Research Article

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Optimizing the performance of concrete tiles using nano-papyrus and carbon fibers

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Abstract: Concrete is considered one of the greatest innovations in the construction industry since it has significant applications in the construction field. The main limitation of concrete is the low flexural and tensile strength, especially for concrete tiles used for floors and roofs. Therefore, this study aims to enhance the behavior of concrete tiles by using both nano-papyrus (NP) and carbon fibers (CF). Eleven different concrete mixtures with different content of NP and CF were prepared using various models, and the percentage of NP content ranged from 1.5 to 7.5%, while the percentage of CF content ranged from 0.2 to 1%; flexural strength and water absorption tests were also conducted. It was found that employing NP enhanced the flexural strength of concrete tile by up to 48%, whereas using both NP and CF optimized the flexural strength by up to 57%. Also, the surface and total absorption rates decreased by up to 47.1 and 52.6%, respectively.

Keywords: concrete tiles, composite materials, nano-papyrus, carbon fibers, flexural strength

1 Introduction

The concrete industry has evolved over the years from using natural components to manufacturing ones [1–3]. Furthermore, it has various usages, such as beams, columns, box girders, and tiles. Concrete tiles appeared around the middle of the nineteenth century and were called "encaustic cement tiles" due to their resemblance to the encaustic clay tiles, which were popular during that period [4]. However, due to the increased expansion of ceramic tiles in the twentieth century, their demand has decreased only to return to increase during the twenty-first [5]. Concrete tiles have various advantages over ceramic tiles, such as their strength and durability, making them more desirable for commercial purposes.

Various characteristics were inspected in concrete tiles, such as ozone deposition velocity [6], permeability [7,8], bulk density and alkali–silica reaction [9], thermal cracking [10], albedo and emissivity, and radiant heating [11,12]. However, concrete tiles usually show a brittle performance when subjected to tensile and flexural loadings, thus resulting in cracking. Therefore, many studies were conducted in order to enhance their behavior. Sánchez de Rojas et al. [13] have demonstrated that employing waste-fired clay materials to clay tile does not affect their microstructure characteristics but provides an economic advantage. Li et al. [14] studied the influence of recycled aggregate on the mechanical characteristics of concrete tiles and it was found to give reasonable enhancement in strength. Olusegun et al. [15] studied the effect of using laterite and granite stones in concrete tiles manufacturing, it was found that the new product met the approved standards. Jain [16] tried to reduce the brittleness of concrete tiles using chopped glass fibers, and it was shown that both the tensile and flexural strengths were enhanced by 10 and 19%, respectively. Narain et al. [17] have investigated the mechanical and thermal characteristics of concrete tiles in the presence of phase-change materials (PCMs). It was shown that PCMs could enhance thermal mass while maintaining sufficient strength. Kumar et al. [18] suggested employing foamed concrete tiles as an alternative that can achieve 90% of the strength of normal concrete tiles. Pati and Sahu [19] investigated the employment of fly ash in concrete tiles and was found that substituting fine aggregate with fly ash shows a significant enhancement in strength and durability. Another study by Regassa [20]

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has demonstrated that partially substituting mixing water with waste paint can enhance the strength of concrete tiles. Furthermore, a patent published by López López et al. [21] presented a reinforced concrete tile using galvanized-steel scales with a flat elongated shape.

However, there are few studies regarding employing nanomaterials and fibers [22–25] in concrete tiles, even though studies demonstrated such materials' positive influence on concrete [26–33]. The cracking of cement-based materials dose occurs at the nano and micro levels. Many studies have demonstrated that utilizing nanofiber and nanoparticles in cementations materials have demonstrated remarkable results in the matter of cracking. That is because such materials play an important role during the formation of calcium silicate hydrate (C–S–H), which is considered the binding phase, thus enhancing the performance [34–38]. Therefore, employing both nanomaterials and fibers can considerably enhance the performance of concrete tiles. However, the known nanomaterials may be scarce and costly in some countries. For that reason, it is important to employ new ones that are available and inexpensive. For instance, Papyrus plants are abundant in many countries such as Iraq, and have commercial and industrial usages. Nevertheless, it still leaves a huge unused amount that is thrown and burned. Hence, this study aims to investigate the potential of applying nano-papyrus (NP) to the performance of concrete tiles. As for fiber materials, carbon fibers (CF) are used since it is available and economical.

2 Materials and methods

2.1 Materials

In this study, six materials were used to produce different concrete tiles: ordinary Portland cement (OPC), fine aggregates (sand), coarse aggregates, superplasticizers, NP, and CF. OPC kind I, depending on Iraqi Standard No. 5 in 1984, was used, and Tables 1 and 2 illustrate its chemical characteristics.

Sand with a specific gravity of 2.65 according to standard No. 45 in 1984 [39]and with 0.35% percent sulfate was used (Table 3 for grading). Coarse aggregates with 10 mm as a maximum size have been employed. It has a specific gravity of 2.6 and its water absorption is around 1.92%. Kut Plast SP400 has been utilized as a superplasticizer, a chloride-free additive material depending on modified sulfonated naphthalene formaldehyde condensate, which is non-flammable and complies with ASTM494-2004 [40].

Table 1: Chemical characteristics of cement

Components		Cement		NP
		Test results	Limit of IQS No. 45/1984	Test results
Lime (%)	CaO	61.72	—	7.43
Silica (%)	SiO_2	21.28	—	72.43
Alumina (%)	Al_2O_3	4.72	—	9.32
Iron oxide (%)	Fe_2O_3	3.39	—	0.5
Sulfate (%)	SO_3	2.42	≤2.8%	1.34
Magnesia (%)	MgO	3.12	≤5%	4.52
Potash (%)	K_2O	0.36		—
Soda (%)	Na_2O	0.27		—
Loss of ignition (%)	L.O.I	2.16	≤4%	4.46
Lime saturation factor	L.S.F	0.91	0.66–1.02	—
Insoluble residue (%)	IR	0.60	≤1.5%	—
Main compound (Bogue's equation)	—			
Tricalcium silicate	C_3S	46.95	—	—
Dicalcium silicate	C_2S	25.85	—	—
Tricalcium aluminate	C_3A	6.52	—	—
Dicalcium aluminate	C_4AF	10.19	—	—

NP was produced in the engineering lab at the University of Technology, Baghdad, Iraq. It has a surface area of 15,000 cm^2/g and the chemical composition is as shown in Table 4. Finally, CP with a diameter of 0.001 mm and a length of 8 mm were utilized, Figure 1 shows the image for nanofibers and CFs.

2.2 Methods

The mix proportion, preparation of the samples, and test methods will be discussed as follows.

2.2.1 Mix proportions and sample preparation

Eleven different mixtures were prepared for this experiment; however, they have various mixtures. The first

Table 2: Physical characteristics of cement

Compressive strength	Value (N/mm^2)
3 days	21.8
7 days	25.9

Table 3: Grading of fine aggregates

Sieve size (mm)	Passing %	Limit of IQS no. 45-1948
4.75	97	90–100
2.36	87	75–100
1.18	62	55–90
0.6	45	35–59
0.3	14	8–30
0.15	4	0–10

Table 4: Chemical composition of NP in percent by weight

Oxide composition	NP (%)
SIO_2	72.43
Al_2O_3	9.32
Fe_2O_3	0.5
SO_3	1.34
MgO	4.52
CaO	7.43
Total	95.54
Ignition loss	4.46

sample (CFT) with no additives is considered the reference sample, and the others are divided into two groups. The first group (Table 5) has various NP contents (1.5–7.5%). The second group has constant NP content (4.5%) and various CF contents (0.2–1.0%), as demonstrated in Table 6.

2.2.2 Specimens

All samples have the same dimensions (300 mm × 300 mm × 30 mm) as shown in Figure 2. Each specimen component was mixed carefully in the mixer. After that, the mixtures

Table 5: Characteristics of first group samples

Sample	Materials				
	Cement (kg/m^3)	Sand (kg)	Gravel (kg)	NP (%)	W/C (%)
CFT	425	765	945	0.0	55
NP1.5		765	945	1.5	55
NP3		765	945	3	55
NP4.5		765	945	4.5	55
NP6		765	945	6.0	55
NP7.5		765	945	7.0	55

were placed in steel molds and vibrated for 20 s utilizing a vibration table. After 24 h, they were de-mold and placed in water tanks for curing.

2.2.3 Testing methods

After curing, the samples were subjected to two tests: flexural strength and water absorption.

2.2.3.1 Flexural strength

The flexural strength of tiles was determined according to the Iraqi Standard Specifications No. 1043 in 1984 [41]. The flexural test was achieved by UTEST material testing equipment digital of 200 kN/s as indicated in Figure 3. The device measures a tile's flexural strength by applying a three-point load. The tiles were horizontally placed on two parallel steel rods (with the wearing face upwards), and a third rod was exactly fixed at the center. The test is initiated by driving the tile until it snaps, and the

(a) (b)

Figure 1: Image of (a) NP and (b) CF.

Table 6: Characteristics of the second group samples

Sample	Materials						
	Cement (kg/m^3)	Sand (kg)	Gravel (kg)	NP (%)	CF (%)	SP (%)	W/C (%)
CFT	425	765	945	–	–	–	55
NPCF1	425	765	945	4.5	0.2	2	35.5
NPCF2	425	765	945	4.5	0.4	2	34.1
NPCF3	425	765	945	4.5	0.6	2	35.5
NPCF4	425	765	945	4.5	0.8	2	36.1
NPCF5	425	765	945	4.5	1.0	2	37

maximum flexural strength (in which the tile breaks) is recorded.

2.2.3.2 Absorption test

As for the absorption test, two tests were conducted: surface absorption and total absorption. Both were carried out according to the Iraqi Standard Specifications No. 1275 in 1985 [42], and only the second group was employed. For surface absorption, the tiles were dried in an oven at 105°C for 8 h and then were left to cool in the air for 24 h. The dry weight (W_1) of the tiles was recorded. After that, the tiles were hung in a tub with their face downward, and water (with a temperature of 20°C) was carefully poured into the tub until the water slightly touched the tile face. After 24 h., the tiles were removed and wiped dry, and their weight (W_2) was taken. The values of surface absorption are obtained from the following equation:

$$\text{Surface absorption} = \frac{W_2 - W_1}{A_s}, \qquad (1)$$

Figure 3: Testing equipment.

Figure 2: Specimens for testing.

where W_1 is the weight of the dry tile (g), W_1 is the weight of the wet tile (g), and A_s is the area of the tile surface (cm^2).

As for the total absorption, the samples were oven-dried and cooled the same way as the surface-absorption test, and their weight was taken (W_D). After that, they were submerged in the water tub and kept there for 24 h. After wiping them dry, their weight was recorded (W_W). The percentage of total absorption can be calculated from the following equation:

$$\text{Total absorption} = \frac{W_W - W_D}{W_D} \times 100, \quad (2)$$

where W_W is the weight of the wet tile (g) and W_D is the weight of the dry tile (g).

3 Results and discussion

Different concrete tiles were prepared for the experiment and subjected to flexural and water absorption tests. The results of both tests are discussed separately.

3.1 Flexural strength

Figure 4 displays the flexural strength results obtained from the reference sample (CFT) and the first group of concrete tiles, and shows that all of them have exceeded 2.5 N/mm^2, consequently satisfying the IQ standards [43]. In addition, it was found that adding NP up to 4.5% can enhance the flexural strength by approximately 48%, which could be attributed to the filler action of nanoparticles, which increase the bonding between the cement matrix and aggregate, and the pozzolanic reactions between the silica (in the nanomaterials) and the calcium hydroxide (in the cement); these results agreed with Abdulhussein et al. [44] who showed that NP proved its activity as a pozzolanic additive and can be as feasible additive to concrete. However, increasing the NP content further can have the opposite effect where the nanoparticles start agglomerating, negatively affecting the bond between the aggregate and cement and decreasing the flexural strength. For example, applying 6 and 7.5% of NP increases the strength by only 39.5 and 16.6%, respectively, when compared to those of the CFT.

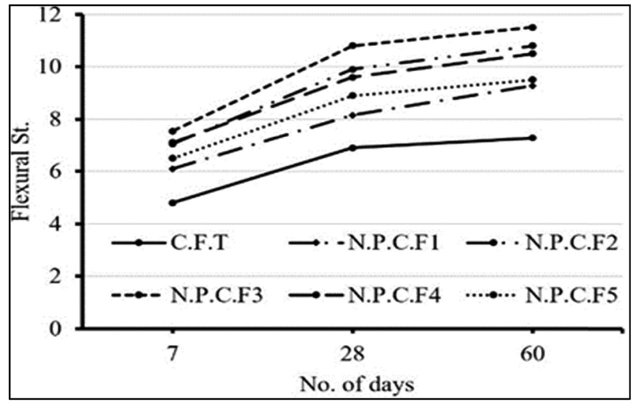

Figure 5: Flexural strength results for the second group.

Figure 5 demonstrates the flexural strength results from the second group and shows that all samples' strength increases with curing time. Also, it can be seen that the presence of CF can increase the strength by up to 57% due to the fiber pozzolanic action, which enhances the characteristics of concrete by increasing the C–S–H according to refs. [21,45]. However, the flexural strength drops once the content exceeds 0.6%, regardless of the number of days. For instance, adding CF by 0.8 and 1.0% increases the 28 day strength by only 39 and 29%, respectively, compared to the reference sample (CFT). This was consistent with the findings of the work of refs. [31,46], which is attributed to

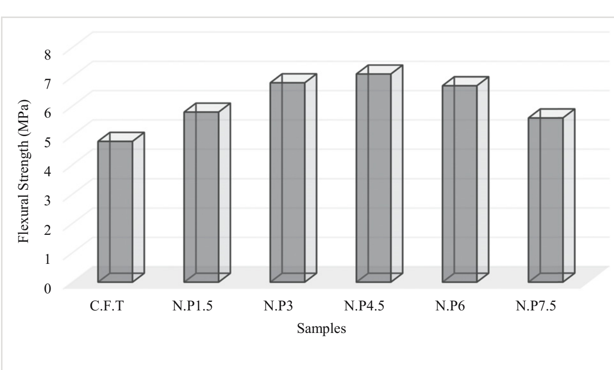

Figure 4: Flexural strength results for the first group.

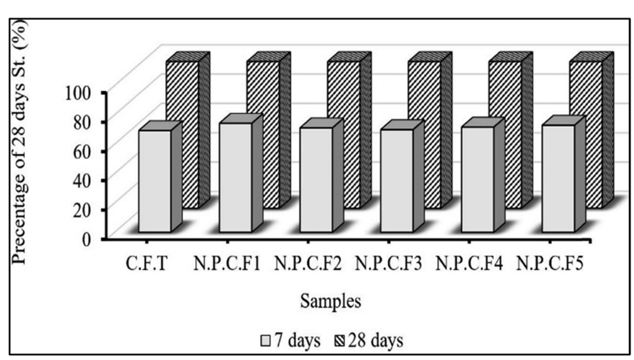

Figure 6: Percentage of 7 days flexural strength for the CFT and the second group.

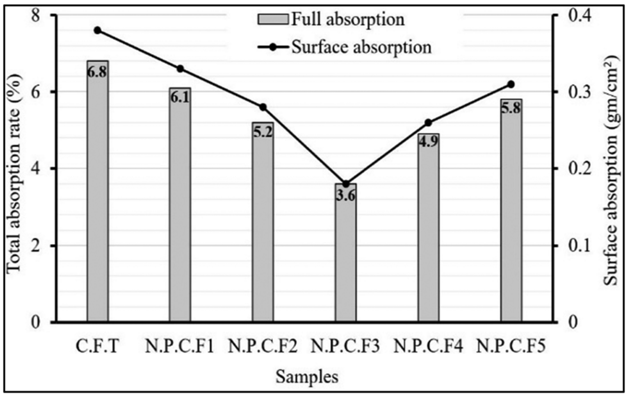

Figure 7: Total and surface absorption results for the second group.

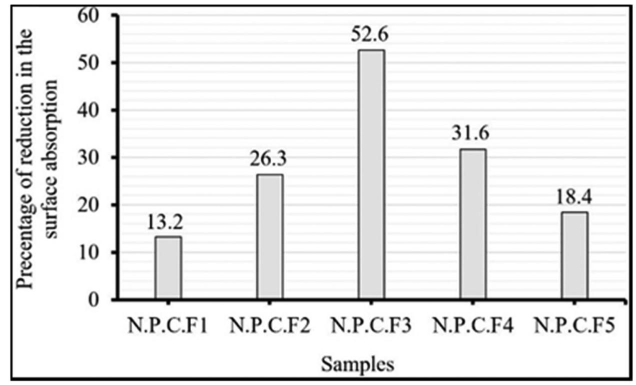

Figure 9: Comparison of the surface absorption results of the second group with the CFT.

the lack of regularity in the internal structure and the lack of regularity in the distribution of fibers (due to the increasing balling effect), which occurs when they are used in large quantities, and reduces the bridging phenomenon, thus reducing the flexural strength.

Figure 6 demonstrates the percentage of the 7/28 days flexural strength of concrete tiles, and shows that all 7 days samples have gained more than 60% of the 28 days strength. Furthermore, it can be seen that samples with lower water/cement ratios have gained more strength than the others because the gel system forms more rapidly due to the cement grains being closer [47].

3.2 Absorption test

Figure 7 demonstrates the results of the total absorption and surface absorption for the second group. For all samples, the total absorption and surface absorption did not exceed 8 and 0.4 g/cm^2, respectively, which coincide with the Iraqi standards. Furthermore, when comparing the reference sample and the samples with additives, as illustrated in Figures 8 and 9, the samples with CFs displaced less absorption than the reference sample (CFT). For example, the total and surface absorption reductions for NPCF2 is about 23.5 and 26.3, respectively, due to the formation of secondary C–S–H in concrete, causing a nonporous structure. However, the total and surface absorption reduction started to decrease when the CF content exceeded 0.6% due to the balling effect of fibers, causing them to randomly distribute during the mixing process, thus affecting the concrete porosity. This reduction in absorption in modified mixes can be attributed to microstructure development for tiles as a result of the introduction of NP and CF into the concrete structure, which exhibited a denser structure and less permeability. Also, improving the durability of concrete in general, these results are consistent with the results obtained in other studies [19–35,45].

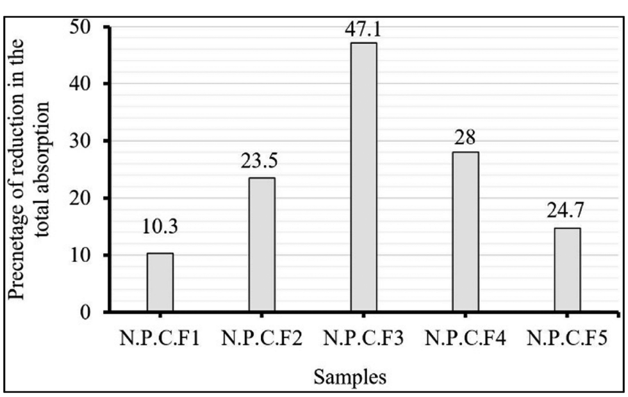

Figure 8: Comparison of the total absorption results of the second group with the CFT.

4 Conclusions

In this study, we have investigated the potential of optimizing the structural performance of concrete tiles using NP and CF. Flexural strength and absorption tests were conducted according to Iraqi standards, and the following conclusions were drawn:

- The optimum content of NP for concrete mixes was found to be 4.5% by the weight of cement, which provided a maximum enhancement of 48% in flexure strength for concrete tiles.
- The flexural strength values of all samples (with and without additives) exceeded 2.5 N/mm^2, thereby satisfying the IQ standard. Similar results were observed for the total and surface absorption, in which the results did not exceed 8% and 0.4 g/cm^2.

- Employing both NP and CF in concrete can increase the flexural strength of concrete tiles by approximately 57%.
- Increasing the content of NP by more than 4.5% and CF by more than 0.6% decreased the strength enhancement.
- Increasing the CF content by up to 0.6% decreased the total and surface absorption by up to 47 and 52% approximately. Further increasing the content resulted in the balling effect of the fibers, thus increasing the absorption.

Conflict of interest: Authors state no conflict of interest.

Data availability statement: Most datasets generated and analyzed in this study are comprised in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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