Cement Pastes Containing Polypropylene Fibers - Part I: Physical, Chemical and Mechanical Properties

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Abstract

The influence of polypropylene fibers (PPF) addition on the physical, chemical, and mechanical properties of Portland cement pastes (OPC) was clearly evaluated. Results showed that as the PPF content increased, the water of consistency (WC) decreased, while the setting times (IST and FST) increased due to the presence of the water reducing mineral admixture (PPF). The Chemically-bound water content (BWn), bulk density (BD), and compressive strength (CS) improved and enhanced up to 0.6 wt. % PPF content, and then decreased onward at all curing times up till 90 days, while the apparent porosity shortened and then enhanced. Above 0.6 wt. % PPF content, all properties were adversely affected. The free lime content (FLn) of the OPC (PP0) increased continuously up till 90 days but decreased with PPF content at all curing ages and with all mixes (PP1-PP7).

Keywords: OPC, PPF, Consistency, Setting Times, Free Lime, Combined Water, Density, Porosity, Strength.

1. Introduction

1.1. Scope of the problem

Polypropylene (PP) is a thermeoregular polymer that has achieved industrial importance. The fibers made from Polypropylene were introduced to the textile arena in the 1970s, and have become an important member of the rapidly growing family of synthetic fibers. Today, Polypropylene enjoys fourth spot behind the "big three" fiber classes, i.e. polyester, nylon and acrylic. However, as opposed to other basic fibers, its use as clothes and home textiles has been rather limited where the bulk of the fiber produced was used for industrial applications. Polypropylene (PP) is a by-product which is coming from oil refining processes. PP is a thermoplastic polymer. It is a linear structure based on the monomer CnH2n. It is manufactured from propylene gas in presence of a catalyst such as $TiCl_2$ (Mansfield 1999; Siddique , 2011).

Most of the used polypropylene is highly crystalline and geometrically regular, i.e. isotactic, and it is opposite to amorphous thermoplastics, such as polystyrene, PVC, polyamide, etc., which their radicals are placed randomly, i.e. atactic (Fig. 1), and the chemical structure of PPF is shown in Fig. 2.

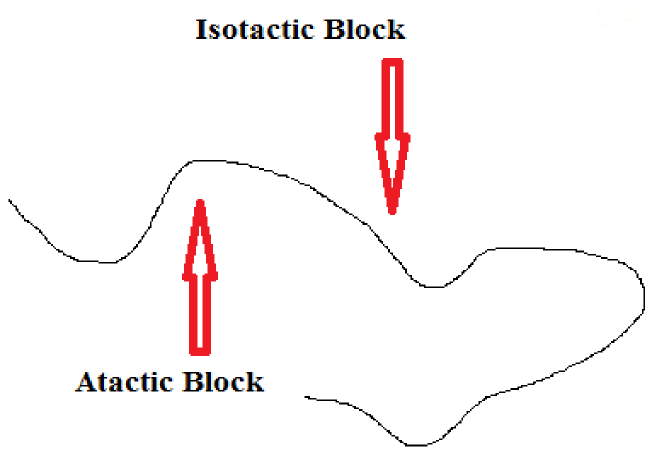

Fig. 1- Radicals of the most used Polyproylene fibers.

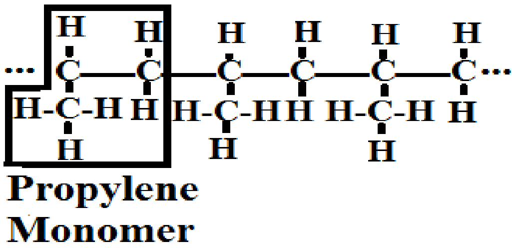

Fig. 2- The chemical structure of Polyprpylene polymer.

1.2. Properties of PPF

Generally, PPF is a very light fiber due to its lowest density (0.91 g/cm^3) when compared to all other synthetic fibers. PP fibers have a softening point at 140 ºC and a melting point at 165 ºC. At ≤ -70 ºC, PP fibers keep its excellent flexibility. At ≤ 120 ºC, the normal mechanical properties PP fibers do not affect. PP fibers have the lowest thermal conductivity compared to all other commercial fibers. PP fibers have excellent chemical resistance to acids and alkalis as well as it has a high abrasion resistance. It could not absorb moisture, which in turn helps the quick transport of moisture (Siddique, 2011; Chindaprasirt et al., 2011; Darweesh, 2018; Ochia et al., 2007).

1.3. Advantages of PPF

PPF is a light fiber and it has the lowest density (0.91 g/cm^3) of all synthetic fibers. It does not absorb moisture, i.e. the wet and dry properties of the fiber are identical. It has excellent chemical resistance to most acids and alkalis. Its thermal conductivity is lower than those of other fibers and may be used in applications as thermal wear.

1.4. Effect of PPF in concrete

The concrete of tunnel linings incorporated PPF improve mix cohesion, pumpability over long distances, freeze-thaw resistance, impact and abrasion resistance, structural strength and ductility. PPF increases the concrete resistance to plastic shrinkage during curing, but reduces steel reinforcement requirements, crack widths and control the crack widths tightly. This in turn improves durability (Siddique, 2011; Chindaprasirt et al., 2011; Darweesh, 2018).

Blends of both steel and polymeric fibers are often used in construction projects in order to combine the benefits of both products; structural improvements provided by steel fibers and the resistance to explosive spalling and plastic shrinkage improvements provided by polymeric fibers (Darweesh, 2018; Ochia et al., 2007).

1.5. Objectives of the study

Due to the superior performance characteristics and comparatively low-cost of PPF, PPF is a very important fiber in Cement and/or concrete industry. On this basis, the effect of the polymeric fiber on the physical, chemical and mechanical of cement pastes was conducted.

2. Experimental and methods

2.1 Raw Materials

The used raw materials in this study are Ordinary Portland cement (OPC Type I- CEM I 42.5R) with standard blaine surface area of 3400 cm^2/g, and polypropylene Fibers (PPF). The OPC was supplied from Sakkara cement factory, Giza, Egypt with the commercial name of "Asmant El-Momtaz", while PPF sample was provided by Belgium Fibers Manufacturing Industrial Poulevard 91, B-7700 Mouscron, Belgium. The PPF sample was first processed to become suitable for using in cement. The chemical composition of the OPC is shown in Table 1. The mineralogical phase composition of the used OPC as calculated from Bogue equations (Neville, 2011; Hewlett and Liska, 2017) is given in Table 2, while the mix composition is illustrated in Table 3.

Table 1- Composisition of the used raw materials, mass, %.

Oxide / Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI	Specific gravity
OPC	21.78	4.13	3.15	61.11	2.16	2.78	0.11	0.65	0.87	3.14

Table 2- Mineralogical composition of the used OPC sample, Mass %

Phase / Material	C_3S	β-C_2S	C_3A	C_4AF
OPC	43.01	30.00	5.65	9.58

Table 3- The batch composition of cement mixes, mass%

Mixes / Materials	PP_0	PP_1	PP_2	PP_3	PP_4	PP_5	PP_6	PP_7
OPC	100	99.9	99.8	99.7	99.6	99.5	9904	99.3
PPF	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7

2.3. Preparation and methods

There are 8 cement batches from OPC and PPF (Table 1) having the symbols: PP_0, PP_1, PP_2, PP_3, PP_4, PP_5, PP_6 and PP_7, respectively. The PPF must be cut and separate manually or mechanically by using a suitable machine. Then, the blending process of the various cement blends was done in a porcelain ball mill for two hours to assure the complete homogeneity of all cement blends. The standard water of consistency (WC) as well as setting time (initial and final) of the various cement pastes were directly determined using Vicat Apparatus (ASTM-C187, 1993; ASTM-C191, 1993) from the following relation:

$$WC, \% = A / C \times 100 \qquad (1)$$

Where, A is the amount of water taken to produce a suitable paste, C is the amount of cement mix (300 g). The cement pastes were then cast using the predetermined water of consistency, moulded into one inch cubic stainless steel moulds (2.5 x 2.5 x 2.5 cm^3) using about 500 g cement mix, vibrated manually for three minutes and then on a mechanical vibrator for another three minutes. The surface of the moulds was smoothed using a suitable spatula. Thereafter, the moulds were kept in a humidity chamber for 24 hours under 95 ± 1 RH and room temperature, demoulded in the following day and soon cured in tap water till the time of testing at 1, 3, 7, 28 and 90 days. The bulk density (BD) and apparent porosity (AP) of the hardened cement pastes (Hewlett and Liska 2017; Darweesh, 2014; Darweesh and Ragab, 2015; Darweesh, 2017) were calculated from the following equations:

B.D, (g/cm3) = W1/(W1–W2) × 1 (2)

A.P, % = (W1 – W3)/(W1–W2) × 100 (3)

Where, W1, W2 and W3 are the saturated, suspended and dry weights, respectively. The compressive strength (CS) of the various hardened cement pastes (ASTM-C170, 1993) was measured as follows:

CS = L (KN)/Sa (cm2) KN/m2 x 102 (Kg/cm2)/10.2 (MPa) (4)

Where, L is the load taken, Sa is the surface area. Thereafter, about 10 grams of the broken specimens were first well ground, dried at 105 °C for 30 min. and then were placed in a solution mixture of 1:1 methanol: acetone to stop the hydration (Hewlett and Liska 2017; Darweesh and Ragab, 2018). The kinetics of hydration in terms of chemically bound water and free lime contents were measured. About one gram of the sample was first dried at 105°C for 24 hours, and then the chemically bound water content (Darweesh and Ragab, 2018; Chusilp et al., 2009; Agarwal and Deepali, 2006) at each hydration age was determined on the basis of ignition loss at 1000 °C for 30 minutes as follows:

BWn, % = W1-W2/W2 x 100 (5)

Where, BWn, W1 and W2 are bound water content, weight of sample before and after ignition, respectively. The free lime content (FLn) of the hydrated samples pre-dried at 105 °C for 24h was also determined. About 0.5 g sample + 40 ml ethylene glycol → heating to about 20 minutes and avoiding boiling. About 1–2 drops of Ph. indicator were added to the filtrate, and then titrated against freshly prepared 0.1N HCl until the pink color disappeared. The 0.1N HCl was prepared using the following equation:

V1 = N × V2 × W (7) × 100/D × P × 1000 (6)

Where, V1 is the volume of HCl concentration, V2 is the volume required, N is the normality required, W is the equivalent weight, D is the density of HCl concentration and P is the purity (%). The heating and titration were repeated several times until the pink color did not appear on heating. So, the free lime content (Hewlett and Liska 2017; Darweesh, 2014; Darweesh and Abo El-Suoud, 2014; Rukzon and Chindaprasirt, 2012; Ayoub et al, 2005) was calculated from the following relation:

FLn, % = (V × 0.0033/1) × 100 (7)

Where, FLn and V are the free lime content and the volume of 0.1 N HCl taken on titration, respectively.

3. Results and Discussion

3.1. Characteristics of PPF

The characteristics of the used polypropylene fiber (PPF) in the current study are recorded in Table 4. The moisture absorption, elongation, melting point, softening point, relative density are 0.05 %, 40-100 %, 165 °C, 140 °C and 91 g/cm^3, respectively. The mechanical properties in terms of tensile strength, compressive strength and thermal conductivity are 3.5-5.5 and 4.2-6.5 g/cm^3 and 6.0, respectively. The abrasion resistance, chemical resistance, electric insulation and mildew resistance are all excellent.

Table 4- Characteristics of Polypropylene fiber (PPF).

Property	Value
Elongation (%)	40-100
Moisture absorption, %	0.05
Melting point, °C	165
Softening point, °C	140
Relative density, g/cm^3	0.91
Tensile strength, g/cm^2	3.5 to 5.5
Compressive strength, g/cm^3	4-6
Thermal conductivity	6.0
Abrasion resistance	Good
Chemical resistance	Excellent
Electric insulation	Excellent
Resistance to mildew, moth	Excellent

From Table 4, it could be concluded that in general, PPF has an excellent chemical resistance to acids and alkalis, a high abrasion resistance and it is easy to process. It is inexpensive if compared to other synthetic fibers. Its low moisture absorption helps in the quick transport of moisture. It also has a softening point in the region of 140 °C and a melting point of 165 °C. At 70 °C or lower, it retains their excellent flexibility. At 120 °C, it nearly remains their normal mechanical properties. In this respect, it often has the lowest thermal conductivity, the lightest and warmest and its density (0.91 g/cm^3) is the lowest of all synthetic fibers. Moreover, it does not absorb moisture, i.e. the wet and dry properties of PPF are identical. Its low moisture regain is not considered a disadvantage because it helps in quick transport of moisture as is required in special applications. The thermal conductivity of PPF is lower than those of other fibers (Mansfield 1999; Siddique , 2011; Chindaprasirt et al., 2011; Darweesh, 2018; Ochia et al., 2007).

3.2. Water of consistency and setting times

The water of consistency and setting times (initial and final) of cement pastes incorporated with different ratios of PPF (PP0-PP7) are graphically represented in Fig. 3. It is obvious that the water of consistency gradually decreased with the increase of PPF content. This is mainly due to that the PPF controls the cracks of the hardened cement pastes, and so it reduces its permeability. This is related to its lower plastic and drying shrinkage. This means that PPF acts as a water reducing admixture or as plasticizers because the amount of the decreased water is low (Ayoub et al, 2005; Ayoub et. al., 2006; Amin et. al., 2011; Amin et al., 2011; Amin et al., 2012; Amin et al., 2013; Ibrahima et. al, 2015; Darweesh et al. 2013; Darweesh, 2014). On contrast, the setting times either initial (IST) or final (FST) were increased. This means that PPF acts as a redarder (Ibrahima et. al, 2015; Darweesh et al. 2013; Darweesh, 2014; Darweesh, 2017; Darweesh and Ragab, 2019; Darweesh,2020; Darweesh and Ragab, 2020) On this basis, the PPF diminished the w/c ratio and retarded the setting times.

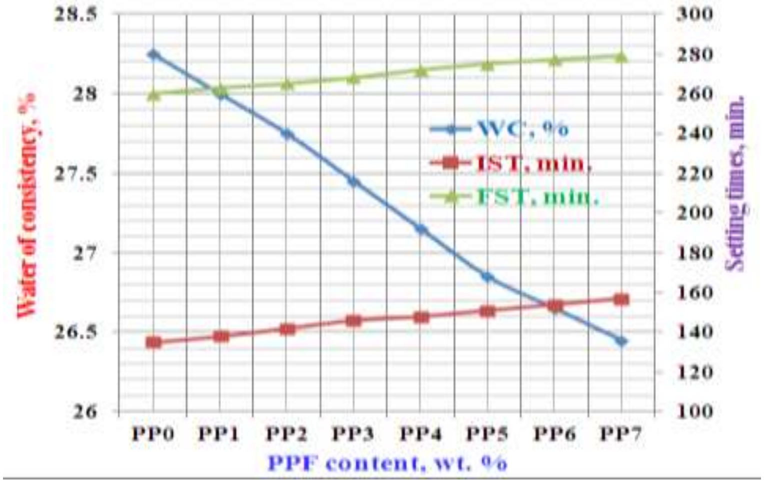

Fig. 3- Water of consistency and setting times of cement pastes mixed with different rates of PPF.

3.2. Chemically-bound water content

The chemically combined water contents of the different cement/PPF pastes (PP0-PP7) are plotted as a function of curing time in Fig. 4. In a general sense, the combined water contents increased stepwise up to 90 days of hydration. This is mainly attributed to the normal hydration process of cement phases which resulted in a gradual and continuous formation of hydration products (Neville, 2011; Hewlett and Liska 2017; Rukzon and Chindaprasirt, 2012; Darweesh, 2005). The combined water contents were continuously increased with PPF content up to 0.6 wt. %, and then decreased with its further increase. The same trend was displayed by all cement blends. Therefore, the optimum addition of PPF was 0.6 wt. % (PP6). As a result, the higher replacement of PPF more than 0.6 wt. % at the expense of the cement was reflected negatively on the specific characteristics of the cement (Neville, 2011; Hewlett and Liska 2017; Darweesh and Abo-El-Suoud, 2015) ; Rukzon and Chindaprasirt, 2012; Ayoub et. al., 2006; Amin et. al., 2011; Amin et al., 2011; Amin et al., 2012; Amin et al., 2013; Ibrahima et. al, 2015). So, the higher amounts of PPF must be avoided as much as possible (PP7).

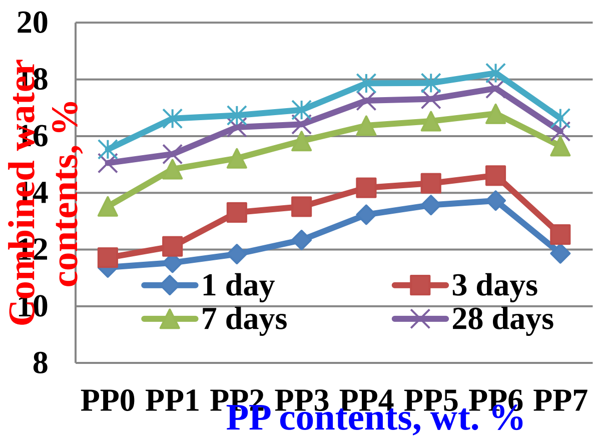

Fig. 4- Combined water contents of the cement pastes mixed with different ratios of PPF and cured up to 90 days.

3.3. Free lime content

The free lime contents of the different cement/PPF pastes (PP0-PP7) are graphically represented versus hydration time in Fig. 5. Generally, the free lime contents of the different cement/PPF pastes (PP0-PP7) increased up to 90 days. This is due to the hydration of C_3S in the early ages of hydration and β-C_2S in the older ages (Neville, 2011; Hewlett and Liska 2017; Darweesh, 2017); Agarwal and Deepali, 2006; Rukzon and Chindaprasirt, 2012; Ayoub et. al., 2006; Amin et. al., 2011; Amin et al., 2011) as the following relations:-

$$3\ C_3S + 6\ H_2O \rightarrow C_3S_2H_3 + 3\ Ca(OH)_2 \quad (8)$$

$$2\ \beta\text{-}C_2S + 4\ H_2O \rightarrow C_3S_2H_3 + Ca(OH)_2 \quad (9)$$

Moreover, as the PPF content increased in the cement mix, the free lime content decreased bit by bit. This is contributed to the deficiency of the essential hydration cement portion responsible for the hydration (Hewlett and Liska 2017; Darweesh and Abo-El-Suoud, 2015; Rukzon and Chindaprasirt, 2012; Ayoub et. al., 2006; Amin et. al., 2011; Amin et al., 2011; Amin et al., 2011; Amin et al., 2012; Amin et al., 2013; Ibrahima et. al, 2015) . Accordingly, the rate of hydration was decreased with the increase of PPF content.

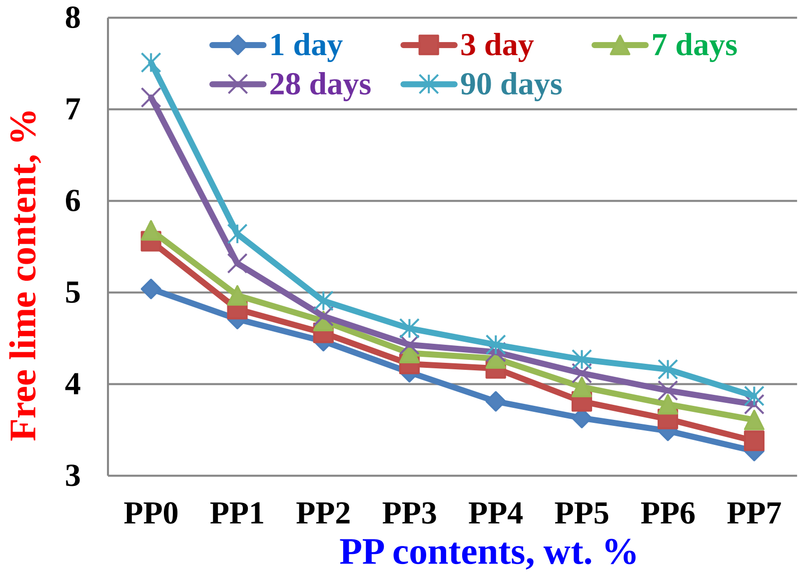

Fig. 5- Free lime contents of the cement pastes mixed with different ratios of PPF and cured up to 90 days.

3.4. Bulk density and apparent porosity

Figures 6 and 7 demonstrate the graphs of the bulk density and apparent porosity of the various cement/PPF pastes (PP0-PP7) versus the hydration ages up to 90 days, respectively. Generally, the bulk density of the various cement mixes increased as the hydration period progressed up to 90 days, while the apparent porosity decreased. This is mainly contributed to the fact that: as the hydration ages proceeded, the hydration process started to produce CSH which soon deposited in the pore structure of the hardened cement pastes leading to a decrease in the apparent porosity. This reflected positively on the bulk density, i.e. the bulk density improved and enhanced, while the apparent porosity decreased (Neville, 2011; Hewlett and Liska 2017; Darweesh and Abo-El-Suoud, 2015; Darweesh, 2017; Rukzon and Chindaprasirt, 2012). The bulk density of the cement mixes containing PPF (PP1-PP7) gradually increased as the PPF content increased only up to 0.6 wt. % (PP6), whereas the apparent porosity decreased, i.e. the cement blends PP1-PP6 are slightly higher than those of the of the OPC (PP0) at all hydration ages. This is evidently due to the activation of cement phases by PPF which resulted with some additional CSHs. The addition of more than 0.6 wt. % PPF, the BD suddenly was decreased, while the apparent porosity increased at all hydration ages. This is principally due to the higher decrease in the main binding material of the OPC, and also the higher quantity of PPF may obstructed and hindered the hydration process of the cement, i.e. it affects negatively and decrease the rate of hydration accompanied by a decrease of BD and an increase of apparent porosity (Darweesh and Nagieb, 2007; ACI 544.3R-93, 1998; Darweesh, 2017; Ochia et al,, 2007, Darweesh, 2017). Hence, the increase of apparent porosity and the decrease of BD resulted with the incorporation of large amounts of PPF affected the amount of the used OPC. As a result, it was not induce the reactions of cement phases with water.

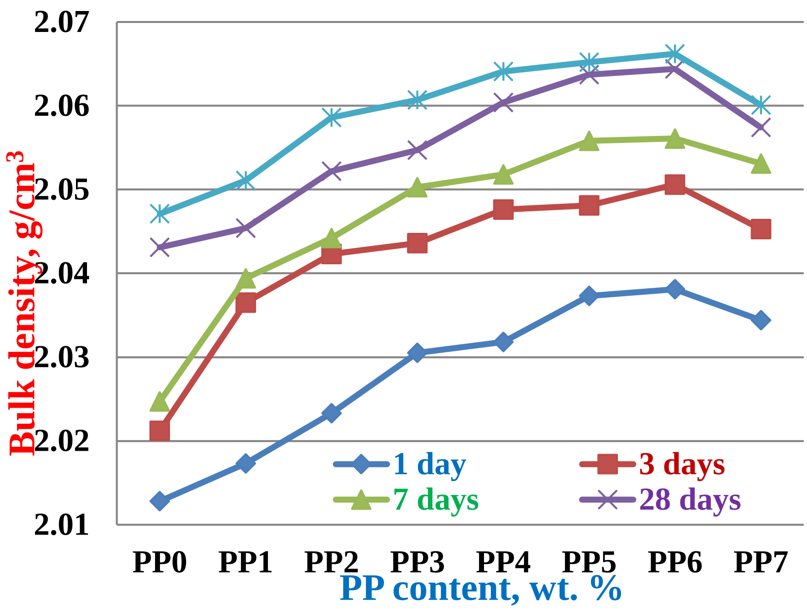

Fig. 6-Bulk density of the cement pastes mixed with different ratios of PPF and cured up to 90 days.

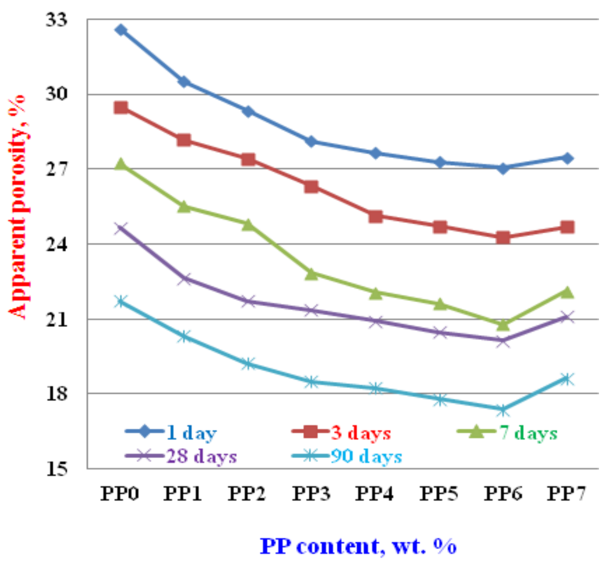

Fig. 7-Apparent porosity of the cement pastes mixed with different ratios of PPF and cured up to 90 days.

3.5. Compressive strength

It is well known that the w/c ratio influences the workability and resistance of cement pastes and concrete, which in turn influences its strength and durability, i.e. the decrease of w/c-ratio results in an increase of workability accompanied by an increase in the strength, and the opposite is right. The compressive strength results of the various cement pastes mixed with different ratios of PPF (PP0-PP7) and cured in water up to 90 days are shown in Fig. 8. Generally, the compressive strength improved and gradually increased as the hydration time proceeded till reach 90 days. This is mainly attributed to the formation of hydration products (CSHs and/or CAHs), which are due to hydration. These CSHs and/or CAHs are always precipitated into the pore system of the hardened cement pastes. This results in a decrease in the apparent porosity and an increase in the bulk density. This may be due to the good dispersion by the used PPF and good compaction of the hardened samples during mixing and casting. This in turn was reflected positively on the mechanical properties. As a result, the compressive strength improved and enhanced (Neville, 2011; Hewlett and Liska 2017; Darweesh and Abo-El-Suoud, 2015; Agarwal and Deepali, 2006; Rukzon and Chindaprasirt, 2012; Darweesh and Abo El-Suoud, 2014). The compressive strength also enhanced as the PPF content increased only up to 0.6 wt. % at all curing ages of hydration. With more addition of PPF, all of the specific properties of the used cement declined and shortened clearly, i.e. suddenly decreased. The increase of compressive strength is related to the improvement of the workability of cement pastes in addition to the decrease of w/c ratio (Amin et al., 2012; Amin et al., 2013; Ibrahima et. al, 2015; Darweesh et al., 2013). Furthermore, the PPF supported and improved the mechanical strength, i.e. PPF could be acted as a reinforcement (Agarwal and Deepali, 2006; Ayoub et al., 2005; Amin et al., 2012; Darweesh et al., 2013; Darweesh and Nagieb, 2007). This would be led to the segmentation of large capillary pores and nucleation sites due to the continuous deposition of hydration products, CSHs from the normal hydration process of cement phases (Darweesh and Abo El-Suoud, 2020; Darweesh and Nagieb, 2007; ; ACI 544.3R-93, 1998; Darweesh, 2017; Ochia et al., 2007). The decrease in mechanical strength is only due to the replacing of higher amount of PPF at the expense of cement, which stands as an obstacle against the normal hydration of cement phases. So, the rate of hydration declined, and accordingly, this would be reflected negatively on the compressive strength (Neville, 2011; Hewlett and Liska 2017; Darweesh, 2017; Darweesh and Abo El-Suoud, 2020; Darweesh, 2005; Darweesh and Nagieb, 2007; ACI 544.3R-93 (1998; Darweesh, 2017; Ochia et al., 2007). The cement mix of PP6 recorded the highest values of compressive strength. Though the PP7 mix exhibited a lower value, it is still higher than those of the blank mix (PP0) as clear from Fig. 8. On this basis, the cement batch containing 0.6 % PPF (PP6) is the optimum cement composite. Hence, the PPF does not only improve the various characteristics of the OPC (PP0), but from an economical point of view, it also improves the morphology and permeability of it. Also, it is easy to process and inexpensive compared to other synthetic fibers. Moreover, its low moisture absorption helps in the set hardening of cement pastes.

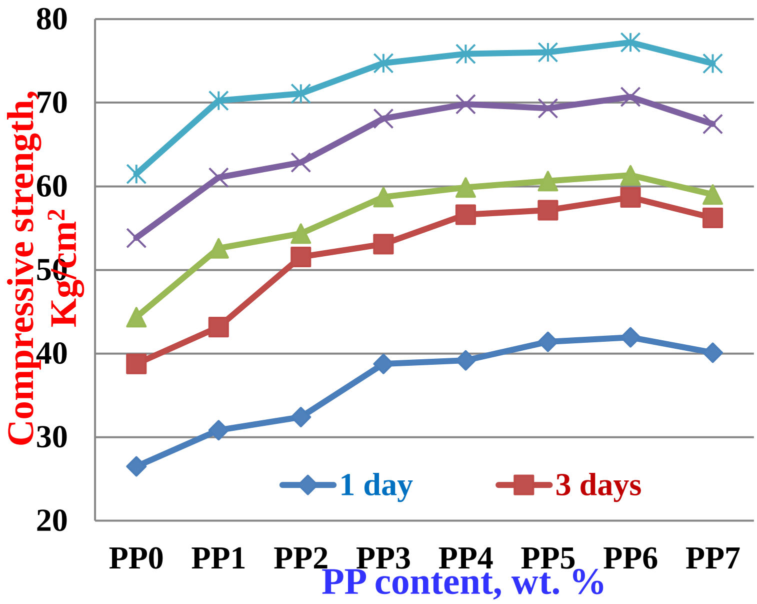

Fig. 8–Compressive strength of cement pastes mixed with different ratios of PPF and cured up to 90 days.

Conclusions

1. The following overall conclusions could be obtained: -
2. The PPF decreased the water of consistency, but increased the setting times (Initial and final).
3. The bounwater contents increased up till 0.6 wt. % PPF addition and then decreased at all curing ages of hydration.
4. With the addition of PPF to the cement, the free lime contents decreased gradually.
5. The bulk density increased bit by bit due to the incorporation of PPF at all hydration times only up to 0.6. wt. %, and then decreased, whereas the apparent porosity recorded the opposite.
6. The compressive strength of the various cement pastes (PP0-PP7) increased with hydration periods up till 0.6 wt. %, and then decreased.
7. The PPF improved the workability and permeability of the cement pastes.
8. The PPF supported and improved the mechanical strength of the hardened cement pastes.
9. The PPF improve the external appearance of the hardened cement pastes.

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Compliance with ethical standards

Conflict of interest: There is no conflict of interest anywhere.

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