Development of green and sustainable ultra-high-performance concrete composite reinforced with date palm fibers

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Abstract. In a sustainable approach, it is essential to reduce the volume of agricultural waste materials in order to minimize environmental and health concerns. To pursue this goal, agricultural wastes, mainly date palm fibers (DPFs), was used as a partial replacement of conventional steel fibers to produce ultra-high-performance concrete (UHPC). The UHPC has been used to describe a steel-fibers-reinforced cementitious composite with a very low water-binder ratio. It is one of the most significant breakthroughs in concrete technology in the 20th century due to its outstanding mechanical performance, such as compressive strength over 150 MPa and flexural strength over 30 MPa. The cost of UHPC is known to be significantly higher compared to ordinary reinforced concrete because it requires large quantities of steel fibers. This paper aims to study the feasibility of utilizing DPFs as a partial replacement of steel fibers to produce green, low-cost and sustainable UHPC. The process of extraction and treatment of the DPFs before incorporating it into the mix design was discussed. Several concrete samples were prepared with different weight percentages of DPFs as a partial replacement of steel fibers (from 0% to 25 wt.%). Compression strength, flexural strength, water absorption, and fresh/hardened densities were experimentally investigated. The morphology and the bonding interface between the fibers and cementitious composite were characterized by scanning electron microscopy (SEM). The results reveal that the DPFs has the potential to be utilized to produce UHPC with comparable performance to the traditional UHPC that is normally reinforced with steel fibers.
1. Introduction
The ultra-high-performance concrete (UHPC) has been used to describe steel-fibers-reinforced cementitious composites compromising silica fume, fine sand, and high dosage of high range water reducing agent with very low water-binder ratio. It is one of the most significant breakthroughs in concrete technology at the 20th century due to the outstanding mechanical performance, such as compressive strength over 150 MPa and flexural strength over 30 MPa. [1–7].

UHPC can be produced traditionally with dense microstructure leading to remarkable mechanical and durability characteristics of UHPC [8–12]. The relatively high initial cost of UHPC has restricted its wider use in the construction industry. However, ongoing research and investigations are filling knowledge gaps in order to commence development of low-cost UHPC. Furthermore, the development and wide acceptance of an UHPC design code provisions should encourage stakeholders in the construction industry to implement large scale applications [13]. Therefore, UHPC has potential applications in bridge and industrial products as pre-cast structure members to ensure light-weighted, flexible, durable, and aesthetic structures [14,15].

The procurement of silica fume and steel fibers has been surrounded with some difficulties. They are not only costly to procure but also unavailable for the construction work at many places over the world especially at the development countries [16]. These difficulties open the door to look for alternative materials that would be suitable for the development of cementitious composites. High quantity of supplementary cementitious materials (SCMs) normally utilized as partially replaced of cement or silica fume for the purpose of producing low-cost, durable and sustainable concrete [17–21].

The utilization of alternative fibers materials (e.g., natural or artificial fibers) to substitute steel fibers have been investigated by many researchers [22–27]. Mohamed A. Ismail et al [28] studied the strength of concrete using palm oil fibers. The study found that the optimum length to achieve a significant increase in strength at 0.25 % and 0.50 % fibers content was 5 cm and 3 cm respectively. The properties of lightweight crushed brick concrete containing palm fibers of different volume fractions were studied by Mahyuddin et.al [29]. They concluded that the use of palm fibers with lightweight crushed brick concrete enhances the mechanical properties (compressive strength and flexural strength) of the concrete. Pradeep, P. et. al [30] investigated chemical and physical properties of various fibers extracted from palm tree. The density of palm fibers is significantly lower than any other natural fibers, giving better compressive strength, tensile strength, and Young’s modulus. Thus, these results confirm the possibility of using palm fibers for the manufacture of sustainable fibers reinforced polymer composite. The possibility of using the waste of date palm tree fibers as a natural alternative to the conventional fibers was investigated by Faesal Alatshan et. al. [31]. The study concentrated on examining the behaviour of specimens for higher dosages with longer length of fibers than previously used. The results show clear improvement in flexural strength and compressive strength as well as the ductility of the specimens.

The goal of this paper is to study the feasibility of utilizing agricultural waste materials, mainly date palm fibers, as a partial replacement of steel fibers to develop green, low-cost and sustainable UHPC composite.

2. Experimental Program

2.1. Materials
Type I ordinary Portland cement (OPC I) and silica fume were used in this study. The specific gravities of cement and silica fume were respectively 3.15 and 2.25. The chemical compositions of the materials are presented in Table 1. Fine aggregate (dune sand) with a specific gravity of 2.56 and a water absorption capacity of 0.4% was used to prepare the mixtures. A Superplasticizer obtained from a local supplier (BASF) was used in all mixtures. A smooth plain copper coated steel fibers with length of 12.7 mm, diameter of 0.15mm, and an aspect ratio of 84 was used as a reinforcement agent in the cementitious composite. The tensile strength of steel fibers is 2500 MPa as reported by the manufacture. Date palm fibers (DPF) were manually extracted from the mesh part on top of the date palm trees found abundantly at Najran city. Figure 1 shows the process of DPFs extraction from the palm tree. The fibers were cleaned with water and stored at room temperature for a week. The fibers were then cut into smaller size to resemble the length of conventional steel fibers. The average diameter and length of single DPF used in
this study were 0.85 mm and 12 mm respectively. The physical and mechanical properties of DPFs were examined after alkaline treatment with 3% sodium hydroxide (NaOH), following procedures mentioned elsewhere [32], in order to remove any layers of wax, oil and other impurities covering the top surface of the fibers as well as to reduce the water absorption of fibers. It was found that the average tensile strength of a single DPF was 112 MPa.

Table 1. Chemical composition of raw materials (in wt. %)

| Items      | OPC I  | Silica Fume |
|------------|--------|-------------|
| CaO        | 64.35  | 0.48        |
| SiO₂       | 22     | 92.5        |
| Al₂O₃      | 5.64   | 0.72        |
| Fe₂O₃      | 3.8    | 0.96        |
| K₂O        | 0.36   | 0.84        |
| MgO        | 2.11   | 1.78        |
| Na₂O       | 0.19   | 0.5         |
| Alkali     | 0.33   | -           |
| SO₃        | 2.1    | -           |
| LOI        | 0.7    | 1.55        |
| C₃S        | 55     | -           |
| C₂S        | 19     | -           |
| C₃A        | 10     | -           |
| C₄AF       | 7      | -           |

Figure 1. Date palm fibers cutting form the mesh part of the tree-top

2.2. Mixing and Sample Preparation
Several samples were designed using absolute volume method. The mix design of the reference UHPC composite is presented in Table 2. The water-to-binder ratio of all mixtures was 0.15. Steel fibers were replaced by DPF in different levels of 5, 10, 15, 20 and 25 % by weight of steel fibers. Initially, dry cement, silica fume, and fine sand were dry mixed at a low speed for two minutes in a medium-size standard mixer. The superplasticizer and water were mixed separately, then gently added into the mix.
until the mix converted into a fluid with a clear viscosity. Afterward, the fibers were slowly introduced into the mixture, making sure a uniform dispersion of the fibers within the mixture. After the mixing, the mixtures were casted into several cube (2 x 2 x 2 inches) and prism (1 x 1 x 12 inches) moulds. The moulds were gently vibrated for one minute using mechanical table until complete consolidation was achieved [33]. After the casting, the specimens were covered with a plastic sheet for 24 hours and stored at the room temperature (22 ± 2 °C). After the 24 hours curing at room temperature, the specimens were demolded and placed in an oven for accelerated heat curing at 90 °C for three days.

| Mix ID | DPF (%) | Steel Fibers | DP F | Silica fume | Fine sand | water | cement | Superplasticizer | w/b |
|--------|---------|--------------|------|-------------|----------|-------|--------|------------------|-----|
| DPF-0  | 0       | 206          | 0    |             |           |       |        |                  |     |
| DPF-5  | 5       | 196          | 10   |             |           |       |        |                  |     |
| DPF-10 | 10      | 186          | 21   |             |           |       |        |                  |     |
| DPF-15 | 15      | 175          | 31   |             |           |       |        |                  |     |
| DPF-20 | 20      | 165          | 41   |             |           |       |        |                  |     |
| DPF-25 | 25      | 155          | 52   |             |           |       |        |                  |     |

2.3. Methods

2.3.1. Physical properties. The density of the sample was determined by the gravimetric method in accordance with the ASTM C138/C138M-17a using a balance with a precision of 0.1%. Water absorption of the samples was measured in accordance with the ASTM C1585-20 standard.

2.3.2. Compressive strength. The compressive test was performed as per ASTM C 469 using universal testing machine (Instron) for the cube specimens after the curing. Three specimens were tested at each age and the average values was reported.

2.3.3. Flexural strength. The flexural (four-point bending) test was performed as per the ASTM C 78 using universal testing machine (Instron) with a constant loading rate of 0.5 mm/min. The test was performed on the prism specimens after the curing. Three specimens were tested at each age and the average values was reported.

2.3.4. Scanning Electron Microscopy (SEM). The morphology of the samples and the interfacial bonding of fibers with the cementitious matrix was observed using a scanning electron microscope (JEOL). A small portion of the sample was gently cut from the specimens. The sample was then mounted on a standard holder using carbon adhesive tabs prior to the analysis. The sample was scanned at magnification between 100x to 1000x under 5 kV accelerating voltage.

3. Results and Discussion

3.1. Compressive Strength

The compressive strength of developed UHPC cubes is presented in Figure 1. Three specimens were tested, and the average values were reported. The average compressive strength decreases with increasing in the percentages of DPFs (i.e., 25% DPFs replacement resulted in 48% reduction in the compressive strength with respect to DPF-0). This could be attribute to the difference in the aspect ratio
between steel fibers and DPFs. Steel fibers with aspect ratio of 65 compared to average DPFs with aspect ratio of 14. This finding also supported by previous investigation which have reported that the aspect ratio of steel fibers greatly influenced the compressive strength of UHPC. At constant steel fibers replacement amount, a higher steel fibers aspect ratio corresponded to better compressive strength [12,22,24,34]. Steel fibers with a high aspect ratio resisted large cracks and thus improved compressive strength; in contrast, steel fibers with a low aspect ratio could only control the opening and propagation of micro cracks.

Furthermore, the differences in material properties between steel fibers and DPFs such as specific gravity, density, absorption, modulus of elasticity could have such reduction in the compressive strength. Additionally, the increased concentration of fibers can create fibers bundling, thus leading to weak spots, which can reduce the efficiency of fibers, hence decreasing compressive strength.

All specimens containing DPFs showed a ductile mode of failure by appearance of multiple small cracks on the surface of the specimens. As the load reached its maximum, there was no fractures in the specimens even at the peak load, indicating ductility behaviour during failure. The addition of DPFs also improve the intact of the matrix and prevent the brittle failure under compressive loading. The optimum level of replacement of DPFs by steel fibers based of the compressive strength results was 10% which produced compressive strength close to DPF-0.

As you can see from Figure 3 that, regardless of the percentage of replacement, the uniaxial compressive strength showed a trend of first increasing and then decreasing. Only little variations during the ascending part but the effect is clear with higher discrepancies during the descending part of the stress-strain relationship. It can also be seen from this Figure 3 that the change in replacement percentage of fibers has tremendous effect on the peak stress, which is lower for higher percentage of fibers up to 25%.
Figure 3: Typical compressive stress-strain curve for all UHPC Mixtures

3.2. Flexural Strength

The overall flexural strength results for all specimens tested under 4-point bending is shown in Figure 4. The flexural strength reduced as the percentage of replacement of DPFs increased. This reduction could be explained due to the orientation and dispersion of these hybrid fibers during mixing and casting of specimens. Additionally, the different in the aspect ratio of both types of fibres may result improper alignment of fibres in the UHPC matrix as shown also in Figure 6. The results revealed that the maximum flexural strength of 31 MPa and maximum deflection under the maximum load was 2.3 mm for DPF-0 compared to DPF-25 with a value of 18 MPa with deflection of 1.4 mm. The test also indicated that the optimum replacement level of DPFs by steel fibres in the range of 5-10%.

Figure 4: Results of flexural strength tests of all UHPC mixtures

The ductile mode of failure of all mixtures showed softening mode of failure with prolonged deformation as shown in load-deflection curve in Figure 5. It was observed that after the cracking load, i.e., the load corresponding to the development of first crack at the bottom, the specimens continue to
carry more loads with increase in deflection until the maximum load (peak load) was reached. This increase in load is attributable to the presence of both hybrid fibres, which become fully mobilised and function as crack arrestor after first cracking. Following the attainment of peak load, softening mode of collapse takes place, exhibiting gradual decrease in load with increased deflection and crack-growth but the specimen kept good integrity due to the bridging effect of steel fibre as shown in Figure 6. Unlike normal concrete, the UHPC-DFPs failure occurs due to development of single vertical crack in the presence of fibers. In flexural test, for all specimens showed ductile mode of failure with the occurrence and advancement of a single crack through the bottom of the specimens (Figure 6).

![Figure 5: load-deflection curve under flexure flexural loading](image)

![Figure 6: Mode of failure of specimens under flexure showing the bridging effect of fibers.](image)

3.3. Fresh and Hardened Densities

The fresh density was measured based on the quantities of materials used in the in each mix while the hardened density was estimated after curing period was completed. Figure 7 presented that the difference in the calculated and tested density of all developed mixtures due to the curing regime and type and contents of ingredients. Packing density is observed to increase with increasing concrete strength, which is expected due to the lower porosity of concrete materials with higher packing densities. As the percentage of replacement increase, the density of concrete is reduced due to the difference in the density
of steel fibers and DPFs as steel fibers has density about 7850 kg/m³ while DPFs has about 920 kg/m³. Due to this reason, the density was reduced from almost 2500 kg/m³ to about 2354 kg/m³ with 25% replacement of steel fibers by DPFs. This may lead to reduce the packing density of the materials due to this hybrid fibers following by increasing the water absorption and reduction in the compressive strength.

The compressive strength could be correlated to the hardened concrete with good agreement (Figure 8) with the equation of $y = 9E-31x^{9.4986}$ with $R^2 = 0.7232$, where $y$ represents the compressive strength and $X$ is the hardened density.

The water absorption results of all mixtures are presented in Figure 9. As expected, the test results indicated that as the replacement level increased, the water absorption also increased due to the presence of DPFs. It was observed that the water absorption can be correlated to density of hardened concrete (as shown in Figure 10). As the level of replacement of DPFs by steel fibers increase, the density of the UHPC decrease leading to increase the water absorption. The predicted correlations equation $y = -30.486x + 2543.8$ with $R^2 = 0.9655$, in which $y$ is the hardened density and $X$ is representing the
percentage of water absorption. The higher value of R2 about 0.97 revealed good agreement in the above equation.

![Figure 9: Water absorption results of all mixtures](image)

![Figure 10: Density-Water absorption relationship](image)

3.5. Morphology and Fibers-matrix Bonding

Figures 11 show the SEM micrographs performed for UHPC composites reinforced with steel fibers and DPFs. Generally, the cementitious matrix appears smooth and dense indicating a robust composite. The SEM micrographs for composites containing DPFs (Figure 11a) clearly indicate that the bond between the fibers and cementitious matrix is strong. This is clearly demonstrated by the presence of physical contact between the two components. The high surface energy of cellulose materials (DPFs) might be the reason of the strong bond between the cementitious matrix and DPFs. In contrast, the composite containing steel fibers (Figure 11b) shows a loose adhesion between cementitious matrix and the fibers, indicating a lack of compatibility and contact between the matrix and steel fibers. Based on these observations from SEM, the introduction of DPF as reinforcement in UHPC composite generally improves the fibers-matrix interfacial bonding of composites. Thus, it is most likely to obtain better ductility behaviour for UHPC composites reinforced with DPFs as observed in this study.
4. Conclusion

This paper experimentally investigates some physical and mechanical properties of ultra-high-performance concrete (UHPC) reinforced with date palm fibers (DPFs) as a partial replacement of conventional steel fibers. A study of morphology and fibers-matrix bonding of UHPC composite was carried out by scanning electron microscope. The goal of this paper is to study the feasibility of utilizing agriculture wastes (e.g., DPFs) to produce green, low-cost, and sustainable UHPC composite.

The use of DPFs as a partial replacement of conventional steel fibers allows obtaining a UHPC composite with comparable physical and mechanical properties to conventional UHPC. The increase in fibers content reduces the mechanical strength of the samples. The interesting mechanical behaviour was obtained at low DPF replacement level, ranging between 5–10%. The experimental investigations also indicated that the increase of DPF content reduces the weight of the UHPC composite by decreasing its density. It can be concluded that the DPF-reinforced UHPC can well be used as a new bio-composite building material.

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