Journal of Al-Azhar University Engineering Sector

Vol. 20, No. 74, January 2025, 78-94

EXPERIMENTAL STUDY OF FLEXURAL BEHAVIOR OF REINFORCED CONCRETE BEAMS WITH NANO CLAY ADDITIVE

Khaled M. Hassan*, Eslam M. Ali, Dalia F. Arafa, Nihal A. Taha

Reinforced Concrete Structures Institute, Housing and Building National Research Center (HBRC), Egypt

Correspondence*:* *drkhaledhbrc@gmail.com*

Citation:
K. M. Hassan, E. M. Ali, D. F. Arafa and N. A. Taha, "Experimental Study Of Flexural Behavior of Reinforced Concrete Beams with Nano Clay Additive", Journal of Al-Azhar University Engineering Sector, vol 20, pp. 78-94, 2025.

Received: 31 August 2024

Revised: 30 October 2024

Accepted: 17 Novamber 2024

Doi:10.21608/auej.2024.317104.1708

ABSTRACT

Using nanoparticles as a partial replacement for cement components has become an issue of rapidly growing importance in the last few years to promote sustainable concrete and to avoid the adverse effect of carbon dioxide and CO_2 emissions from the cement production process on the environment. The current study investigates the efficiency of using Nano Clay particles as a partial replacement for cement. The practical study mainly focused on the flexural behavior of reinforced concrete beams made with replacement Nano-clay particles by a 6% ratio of cement matrix to achieve the same compressive strength of the corresponding traditional concrete mix. To achieve the experimental study, sixteen beams were designed, cast, and experimentally tested. The sixteen specimens were cast using two types of concrete mixture. Eight of them were cast using a concrete mix with a Nano-clay ratio of 6% as a replacement for cement, and the others were cast using traditional concrete mix without Nano-clay additive. The flexural behavior of the RC beams specimens concerning failure mode, and load-deflection behavior were presented and discussed. It can be concluded that the concrete enhanced with Nanoparticles gives better crack distribution and more ductile behavior than the traditional concrete during the different loading stages due to the enhancement of both, tensile and bond strengths produced by adding Nano-clay as a replacement for cement.

KEYWORDS: Nano Clay Additive, Normal Concrete, Replacement, Beams, Flexure

---

دراسة معملية لتقييم سلوك الانحناء للكمرات الخرسانية المسلحة المنفذة باستخدام اضافات من النانو- الطينى

خالد مصطفى حسن، اسلام موسى على، داليا فوزى عرفة، نهال عبد الحميد طه

معهد المنشآت الخرسانية – المركز القومى لبحوث الاسكان والبناء ، الجيزة، مصر.

***البريد الاليكتروني للباحث الرئيسي :** *drkhaledhbrc@gmail.com*

الملخص

أصبح استخدام جزيئات النانو كبديل جزئي لمكونات الأسمنت ذو أهمية كبيرة في السنوات القليلة الماضية ، وذلك لتعزيز الخرسانة المستدامة وتجنب التأثير الضار على البيئة لانبعاثات ثاني أكسيد الكربون CO_2 الناتج من عملية إنتاج الأسمنت. الدراسة الحالية، تبحث في كفاءة استخدام جزيئات نانو الطين كاحلال جزئي للأسمنت فى مكونات الخرسانة. حيث تركز الدراسة العملية بشكل أساسي على اختبار سلوك الانحناء للكمرات الخرسانة المسلحة والمنفذة عن طريق استبدال جزيئات النانو الطينى بنسبة 6٪ بهدف تحقيق نفس مقاومة الخرسانة للضغط بالمقارنة بالخرسانة التقليدية. تم تصميم ستة عشر عينة من الكمرات وصبها واختبارها معمليا. تم صب العينات الستة عشر باستخدام نوعين من خليط الخرسانة ،حيث تم تنفيذ ثمانية منهم باستخدام خليط خرساني بنسبة 6٪ من النانو الطينى وذلك كبديل للأسمنت، وتم صب العينات الأخرى باستخدام خليط خرساني تقليدي بدون إضافة النانو الطينى الى الخرسانة. تم دراسة سلوك الانحناء للكمرات الخرسانية من حيث شكل الانهيار والعلاقة بين الحمل والانحناء أثناء تجربة التحميل. ومن نتائج الدراسة يمكن الاستنتاج أن الخرسانة المحسنة بجزيئات النانو تعطي توزيعًا أفضل للشروخ وسلوكًا أكثر للمطولية مقارنة بالعينات المنفذة باستخدام الخرسانة التقليدية أثناء مراحل التحميل المختلفة ، وذلك بسبب التحسين الناتج عن استخدام النانو الطينى فى الخلطة الخرسانية لكل من مقاومة الشد وقوة الترابط بين الخرسانة والتسليح فى الخرسانة المنفذة باستخدام النانو الطينى كبديل جزئى للأسمنت.

الكلمات المفتاحية : اضافات النانو الطينى، الخرسانة العادية، الإحلال، الكمرات، الانحناء .

1. INTRODUCTION

Nano-materials can be classified according to the category of material into the pozzolanic type and fiber type. Nano-alumina, Nano-silica, and Nano-clay were classified as pozzolanic category, on the other hand, carbon nano-fiber and carbon nanotubes were classified as fiber category. Concrete enhanced with Nanoparticles is considered a type of green concrete utilizing the technology of nanoparticles less than 500 nm (nano-meters) to become a more environmentally friendly material with less water/binder ratio [1-2]. The implementation of the nano technique in the concrete industry began with a line of the increasing demand for UHPC (ultra-high-performance concrete). The mix formulation containing silica fume improves strength and durability. Yet it is still available to a very restricted limit because of high cost, UHPC is less demanding than HSC (high strength concrete). Following an extensive investigation, nanomanufacturing has emerged as an alternative to silica fume. It was discovered that adding nanoparticles to concrete enhances and improves the strength of traditional concrete; they can act as a filler by improving the cement hydration resulting in a denser concrete. Their modification in the cement matrix system results in a new nanoscale component, making them an excellent filler. Nano-particles become a new binding agent that is lesser than cement particles, increase the cement hydration process, and result in a more durable concrete mixture [3-5]. Several types of nanomaterials were developed such as nano-silica which is the alternative to silica fume [6], nano alumina [7], titanium oxide [8], carbon nanotube [9], nano clay or nano kaolin [9] and polycarboxylates [10]. Metakaolin (MK), also known as calcined kaolin, is one of the nanomaterials used in this research as a partial cement substitution and a secondary product of kaolin after heat treatment. It is a calcined clay-based material that boosts compressive and flexural strength, increases durability, reduces water and chloride permeability, and improves concrete absorption as the replacement percentage increases. This is attributable to the filling effect of MK particles, which have significantly minimized the permeability of the concrete [11].

Hamed et al. investigated the addition of NC with different percentages of (5, 7.5, and 10%) as cement partial substitution using it by addition as-received to the concrete mix or by adding it after being dispersed in water by using a bath sonicator. The results found that the sonication of nano-clay particles significantly improved concrete characteristics compared with those added as-received nano-clay to the concrete mix. The amelioration in mechanical characteristics of concrete mixes with Sonicated NC mixes ranged from 1.42 to 3.74 times the gains with those of as-received NC mixes. The optimum percentage explored from the studied cement replacement was 7.5% for both two methods of use [12]. A study by Morsi et al. proved that nano metakaolin additives in concrete enhanced the compressive strength by 8-10% compared to concrete made with plain Ordinary Portland cement only [13]. Wild et al. examined how metakaolin (MK) replacement of OPC (ordinary Portland cement) in concrete. The change of relative strength with curing time profiles and relating the observed behavior to the reaction process occurring was studied. Replacement amounts of Ordinary Portland cement by MK were 0,5,10,20,25 and 30%, respectively. The study found that the filler effect, the acceleration of OPC hydration, and the pozzolanic reaction of MK with calcium hydroxide (CH) are three aspects impacting the participation that metakaolin makes to concrete strength when it is partially substituted by cement. MK's optimal OPC replacement level for the greatest long-term strength increase was approximately 20%.[14]. Mohamed analyzed the influence of nanoparticles such as nano-silica (NS), nano-clay (NC), and a combination of NS and NC with varying percentages at different ages of concrete. One of the findings was that nano-clay in dry and nano-silica in wet conditions improved compressive strength by up to 18% for NS and 11% for NC after 90 days. A further finding was that the ideal addition ratio for replacing cement with nanoparticles was 0.75% for NS and 3% for NC to avoid negative influence on the compressive and flexural strength of concrete owing to a conglomerate of nanoparticles and producing an affordable concrete mix. [15].

Abd Elbaky and S.Yehia investigated using Nano clay (NC) with various percentages of 3%, 5%, and 7% as a cement replacement in concrete to set the best NC replacement ratio. They found that, utilize of 7% NC as a cement replacement ratio can be the best for the mechanical qualities of the hardened concrete. [16]. E. Badogiannis et al. tested the influence of using poor Greek kaolin (K) thermally treated and commercial metakaolin (MKC) purified on the concrete compressive strength. The effects of metakaolin as an additive were examined. Metakaolin was replaced for both cement and sand at percentages of 10% or 20% by weight of the control cement content, respectively. The strength developed was evaluated using the efficiency factor (k value), which is the ratio of cement mass to metakaolin mass when they had an equal effect on the water-to-cement ratio. Both metakaolins exhibit very high k-values (close to 3.0 at 28 days) and are characterized as highly reactive pozzolanic materials that can lead to concrete production with excellent performance [17]. Suneel et al. used Nano-TiO2 (nano-titanium dioxide) as a filler material to investigate how M40 grade standard strength concrete performs when nanomaterials are partially replacing the cement content in concrete, with a partial substitution of nano-titanium dioxide (TiO2) with a range of 0.5 to 2%. Both types of concrete's strength properties were investigated using compression, split tensile, and flexural tests. Test results attained the replacement of cement by 1%, and the compressive strength of the concrete improved by 8% compared to the traditional concrete[18].

Kancharla et al. demonstrated through experimental examination that particles of microsilica (MS) and nano-silica (NS) are extremely beneficial to the concrete mix. Concrete has become more dense as mechanical qualities, particularly compressive strength, have improved significantly. This proposed methodology involves a comparable study for the flexural bending behavior of regular reinforced concrete slabs (without MS or NS) and other slabs. Each has varying amounts of NS and MS particles added to the concrete mixture. By replacing a portion of the cement with an equivalent amount of NS or MS particles, or both, the material composition of the slabs is preserved. For MS particles, the modifications range from 0, 5, and 10%, and for NS particles, from 0, 0.5, and 1.0%. One of the main results was that the flexural strength was enhanced by 9.9 and 17.3% at the cracking state and 6.6 and 9.5% at the failure state at 0.5% and 1.0% Nano silica, respectively. When replacing a portion of the cement with a merging of Nano silica and 5% micro silica, it was also revealed that, according to the load-deflection curve, higher loads were reached at lower deflections for reinforced slabs with 10% micro silica and 1.0% Nano silica of cement substitution [19].

A. Mansi et al.provided an overview of how Nano clay, as a replacement for cement in concrete, affects positively the performance of both standard and high-performance concrete mechanical properties and durability due to the cement hydration reaction enhancement. It was found that adding Nano clay to high-performance concrete improved durability characteristics like resistance to sulfate attack and increased temperatures as well as compressive and flexural strength. In other ways, it lowered porosity, permeability, and water absorption [20]. Hanadi et al. tested the varying percentages of Nano clay and its effects on the mechanical characteristics of concrete and the flexural capacity of reinforced concrete slabs in two-way action. The percentage of Nano clay content was (0%, 2%, 4%, 6%, 8%, 10%) weight percent of cement, in addition to the usage of polypropylene content of 1.5%. The investigated mechanical parameters of concrete were compressive strength, splitting tensile strength, and flexural strength. Six concrete slabs were cast and tested under uniform load in simply supported condition. The Nano clay usage resulted in a significant boost in the mechanical properties of concrete attributed to its strong pozzolanic activity that confirms the enlarged production of C-S-H gel in the presence of nano-particles. Increasing the percentage of Nano clay from 2% to 8% resulted in 3% and 12.4% improvement in compressive strength for samples containing 1.5% polypropylene, respectively. When utilizing the same Nano clay proportion of around 2% to 8%, the splitting tensile strength improved by 4% up to 39.4%. For the identical Nano clay content, the ultimate load capacity was raised by 12.5% to 66% [21].

Mahdi et al. investigated the effect of hybrid marble powder (MP) and Nano clay (NC) and additions on column behavior, concerning axial strain, ultimate capacity, toughness, lateral strain, and failure pattern. Ten RC column specimens were cast of both regular (NSC) and high-strength reinforced concrete (HSC) and tested under axial compressive loading. Incorporating optimal hybrid additive ratios from (NC and MP) raised both the ductility and strength of HSC and NSC columns [22]. X. Wang, aimed to assess the outcome of nano-particles on the characteristics of cement-based products. The Nano-materials researched include Nano-limestone, Nano-silica, and Nano-clay particles, whereas the cementitious materials studied are mixtures of ordinary Portland Cement (OPC), fly ash (FA), and metakaolin (MK). One of the main findings of the study was that, regardless of the type of nanomaterial, adding 1% increases the compressive strength of both cement and cement-fly ash pastes at ages up to 28 days examined. In the group of the three Nano-materials observed, NS seems to be the most efficient in strength development, probably due to its small particle size and high reactivity. Another conclusion was that, the replacement of 15% Metakaolin (MK) for cement enhanced compressive strength and freeze-thaw resistance, in addition to reducing the penetration of chloride and free-drying shrinkage [23].

Maha Ahmed et al. examined the use of marble powder as a partial substitute for cement in producing high-performance, self-compacting concrete (SCC). The study concluded that at the same water-to-powder (W/P) volume ratio, marble powder (MP) behaves similarly to cement. This suggests that partially replacing cement with MP would maintain comparable workability, as indicated by the linear regression analysis based on relative slump. In addition, due to the higher water absorption of MP, the water-to-powder volume ratio (w/p) rose, while the superplasticizers (SP) dosage dropped by 0.03%. As a result, the workability decreased, and the mix's viscosity with MP increased slightly. Also, the V-funnel confirmed that the self-compacting concrete (SCC) containing MP could flow quickly under gravity. While the mortar mix with MP showed a slightly longer flow time due to increased viscosity, the difference of 0.3 seconds was minimal. Given the large-scale production of cement today, incorporating up to 10% of MP waste as a substitute for ordinary Portland cement (OPC) or gypsum in the cement industry could offer genuine savings in energy and costs, while also conserving natural resources and reducing the environmental impact of marble waste and CO_2 emissions. Test results demonstrated that recycled MP possesses rheological properties suitable for construction applications [24].

2. EXPERIMENTAL WORK

Sixteen reinforced concrete beam elements with the same dimensions were cast and tested under two-point loading. The concrete mix used for beams was divided into two types depending on using of Nano-clay additive or not. The proportion of concrete mix, mechanical properties for steel and concrete, specimen details, and test sequence are explained in the next sections.

2.1. Concrete Mix Proportion.

Ordinary Portland cement (OPC CEM I 52.5 N) had been used in the study. Siliceous sand was utilized as a fine aggregate with particle size from 0.06 to 5mm. Crushed clean dolomite with a nominal maximum size of 10 mm was employed as coarse aggregate. A water reducer super-plasticizer has been added to ensure good workability and the absence of segregation would occur.

The Nano-Clay (NC) employed in the research was kaolinite clay. The kaolin clay was chemically treated in addition to thermal treatment. The ammonium chloride powder (NH_4Cl) was added to Kaolinite with a ratio of (7 mg NH_4Cl to 1 gm kaolinite clay). Then a proper amount of water will be added to form a slurry after that left for 2 hours to allow NH_4Cl particles to penetrate among the kaolinite clay platelets. Then, it activated thermally for 2 hours at 750ºC to produce active amorphous Nano-metakaolin. The used Nano-clay has a surface area of about 48000000 mm2 /g with dimensions of 200*100*20 nm. The thermal treatment helps the transformation of nano-clay from a crystalline state to an amorphous state with the reduction in grain size. Table (1) illustrates the mix proportions by weight to produce one cubic meter of concrete (without Nano-Clay additive - C400) and the other type of concrete with 6% Nano-Clay additive (NC6) used for casting R.C. beam elements [1,2]. The preparation of the normal concrete

(C400) was conducted by mixing dry components of the mixture in a rotary mixer for 30sec., then adding 50% of the mixing water to the dry constituents and mixing for another minute. After that, the rest of the mixing water including the super-plasticizer was added into a rotary mixer. The concrete mixture was mixed for an additional 5 minutes. To obtain a concrete mix enhanced with nano-clay particles (NC6) used as a replacement of cement with a 6% percentage of the weight of cement, the mixing method was the same process as applied in the normal concrete mixture. The NC particles and super-plasticizer were first stirred in 50% water using an ultrasonic process instrument model VCX500 for 15 minutes to form an aqueous solution, then poured into a rotary mixer with the remaining water and all ingredients mixed for another 5 minutes.

Table (1): Concrete Mix Proportion

Mix No.	Mix type	Cement (kg)	Coarse Aggregates (kg)	Fine Aggregates (kg)	Water (Liter)	Nano-Clay (kg)	Super Plasticizer (kg)	W/c ratio	Slump (mm)
1	C400	400	1086	724	188	--	0.06	0.47	130-150
2	NC6	350	1058	706	175	0.21	0.0556	0.47	130-150

The NC used in this investigation was kaolinite clay provided by the Middle East Mining Investment Company (MEMCO). To prepare the clay, it underwent both chemical treatment and thermal activation. Specifically, organic ammonium chloride (NH_4Cl) powder was mixed with the clay at a ratio of 7 mg NH_4Cl to 1 g of clay. Water was then added to form a slurry, which was allowed to stand for 2 hours, enabling NH_4Cl particles to penetrate between the clay platelets. Following this, the slurry was subjected to thermal activation by sudden heating at 750°C for 2 hours, resulting in the production of activated amorphous nano metakaolin (NMK) [25].

2.2. Concrete and Steel Test Results.

Concrete compressive strength was determined by examination of three concrete cubes of 150*150*150 mm after 28 days from each batch. Furthermore, the splitting tensile strength was evaluated by testing cylinders 150mm in diameter and 300 mm in height. Table (2) illustrates the mean compressive strength and splitting tensile strength results after 28 days. It was noticed from Table (2) values, that a slight enhancement for the compressive and splitting tensile strength values for the mixture enhanced by Nano-clay replacement compared with normal concrete mixture. The main purpose taken into consideration while creating the concrete mixture was to produce nearly the same compressive strengths in both ordinary concrete (C400) and concrete augmented with nano-particles (NC6). As a result, the cement content was lowered by 0.50 kN/m^3 in concrete improved with nano-clay, which plays an essential role in improving concrete compressive strength.

Table (2): Hardened Concrete Mechanical Properties.

Mix type	Average Compressive Strength (MPa)	Average Splitting Tensile Strength (MPa)
C400	54.08	2.72
NC6	55.41	2.85

To evaluate the mechanical properties of used reinforcement, samples of steel bars used as tensile reinforcement and stirrups in the R.C. steel specimens were prepared and tested according to *ASTM A370-15*[26]. Table (3) illustrates the Nominal diameter and mechanical characteristics of steel specimens with bar diameters of 8, 10, and 12mm.

Table (3): Steel Reinforcement Mechanical Properties

Reinforcement Type	**Nominal Diameter (mm)**	**Yield Strength (*fy*) MPa**	**Ultimate Strength (*fu*) MPa**	**% Elongation**
Mild steel (MS)	8	444.13	613.16	29.00
High tensile steel (HTS)	10	515.45	670.30	22.30
High tensile steel (HTS)	12	565.66	712.96	21.26

2.3. Experimental Program and Specimen's Details.

The experimental program aims to explore the efficiency of using nano-clay particles on the flexural behavior of reinforced concrete beams. The testing program was carried out at the Reinforced Concrete Laboratory at the Housing and Building National Research Center (HBRC), Egypt. The studied specimens comprised sixteen reinforced concrete beams cast using the two above-mentioned types of concrete mixtures, with eight beams poured using each type of concrete mixture. The dimensions of each of the reinforced concrete beams were 125 mm wide, 250mm depth, and 2000mm span. The beams were arranged into two sets concerning the longitudinal reinforcement details. The first set (Set I) is the RC beams with upper reinforcement at the middle span; whereas the second set (Set II) is the RC beams without upper reinforcement at mid-span. The upper reinforcement was cut off at the constant moment region so that the compression force would be withstood by concrete only. Figures (1) and (2) show longitudinal sections and cross-sections of beams with and without top reinforcement, respectively. The specimens' details are summarized in Table (4).

As shown in Table (4), the beam's bottom tensile reinforcement ratios were 0.78% (3Ø10) and 0.75% (2Ø12) for beams with concrete cover equal to 10 mm. On the other hand, the bottom reinforcement ratios for beams with 30mm cover were 0.85% (3Ø10) and 0.82% (2Ø12). The aim of using nearly the same reinforcement ratios at the bottom with different numbers of steel reinforcement was to investigate the effect of diameter in addition to the number of bottom bars on the behavior of beams in flexural with and without Nano-clay additive. Another parameter addressed in the current research was the potentiality of the existence of the upper reinforcement at the middle third of beams where the location of the maximum moment with and without Nano-clay additive. Furthermore, the impact of the value of the bottom concrete cover was explored in the current study.

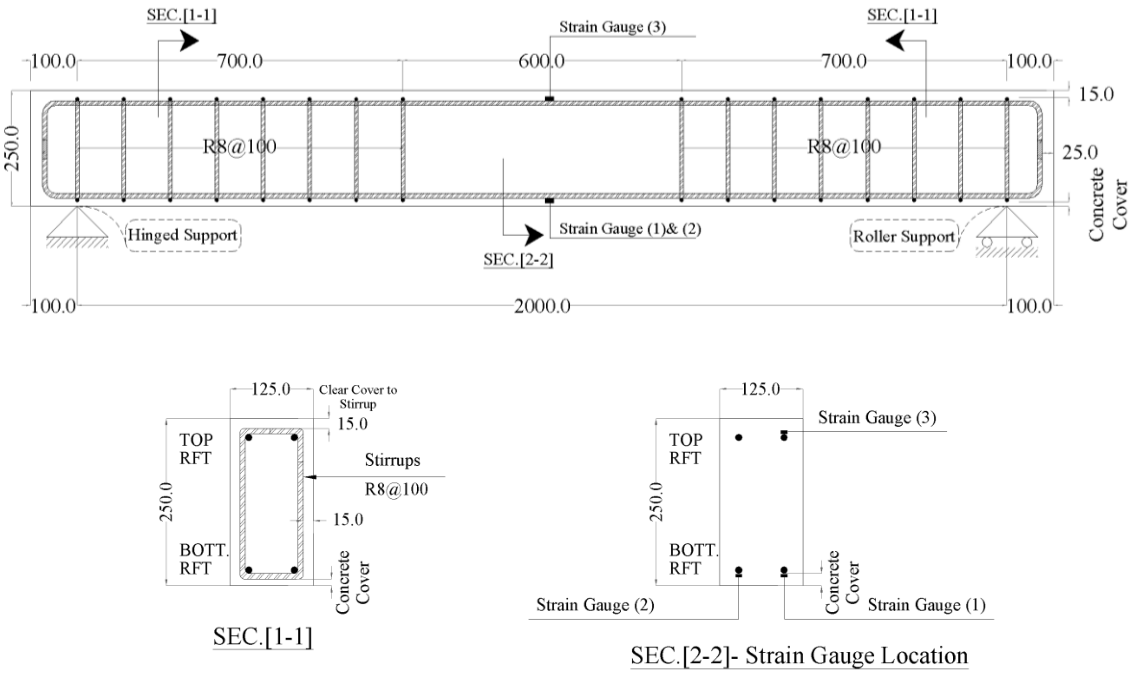


Figure (1): Longitudinal and Cross Section for R.C. Beam with Top RFT (Set I).

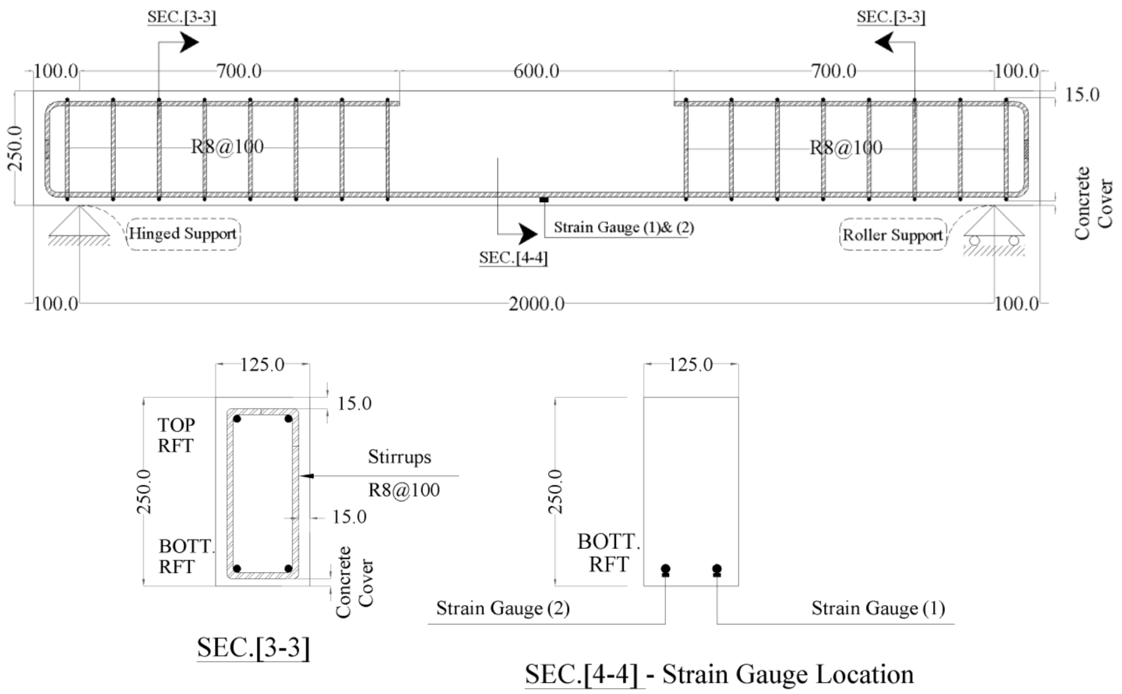


Figure (2): Longitudinal and Cross Section for R.C. Beam without Top RFT (Set II).

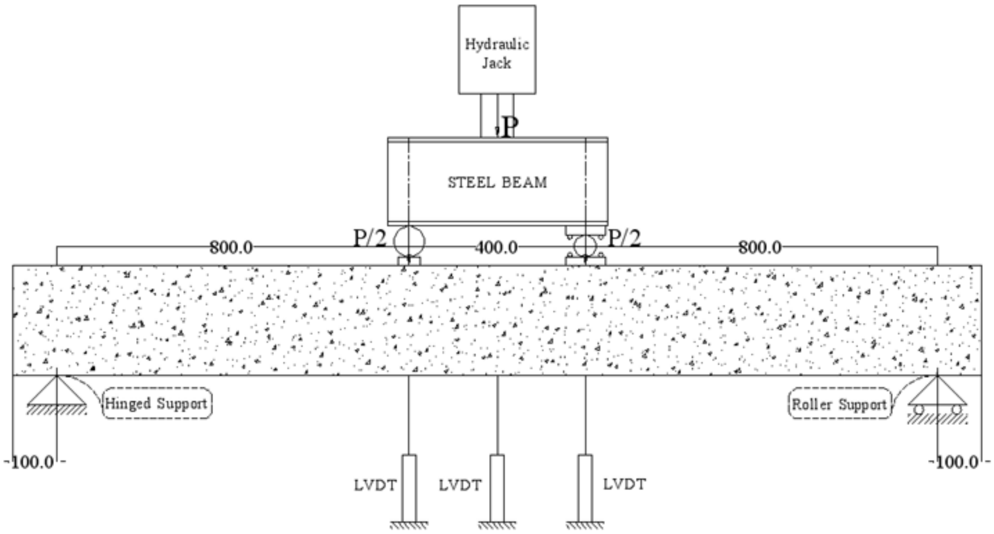
Table (4): Details of Test Specimens.

Concrete Mix	Group No.	Specimen ID	Fcu (MPa)	Bottom Concrete Cover (mm)	Bottom RFT.	Reinforcement Ratio (μ)	Top RFT.at Mid Span	Stirrups
C400	I	10C1	57.90	10	3Φ10	0.78%	---	Φ8@100mm
		12C1	55.77	10	2Φ12	0.75%	---	Φ8@100mm
	II	10C3	66.52	30	3Φ10	0.85%	---	Φ8@100mm
		12C3	59.87	30	2Φ12	0.82%	---	Φ8@100mm
	III	10C1T	56.01	10	3Φ10	0.78%	2Φ10	Φ8@100mm
		12C1T	66.67	10	2Φ12	0.75%	2Φ10	Φ8@100mm
	IV	10C3T	42.30	30	3Φ10	0.85%	2Φ10	Φ8@100mm
		12C3T	38.25	30	2Φ12	0.82%	2Φ10	Φ8@100mm
NC6%	I	10N1	61.63	10	3Φ10	0.78%	---	Φ8@100mm
		12N1	53.38	10	2Φ12	0.75%	---	Φ8@100mm
	II	10N3	57.98	30	3Φ10	0.85%	---	Φ8@100mm
		12N3	61.20	30	2Φ12	0.82%	---	Φ8@100mm
	III	10N1T	53.73	10	3Φ10	0.78%	2Φ10	Φ8@100mm
		12N1T	63.08	10	2Φ12	0.75%	2Φ10	Φ8@100mm
	IV	10N3T	40.53	30	3Φ10	0.85%	2Φ10	Φ8@100mm
		12N3T	41.15	30	2Φ12	0.82%	2Φ10	Φ8@100mm

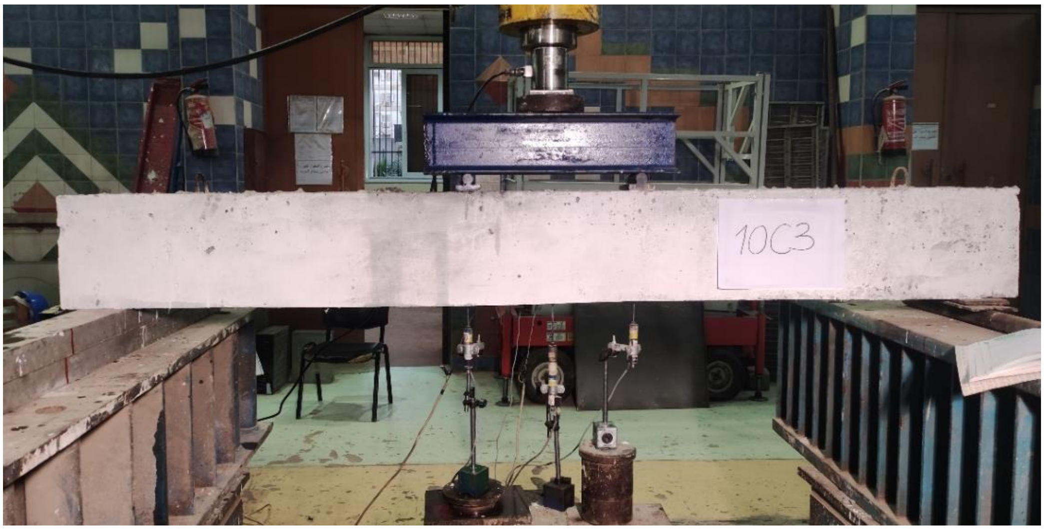
2.4. Test Procedure and Instrumentation.

The tested beams were simply supported at each end using two rigid steel supports. The specimens were tested by two- loading points applied through a distribution beam that is a part of the loading system. Two-point load was applied 400 mm apart as shown in Figure (3) to make a constant moment in the middle third of beams examined under flexural.

The deflections were measured using three linear variable transducers (LVDT) as shown in Figure (3). Two of the LVDTs were located beneath the point applied loading and the third one was located in the middle of the tested beam span. Three strain gauges were mounted on the longitudinal top and bottom reinforcement, two of them were fixed on the main tensile bars at mid-span, and the third strain gauge to monitor the compression strain of the top bars in the case of beams with top reinforcement at mid-span. Concrete Pi-Gauge was installed on the upper face of the concrete section at mid-span to get measurements of the concrete's top compressive strain. The measured data were recorded by a data logger attached to the Computer System Program using "Lab View" software.



(a) Schematic drawing of the lab setup



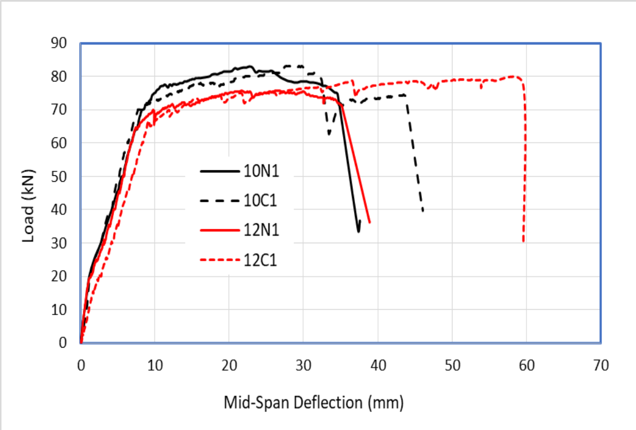
(b) Lab test setup

Fig.(3): Loading Setup and Instrumentation.

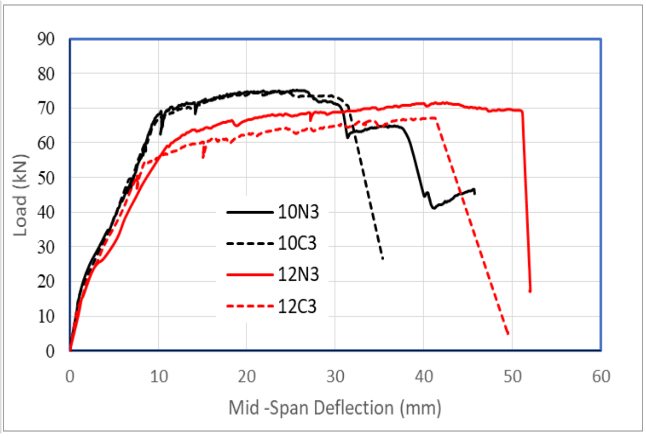
3. TEST RESULTS AND DISCUSSIONS

3.1. Load-Deflection Curve.

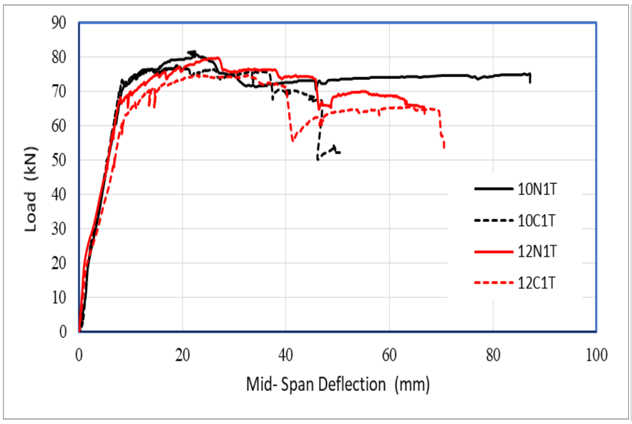
To evaluate load versus deflection and other outcomes, the specimens were categorized into four groups based on their bottom concrete cover value and the existence of top reinforcement at the mid-span. Refer to Table (4), groups I and II contain specimens with concrete cover of 10mm and 30mm, respectively, without top reinforcement at mid-span. Groups III and IV contain specimens with a concrete cover of 10 mm and 30 mm, respectively, and top reinforcement at mid-span. Figures (4-a) to (4-d) illustrate the Load versus mid-span deflection curve for each specimen's groups.



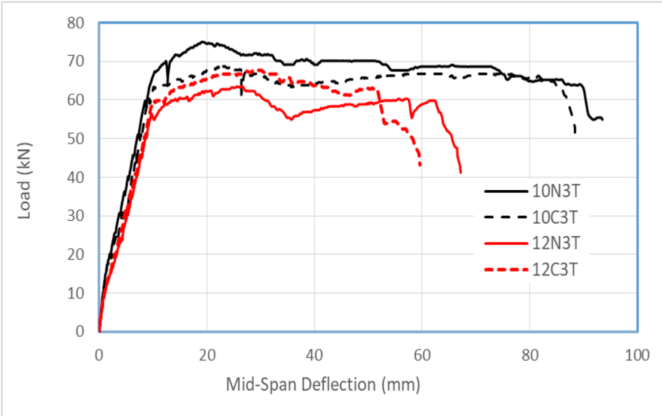
a) Specimens of Group I



(b) Specimens of Group II



(c) Specimens of Group III



(d) Specimens of Group IV

Figure (4): Curve of Load-Displacement at Mid-Span for all Specimens Groups

Figure (4-a) presents the load-displacement curves for specimens of Group I, including specimens 10N1, 10C1, 12N1, and 12C1. The experimental results reveal that specimens 10C1 and 10N1 have ultimate loads of 83.0 and 82.70 kN, respectively, and yield loads of 71.72 and 72.90 kN, which are nearly the same values. On the other hand, specimen 10N1 has maximum deflection at failure of 37.36 mm which decreased by 17% compared with the corresponding value of specimen 10C1. Furthermore, the results of specimen 12N1 reveal a decrease in ultimate loads and displacement at failure by roughly 4.3% and 38.95%, respectively compared to the same values of specimen 12C1. Experimental results of Group (II) show that specimens 10C3 and 10N3 have an ultimate load of 74.9 and 75.21kN, respectively which are almost identical. On the other hand, specimen 10N3 has a maximum deflection at failure of 39.35 mm, which raised the equivalent value of specimens 10C3 by approximately 19.25%. The load-deflection curves of specimens 12C3 and 12N3 reveal an increase in ultimate loads and displacement at failure for specimen 12N3 of approximately 6.4% and 20.6%, respectively, as compared to the same values for specimen 12C3. The load-deflection curve for specimens of Group (III) demonstrates an increase in ultimate loads and displacement at failure for specimen 10N1T by approximately 4.2% and 85.6%, respectively, compared to specimen 10C1T. On the other hand, ultimate loads for specimen 12N1T increased by about 6.6% compared with specimen 12C1T, while displacement at failure decreased by 4.0% compared with specimen 12C1T. Group (IV) results reveal that the ultimate loads and displacement at failure for specimen 10N3T increase by approximately 9.2% and 5.50%, respectively, as compared to the same values for specimen 10C3T. In contrast, specimen 12N3T data show a 12.7% increase in displacement at failure compared to specimen 12C3T and a 6.2% decrease in ultimate load compared to specimen 12C3T. Table (5) summarizes the experimental results of all specimens in terms of load compared with mid-span displacement at yield and ultimate stage, moreover, it presents steel strain value at ultimate load, and the value of mid-span deflection at failure. As a result, most of the specimens with Nano-clay additive exhibited more ductile behavior, particularly when top reinforcement was present or a larger concrete cover was used at the tension side of reinforced concrete beams.

Table (5) Mid-Span Deflection at Yield and Ultimate Stage, Steel strain, and Mid-Span Deflection

Concrete mix	Group No.	Specimen ID	Yield of Steel		Ultimate load			Maximum Deflection at failure Δ_m (mm)
			Load P_y (kN)	Deflection Δ_y (mm)	Load P_u (kN)	Deflection Δ_u (mm)	Bottom steel Strain ε_s	
C400	I	10C1	71.72	8.91	83.00	29.83	0.033	45.0
		12C1	68.52	11.26	79.10	52.64	0.043	60.0
	II	10C3	67.81	10.51	74.90	23.40	0.022	33.0
		12C3	55.54	10.1	67.00	41.16	----	43.0
	III	10C1T	72.41	8.46	77.50	19.38	> 0.03	47.20
		12C1T	64.54	10.0	74.70	25.12	0.06	69.70
	IV	10C3T	63.14	10.47	68.67	23.43	> 0.0186	88.47
		12C3T	60.00	11.33	67.44	22.17	> 0.0158	59.14
NC6%	I	10N1	72.90	9.34	82.70	23.11	0.025	37.36
		12N1	67.14	8.50	75.70	26.86	0.037	36.63
	II	10N3	69.15	10.90	75.21	25.67	0.021	39.35
		12N3	62.36	12.90	71.29	43.04	0.040	51.85
	III	10N1T	72.22	9.62	80.70	22.52	> 0.025	87.63
		12N1T	68.66	9.09	79.63	25.99	0.029	66.90
	IV	10N3T	67.42	10.54	75.0	20.0	---	93.39
		12N3T	56.0	10.90	63.49	25.67	> 0.0158	66.70

Figure (5) illustrate crack pattern for specimens 10N3T and 10C3T at serviceability loading stage, and Figure (6) represent the failure pattern for specimens 10N1T and 10C1T. All specimens show the same failure pattern, with the principal cracks characterized as flexural tension cracks. Furthermore, specimens with Nano-clay additive display a greater number of cracks, thus smaller crack spacing than C400 specimens.

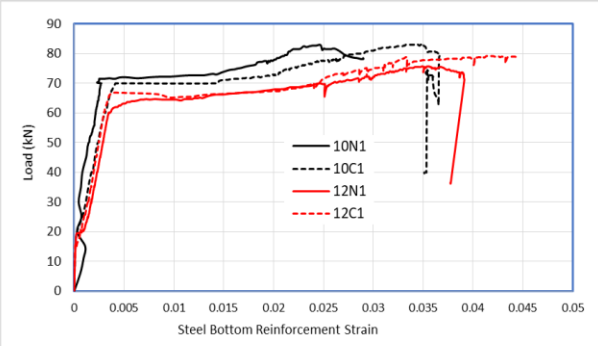
Figure. No. 5: Cracks of Specimens 10N3T and 10C3T at serviceability loading stage

Figure. No. 6: Cracks of Specimens 10N1T and 10C1T at Failure

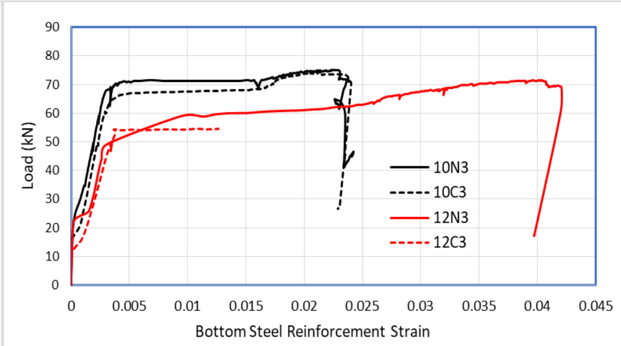
3.2. Strain Characteristics.

Table (5) shows strain values for bottom reinforcement at the ultimate load stage. The smallest strain value was equivalent to 0.021, measured for specimen 10N3, while the maximum value was equal to 0.06, observed in the 12C1T specimen. It can be revealed that, the measured strain at ultimate loads in the bottom reinforcement (beam tension side) for all specimens with Nano-clay additive is lower than the equivalent specimen without Nano-clay additive. This relationship might be related to the higher tensile strength of the concrete with the Nano-clay additive than the concrete without the Nano-clay additive.

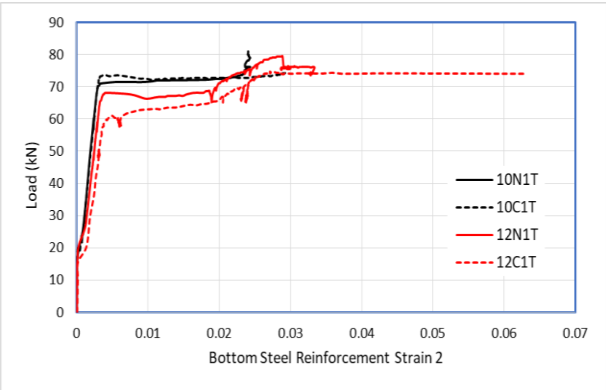
The relation between the applied load and steel strain at bottom reinforcement is shown in Figures (7-a) to (7-d) for all specimen groups.



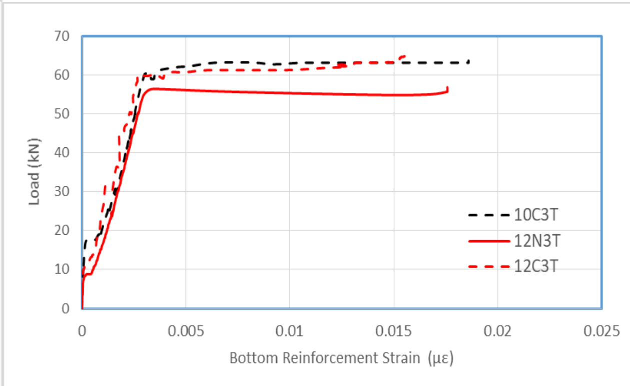
a) Specimens of Group I



(b) Specimens of Group II



(c) Specimens of Group III



(d) Specimens of Group IV

Figure (7): Load versus Bottom Reinforcement Strain

3.3. Ductility, Toughness, and Stiffness.

Table (6) illustrates the toughness, initial stiffness, post crack stiffness, and ductility of all specimens. Toughness is defined as the measured area under the load-deflection curve up to failure [27, 28]. A specimen is considered to be ductile if it is capable of withstanding large displacement under loading before failure occurs. These large deflections are accompanied by a visible change in cross-sectional dimensions and therefore give a warning of awaiting failure [29]. Thus, the ductility factor is defined as the ratio of the ductility of the Nano-specimen (D_N) to that of the corresponding concrete specimen (Dc). Furthermore, the Stiffness Degradation Factor is defined as the ratio of post-crack stiffness (K) to initial crack stiffness (Ki) and was computed for each Group, as shown in Table (6). Specimen 10N1T exhibits the highest area under the load-deflection curve, indicating more ductile behavior and energy dissipation. On the other hand, specimens of Group II (RC beams with 30 mm bottom concrete cover and without topping reinforcement at mid-span) provide approximately reduced toughness and ductility, which indicates it has a brittle behavior in which energy is barely absorbed. In addition, specimens 10N1T and 10N3T provide the highest ductility values with an enhancement of 63% and 4.9%, respectively, compared with the corresponding value of beams 10C1T and 10C3T. Furthermore, specimens 12N1T and 12N3T exhibit better ductility compared to beams 12C1T and 12C3T, with increases of 5.6% and 17.2%, respectively. These findings suggested that, the specimens treated with Nano-clay additive exhibited greater ductile behavior in the case of the presence of top reinforcement at the mid span of the tested beams.

Stiffness at the main loading stages is illustrated in Table (6). There are two values of the estimated stiffness. The first one is measured before the cracking load which is defined as “Initial Stiffness”, and the second value is measured after the cracking load till the yielding of reinforcement which is defined as “Post Cracking Stiffness”. Specimens 12N1T and 12N1 show the highest initial stiffness, while specimens 12N3 and 12C1 give the smallest initial stiffness. On the other hand, specimens 12C1 give the smallest degradation of stiffness, while specimen 12N1T shows the highest degradation of stiffness. As a result, using of Nano-clay additive showed a negligible effect on the flexural stiffness of the reinforced concrete beams.

Table (6). Stiffness, Toughness, and Ductility Factor

Concrete Mix	Group ID	Specimen ID	Toughness (kN.mm)	Initial Stiffness K_i (kN/mm)	Post Crack Stiffness K (kN/mm)	Stiffness Degradation Factor (K/K_i)	Ductility	Ductility Factor (D_N/D_C)
C400	Group I	10C1	3180	15.74	7.52	0.523	5.00	1.0
		12C1	4131	10.05	7.10	0.294	5.47	1.0
	Group II	10C3	2129	15.1	5.87	0.611	3.09	1.0
		12C3	2618	14.95	5.43	0.637	4.25	1.0
	Group III	10C1T	3345	17.73	8.46	0.523	5.58	1.0
		12C1T	4493	13.67	5.60	0.590	6.97	1.0
	Group IV	10C3T	5420	13.46	6.42	0.523	8.45	1.0
		12C3T	3417	11.41	5.70	0.50	5.22	1.0
NC6%	Group I	10N1	2566	18	8.23	0.543	4.0	0.80
		12N1	2490	18.82	7.30	0.613	4.31	1.0
	Group II	10N3	2721	14.80	5.58	0.623	3.61	1.17
		12N3	3151	11.26	4.61	0.590	4.02	0.945
	Group III	10N1T	6290	12.48	7.71	0.382	9.11	1.63
		12N1T	4575	22.03	6.95	0.685	7.36	1.056
	Group IV	10N3T	6107	13.76	5.63	0.590	8.86	1.049
		12N3T	3660	11.55	5.31	0.544	6.12	1.172

CONCLUSIONS

Experimental investigations of flexural cracking performance at ultimate loads for reinforced concrete beams in the case of casting with conventional concrete mix or concrete with Nano-Clay additives were carried out. The main issue taken into consideration in designing concrete mix, achieving approximately the same compressive strengths in both traditional concrete (C400) and concrete enhanced with Nano-particles (NC6%) as replacement of cement, as long as the concrete compressive strength is the important item in design equations. Thus, the cement content was lesser by 50 kg/m^3 in concrete enhanced by Nano-clay additive as the Nano-clay plays an important role in improving the concrete compressive strength. Sixteen RC beams with the same cross-section and span were cast and tested. From the research test results the main findings and conclusions are as follows:

1- The utilization of Nano-particles as a partial replacement for cementitious material is very useful; it has an environmental impact, as the use of Nano-particles reduces the amount of the cement content, while maintaining the same compressive strength for both concrete mixtures by using less weight of cementitious material as in case of NC6% concrete mix.
2- The incorporation of nanoparticles has a good outcome on the crack distribution of beams, providing a better distribution than ordinary concrete due to improved flexural tensile and bond strength.
3- In terms of ultimate load and deflection values, RC beams with Nano-Clay exhibit more ductile behavior than beams with traditional concrete, particularly when top reinforcement is present. Specimens 10N1T and 10N3T have the highest ductility values, up 63% and 4.9%, respectively, when compared to beams 10C1T and 10C3T.
4- The experimental results demonstrated that, RC beams with Nano-Clay exhibited more ductile behavior than beams with standard concrete in the presence of a large concrete cover at the tension side of reinforced concrete beams.
5- It was remarked that the measured strain at ultimate loads at the bottom reinforcement (beam tension side) for all specimens with Nano-clay addition was lower than for the corresponding specimens without Nano-clay. This link can be explained by the fact that the tension strength of the concrete with Nano-clay additive is higher than that of the concrete without it.
6- Using of Nano-clay additive shows a negligible effect on the flexural ultimate capacity or stiffness of the reinforced concrete beams for specimens with the same concrete compressive strength.

ACKNOWLEDGMENT

The authors are grateful to **Prof. Dr. Hadad Said Hadad**, Head of the Concrete Structures Research Institute, for his valuable technical, financial, and psychological assistance and support in completing this research. Also, the authors would like to thank **Prof. Dr. Tamer H. K. El-Afandy** and Prof. **Dr. Sherief M. Elzeinny** for their ongoing assistance, technical guidance, and encouragement.

REFERENCES

[1] P.C. Aïtcin, "Cement of yesterday and today: concrete of tomorrow", Cement and Concrete Research, Vol.30 (9), (2000),pp.1349–1359.

[2] P. Hou,Jueshi Qian, Xin Cheng and Surendra P.Shah, "Effects of the pozzolanic reactivity of nano SiO_2 on cement-based materials", Cement and Concrete Composites, 55 (2015), pp.250–258.

[3] S. Zhao, W. Sun, "Nano-Mechanical behavior of a green ultra-high-performance concrete", Construction and Building Materials Vol.63 (2014),pp.150–160.

[4] A.K.M. Bjorn Birgisson, Georgene Geary, Mohammad Khan, Konstantin Sobolev, "Nanotechnology in Concrete Materials", (2012), Transportation Research Circular E-C170, ISSN 097-8515.

[5] A.B. Aref Sadeghi Nik, "Nano-particles in concrete and cement mixtures", Applied Mechanics and Materials,Vols.110–116 (2012), pp.3853–385.

[6] E. Güneyisi, Mehmet Gesoğlu, Seda Karaoğlu and Kasım Mermerdaş, "Strength, permeability and shrinkage cracking of silica fume and metakaolin concretes", Construction and Building Materials, Vol.34 (2012), pp.120–130.

[7] D. Adak, M. Sarkar, S. Mandal, "Effect of nano-silica on strength and durability of fly ash based geopolymer mortar", Construction and Building Materials, Vol.70 (2014), pp.453–459.

[8] Miguel A Massa, Cristian Covarrubias, Mauricio Bittner, Ignacio Andrés Fuentevilla, Pavel Capetillo, Alfredo Von Marttens, Juan Carlos Carvajal , "Synthesis of new antibacterial

composite coating for titanium based on highly ordered nanoporous silica and silver nanoparticles", Material Science Engineering, C 45 (2014),pp.146–153.

[9] M.S. Morsy, S.H. Alsayed, M. Aqel, Hybrid effect of carbon nanotube and nano-clay on physico-mechanical properties of cement mortar, Construction and Building Materials, Vol.25 (1) (2011), pp. 145–149.

[10] Navarro-Blasco, M. Pérez-Nicolás, J.M. Fernández, A. Duran, R. Sirera, J.I. Alvarez, "Assessment of the interaction of polycarboxylate superplasticizers in hydrated lime pastes modified with nanosilica or metakaolin as pozzolanic reactives", Construction and Building Materials, Vol.73 (2014), pp.1–12.

[11] P. Dinakar, Pradosh K. Sahoo, G. Sriram , "Effect of Metakaolin Content on the Properties of High Strength Concrete", International Journal of Concrete Structures and Materials Vol.7, No.3, pp.215–223, September (2013), DOI 10.1007/s40069-013-0045-0, ISSN 1976-0485 / eISSN 2234-1315.

[12] N. Hamed, M.S. El-Feky, M. Kohail, E.-S. Nasr, "Effect of nano-clay de-agglomeration on mechanical properties of concrete", Construction and Building Materials, Vol.205 (2019), pp. 245–256.

[13] M.S. Morsy, S.A. Alsayed and M. Aqel, Effect of nano-clay on mechanical properties and microstructures of ordinary Portland cement mortar, Int. J. Civ. Environ. Eng. 10 (01) (2010).

[14] S.wild, J.M. Khatib, A. Jones, "Relative strength, Pozzolanic Activity and Cement hydration in super plasticized Metakaolin Concrete", Cement and Concrete Research, Vol.26, No.10, (1996), pp.1537-1544.

[15] Anwar M. Mohamed, "Influence of nano materials on flexural behavior and compressive strength of Concrete", HBRC Journal (2016) 12, 212-225.

[16] S. Ab Elbaky and S.Yehia, "Fresh and Hardened Properties of Nano Concrete An Overview on the Laboratory Investigation of Using Nano-Materials in Concrete", JöKKUL Journal (2018);Vol.68 No.3, March, pp.93–117.

[17] E.Badogianniset, V.G. Papadakis, E. Chaniotakis, S. Tsivilis, "Exploitation of poor Greek kaolin's strength development of metakaolin concrete and evaluation by means of k-value", Cement and Concrete Research 34, (2004), pp.1035–1041.

[18] M.Suneel, K. Jagadeep, K. K. MahaLakshmi, G. Praveen Babu, G. V. Ramarao, "An Experimental Study on Workability and Strength Characteristics of M40 Grade Concrete by Partial Replacement of Cement with Nano-TiO2" ,Sustainable Construction and Building Materialsonference, Conference paper, (2018), Proceedings of ICSCBM, pp. 253–263.

[19] Rakesh Kancharla, Venkata Rao Maddumala, T. V. N. Prasanna, T. V. N. Prasanna, Ratna Raju Mukiri, M. Viju Prakash, "Flexural Behavior Performance of Reinforced Concrete SlabMixed with Nano and Microsilica", Hindawi, Journal of Nanomaterials, Volume (2021), Article ID 1754325, 11 Pages.

[20] Aseel Mansi, Nadhim Hamah Sor, Nahla Hilal and Shaker M.A.Qaidi, "The Impact of Nano Clay on Normal and High-Performance Concrete Characteristics: A Review", IOP Conf. Series: Earth and Environmental Science 961, (2022).

[21] Hanadi F. Naji, Nibras N. Khalid and Wissam K. Alsaraj," Influence of Nanoclay on the Behavior of Reinforced Concrete Slabs" 1st International Conference on Engineering and Advanced Technology (ICEAT), IOP Conf. Series: Materials Science and Engineering 870, (2020), pp.1-7.

[22] Mostafa Ahmed Mahdi, Ahmed Hassan Ghallab, El-Saaid Ibrahim Zaki and Ahmed Sayed Elmannaey," Effect of Nano clay and Marble Powder Waste as a Hybrid Addition on the Behavior of Normal and High Strength RC columns Subjected to Axial compressive loading", Advances in Science, Technology and Engineering System, vol. 6, No. 3, (2021), pp.367-384.

[23] Xin Wang, “Effects of nanoparticles on the properties of cement-based materials”, Doctor of Philosophy Thesis, Iowa State University, Ames, Iowa, (2017).

[24] Maha Ahmed Shawki[1], Amr Elnemr[1], Carsten Koenke[2] and Carlos Thomas[3], “Rheological properties of high-performance SCC using recycled marble powder”, Innovative Infrastructure Solutions (2024) 9:176, (Vol. 9, Issue 5). Springer Science and Business Media LLC. https://doi.org/10.1007/s41062-024-01460-2.

[25] M.M. Mokhtar [a, *], M. Morsy[a,b], N.A. Taha[c], Emad M. Ahmed[d], “Investigating the mechanical performance of Nano additives reinforced high-performance concrete” 2021 Elsevier Ltd. Construction and Building Materials 320 (2022) 125537, https://doi.org/10.1016/j.conbuildmat.2021.125537.

[26]ASTM A370-15,“Standard Test Methods and Definition for Mechanical Testing of Steel Products”.

[27] James M. Gere and Stephan P.Timoshenko, “Mechanics of Materials”, Fourth Edition, (1997).

[28] Gopalaratnam, V.S.; Gettu, R. “On the characterization of flexural toughness in fiber reinforced concretes”, Cement and Concrete Composites Vol.17 (1995), pp.239–254.

[29] T. Paulay and M.J.N. Priestley, “Seismic Design of Reinforced Concrete and Masonry Buildings”, (1992), pp.1-735.