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Research Article

Mechanical and rheological performance of plastic concrete: Investigation of several properties

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Abstract

Incorporating carbon-based materials, particularly carbon nanotubes (CNTs), into the initial composition of plastic concrete has demonstrated potential in enhancing properties such as particle cohesion and resistance to corrosive environments. This study investigates the influence of CNTs on the mechanical and durability characteristics of concrete through 24 distinct mix designs, all maintaining a constant water-to-cement ratio of 0.5. The CNT content varied at levels of 5%, 10%, 15%, and 20% by weight of cement. For each mix, six cylindrical specimens (15 × 30 cm) and three cubic specimens (15 × 15 × 15 cm) were prepared for evaluating compressive strength, permeability, and modulus of elasticity. The experimental results indicate that under a fixed water-to-cement ratio, increasing the cement content significantly raises the viscosity of the concrete mixture, often resulting in a slurry-like consistency. Conversely, an increase in bentonite content at a fixed water-to-cement ratio enhanced fluidity, thereby increasing the slump of fresh concrete. However, this fluidity caused segregation of aggregate particles during placement into molds, adversely affecting compressive strength. Furthermore, for designs containing 30 kg of bentonite, the water absorption and particle segregation rates increased with a higher cement content. In contrast, as the bentonite content increased from 30 kg to 60 kg, water absorption at the concrete surface and particle segregation decreased, suggesting improved homogeneity and resistance to moisture penetration. These findings provide insights into optimizing the composition of plastic concrete containing CNTs and bentonite for enhanced performance in structural applications.

1. Introduction

From a long time until now, one of the major challenges for the advancement of the dam industry has been the issue of water escaping from the sides and foundations of dams [1]. So that the foundations and flanks of dams have always been among the places that have been allocated the largest amount of geotechnical research [2-4]. Due to the importance of this issue, examining the characteristics of the permeability of the lower layers of the foundation and the sides of the dam has been included in most of this research [5]. Since there is always an underground flow of water under the bed of the lower layers of the construction site of the dam, therefore, with the increase in the height of the water behind the dams, the pore water pressure in the lower layer of the dam increases, which itself causes destruction [6-8], washing Inefficiency, the lower layers of the dam become blocked [9]. Also, the conducted research shows that the increase in pore water pressure in the lower layer of the dam causes soil flotation in the heel of the dams [10-12]. To prevent water

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penetration and reduce seepage behind dams, there are various methods [13], one of these methods is digging a trench behind the dam and filling it with plastic concrete materials [14-16]. In plastic concrete, in addition to the primary materials available in ordinary concrete such as cement, stone materials and water, a type of clay called bentonite is also used, to which ordinary clay, pozzolans, etc [17,18] may also be added [19]. Also, more water-cement ratios are used in plastic concrete [20]. In addition to high deformability and low permeability, plastic concrete has a shear resistance proportional to the applied pressure [21]. The high ratio of water to cement as well as the presence of bentonite in plastic concrete has caused this concrete to have different properties than normal concrete, among these properties we can mention its low strength and high plasticity [22-24]. In addition to having high ductility and low resistance, plastic concrete has low permeability, which sometimes we can minimize this permeability by increasing the concentration of bentonite slurry [25-27]. Plastic concrete is mainly used in hydraulic structures such as dams, and retaining walls [28]. These structures need materials that can minimize water leakage and at the same time have the ability to withstand changes in water pressure and relative soil movements [29]. The high plasticity of this concrete allows the structure to change its shape against volume changes and relative movements between the soil and the structure without causing large cracks or fractures [30]. In retaining walls and underground structures, plastic concrete is used as a protective layer against non-uniform soil deformations and lateral pressures [31]. Plastic concrete in these applications can withstand non-uniform settlements and dynamic pressures caused by earthquake vibrations or heavy machinery due to its high ability to absorb energy and plastic deformation [32]. In areas affected by strong vibrations or mechanical vibrations, plastic concrete acts as an energy absorbing material. The internal structure of this concrete due to the presence of clay particles; Like bentonite, it can absorb and dissipate vibration energy, which reduces local stresses and prevents premature failures in the structure [33-35]. Plastic concrete has high viscosity and significant plastic deformation. This behavior is caused by the use of clay materials; It is like bentonite which strengthens the matrix structure of cement and reduces the speed of free flow of water in concrete. Compared to normal concrete, the constituent ratios in plastic concrete are completely different. About 80% of the composition of ordinary concrete is sand [36]. The amount of cement is on average between 12% and 14% and the amount of water is between 6% and 8%. But these proportions in plastic concrete are such that sand is about 65-75% (average 10% less), cement about 5-10%, bentonite slurry (combination of water, and bentonite) about 20-25%. is Due to this amount of combination ratios, plastic concrete has high fluidity and has less resistance than normal concrete. Therefore, the main ingredients of plastic concrete are water, sand, cement and bentonite, which are briefly mentioned below. Among the most important properties of plastic concrete that are studied more, we can mention permeability, modulus of elasticity, compressive strength, durability and abrasion resistance, ductility and efficiency [37]. One of the most important features that plastic concretes should have is that they show good durability in normal and corrosive environmental conditions [38]. The durability of plastic concrete means its resistance and waterproofness in non-corrosive and aggressive (corrosive) environments, which is achieved by proper concrete mixing design. For watertight wall structures, the concept of appropriate abrasion resistance should be compared to the concept of permeability, as this concept is expressed as the resistance of concrete materials to percolation under hydraulic gradient [39]. By conducting experiments, it has been found that the resistance to wear depends on the compressive strength, the amount of air, the granulation of materials, slump, etc [40]. Plastic concrete offers notable advantages over conventional concrete, including reduced permeability, increased flexibility, and enhanced workability. Economically, it also proves to be more cost-effective compared to ordinary concrete. Studies conducted by Pashang Pisheh et al. (2018) and Kazemi et al. (2016) on the properties of plastic concrete used in dam sealing curtains revealed that increasing the cement content improves both compressive strength and the modulus of elasticity. Conversely, these properties decrease as the proportion of bentonite increases. These findings were derived from analyzing various compositions of plastic concrete materials. In 2024, Derakhshan Nezhad et al. investigated the mechanical performance of self-compacting concrete (SCC) enhanced with palm fibers at dosages of 0%, 0.5%, 1%, 1.5%, and 2% by cement weight. Their experimental results demonstrated that incorporating palm fibers significantly improved tensile strength at 7 and 28 days of curing. Specifically, the increases in tensile strength for SCC containing 0.5%, 1%, 1.5%, and

2% palm fibers were 16.37%, 34.27%, 56.39%, and 82.24% at 7 days, and 13.56%, 27.61%, 46.96%, and 67.6% at 28 days, respectively, compared to plain SCC without fibers.

The importance of using plastic concrete in the discussion of concrete structure and technology is as follows; Plastic concrete is capable of exhibiting controlled plastic behavior that allows the structure to withstand excessive loads to temporarily deform without breaking. This feature is very important for areas with high vibration and lowest dynamics such as earthquakes, because ordinary concrete in similar conditions may become brittle and irreparable. In environments with thermal variations or web text loadings, cracking is a common material in conventional concrete. But plastic concrete, due to its low modulus of elasticity and non-linear behavior, greatly reduces this type of cracking. This feature is one of the most important in dams and marine structures that are exposed to constant pressure and temperature changes. Due to its good density and chemical resistance, plastic concrete is suitable for use in chemical storage tanks, and underground structures in leak-sensitive areas. These features help reduce environmental risks and increase the lifespan of structures. The low modulus of elasticity in plastic concrete makes it more difficult to compress. This allows for controllable deformations in bulk structures and results from transmission. The creep behavior of plastic concrete is one of its main advantages. Plastic concrete can change long-term and static paths in the form of creep, which prevents the creation of high internal stresses in the structure. Plastic concrete is ideal in earthquake and explosion resistant structures due to its controllable plastic behavior and energy absorption during deformation. This prevents vandalism and creates security. The composition of plastic concrete is designed in such a way that it is viscous. This feature prevents the separation of particles and makes the concrete stable in different stages of construction and processing. This feature is special in tall and bulky structures that require high stability and uniform filling. Plastic concrete is such that under low stresses, it shows elastic behavior, but high loading should enter the plastic state. This characteristic gives those concrete changes its shape when critical stresses occur and absorbs energy and prevents cracks from spreading and digging. Plastic concrete typically provides a longer, more controlled setting time to reduce initial stresses and prevent early cracking. This feature is very important in bulky structures such as dams and tunnels where the risk of early cracks is high. In this research, the fresh properties of plastic concrete were investigated through slump test and hardened plastic concrete test through modulus of elasticity, compressive strength and tensile strength.

2. Sample Mixing and Processing Plan

In this study, 24 distinct concrete mix designs were developed and executed. For each mix design, six cylindrical specimens measuring 30×15 cm and three cubic specimens measuring 15×15×15 cm were prepared to evaluate the tensile and compressive strength at 28 days. The detailed mix design configurations are presented in Table 1. The research employed three distinct cement quantities and two bentonite dosages. Due to the inherently fluid nature of plastic concrete, a fixed water-to-cement (W/C) ratio of 0.5 was adopted across all mix designs. once at night. This process was meticulously followed to maintain consistent hydration and achieve reliable mechanical property results for plastic concrete.

Table 1. Plastic concrete mixing plan [35]

Naming each design	W/C	Carbon (%)	Bentonite (Kg/m^3)	Cement (Kg/m^3)	Gravel (Kg/m^3)	Water (Kg/m^3)	Sand (Kg/m^3)
PC-1	0.5	5	30	100	1000	250	500
PC-2	0.5	10	30	100	1000	250	500
PC-3	0.5	15	30	100	1000	250	500
PC-4	0.5	20	30	100	1000	250	500
PC-5	0.5	5	30	150	1000	250	500
PC-6	0.5	10	30	150	1000	250	500
PC-7	0.5	15	30	150	1000	250	500
PC-8	0.5	20	30	150	1000	250	500

PC-9	0.5	5	30	200	1000	250	500
PC-10	0.5	10	30	200	1000	250	500
PC-11	0.5	15	30	200	1000	250	500
PC-12	0.5	20	30	200	1000	250	500
PC-13	0.5	0	60	100	1000	250	500
PC-14	0.5	5	60	100	1000	250	500
PC-15	0.5	10	60	100	1000	250	500
PC-16	0.5	15	60	100	1000	250	500
PC-17	0.5	20	60	100	1000	250	500
PC-18	0.5	5	60	150	1000	250	500
PC-19	0.5	10	60	150	1000	250	500
PC-20	0.5	15	60	150	1000	250	500
PC-21	0.5	20	60	150	1000	250	500
PC-22	0.5	5	60	200	1000	250	500
PC-23	0.5	10	60	200	1000	250	500
PC-24	0.5	20	60	200	1000	250	500

The primary objective of utilizing plastic concrete is to enhance its modulus of softness for specific applications. Consequently, the mix design with the maximum W/C ratio was selected as the baseline configuration to achieve optimal performance. The curing of the specimens in this research followed wet environmental conditions. After demolding, the specimens were wrapped in hemp cloth and placed in a controlled environment within the concrete research laboratory, maintained at an average temperature of 25°C. To preserve the moisture of the hemp covering and ensure adequate curing, the specimens were thoroughly moistened twice daily—once during the day and

2.1. Materials Used in Plastic Concrete

2.1.1. Cement

In this study, Type 5 Portland cement produced by Behbehan Cement Factory was employed. The cement's physical and chemical properties are presented in the table below, in compliance with the ASTM C150 [41] standard (see Table 2).

Table 2. Chemical and Physical Properties of Type 5 Portland Cement

Feature	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	SO_3	K_2O	Insoluble residue	Specific weight (kg/m^3)
Percentage	21.18	4.96	5.04	1.40	62.4	2.12	0.57	0.74	3050

2.1.2. Aggregates

Fine-grained aggregates (washed sand) and coarse aggregates of broken type with granulation of residue on sieve 8 and residue on sieve 16 have been used in the mixing plan. The material of these aggregates is limestone, and they were supplied from Behbahan mines, and their physical characteristics and granularity are given in Table 3, which is in accordance with the ASTM C33 standard [42].

Table 3. Physical characteristics of aggregates

Water absorption percentage	(kg/m^3) specific weight	Aggregate type
0.85	2200	Coarse grain
0.65	1900	Fine grain

2.1.3. Water

In order to make the samples, the consumption (urban) water of Behbahan city was used, which conforms to the requirements of ASTM C 94 [43] (according to Table 4).

Table 4. Characteristics of drinking water

Chloride ion concentration	PH	Temperature (°C)
50	6	20

2.1.4. Bentonite

Bentonite produced in Avin Bentonite Company was used to make the samples, the specifications and values of each of them are given in Table 5.

Table 5. Characteristics of bentonite components

Feature	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	TiO_2	K_2O	Na_2O	Specific weight (kg/m^3)
Percentage	69.8	11.88	1.3	1.42	8.17	0.2	0.47	4.88	2105

2.1.5. Carbon

The carbon produced in Gerd Asia Company has been used for mixing in the mixing plan. According to the manufacturer's announcement, this product does not contain harmful elements for the environment and is suitable for the southern regions of the country that have relatively corrosive soil (according to Table 6).

Table 6. Characteristics of carbon components

Feature	Sulfur	Carbon
Percentage	1.6%	98.4%

3.Steps of Plastic Concrete Mixing Plan

The bentonite needed for each series of samples is soaked in 70% of the water of the mixing plan 24 hours before making the samples, and every 4 to 6 hours, it is mixed with a rod for 5 minutes in the container until it is well mixed. Dissolve in water ASTM C595 [44] (according to Figure 1).

Fig. 1. Adding water to bentonite and preparation for making concrete

Fig. 2. A sample of sand in order to measure the moisture content of the materials

To prepare the mix design, the moisture content of the aggregates was determined by oven-drying the samples to a constant weight. Based on the measured moisture content, the mix proportions for the concrete were adjusted to ensure the aggregates were in a saturated surface dry (SSD) condition. Figure 2 illustrates the moisture level of the aggregate samples subjected to this process. For sample preparation, sand was initially introduced into the mixer, followed by gravel. The aggregates were mixed for approximately two minutes to ensure homogeneity. Cement was then gradually added to the mixer, allowing it to integrate thoroughly with the aggregates. Before introducing water and bentonite, the mixture was manually stirred using a rod to achieve preliminary uniformity. The water and bentonite were then slowly poured into the mixer while it was in operation. In the final step, carbon was carefully added to the mix to prevent clumping and ensure even dispersion. The angle of the mixer's stirrer significantly influenced the uniform distribution of the aggregates, directly affecting the homogeneity of the concrete. Due to variations in the flow rate of concrete across different mixtures, adjustments were made to the stirrer angle to optimize the mixing process and achieve a consistent and evenly blended concrete mix.

(a) (b)

Fig 3. (a) Adding water, bentonite and carbon to concrete and (b) molding samples with concrete

The method of making, and the time of composition and mixing were tried as much as possible to be done in the same way for all the current research projects. The arrangements considered in the research include the same operators performing the tests, making concrete in a short time, the same sand, the same moisture content of the materials, and the same mixing time of the concrete in the mixer are some of these factors.

4. Slump Test Results and Appearance Characteristics of The Samples

The slump test results conducted during the preparation of each series are presented in Table 7. This study demonstrated that at a constant water-to-cement (w/c) ratio, increasing the cement content significantly raises the viscosity of the concrete, transforming it into a slurry-like consistency. Conversely, an increase in bentonite content at a fixed w/c ratio enhanced the fluidity of the mix, leading to a corresponding increase in the slump of the fresh concrete. When comparing the results of carbon-free plastic concrete at a cement dosage of 100 kg/m^3, the inclusion of carbon was found to reduce the slump, whereas at higher cement contents, its influence was comparable to that observed under carbon-free conditions. The increased fluidity of the concrete mix occasionally resulted in segregation of the aggregate components during placement into the sampling molds. This segregation effect is likely to negatively impact the compressive strength of the concrete as specified in ASTM C143 [45].

Figure 4 illustrates representative slump measurements obtained during the experiments conducted in this study. Farajpour [10], in his research on plastic concrete without carbon, observed that slump effectiveness and slump loss were more pronounced compared to plastic concrete containing carbon. He attributed this to the lower adhesion between cement particles and aggregates in the absence of carbon. Similarly, Rafiq [40] investigated the slump behavior of plastic concrete with and without carbon and found that the addition of carbon significantly reduced the slump. This reduction was linked to the surface characteristics and strong water-absorbing properties of carbon, which decrease the amount of free water in the mixture.

Table 7. Slump measurement results of samples of this research

Naming each design	W/C	(%)Carbon	Bentonite (Kg/m^3)	Cement (Kg/m^3)	Water (Kg/m^3)	(cm) Slump
PC-1	0.5	5	30	100	250	19.5
PC-2	0.5	10	30	100	250	19
PC-3	0.5	15	30	100	250	22
PC-4	0.5	20	30	100	250	17
PC-5	0.5	5	30	150	250	slurry
PC-6	0.5	10	30	150	250	25
PC-7	0.5	15	30	150	250	slurry
PC-8	0.5	20	30	150	250	slurry
PC-9	0.5	5	30	200	250	slurry
PC-10	0.5	10	30	200	250	slurry
PC-11	0.5	15	30	200	250	slurry
PC-12	0.5	20	30	200	250	slurry
PC-13	0.5	5	60	100	250	24
PC-14	0.5	10	60	100	250	25
PC-15	0.5	15	60	100	250	24.5
PC-16	0.5	20	60	100	250	25
PC-17	0.5	5	60	150	250	25
PC-18	0.5	10	60	150	250	21.5
PC-19	0.5	15	60	150	250	26.5
PC-20	0.5	20	60	150	250	27
PC-21	0.5	5	60	200	250	slurry
PC-22	0.5	10	60	200	250	29
PC-23	0.5	15	60	200	250	28.5
PC-24	0.5	20	60	200	250	slurry

Carbon additives, by partially absorbing the mixing water, limit the lubricating effect within the concrete, resulting in a stiffer mixture with reduced slump. The incorporation of carbon with a high specific surface area amplifies this effect, as the larger surface area enhances water absorption and subsequently reduces fluidity. Conversely, plastic concrete without carbon admixtures demonstrated higher slump values, indicating superior fluidity and workability in its fresh state. This increased slump is attributed to the unrestricted movement of water throughout the mixture in the absence of carbon, allowing for greater flowability and easier handling.

Fig 4. Slump test: (a) flowability of plastic concrete with carbon, (b) height difference of plastic concrete with slump, (c) determination of slump of plastic concrete with carbon and (d) efficiency and fluidity of plastic concrete with carbon on a flat plate

Table 8. Measured Weight of Fresh Concrete and Observational Insights During Sample Preparation

Naming each design	(%) Carbon	Minimum weight of fresh concrete is 2 (kg)	Weight of the most fresh concrete is 2 (kg)	segregation of aggregates	surface bleeding
PC-1	5	5.730	5.810	Average	Average
PC-2	10	5.9	5.960	Average	Average
PC-3	15	5.740	5.770	Average	Low
PC-4	20	5.890	5.920	Average	Average
PC-5	5	5.770	5.850	A lot	Intense
PC-6	10	5.850	5.920	Very Little	Intense
PC-7	15	5.820	5.870	A lot	Intense
PC-8	20	5.610	5.680	A lot	Intense
PC-9	5	5.590	5.598	A lot	Intense
PC-10	10	5.880	5.920	A lot	Intense
PC-11	15	5.855	5.870	A lot	Intense
PC-12	20	4.950	5.370	A lot	Intense
PC-13	5	5.815	5.830	Average	Average
PC-14	10	5.840	5.880	Weak	Have not
PC-15	15	5.680	5.750	Average	low
PC-16	20	5.560	5.660	Average	low
PC-17	5	5.680	5.710	Very Little	low
PC-18	10	5.590	5.620	Very Little	Average
PC-19	15	5.470	5.690	Very Weak	low
PC-20	20	5.570	5.610	Very Weak	low
PC-21	5	5.670	5.790	Too much	Intense
PC-22	10	5.550	5.560	Very Weak	Low
PC-23	15	5.760	5.8	Very Weak	Low
PC-24	20	5.520	5.610	Too much	Intense

These properties are particularly advantageous for concrete mixtures requiring enhanced workability. The addition of carbon may improve the compressive strength of hardened concrete; however, the reduction in slump and increased stiffness of fresh concrete necessitate the optimization of the water-cement ratio, along with the use of superplasticizing admixtures, to achieve a balanced performance between fresh and hardened properties of plastic concrete. In this study, the weight of fresh concrete was measured using two identical containers, as shown in Table 8. The table also includes other characteristics, such as surface water absorption and grain separation during the molding of the samples. Based on the results presented in Table 8, it is observed that increasing the cement content in mixtures with 30 kg of bentonite leads to higher water absorption and increased grain separation. Notably, the addition of carbon does not influence these characteristics. On the contrary, increasing the bentonite content from 30 to 60 kg reduces the surface water absorption and minimizes grain separation.

5. Appearance of Concrete After Initial Setting

The incorporation of bentonite in the concrete mixture significantly delays the setting time of the samples, resulting in a later setting period. During sample preparation, due to the soft nature of the concrete after 48 hours, the setting time was extended to 72 hours, as per ASTM C1602 [46]. Moreover, in the designs exhibiting significant slump, a sharp decrease in concrete level was observed. The drop in the surface level of fresh concrete is directly correlated with the amount of slurry present in the mixture.

6. Choosing Optimal Conditions for Processing Samples

In similar conditions for processing plastic concrete samples, based on ASTM C31 standard [47], the method of wetting the surface with coating was chosen and the resistance of concrete in wet coating conditions increases according to the standard and research precedent in this field, and from this processing method used for the samples of the present research.

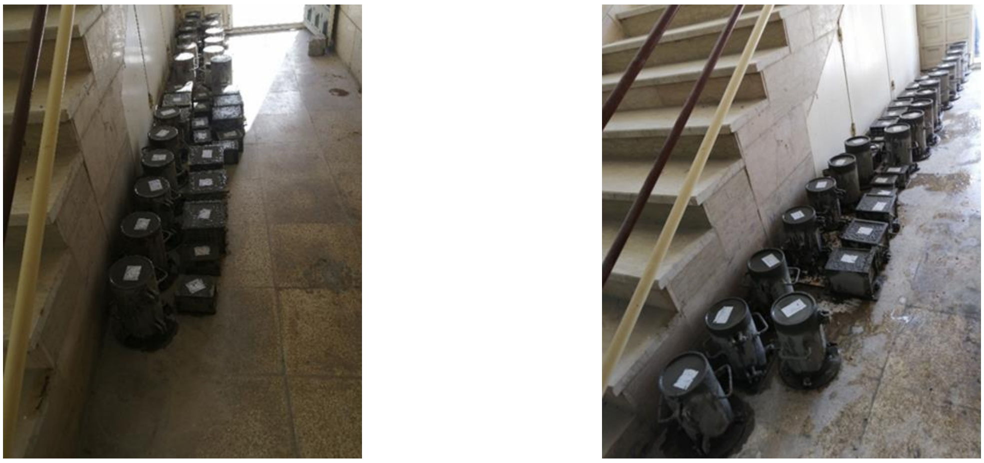


Fig. 7. (a) Fresh concrete in a cylindrical mold, (b) Putting fresh concrete in the mold

Fig. 8. Processing samples with a wet cover in the concrete laboratory

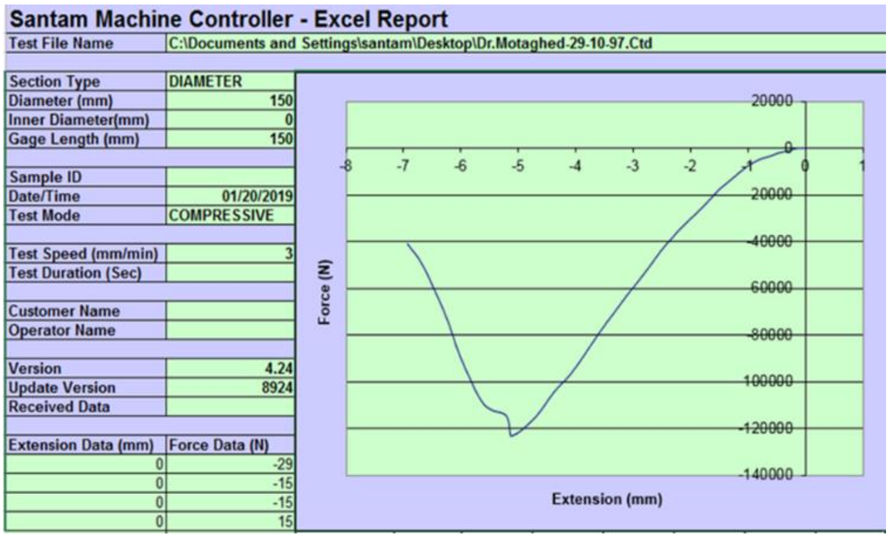
The samples of the present research were kept at room temperature after being placed in the molds to protect them from wind conditions and temperature changes during the time of placement in the sample molds (according to Figure 7). The duration of placing the samples was 24 hours ASTM C31 [47]. After being separated from the mold with wet coating, the samples were processed in the concrete laboratory, which has a wet environment, and a part of it is shown in Figure 8.

7. Failure of Samples

The compressive strength of both cylindrical and cubic concrete samples was evaluated in accordance with the standard PART116: BS1881, with a 15 cm diameter for cylindrical samples and 15 cm dimensions for cubic samples, after 28 days of curing, as specified by ASTM C39 [48]. To calculate the elastic modulus for various concrete designs, the Universal testing machine was employed, with the compressive strength measurements serving as the basis, as shown in Figure 9, following ASTM C78 [49]. In the modulus of elasticity and compressive strength tests using the Universal testing device, it was observed that for plastic concrete incorporating carbon, the combination of carbon particles within the cement matrix induces slight deviations in the initial linear stress-strain curve. These deviations are attributed to phenomena such as interparticle sliding and deformation mechanisms occurring at the nanoscale. Carbon particles play a critical role in the uniform distribution of stress across the sample. Their high strength contributes to a more even stress distribution, preventing localized stress concentrations, which in turn enhances the modulus of elasticity. This effect can be further analyzed through microscopic examination of strain and fracture mechanics. In the plastic deformation region, increased loading leads to the propagation and bridging of microscopic cracks within the concrete matrix. However, in samples containing carbon, the carbon particles act as inhibitors of crack growth. This retarding effect is due to the high resistance of carbon particles and their ability to absorb fracture energy, thereby enhancing the toughness of the concrete through energy-dissipation mechanisms.

Fig. 9. Example under universal device

Plastic concrete with carbon has a greater tendency to fail in shear paths than a completely vertical and brittle failure. Due to the fact that carbon can be distributed homogeneously or in the form of small groups (agglomerates) in concrete, the place of crack growth in this concrete will be different. In plastic concretes, it is possible for cracks to accumulate around these particles or interparticle contact surfaces. In plastic concrete with carbon, the failure behavior is heterogeneous due to the presence of carbon particles; In the sense that the failure proceeds in a more localized and controlled manner. As the loading increases, it can be observed that the finer cracks spread throughout the specimen and connect to each other, and eventually total failure occurs. This process leads to a type of pseudo-plastic behavior in concrete failure, which is called pseudo-ductile failure. The final strength of plastic concrete with carbon is related to the nanoscale and microscopic effects of carbon particles in the cement matrix. In tests, these materials using a universal device can show characteristics such as higher compressive strength and gradual changes in fracture. In this way, plastic concrete containing carbon has less tendency to brittle failure and instead, it faces discontinuous and gradual failure, which is caused by better adhesion of particles and reduction of stress concentration.



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Gage Length (mm)	150
Sample ID	
Date/Time	01/20/2019
Test Mode	COMPRESSIVE
Test Speed (mm/min)	3
Test Duration (Sec)	
Customer Name	
Operator Name	
Version	4.24
Update Version	8924
Received Data	

Extension Data (mm)	Force Data (N)
0	-29
0	-15
0	-15
0	15

Fig. 10. The output diagram of the sample in the universal device

For a more accurate evaluation, it is particularly important to use a universal device to record strain-stress changes at high levels and electron microscope images to examine the cracked areas. Also, tools such as digital image analysis (Digital Image Correlation) can accurately show surface strain distribution. In the Universal testing device, both the stress-strain diagram and force-displacement curve are generated simultaneously. Using the output data from this device, the maximum stress and strain values are calculated, as illustrated in Figure 9. The Universal device produces a curve representing the variations in force and displacement, an example of which for a cylindrical sample is shown in Figure 10, following ASTM C39 [48]. For evaluating the permeability of plastic concrete, cubic specimens with dimensions of 15×15×15 cm were used. This test is essential to assess the concrete's resistance to water, ions, sulfates, and its overall durability, which is crucial for its long-term performance under environmental exposure, as per ASTM C78 [49]. Permeability is a critical factor in the durability of concrete, influencing its resistance to progressive degradation due to water penetration, particularly when exposed to aggressive gases or dissolved minerals. The permeability of concrete, including its susceptibility to water infiltration and corrosion caused by carbonation, is one of the key determinants of concrete's durability. In this study, permeability tests were conducted on both cubic and cylindrical specimens subjected to 5 bar hydrostatic pressure, in accordance with established standards. Environmental conditions, including air pressure and temperature, were maintained at 25°C during the 72-hour testing period. The permeability coefficient was then calculated, as depicted in Figure 11.

Fig. 11. Concrete permeability device

8. Summary, and Analysis of Data

Carbon-based materials, including carbon nanoparticles, carbon nanotubes (CNTs), and graphene, significantly influence the mechanical properties of plastic concrete. These materials enhance concrete performance due to their exceptional characteristics, such as high strength, elevated Young's modulus, and superior thermal and electrical conductivity. The experimental findings demonstrated that the plastic concrete produced in this study is approximately 15 times softer than conventional concrete. Furthermore, an increase in the bentonite content within the plastic concrete mixture resulted in a higher softening modulus. Additionally, as the water-to-cement ratio increased, a reduction in the concrete's resistance was observed, accompanied by an increase in the modulus of concrete softening. This softening modulus is a critical parameter, particularly with respect to the permeability of plastic concrete. The data corresponding to a water-to-cement ratio of 0.5, which was consistently applied in this research, are presented in Table 9. The analysis of compressive strength reveals that plastic concretes exhibit heterogeneous distributions of carbon particles, with variations in their density and dispersion. Carbon particles, owing to their intrinsic strength and stiffness, are capable of resisting local deformations; however, this resistance is contingent upon both the dispersion of the particles and the bond formation between the carbon particles and the cement matrix. For samples demonstrating higher compressive strength (e.g., PC-14 and PC-17), it is likely that a stronger interface bond between the carbon particles and the cement matrix is formed, resulting in a more uniform distribution of carbon particles throughout the matrix, which consequently enhances compressive strength.

Table 9. Results of failure of cylindrical concrete samples

Mixing plan	Compressive strength (MPa)	Displacement equivalent to maximum force (mm)	Displacement corresponds to 0.45 max (mm)
PC-1	2.718	3.85	1.48
PC-2	3.121	3.63	1.72
PC-3	2.639	5.6	3.56
PC-4	3.301	5.1	2.7
PC-5	2.519	3.22	1.41
PC-6	1.586	2.6	1.16
PC-7	2.418	3.48	1.33
PC-8	2.492	2.86	2.62
PC-9	3.107	3.33	1.36
PC-10	1.843	5.8	2.7
PC-11	2.270	4.8	1.45
PC-12	3.108	4.51	1.97
PC-13	3.592	6.47	3.63
PC-14	3.980	4.89	2.3
PC-15	1.901	4.81	0.26
PC-16	3.927	4.56	2.47
PC-17	3.839	8.41	4.66
PC-18	2.842	3.15	1.27
PC-19	2.263	3.81	1.77
PC-20	2.183	2.63	1.18
PC-21	2.266	3.42	1.01
PC-22	2.394	2.9	1.1
PC-23	2.328	4.03	1.39
PC-24	1.922	2.45	0.96

The transition zones between the carbon particles and the cement matrix are particularly susceptible to stress concentration. In samples exhibiting greater softness and mobility (such as PC-17), these regions effectively withstand higher stresses without failure, owing to the improved distribution and uniform transfer of stress between the carbon and cement phases. The larger displacements observed at maximum force indicate a softer behavior and a more gradual failure of the concrete, a phenomenon attributed to the energy-absorbing properties of the carbon particles and their contribution to increased flexibility in the fracture zone. For samples such as PC-13 and PC-17, which exhibit higher equivalent displacements, it can be inferred that the incorporation of carbon particles in the concrete improves its plastic deformation capacity, thereby reducing stress concentrations and intensities at the failure point. This behavior in concretes that have a soft failure behavior is usually associated with small and controlled failures in the entire structure, and therefore they do not suffer brittle failure. In plastic concretes, softness can vary due to density, size and shape of carbon particles. For specimens with lower displacements, such as PC-6 and PC-20, the carbon particles may not be effectively distributed and stress concentration at certain points leads to rapid and brittle failure. In this case, the fracture area is limited and brittle. Displacement values equivalent to 0.45 times the maximum force indicate the tolerance of the sample in initial deformations. Samples such as PC-17 and PC-13, which have higher displacements, show greater flexibility against initial stresses and can absorb more energy in the inelastic region. This behavior somehow has the property of increasing the resistance to crack propagation, which is also known as "property of preventing crack propagation". More stainability in this area most likely indicates more effective connection between carbon particles and reduction of stress concentration along the matrix.

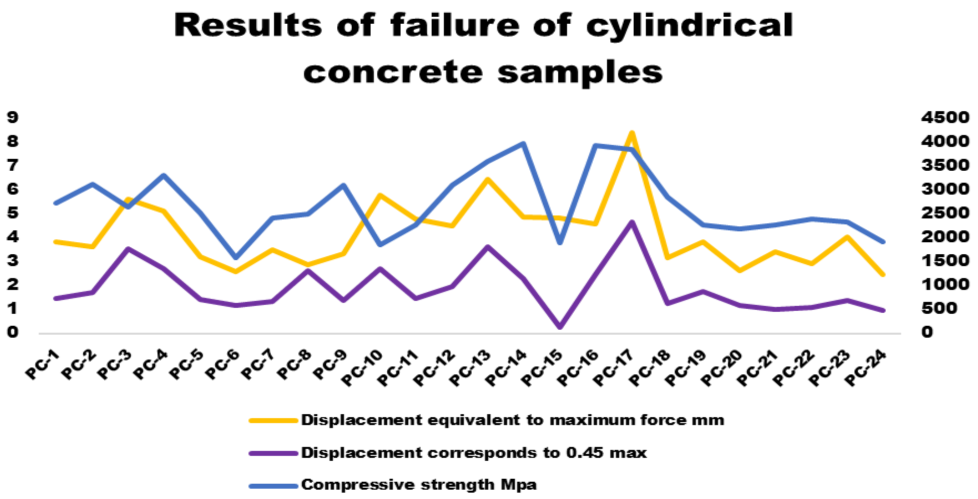

Fig. 12. Compressive strength results obtained from the failure of cylindrical plastic concrete samples

Table 10. Results of failure modulus of elasticity of cylindrical concrete samples

Mixing plan	Maximum force 0.45max (kg)	Ultimate modulus of elasticity (kg)
PC-1	21600	292447
PC-2	24800	404574
PC-3	20977	249576
PC-4	26235	254694
PC-5	20024	295834
PC-6	12607	400095
PC-7	19216	315452
PC-8	19805	335240
PC-9	24692	363154
PC-10	14647	317753
PC-11	18037	336409
PC-12	24705	213198
PC-13	28546	210993
PC-14	31632	291872
PC-15	15111	824787
PC-16	31208	214794
PC-17	30513	196486
PC-18	22586	424147
PC-19	17984	303940
PC-20	17375	407902
PC-21	18011	303160
PC-22	19030	230839
PC-23	18501	255709
PC-24	15276	288558

In these samples, the matrix structure acts with carbon distribution to make microscopic cracks more dispersed and crack propagation more controlled in the early stages of loading. Samples such as PC-17 and PC-13, which have higher ductility, have a better distribution of carbon particles in the cement structure and the ability to absorb energy, more effectively distributing stresses throughout the sample. In this situation, instead of sudden failure, a controlled and gradual failure occurs, which is a valuable feature in earthquake-resistant building applications. Samples with lower displacement and ductility (such as PC-6 and PC-20) behave more brittlely against loading. In these samples, stress concentration at certain points is probably due to non-uniform distribution of carbon particles, which leads to rapid and inefficient failure. This brittle behavior in concrete is usually associated with severe and sudden failures, which can be dangerous for structures. According to the obtained data, it can be concluded that the optimal composition and distribution of carbon particles in the cement matrix can have a significant effect on the softness and final strength of concrete. To achieve optimal mechanical behavior, using methods such as optimization of composition ratios, and advanced carbon dispersion processes can help reduce stress concentration and increase concrete strength.

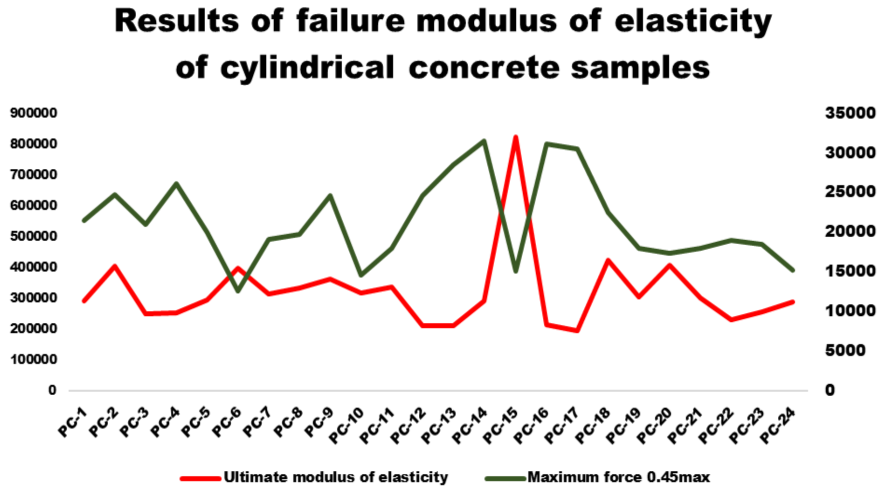

Fig. 13. Results of modulus of elasticity obtained from the failure of cylindrical plastic concrete samples

The analysis of the data presented in Table 10 indicates a direct relationship between the final modulus of elasticity and the force equivalent to 0.45 times the maximum force in carbon-reinforced concrete samples, with the samples' softness and failure behavior. For samples exhibiting a high modulus of elasticity, such as PC-15 and PC-18, significant elastic resistance is observed. This resistance correlates with an increased load-bearing capacity, which helps prevent stress concentration and sudden crack formation. These samples demonstrate enhanced energy absorption due to their higher softness under load, leading to a gradual and controlled failure behavior. This suggests a more effective distribution of carbon particles and a stronger bond between the carbon phase and the cement matrix. In contrast, samples with lower values of elastic modulus, such as PC-13 and PC-17, exhibit a greater tendency toward brittle failure. This behavior can likely be attributed to an uneven distribution of carbon particles or insufficient bonding between the carbon particles and the matrix, which increases stress concentration at specific points and reduces the overall elastic capacity of the samples. For instance, samples PC-12 and PC-13, which exhibit lower ultimate modulus values, likely suffer from poor dispersion of carbon particles. Consequently, stress concentrations in localized regions promote faster failure. Additionally, samples with high equivalent forces, such as PC-15, which reaches 824,787 kg, show greater flexibility and are capable of withstanding larger elastic deformations. This enhanced behavior is likely due to the uniform dispersion of carbon particles in the cement matrix, which contributes to the formation of a continuous structure in the transition zone. In these samples, stress is more uniformly distributed across the material, leading to a gradual failure rather than an abrupt fracture. Samples exhibiting higher values of modulus of elasticity and equivalent force demonstrate softer properties, which correlate with better resistance to dynamic and cyclic loading conditions. To optimize the mechanical performance of carbon-reinforced concrete, controlling the distribution of carbon particles and enhancing the bond between the carbon phase and the cement matrix is essential. This approach helps reduce stress concentrations, improving both the softness and strength of the concrete.

Table 11. Compressive strength failure results of cubic plastic concrete samples

Mixing plan	Compressive strength (MPa)	Displacement equivalent to maximum force (mm)	Displacement corresponds to 0.45 max (mm)
PC-1	2.78	6.19	2.43
PC-2	3.74	5.75	2.93
PC-3	3	4.33	1.69
PC-4	4	3.73	1.22
PC-5	3.74	3.16	1.02
PC-6	2.98	8.28	3.9
PC-7	2.85	4.59	1.84
PC-8	2.87	9.3	5.57
PC-9	2.88	6.57	3.03
PC-10	2.71	7.38	4.16
PC-11	3	5.04	2.14
PC-12	3.46	3.1	1.04
PC-13	4.31	4.45	1.75
PC-14	5.22	4.07	1.98
PC-15	1.52	3.62	1.38
PC-16	1.46	3.05	1
PC-17	3.42	4.22	1.45
PC-18	3.75	4.85	1.97
PC-19	2.98	3.6	1.15
PC-20	2.8	3.9	1.28
PC-21	2.46	5.09	1.16
PC-22	2.83	3.55	1.23
PC-23	2.17	3.3	1.27
PC-24	2.2	3.35	0.82

Samples with high compressive strength such as PC-14 (5.22 MPa), and PC-13 (4.31 MPa) are much harder and more resistant due to stronger connection, and better distribution of carbon particles within the cement matrix. These samples with less equivalent displacement at maximum force (4.07 mm and 4.45 mm, respectively), show a more quasi-elastic behavior and show a greater ability to resist compressive loads. In this way, the carbon particles in these samples act as reinforcing elements and by improving the connection in the transition zone (ITZ), they increase the hardness and reduce the stress concentration. Samples with higher displacement (such as PC-8 with 9.3 mm displacement and PC-10 with 7.38 mm displacement) exhibit more softness and have a softer recoil behavior, which could be due to a more uniform distribution of carbon particles. Such a distribution allows the cement matrix to absorb and release energy more effectively, enabling gradual failure. This behavior, which is also known as pseudo-plastic or pseudo-ductile behavior, helps to increase the durability and flexibility of the structure, especially under dynamic loading conditions. Some samples, such as PC-5 and PC-16, have a lower displacement at the time of reaching the maximum force and at a displacement equivalent to 0.45 of the maximum force, which indicates a decrease in ductility and brittle behavior at failure. This behavior probably occurs due to the irregular density or defects in the distribution of carbon particles, which leads to stress concentration in certain areas and leads to rapid and uncontrollable failure. In these samples, the inefficient connection between the carbon particles and the cement matrix causes a decrease in cohesion and, as a result, a decrease in resistance to compressive loads. Samples with higher displacements at the moment of failure, such as PC-6 and PC-8, show pseudo-ductile behavior and higher deformation capacity. This soft and discontinuous behavior is due to the optimal presence of carbon particles and the creation of an efficient energy absorption system in the fracture zone. This phenomenon is linked to a reduction in stress concentration and an enhancement in stress transfer between the carbon particles and the cement matrix, allowing the samples to undergo more deformation prior to ultimate failure.

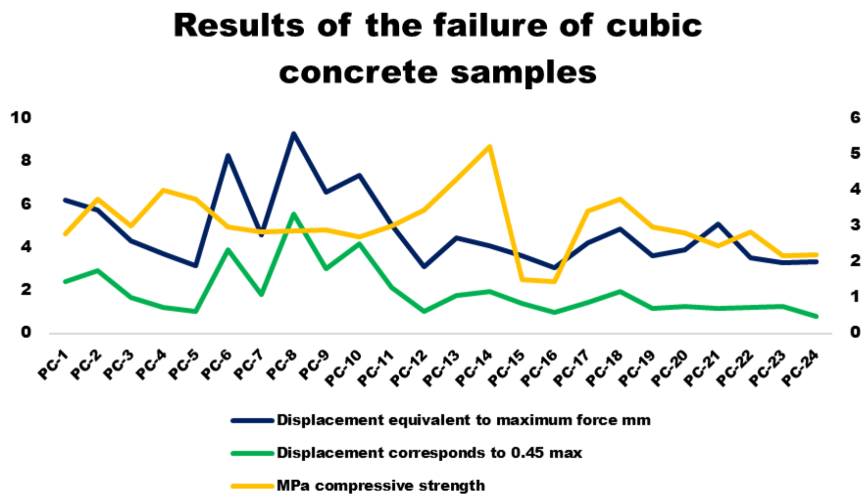

Fig. 14. Compressive strength failure results of cubic plastic concrete samples

Table 12. Results of the failure of cubic concrete samples

Mixing plan	Ultimate modulus of elasticity (kg)	Maximum force 0.45max (kg)
PC-1	1260519	28166
PC-2	1478937	37869
PC-3	1538480	34499
PC-4	3393060	41577
PC-5	3718902	37916
PC-6	923670	30181
PC-7	1227798	28973
PC-8	401759	29036
PC-9	928118	29109
PC-10	475064	27433
PC-11	938395	30426
PC-12	3170617	35068
PC-13	2911800	43677
PC-14	2878082	52729
PC-15	1072357	15435
PC-16	1627213	14792
PC-17	1771179	34618
PC-18	1459237	38028
PC-19	2167131	30208
PC-20	1614400	28374
PC-21	2417842	24911
PC-22	1539571	28692
PC-23	1935622	21944
PC-24	2070789	22328

The optimal distribution and density of carbon particles are critical factors in enhancing the mechanical properties of plastic concrete. In samples with well-distributed carbon particles and a strong bond between the carbon phase and the cement matrix, high compressive strength and pseudo-ductile behavior are achieved. This leads to a substantial improvement in the durability of the structure, particularly in its resistance to sudden and dynamic loading conditions. Conversely, samples with poor distribution and low density of carbon particles exhibit a tendency for brittle and abrupt failure, representing structural vulnerabilities from an engineering perspective.

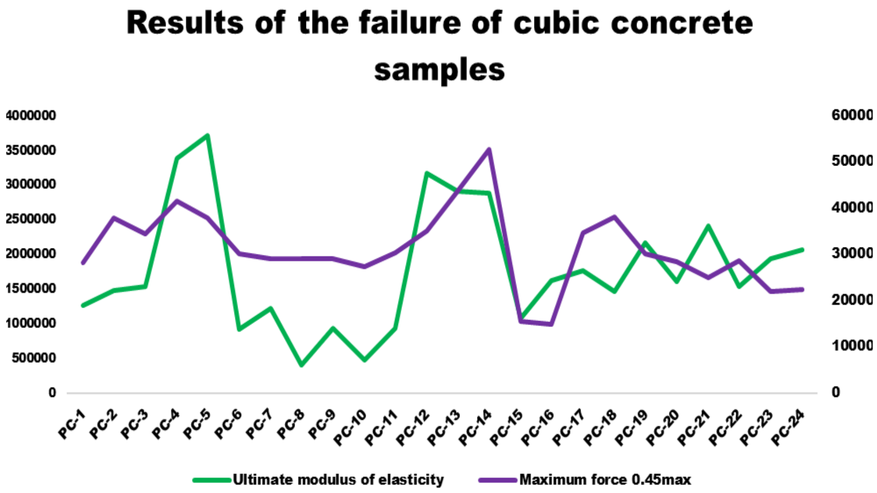

Fig. 15. Results obtained from the failure of cubic plastic concrete samples

The PC-4 and PC-5 samples, exhibiting the highest breaking forces (41,577 kg and 37,916 kg, respectively) and higher moduli of elasticity (3,393,060 kg and 3,718,902 kg, respectively), demonstrate exceptional performance under compressive loads. This performance reflects a well-balanced combination of material properties and an optimized concrete mix design. In contrast, the PC-15 and PC-16 samples, with the lowest breaking forces (15,435 kg and 14,792 kg, respectively) and moduli of elasticity (1,072,357 kg and 1,627,213 kg, respectively), display brittle and softer behaviors. These samples may exhibit brittle failure under load due to the non-uniform distribution of carbon particles and instability in the transition zones (ITZ). The lack of an effective bond between the carbon particles and the cement matrix causes localized stress concentrations, leading to rapid and abrupt failure. In contrast, specimens with a well-balanced mix design, such as PC-12 and PC-13, which possess moderate values for both the modulus of elasticity and breaking force (3,170,617 kg and 2,911,800 kg, respectively), exhibit an optimal balance between softness and strength. Due to the appropriate distribution of carbon particles and a strong bond with the cement matrix, these samples exhibit enhanced energy absorption capacity and can withstand higher stresses without experiencing sudden failure. The ITZ regions between the carbon particles and the cement matrix play a critical role in resisting local deformations and load variations. When these regions are properly designed with a more uniform distribution of carbon particles, the concrete demonstrates improved resistance to stress concentration and deformation. In the PC-4 and PC-5 samples, it is likely that the ITZ zones possess superior mechanical properties, contributing to the overall improved performance of the concrete under compressive loads. Energy absorption and failure behavior are closely linked to both softness and modulus of elasticity. Samples with higher moduli of elasticity generally exhibit better elastic behavior, offering greater resistance to compressive loads. This enhanced behavior allows microscopic cracks to propagate more evenly under load, preventing rapid failure. Conversely, samples with lower moduli of elasticity, such as PC-10 and PC-8, tend to fail more quickly due to insufficient energy absorption and localized stress concentrations. The data also indicate that increasing the carbon content from 5% to 10% (as seen in PC-1 and PC-2) leads to a notable increase in the modulus of elasticity (from 277.1 to 304.14 GPa). This improvement can be attributed to enhanced cohesion between the concrete grains and the carbon particles, resulting in superior mechanical properties. However, with a further increase in carbon content to 15% (in PC-3), the modulus of elasticity decreases to 200.65 GPa, possibly due to the saturation point being reached, which may disrupt the cohesion and negatively impact the overall mechanical properties. The observed reduction in the modulus of elasticity suggests that excessive incorporation of carbon into the concrete mix may adversely affect the structural integrity of the material. This negative impact is likely due to the over-accumulation of carbon particles, leading to discontinuities and weak points within the cement matrix.

Table 13. Average Values of the Elastic Modulus for the Cylindrical Samples in the Current Study

Mixing plan	(%) Carbon	(Kg) Bentonite	(Kg) cement	(cm) Slump	Modulus of elasticity (GPa)
PC-1	5	30	100	19.5	277.1
PC-2	10	30	100	19	304.14
PC-3	15	30	100	22	200.65
PC-4	20	30	100	17	229.1
PC-5	5	30	150	slurry	193
PC-6	10	30	150	25	201.28
PC-7	15	30	150	slurry	232.31
PC-8	20	30	150	slurry	306.94
PC-9	5	30	200	slurry	333.71
PC-10	10	30	200	slurry	196.52
PC-11	15	30	200	slurry	186.93
PC-12	20	30	200	slurry	213.19
PC-13	5	60	100	24	210
PC-14	10	60	100	25	202.28
PC-15	15	60	100	24.5	108.16
PC-16	20	60	100	25	138.21
PC-17	5	60	150	25	143.93
PC-18	10	60	150	21.5	157.14
PC-19	15	60	150	26.5	230.81
PC-20	20	60	150	27	226.96
PC-21	5	60	200	slurry	237.35
PC-22	10	60	200	29	234.97
PC-23	15	60	200	28.5	236.60
PC-24	20	60	200	slurry	278.6

Bentonite, as a modifier, can significantly influence the mechanical properties of concrete. When 30 kg of bentonite was added to the mix, as in samples PC-1 and PC-2, the modulus of elasticity was enhanced. For instance, sample PC-9, containing 20% carbon and 20 kg of bentonite, exhibited a modulus of elasticity of 333.71 GPa, highlighting the beneficial role of bentonite in improving cohesion and strengthening the overall mechanical properties of the concrete. The softness of the concrete mix has a direct impact on its mechanical behavior. Concrete in the "slurry" state, such as PC-10 and PC-15, tends to exhibit lower modulus of elasticity values (e.g., 108.16 GPa), suggesting that an increase in softness creates more space between particles, thereby reducing the material's resistance to applied loads. These findings emphasize the importance of mix design in achieving desired mechanical properties. For example, PC-8, which contains 20 kg of bentonite and 5% carbon, demonstrates a higher modulus of elasticity (306.94 GPa), suggesting that optimizing material proportions can yield a notable improvement in concrete performance. In terms of permeability, samples with higher carbon content (e.g., PC-8 and PC-9) typically exhibited increased permeability. This may result from the non-uniform dispersion of carbon particles within the matrix, as well as the creation of voids and pore channels within the concrete structure. Conversely, samples with lower carbon content (such as PC-1 and PC-2) demonstrated reduced permeability, indicating a more uniform particle distribution and smaller, fewer pore spaces. Variations in the proportion of cement and bentonite in different mix designs can substantially affect the permeability. In the case of PC-5, the permeability was significantly elevated, likely due to the higher proportion of bentonite in the mix. As a water-absorbing material, bentonite influences the pore structure, and under increased load, the concrete's micro and macrostructure may undergo changes, leading to a rise in permeability.

Table 14. Permeability results of carbon-based plastic concrete

Mixing plan	Permeability (mm)
PC-1	4.8
PC-2	4.6
PC-3	5.1
PC-4	4.2
PC-5	10
PC-6	6
PC-7	10.2
PC-8	10.7
PC-9	11.2
PC-10	10.6
PC-11	10.2
PC-12	11.3
PC-13	6
PC-14	6.1
PC-15	5.9
PC-16	6.1
PC-17	6.2
PC-18	5.2
PC-19	7.5
PC-20	8
PC-21	11.2
PC-22	9
PC-23	8.3
PC-24	11

High-permeability samples (such as PC-12 and PC-21) are likely to have a weaker structure that increases the permeability of water and other fluids. The results show that there is an inverse relationship between softness and permeability. Samples that show higher displacement in compression tests (such as PC-8) usually have higher permeability. This means that when concrete is able to withstand more changes, its structure is likely to become more vulnerable to liquid penetration. Samples with less softness (such as PC-1) show better results in reducing permeability, which indicates greater strength and uniformity in the concrete matrix.

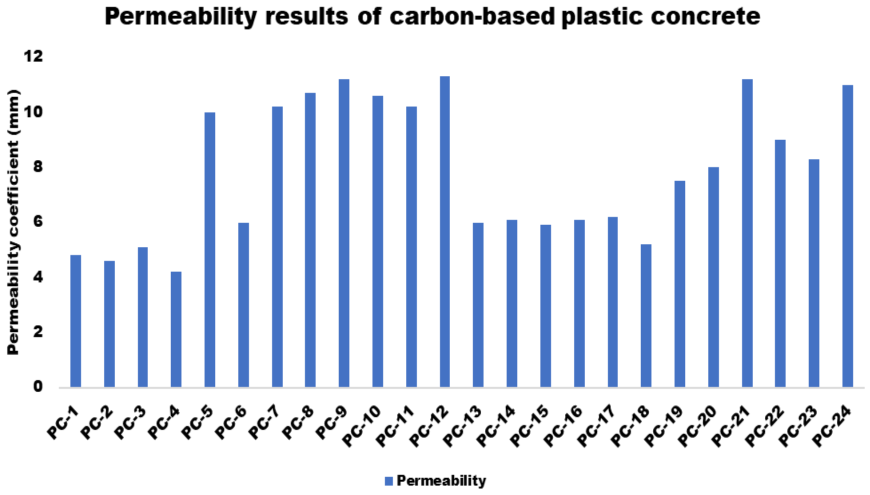

Fig. 16. Carbon-based plastic concrete permeability test results

9. Conclusion

This study investigates the impact of carbon as an additive on the properties of plastic concrete. Out of 24 mix designs, a fixed water-to-cement ratio of 0.5 was maintained, while varying the carbon content at 5%, 10%, 15%, and 20%. The results indicate that incorporating carbon into the plastic concrete mixture enhances its mechanical properties, particularly the adhesion between concrete particles, thereby improving its overall strength. By increasing the amount of cement for designs with 30 kg of bentonite, the amount of water absorption and separation of grains increases, and adding carbon for this part has no effect on these characteristics. On the other hand, by increasing the amount of bentonite from 30 to 60 kg, the level of water absorption on the concrete surface and the separation of grains decreases.

- Increasing the water-to-cement ratio enhances the fluidity of plastic concrete, similar to what is observed in conventional concrete. However, the increase in flow rate of plastic concrete is more pronounced compared to standard concrete due to the inclusion of bentonite.
- The addition of carbon to plastic concrete notably reduces its permeability. This reduction is attributed to the improvement in the microstructure and nanostructure of the concrete, which strengthens the network of cement hydrates.
- A thorough analysis of the test results reveals significant differences in the mechanical behavior of cylindrical and cubic plastic concrete samples under varying loads, particularly in terms of compressive strength, modulus of elasticity, and permeability. These differences are largely influenced by the proportions of carbon and bentonite within the mix.
- The compressive strength of cylindrical samples showed the highest value in sample PC-14 (3.98 MPa) and the lowest in sample PC-6 (1.586 MPa). This variation indicates that the changes in the mixture's components, particularly the carbon and bentonite content, have a considerable impact on strength. The observed percentage differences in compressive strength between cylindrical samples highlight the effective role of composite materials and varying percentages of additives in improving concrete's performance for specific applications.
- Displacement equivalent to the maximum force and displacement at 0.45 times the maximum force: The results show that the PC-17 sample exhibited the highest displacement at maximum force (8.41 mm), while the PC-6 sample showed the lowest (2.6 mm). These results underscore the impact of high carbon and bentonite content on the flexibility of concrete, enhancing its ability to withstand larger displacements.
- Ultimate modulus of elasticity: The highest modulus of elasticity was recorded in sample PC-15 (824,787 kg), while the lowest was in sample PC-12 (213,198 kg). This substantial difference in modulus values suggests significant structural and mechanical changes in the concrete under applied pressure. These variations affect the concrete’s hardness and flexural strength, making the modulus of elasticity a crucial parameter in structural analysis and the design of specialized concrete applications.
- Compressive strength of cubic samples: Similar to the cylindrical samples, the cubic samples demonstrated varying behavior. The highest compressive strength (5.22 MPa) was found in sample PC-14, while the lowest value (1.52 MPa) was in sample PC-15. This indicates notable discrepancies in the distribution of force and strength across the cubic samples.
- Permeability of samples: The highest permeability was observed in sample PC-12 (11.3), and the lowest in sample PC-4 (4.2). The increase in permeability in certain samples is attributed to the structural characteristics and high carbon and bentonite content in the mixtures. These findings are critical for assessing the durability of concrete against environmental factors and for designing concrete for specific structures. Lower permeability generally correlates with improved resistance to environmental degradation and extended service life of the concrete.

The results derived from comparing the mechanical and physical properties of various plastic concrete samples demonstrate that an optimal combination of concrete mixture components, particularly the proportions of carbon and bentonite, significantly influences the material's strength, modulus of elasticity, and permeability. This study provides valuable insights for selecting the most suitable concrete mix, especially for designing structures that demand high strength and long-term durability. It serves as a reference for improving the performance of concrete in specialized applications where enhanced mechanical properties and environmental resistance are essential.

Table 15. Summary of Compressive Strength, Modulus of Elasticity, and Permeability Results for Cylindrical and Cubic Samples

Feature	Highest amount	Lowest amount
(Based on the findings presented in Table 9)		
Compressive strength of cylinder samples	PC-14 3.98 MPa	PC-6 1.586 MPa
Displacement equivalent to maximum force	PC-17 8.41 mm	PC-6 2.6 mm
Displacement corresponding to 0.45 max	PC-17 4.66 mm	PC-15 0.26 mm
(Based on the findings presented in Table 10)		
Ultimate modulus of elasticity of the cylindrical sample	PC-15 824787 kg	PC-12 213198 kg
Maximum force (0.45max)	PC-14 31632 kg	PC-6 12607 kg
(According to the results of Table 11)		
Compressive strength of cubic samples	PC-14 5.22 MPa	PC-15 1.52 MPa
Displacement equivalent to maximum force	PC-8 9.3 mm	PC-4 3.73 mm
Displacement corresponding to 0.45 max	PC-8 5.57 mm	PC-16 1 mm
(According to the results of Table 12)		
Ultimate modulus of elasticity of the cubic sample	PC-4 339306 kg	PC-10 475064 kg
Maximum force (0.45max)	PC-14 52729 kg	PC-15 15435 kg
(According to the results of Table 14)		
Permeability of cubic samples	PC-12 11.3	PC-4 4.2

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