IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 19, Issue 4 Ser. III (Jul. – Aug. 2022), PP 24-33
www.iosrjournals.org

Properties of eco-friendly concrete incorporating by-product materials under different curing conditions

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Abstract:
According to the requirements of eco-friendly concrete, this study investigates using of the waste materials: rubber aggregates (RA) and waste pigments (PPL) as partial replacements of fine aggregates besides partial replacement of ordinary Portland cement with silica fume (SF), metakaolin (MK) and fly ash (FA). A total of ten mixtures were prepared and cured in two groups: with natural water and sea water. Slump test and compressive strength test were carried out for all specimens. It can be concluded that the highest workability was obtained from the mixtures which contains SF as partial replacement of cement by 10% and those which contains PPL as partial replacement of sand by 30%. The combination between both of two parameters (SF and PPL) gave the best slump and resulted lower unit weight. In addition, it was significantly observed with each separated pozzolanic replacement that implementation of PPL in mixture provided better workability. The implementation of PPL as partial replacement (especially with 10% SF) in concrete can be considered as optimum solution to achieve concrete terms that provides appropriate unit weight, workability and compressive strength considering environmental and economic aspects.

Keywords: *Green; sustainable; waste; by-product; rubber aggregates; PPL*

Date of Submission: 10-08-2022 Date of Acceptance: 25-08-2022

I. Introduction

During the last decade, the production of cement increased significantly due to the increasing demand of concrete production in construction industries. The global trend of turning concrete to green requires making reduction of consumption of cement and the emission of CO^2 [1-15]. Therefore, many studies were carried out to maintain or improve concrete characteristics when cement content was replaced partially with other pozzolanic materials such as MK (metakaolin), FA (fly ash) and SF (silica fume) [1-15]. Also according to green terms, the production of metakaolin results lower temperatures (650-800°C) than cement which consumes about (1400-1500°C). Therefore, the production process consumes less cost due to the decreased demand of energy [1-6]. Metakaolin was previously also found that the higher surface area of finer particles of metakaolin absorbed the mixing water and caused reduction in workability. Therefore, the implementation of metakaolin in concrete requires additional mixing water to maintain the workability of 100% cement mixtures [1-9]. Muduli et al., [1] studied the metakaolin as a partial replacement of cement with ratios various from 0% to 20% with recycled coarse aggregates (0, 50 and 100%). In this study, replacing cement with metakaolin by 15% improved all mechanical properties of mixture with maximum rate in this study [1]. A combination of MK and SF was mixed in a previous study to investigate the effect of different pozzolanic materials co-addition as replacement of cement [2]. It was found that the addition of MK with SF increased compressive strength significantly within range of 3% to 6% comparing to sole-addition of SF and about 10% to 14% comparing to sole-addition of MK [2]. Replacement of cement with nano metakaolin was studied by Norhasri et al., [3] by levels of (1-10) % of cement. That replacement resulted significant higher late compressive strength than control mixture [3]. Many researchers studied the effects of finer pozzolanic particles implementation instead of cement with sizes of nano and micro [4-10]. It was proved that micro and nano improved significantly the compressive strength comparing to OPC cement [4-10]. Considering durability terms, using of finer particles and reduction in capillary pores resulted: improvement in resistance to sulphate attack, resistance of corrosion and reduction in chloride permeability [4, 6]. It was proved previously that MK improved the performance of concrete especially compressive strength in higher rates than SF when comparing using the both pozzolanic additives as partial replacement of cement with different levels [5, 9]. In general, it was proved that both of MK and SF reduced the free shrinkage and minimized the cracks width

[6]. Also when considering workability terms, MK offers better workability than SF in several levels of replacement [6]. It was observed in pervious study [7] that the suitable level of MK's inclusion is 10%. That inclusion improved significantly absorption of concrete mechanical properties: compressive strength, splitting strength and tensile strength [7]. In addition, modulus of concrete and the autogenous shrinkage were proved definitely to improve with the replacement level of SF [8]. However, the plastic shrinkage strain increased with higher levels of replacement [8]. Ceramic waste powder (CWP) was investigated previously as partial replacement of cement by levels of 20% and 40% [10]. That replacement increased compressive strength at late ages. Due to durability terms, chloride permeability and electrical resistivity enhanced with CWP than conventional concrete. In addition, that replacement gave two benefits: filler effect that results dense microstructure of concrete and a pozzolanic effect which improved strength at late ages [10]. In the line of sustainability, sewage Sludge Ash (SSA) was studied as partial replacement of cement by Thevaneyan et al., [11]. The study proved definitely that concrete contains SSA achieved characteristic strength of control mixture at 21 days [11]. A comparative study between SF and fly ash (FA) was carried out to investigate the two materials as partial replacement of cement previously [12]. It was found that replacing 30% of cement increased the sustainability. In addition, the replacement level of 50%, enhanced that sustainability. Using FA improved significantly sulphate attack resistance and chloride penetration resistance [12, 13]. FA replacement level of 20% added high performance and improved compressive strength of concrete [13]. Many agriculture wastes presents promising pozzolanic materials and is very suitable materials to replace cement partially [14-15]. Nano cotton stalk ash (NCSA) and palm leaf ash (PLA) which results from burning of cotton stalk and palm leaves were studied as partial replacement of cement in various levels up to 30% [14]. Both of NCSA and PLA caused high performance and ultra-strength in concrete especially at late ages [14]. Rice husk ash (RHA) also was implemented in concrete as partial replacement of cement comparing to SF [15]. Inclusion of RHA in concrete improved the mechanical properties significantly at all ages especially 20% level of replacement [15]. Therefore, and according to green terms and eco-friendly concrete requirements, some alternative suitable pozzolanic materials and some waste materials were studied as partial replacement of fine aggregates were studied in this study.

Research significance:

Many factories resulted some waste materials during its main production process (such as paints and rubber). In this study and with the global trend of green, some of these by-products materials were implemented in concrete as partial replacement of fine aggregates. The disposal of these materials presents environmental problem. So, exploitation of this materials is in line with green and economic aspects. Also the replacing of cement with suitable pozzolanic materials (which consumes less resources during its production process) is the most important term in production of green concrete. That due to the global trend of decreasing the consumption and production of cement worldwide. In this study the cement was replaced by 10% with metakaolin, silica fume and fly ash in various combinations.

II. Experimental investigations

2.1. Materials procurement

The cement used in this study was Ordinary Portland Cement (CEM I) of 42.5N grade in confirmation with BS EN197/1-2011 [16]. Silica fume (SF) and Fly ash (FA) (with specific gravities of 2.13 and 2.15 respectively) which were used in mixtures were obtained from Sika Company, Egypt. Silica fume, fly ash and metakaolin used could be considered as high siliceous materials and are in line with the requirements of ASTM C1240and ASTM C1697-21[17, 18]. Table 1 presents physical properties and the chemical compositions of CEM I, SF, FA and MK used in this study. Dolomite with specific gravity of 2.60 and maximum particle size of 20 mm was used as coarse aggregates. Used sand with the fineness modulus, specific gravity, unit weight, and water absorption of 2.57, 2.66, 1680 Kg/m^3, and 0.83%, respectively, were obtained from Belbas area, Egypt. Properties of sand were obtained as per ASTM C33/C33M-18 [19]. Figure1 illustrates the grading curve of sieved coarse and fine aggregates. The waste Pigments (PPL) is by-product material which was brought from paints factory in El-Obor City – Egypt. All of PPL particles passed the sieve with size of 0.15 mm then it was used as a partial replacement of fine aggregates in concrete as shown in (Figure 2). The composition of PPL are shown in Table 2.Rubber aggregates (Figure 3) was obtained from Marso company for cars' pedals where it resulted as by-product from a main production process. All of RA particles passed the sieve with size of 0.15 mm then it was used as a partial replacement of fine aggregates in concrete. Sika ViscoCrete-5930 high performance superplasticizer as high range water reducing admixtures (HRWR) was utilized to counterbalance the decrease in workability. The workability was reduced due to an increase in the overall surface area of the particles as CEM was partially replaced by smaller sized SF, FA, and MK particles. It was obtained from Sika Company, Egypt. The characteristics of Sitka ViscoCrete-5930 is given in Table 3. The content of HRWR is 2% from binder content for all mixtures.

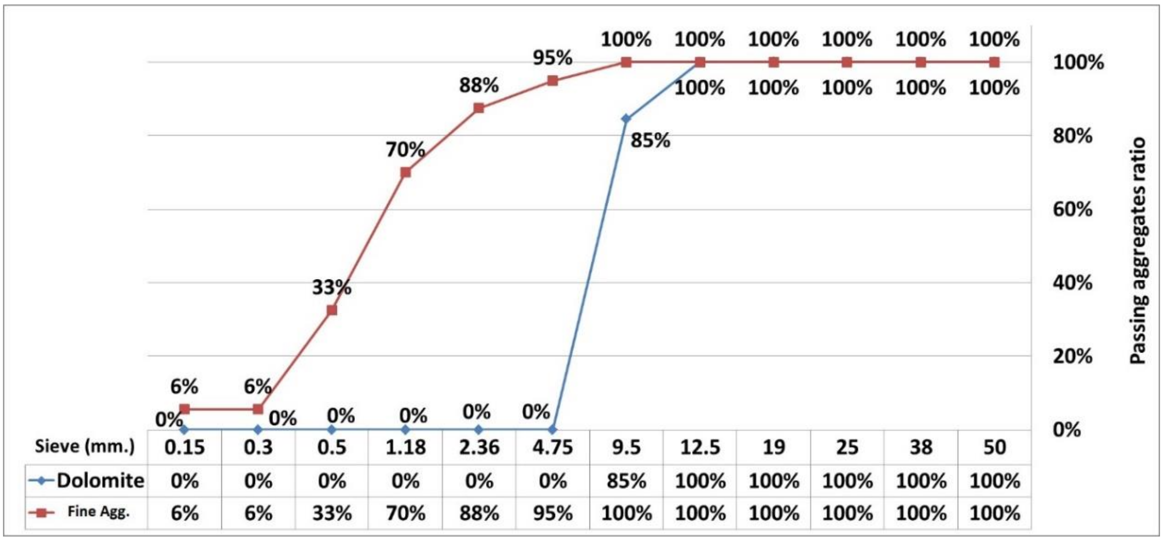


Figure1. Grading curve of sieved aggregates

Figure 2. The waste Pigments (PPL)

Figure 3. The rubber aggregates

Table 1: Properties of cement and pozzolanic materials

Properties	CEM I	Fly ash	Silica Fume	Metakaolin
Physical				
Al_2O_3	4.64	26.35	0.16	38.17
Fe_2O_3	3.35	4.94	0.28	1.40
CaO	59.82	2.82	0.15	0.04
MgO	3.89	0.46	0.28	0.96
SO_3	3.46	1.34	0.16	-
K_2O	1.21	0.037	0.20	2.68
Na_2O	0.87	0.033	0.14	0.04
P_2O_5	-	-	0.01	0.10
TiO_2	0.38	-	0.01	0.95
Cr_2O_3	0.1	-	-	-
MnO	0.08	-	-	0.01
CI	0.05	-	-	-
Loss on Ignition (LOI)	1.915	0.39	0.34	1.85
Specific area (cm^2/gm)	3450	3950	19900	8050

Table 2: The composition of the waste Pigments (PPL)

Component	Weight % (From white paints)
Polyester resin	57
hardener	3
Titanium dioxide	21
Pigments	--
Zn dust	--
Flow control Agent	1.4
Degassing Agent	0.5
$BaSO_4$	17.1

Table (2) Characteristics of HRWR (Sitka ViscoCrete-5930)

Standard compliance	Complies with ASTM-C-494 Type F [20]
Form	Viscous liquid
Basis	Aqueous solution of modified Polycarboxylate
Density	1.095 kg/lt
Appearance	Turbid liquid

2.2. Mixture proportion

Ten different mixes were set up for eco-friendly concrete in this study containing of silica fume, metakaolin and fly ash as a pozzolanic materials which can made partial replacement of cement effectively. Mixtures were prepared by replacing CEM I by weight with SF, MK and FA at a consistent interval of 10% as shown in Table 4. It is clear that the SF, MK, and FA particles are smaller in size than cement particles and are highly pozzolanic; thus, they tend to enhance the characteristics of the hardened concrete significantly, it was concluded in the previous studies [10-15]. PPL and rubber aggregates was used in 6 mixtures as a partial replacement of fine aggregates. The replacement level for both of PPL and RA was 30% by weight with implantation of MK, FA and SF. The final concrete mix design was confirmed after several hit and trial mixes. The water-binder material ratio was kept fixed at 0.4. The reduction in workability due to the increase in surface area of the mix particles was compensated by using superplasticizer. The dosage of HRWR for each mix was 2% by weight of binder material. Table 4 illustrates the total composition of the mixtures in this study.

Table 4: Composition of eco-friendly mixtures kg/m^3

Mix components	CEM	MK10	SF10	FA10	MK10-PPL	SF10-PPL	FA10-PPL	MK10-RA	SF10-RA	FA10-RA
Cement	450	405	405	405	405	405	405	405	405	405
River sand	620	620	620	620	434	434	434	434	434	434
Superplasticizer	9	9	9	9	9	9	9	9	9	9
water	180	180	180	180	180	180	180	180	180	180
Dolomite	620	620	620	620	620	620	620	620	620	620
Metakaolin	0	45	0	0	45	0	0	45	0	0
Silica fume	0	0	45	0	0	45	0	0	45	0
Fly ash	0	0	0	45	0	0	45	0	0	45
PPL	0	0	0	0	186	186	186	0	0	0
Rubber aggregates	0	0	0	0	0	0	0	186	186	186

2.3. Sample preparation

All materials were weighed using digital balance according to the series of mixture proportions as shown in Table 4. Prior to commencing, all materials were placed in the pan mixer and mixed for 2 min for the materials to homogeneously blend. Next, water was poured gradually during mixing until all the materials. After that, Fresh concrete were cast into molds and vibrated. All specimens were placed at drying area for 24 h prior to removal of mould. After removal from the steel mould, the specimens were placed into a tank filled with water for curing at specified days prior to tests, accordant to the B. EN, 12390-8 [21].The specimens was divided to two groups according to curing conditions. The first group was cured by water and the second group was cured by sea water. Both of two groups was tested in both of fresh and hardened states and the compressive strength was measured at two ages of 7 days and 28 days. Figure 4 shows the curing of the specimens in both conditions.

Figure 4. The curing of specimens

2.4. Test procedure

All specimens were weighed using calibrated digital balance to get the unit weight of each mixture. Slump test was carried out on mixtures to determine the workability of concrete in accordance with ASTM C413 [22]. For each mixture, three cubes of 150x150x150 mm dimensions were used to determine the compressive strength at 7 and 28days age. The compressive strength were conducted in accordance with BS EN 12390-3 [23]. For each age and each curing condition, the results presented represent the average of three samples tested.

III. Results and discussion

Fresh and hardened properties of ultra-high performance concrete mixtures for both conditions of curing are presented in Table 5.

Table 5: Fresh and hardened properties of concrete mixtures

Mixture ID	MK %	SF%	FA%	PPL%	RA %	Unit weight (kg/m^3)	Slump (mm)	Water		Sea water	
								Compressive strength (MPa)		Compressive strength (MPa)	
								7 Days	28day	7 days	28days
Control	0	0	0	0	0	2342	131	24.9	37.2	25.9	39.1
MK10	10	0	0	0	0	2318	139	22	33.4	20.8	30.9
SF10	0	10	0	0	0	2379	150	34.7	51.6	32.8	48.9
FA10	0	0	10	0	0	2403	145	27	41	30	45.2
MK10-PPL	10	0	0	30	0	2264	143	10.6	15.9	10	14.7
SF10-PPL	0	10	0	30	0	2255	160	17.2	25.8	15.7	23.8
FA10-PPL	0	0	10	30	0	2312	153	14.8	22.2	14	21.3
MK10-RA	10	0	0	0	30	2266	130	11.3	16.9	10	17.4
SF10-RA	0	10	0	0	30	2253	142	13.5	20.3	15	21.8
FA10-RA	0	0	10	0	30	2249	138	12.2	18.3	12	16.5

3.1. Fresh properties

3.1.1. Workability

Generally, the replacement of cement with the limited ratio of 10% caused slight increase in slump test values. With the usage of sand as 100% present fine aggregates, the slump increased by 6%, 15% and 11% from the control mixture with the replacement of cement by 10% of MK, SF and FA respectively. Also, with the usage of PPL (as a partial replacement of sand by 30%) the slump test increased by 9%, 22% and 17% from the control mixture with the replacement of cement by 10% of MK, SF and FA respectively. By the way, with the usage of rubber aggregates (as a partial replacement of sand by 30%) the slump test enhanced by 8% and 5% from the control mixture with the replacement of cement by SF and FA respectively. It was found that replacing cement with 10% MK almost didn't make change to workability with rubber aggregates usage. It can be summarized that the optimum pozzolanic replacement that gave the highest slump value is SF and the optimum fine aggregates that provided the best slump is PPL with ratio of 30% of fine aggregates. When comparing replacing 30% of sand (with 10% MK and 90% cement), it was found that slump decreased by 7% with RA and increased by 3% with PPL. The replacing 30% of sand (with 10% SF and 90% cement) caused decrease in slump by 6% with RA and increase by 7% with PPL. The replacing 30% of sand (with 10% FA and 90% cement) caused decrease in slump by 5% with RA and increase by 6% with PPL. Therefore, using of SF and PPL in mixture with replacement levels of 10% of cement and 30% of sand respectively gave the highest workability in this study. In general, the results are similar to those of previous studies [1, 3, 5]. Figure 5 shows the effect of replacement on Slump test (mm) for both of pozzolanic materials and fine aggregates.

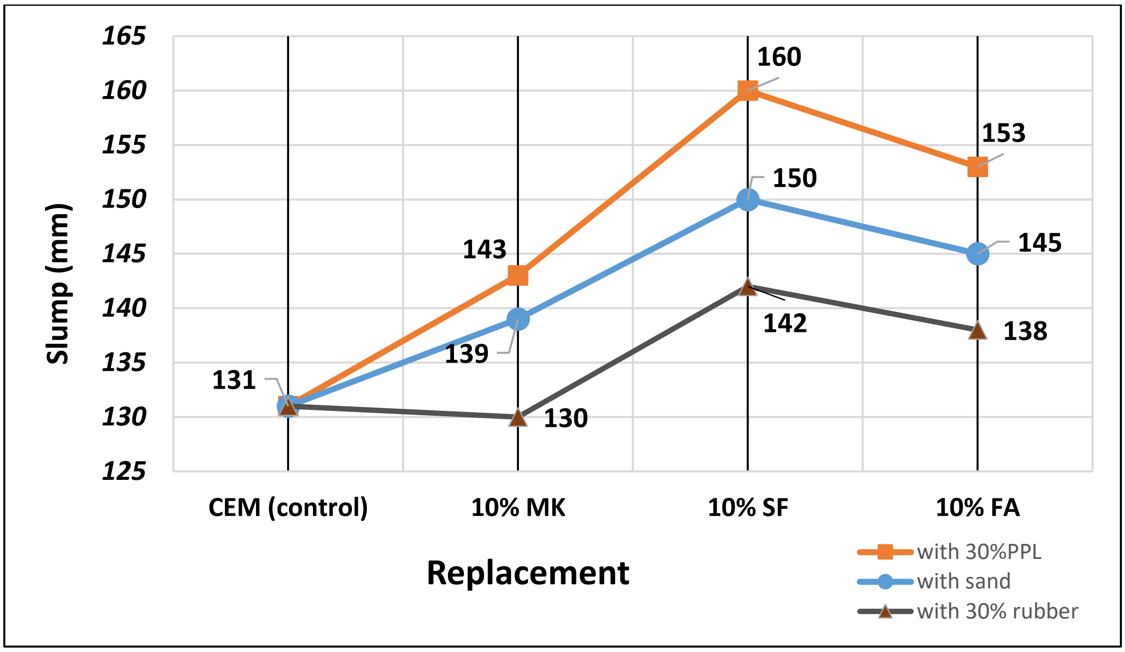


Figure 5. The effect of replacement on Slump test (mm)

3.2. Mechanical properties

3.2.1. Unit weight

Due to the low unit weight of rubber aggregates, using of it in concrete caused reduction of unit weight of concrete. With using 30% of fine aggregates as RA, the unit weight decreased by 3% with 10%MK and by4% with both of 10%SF and 10%FA comparing to control mixture. Using of PPL also with 30% of fine aggregates decreased unit weight by 3%, 4% and 1% with 10%MK, 10%SF and 10%FA respectively than control mixture. In case of using 100% of fine aggregates as sand, the unit weight decreased with 10% MK by 1% and increased by 2% and 3% with 10% SF and FA respectively comparing to control mixture. To evaluate the effect of replacement of 30% sand (with PPL and RA) and keeping the pozzolanic composition constant, it was found that the great effect on unit weight was with 10%FA. The unit weight decreased by 3% with 30% RA and increased by 4% with fly ash. Figure 6 shows the effect of replacement on unit weight.

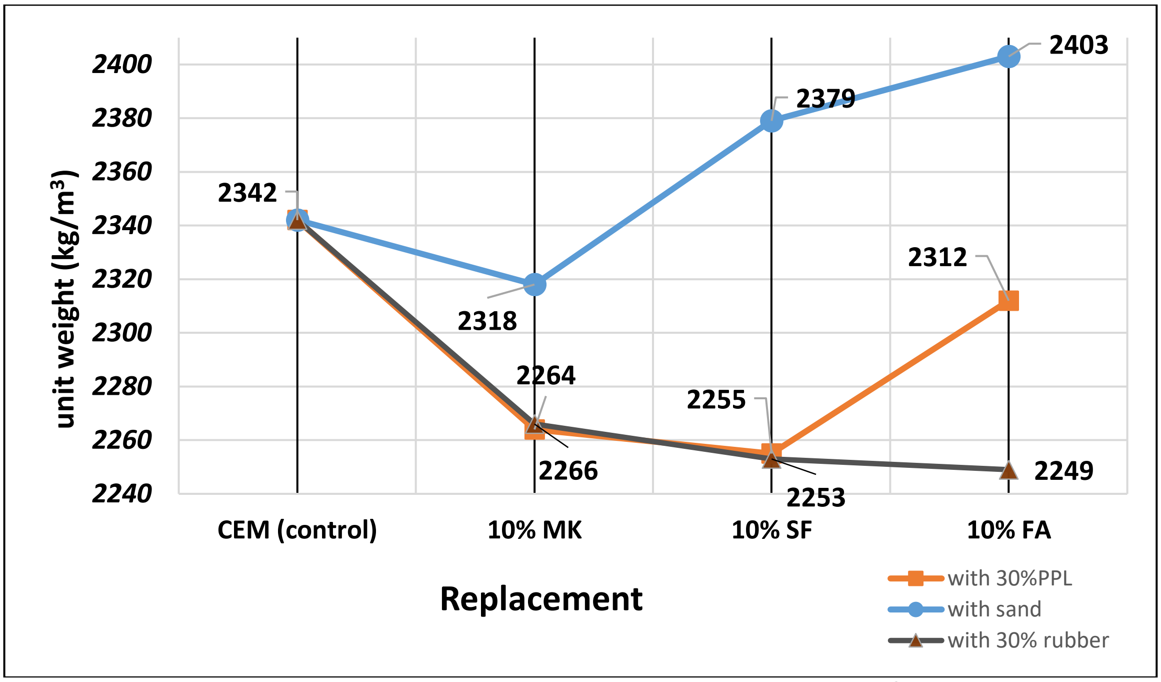


Figure 6. The effect of replacement on unit weight (kg/m^3)

3.2.2. Compressive strength

3.2.2.1. Effect of replacement cement by 10%

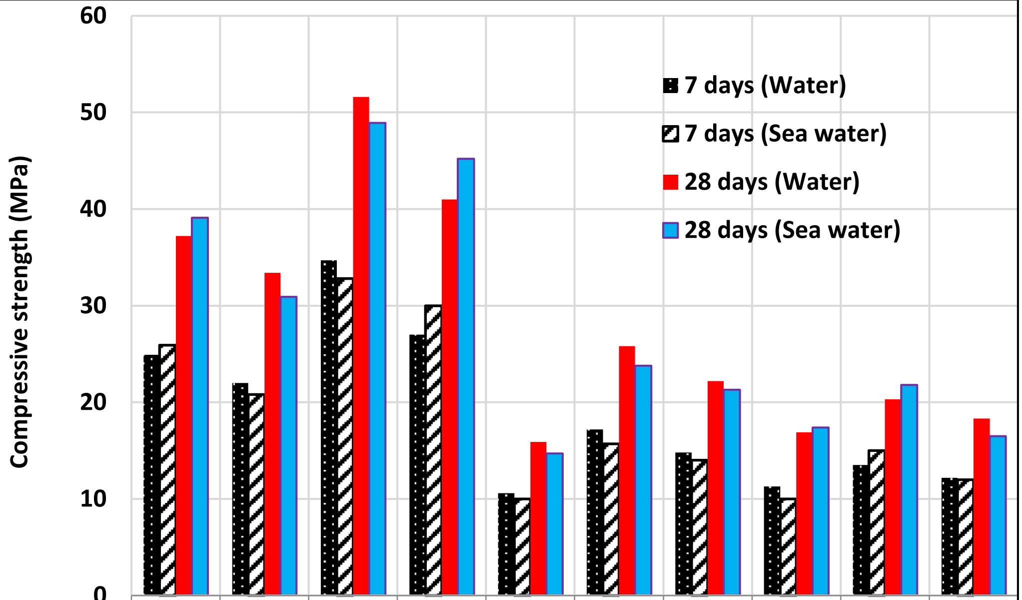
Cement was replaced by 10% with three pozzolanic materials: MK, SF and FA. Those three replacements were evaluated with three combinations of fine aggregates: 100% sand and 70% sand with 30% PPL or RA. All mixtures was cured in two different conditions: water and sea water. With 100% sand, the replacement cement with 10% MK caused reduction in compressive strength by 12% and 10% at ages of 7 days and 28 days respectively when curing with natural water and caused reduction by 20% and 21% at ages of 7 days and 28 days respectively when curing with sea water. However, with 100% sand the replacement cement with 10% SF caused increase in compressive strength by 39% at both of ages of 7 days and 28 days when curing with natural water and caused increase by 27% and 25% at ages of 7 days and 28 days respectively when curing with sea water. By the way with 100% sand, replacement cement with 10% FA caused increase in compressive strength by 8% and 10 at ages of 7 days and 28 days respectively when curing with natural water and caused increase by 16% at both ages of 7 days and 28 days when curing with sea water. When using the second combination of fine aggregates: 70% sand and 30%PPL, it was found that replacing 10%MK with 10%SF caused increase in compressive strength by 60% at ages of 7 days and 28 days when the specimens were cured with natural water and sea water. Also the replacement of 10% MK with 10%FA caused increase in compressive strength by 40% at age of 7 days when the specimens were cured with natural water and sea water and increased by 40% and 45% at age of 28 days when the specimens were cured with natural water and sea water respectively. Also with using the third combination of fine aggregates: 70% sand and 30% RA, it was found that replacing 10%MK with 10%SF caused increase in compressive strength by 19% and 20% at ages of 7 days and 28 days respectively when the specimens were cured with natural water and caused increase by 50% and 25% at ages of 7 days and 28 days respectively when the specimens were cured with sea water. Also the replacement of 10% MK with 10%FA caused increase in compressive strength by 8% at ages of 7 days and 28 days when the specimens were cured with natural water and caused increase by 20% at age of 7 days and decreased by 5% at age of 28 days when the specimens were cured with sea water. Figure 7. Shows the effect of replacement on compressive strength (MPa) under two cases of curing. With 100% sand as fine aggregates, it was noticed that replacing cement with MK by 10% replacement level decreased the compressive strength under the two cases of curing. However, that effect was less in case of curing with sea water. On the other side, the replacement with SF and FA affected the compressive strength positively under the two cases of curing and increased it by high levels up to 40% from control mixture. With 70% sand + 30% PPL as fine aggregates, it was noticed that replacing MK with SF and FA increased the compressive strength under the two cases of curing up to 60% higher strength. With 70% sand + 30% RA as fine aggregates, it was noticed that replacing MK with SF and FA increased the compressive strength especially at early age of 7 days under the two cases of curing up to 50% higher strength. Similar results have been reported in many studies [1-3, 6-8].

3.2.2.2. Effect of replacement sand by 30%

In this section the influence of partial replacement of sand by 30% was studied. The study was carried out with the three combinations of pozzolanic materials. With the first combination of pozzolanic materials (90% cement + 10% MK), it was found that replacing sand with 30% PPL decreased the compressive strength by 52% at both of ages: 7 and 28 days with the two cases of curing with natural water and sea water. By the way, replacing sand with 30% RA decreased the compressive strength by 49% at both of ages: 7 and 28 days with case of curing with natural water and decreased by 52% and 44% at the ages of 7 and 28 days respectively when the specimens were cured with sea water. With the second combination of pozzolanic materials (90% cement + 10% SF), it was found that replacing sand with 30% PPL decreased the compressive strength by 50% at both of ages: 7 and 28 days in case of curing with natural water and decreased by 52% and 33% at the ages of 7 and 28 days respectively when the specimens were cured with sea water. By the way, replacing sand with 30% RA decreased the compressive strength by 55% at both of ages: 7 and 28 days with case of curing with sea water and decreased by 61% at both of ages: 7 and 28 days when the specimens were cured with natural water. With the third combination of pozzolanic materials (90% cement + 10% FA), it was found that replacing sand with 30% PPL decreased the compressive strength by 45% at both of ages: 7 and 28 days in case of curing with natural water and decreased by 53% at both of ages: 7 and 28 days in case of curing with natural water. By the way, replacing sand with 30% RA decreased the compressive strength by 55% at both of ages: 7 and 28 days with case of curing with natural water and decreased by 60% and 64%at ages of 7 and 28 days respectively when the specimens were cured with natural water. Figure 7. Shows the effect of replacement on compressive strength (MPa) under two cases of curing. It was noticed clearly that the compressive strength was highly affected with the replacement ratio of 30% of sand as fine aggregates up to higher than 60% decrease in strength. Therefore, that replacement should by lower level and to highly consider the environmental and economic aspects. It was observed that the less effect was with the using of SF and curing with sea water. Similar results have been reported in many studies [10, 12, 13].

3.2.2.3. Effect of curing water

The influence of curing water was completely discussed (with each parameter in this study) through the previous two sections in the discussion. Therefore, in this section the optimum curing method can be summarized for each parameter. It was observed that curing with the sea water was better and significantly affected the strength positively in mixtures: the control mixture, FA10 and SF10-RA only. The rest of mixtures in various combinations of cementitious and aggregates proved that the natural water curing provided higher strength at both of ages of 7 and 28 days.



	Control	MK10	SF10	FA10	MK10-PPL	SF10-PPL	FA10-PPL	MK10-RA	SF10-RA	FA10-RA
7 days (Water)	24.9	22.0	34.7	27.0	10.6	17.2	14.8	11.3	13.5	12.2
7 days (Sea water)	25.9	20.8	32.8	30.0	10.0	15.7	14.0	10.0	15.0	12.0
28 days (Water)	37.2	33.4	51.6	41.0	15.9	25.8	22.2	16.9	20.3	18.3
28 days (Sea water)	39.1	30.9	48.9	45.2	14.7	23.8	21.3	17.4	21.8	16.5

Figure 7. The effect of replacement on compressive strength (MPa)

IV. Conclusions

Based on the results of this experimental investigation in this study, the following conclusions are drawn:

1- Due to workability terms, it was found that the best workability was obtained from the mixtures which contains SF as partial replacement of cement by 10% and those which contains PPL as partial replacement of sand by 30%. The combination between that two parameters gave the best slump and resulted lower unit weight. In addition, it was significantly observed with each separated pozzolanic replacement that implementation of PPL in mixture provided better workability.

2- Although the usage of RA caused high reduction in unit weight, the replacing sand by 30% RA gave decreased the workability significantly, and usage of it with MK (as a partial replacement of cement) causes the least slump in the study. Therefore it is not recommended to use RA by high level of replacement even using it with MK.

3- Implementation of FA by 10% with 100% sand as fine aggregates resulted the higher unit weight in the study without opposite strength of that high density.

4- It was observed in this study, that replacing cement with SF by 10% caused improved compressive strength at all ages, with all parameters and under the both cases of curing especially at early age of 7 days with sea water (50% higher) and with PPL (60% higher). In addition, curing with natural water provided higher strength than curing with sea water except in two mixtures.

5- The replacing cement with MK by 10% caused decrease in strength at all ages and conditions of curing. However the rete in decrease was lower in case of curing with sea water. While MK was implemented with PPL, the strength was highly decreased up to percent of 52% decrease in strength comparing to 100% sand.

6- The implementation of PPL as partial replacement (especially with 10% SF) in concrete can be considered as optimum solution to achieve concrete terms that provides appropriate unit weight, workability and compressive strength considering environmental and economic aspects.

Declaration
The authors declare that they have no conflict of interest.

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