal Strength Concrete (NSC) along the depth. The moulds were properly prepared, and reinforcement was placed with adequate cover. Initially, the NSC layer was cast at the bottom portion, followed by the placement of the HSC layer after a time interval of 2 hours. The surface of the previously cast layer was roughened to enhance bonding between the layers. Each layer was compacted thoroughly to avoid voids, and the top surface was finished smoothly. After 24 hours, the beams were demolded and cured in water until the testing period.

2.4.10 Testing of beams for Third layer depth for 14 Days

$M_u = 0.36 f_{ck}\, b\, x_{umax}\, (d - 0.42\, x_{umax})$

M_u=WL/3

W_t for 14 days f_{ck} =42 N/mm^2

$M_u = 0.36 f_{ck}\, b\, x_{umax}\, (d - 0.42\, x_{umax})$

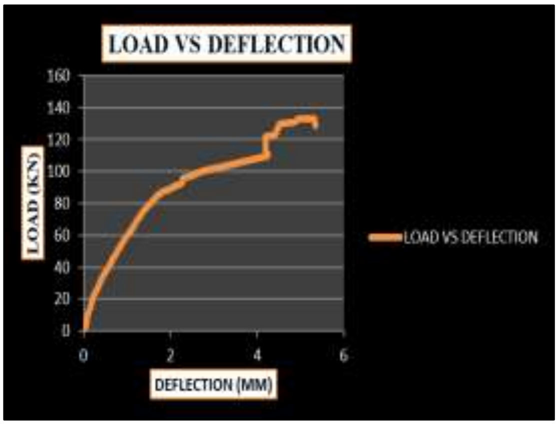
WL/3$= 0.36 f_{ck}\, b\, x_{umax}\, (d - 0.42\, x_{umax})$

Wt=122.51 KN

W_{ex} for 14 days W_{ex} =133.5 KN

$\boldsymbol{W_{ex} > W_t}$

2.4.11 Load Vs Deflection Curve



- **Initial Stiffness (0–1 mm):**

The load rapidly increases to 60 kN, suggesting a high degree of elasticity and stiffness in the initial stage.

- **Elastic Behavior (1-2 mm):**

The load continues to increase from 60 kN to almost 115 kN, suggesting a smooth interface between the layers with decreased stiffness.

- **Ultimate Load (2-3 mm):**

The load reaches 130 kN, marking the ultimate load, after which there is a slight decrease in stiffness.

2.4.12 Testing of beams for Third layer depth for 28 Days

$M_u = 0.36 f_{ck}\, b\, x_{umax}\, (d - 0.42\, x_{umax})$
$M_u = WL/3$

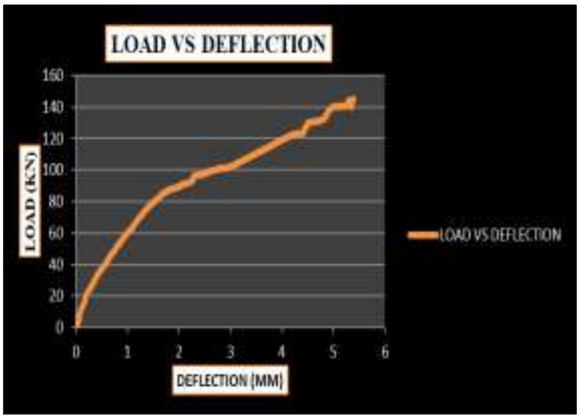
W_t for 28 days
$f_{ck} = 45.6$
N/mm^2

$M_u = 0.36 f_{ck}\, b\, x_{umax}\, (d - 0.42\, x_{umax})$
$WL/3 = 0.36 f_{ck}\, b\, x_{umax}\, (d - 0.42\, x_{umax})$
$W_t = 133.04$ KN

W_{ex} for 14 days $W_{ex} = 146.85$ KN

$W_{ex} > W_t$

2.4.13 Load Vs Deflection Curve



• Initial Stiffness (0-1 mm):

There is a sharp increase in the load from 0 to about 65-70 kN, which signifies a high elastic behavior and initial stiffness.

• Elastic Behavior (1-3 mm):

The load increases from approximately 70 kN to about 110-120 kN, signifying stiffening of the material with the change in elasticity.

• Ultimate Load (3-5.5 mm):

The load increases up to 140-145 kN, which indicates the ultimate strength of the material and then there are

fluctuations due to nonlinear response.

2.4.14 Casting of best layer depth with without stirrups-Third Stage

[3/4TH M70 HSC (11.25cm) + 1/4TH M30 NSC (3.75cm)]

As the configuration of the third layer depth (Stage 3) turned out to be optimum, it became necessary to clean, oil, and correctly assemble the beam moulds. The concrete mixture was also made as per the selection of layers, wherein M70 grade concrete was used for the bottom layer, and M30 grade concrete for the top layer. After placing the bottom layer (¾ depth) and compaction, which can be done by either rodding or vibration to eliminate the air pockets, the top layer (¼ depth) was then placed and compaction was done in such a way that it binds the two layers together well.

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2.4.15 Testing of beams for Third layer depth for 14 Days

$M_u=0.36 f_{ck}\, b\, x_{umax}\, (d-0.42\, x_{umax})$
M_u=WL/3

W_t for 14 days f_{ck} =42 N/mm^2

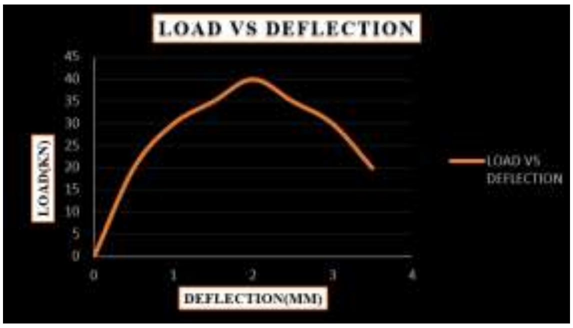
$M_u=0.36 f_{ck}\, b\, x_{umax}\, (d-0.42\, x_{umax})$

WL/3=$0.36 f_{ck}\, b\, x_{umax}\, (d-0.42\, x_{umax})$
Wt=122.51 KN

W_{ex} for 14 days W_{ex} =42 KN

$W_t > W_{ex}$

2.4.16 Load Vs Deflection Curve



•Initial Stiffness (0-1mm):

The load increases suddenly from 0 to approximately 20-25 kN, which suggests that the elastic response is very high, with a considerable level of rigidity for the beam.

•Elastic-to-Nonlinear Transition (1-2.2 mm):

The load increases gradually from approximately 25 kN to 42-43 kN,

implying that the material's rigidity decreases gradually because it changes from an elastic state to a nonlinear state due to the formation and growth of cracks.

•Failure State (2.2-3.5 mm):

The load stabilizes at 42-43 kN, marking the highest point, followed by a gradual decline to approximately 30 kN.

2.4.17 Testing of beams for Third layer depth for 28 Days

$M_u=0.36 f_{ck}\, b\, x_{umax}\, (d-0.42\, x_{umax})$
M_u=WL/3

W_t for 28 days

f_{ck} =42 N/mm^2

$M_u = 0.36 f_{ck}\ b\ x_{umax}\ (d - 0.42\ x_{umax})$

WL/3$= 0.36 f_{ck}\ b\ x_{umax}\ (d - 0.42\ x_{umax})$

Wt=122.51 KN

W_{ex} for 14 days

W_{ex} =50 KN

$\boldsymbol{W_t > W_{ex}}$

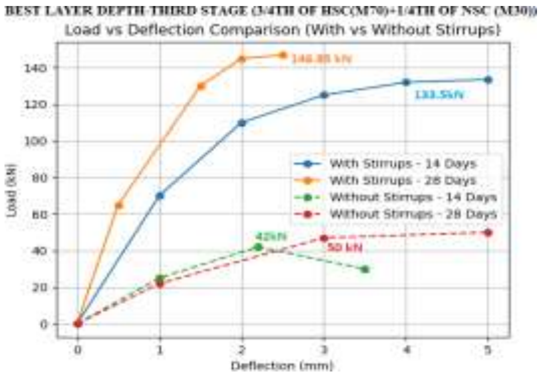
2.4.18 Load Vs Deflection Curve

• **Initial Stiffness (0–1 mm):**
The load rises sharply from 0 to about 18–22 kN, indicating a strong elastic response and good initial rigidity of the beam.

• **Elastic Transition (1–3 mm):**
The load increases from roughly 20 kN to around 45–47 kN, showing gradual stiffness reduction as the material transitions from elastic to nonlinear behavior due to the initiation and propagation of cracks.

• **Ultimate Behavior (3–5 mm):**
The load reaches approximately 50 kN, representing the peak capacity, followed by a slight decrease to about 45 kN, indicating stiffness degradation, crack widening, and the onset of failure.

2.4.19 Load Vs Deflection Curve for with vs without Stirrups



- Beams with stirrups show much higher load-carrying capacity compared to beams without stirrups.
- The maximum load achieved is about 146.85 kN (28 days with stirrups), while without stirrups it is only around 50 kN, showing a large strength difference.
- Load vs deflection curve for beams with stirrups is smooth and gradual, indicating better stiffness and controlled behavior.
- Beams without stirrups show early peak and sudden drop, indicating brittle failure.
- Ductility is higher in beams with stirrups, allowing them to undergo more deformation before failure.
- Crack propagation is controlled in beams with stirrups, whereas without stirrups cracks develop rapidly.
- Strength increases from 14 days to 28 days in both cases, but the improvement is more significant with stirrups.
- Beams without stirrups have poor shear resistance, leading to lower load capacity.

- Stirrups provide confinement and shear strength, improving overall structural performance.
- Overall, providing stirrups results in safer, stronger, and more stable beam behavior.

III. CONCLUSIONS

- All beams with stirrups exhibited combined flexural–shear cracking behavior, where vertical cracks initiated at the tension zone and gradually transformed into inclined (diagonal) cracks near supports.
- The crack pattern showed interaction between bending and shear stresses, indicating that failure was governed by a combined mechanism rather than pure flexure or pure shear.
- The ultimate load capacities recorded were:
- First layer: 119.7 kN (14 days), 131.67 kN (28 days)
- Second layer: 132.3 kN (14 days), 145.53 kN (28 days)
- Third layer: 133.5 kN (14 days), 146.85 kN (28 days)
- Strength increased by 10% from 14 to 28 days, resulting in delayed crack propagation and improved resistance to both flexural and shear stresses.
- Increase in HSC proportion enhanced resistance to combined stresses, with 10.5% improvement from first to second layer and 1% from second to third layer, indicating efficient stress distribution.
- Stirrups played a major role in controlling diagonal shear cracks, ensuring that cracks developed gradually and remained distributed instead of causing sudden failure.
- 42 kN (14 days)
- 50 kN (28 days)
- This corresponds to a strength reduction of 68.5% (14 days) and 66% (28 days), showing that absence of stirrups eliminates the combined crack mechanism and leads to pure shear failure.
- With stirrups, crack development was progressive, showing multiple flexural cracks at midspan and inclined cracks near supports, resulting in ductile and controlled failure behavior.
- The third layer with stirrups exhibited the most stable combined crack pattern and highest load capacity (146.85 kN), making it the most effective configuration.

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