Mechanical Properties of High Performance Concrete Containing Waste Plastic as Aggregate

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ABSTRACT

The world's population growth and the increasing demand for new infrastructure facilities and buildings , present us with the vision of a higher resources consumption, specially in the form of more durable concrete such as High Performance Concrete (HPC) . Moreover , the growth of the world pollution by plastic waste has been tremendous. The aim of this research is to investigate the change in mechanical properties of HPC with added waste plastics in concrete. For this purpose 2.5%, 5% and 7.5% in volume of natural fine aggregate in the HPC mixes were replaced by an equal volume of Polyethylene Terephthalate (PET) waste , got by shredded PET bottles. The mechanical properties (compressive, splitting tensile, and flexural strength) evaluated at the ages of (7 ,28, 56 and 91) days while the static modulus of elasticity tested at (28 and 91) days . The results indicated that HPC containing PET-aggregate presented lower compressive strength and static elasticity . The splitting strength displayed an arising trend at the initial stages, however, they have a tendency to decrease after a while. On the other hand, flexural strength results gave better modulus of rapture at all ages of curing , as compared with reference concrete specimens.

Key words: High Performance Concrete, mechanical properties, Polyethylene Terephthalate (PET), PET-aggregate .

الخواص الميكانيكية للخرسانة عالية الاداء والمحتوية على المخلفات البلاستيكية كركام

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الخلاصة

ان تزايد استهلاك المصادر الطبيعية نتيجة نمو سكان العالم وتنامي الطلب على المباني الجديدة ومرافق البنية التحتية ، وخاصة المنشآت التي تستخدم فيها الخرسانة عالية الأداء لأغراض الديمومة . يضاف الى هذا ، ان نمو التلوث بالفضلات البلاستيكية في العالم بات نموا هائلا .ان الهدف من هذا البحث هو دراسة التغيير في الخواص الميكانيكية للخرسانة عالية الاداء والمضاف اليها مخلفات المواد البلاستيكية . لهذا الغرض تم استبدال (2.5% , 5% و 7.5%) من حجم الركام الناعم بنسب مكافئة من الركام البلاستيكي الذي تم الحصول عليه من مثروم مخلفات القناني البلاستيكية (بولي اثيلين تيريفثاليت) . تم تقييم الخواص الميكانيكية (مقاومة الانضغاط , مقاومة الانشطار ومقاومة الانثناء) بأعمار (56,28,7 و91) يوم في حين تم قياس معامل المرونة بعمر (28 و 91) يوم . أظهرت النتائج إلى انخفاض مقاومة الانضغاط ومعامل المرونة عند زيادة محتوي الركام البلاستيكي في حين كان سلوك الخرسانة عالية الاداء في مقاومة الشد الانشطاري يميل للزيادة عند اضافة مخلفات البلاستيك ثم تنخفض عند زيادة نسبة الاستبدال . من ناحية أخرى، اعطت نتائج مقاومة الانثناء تحسن في معامل الكسر ولكافة نسب الاستبدال مقارنة مع عينات الخرسانة المرجعية غير المحتوية على مثروم الركام البلاستيكي .

الكلمات الرئيسية : الخرسانة عالية الاداء , الخواص الميكانيكية , بولي اثيلين تيريفثاليت , الركام البلاستيكي

1 . INTRODUCTON

Concrete is the most used man-made material in the world since its invention. Worldwide, about three tonnes of concrete are used annually per person. Concrete comprises three major fractions, aggregate: binder and water. The aggregate fraction in concrete is about 75 % of its total volume and therefore it plays a vital role in the overall performance of concrete, **Brito, and Saikia, 2013** . The environmental impact caused by the increase in the extraction of natural resources and higher CO_2 emissions has given rise to the search for more efficient, environmentally-friendly constructions. To address these needs, high Performance Concrete (HPC) , has been employed to increase the durability and economic service life of slender structures, to decrease the specific energy consumption and to reduce the environmental impact of these activities , **Isaia, 2000** . The improvement of mechanical and durability performances of concrete in their service life can indirectly reduce the CO_2 emission by increasing their service life and reducing the requirements of materials for repairing, **Brito, and Saikia, 2013 .**

The modern life style along with the new technologies caused more waste materials productions for which the disposing problem exist. Most of the waste materials are non-disposal and remain for hundreds and thousands of years in the environment, **Rahmani, et al., 2013** .

Since plastic is a non-biodegradable material, land-filling using plastic would mean preserving the harmful material forever. Land-filling of plastic is also dangerous due to its slow degradation rate and bulky nature, **Saikia ,and Brito, 2012** .These non-biodegradable waste materials along with population growth have caused the environmental crisis all around the world, **Rahmani, et al., 2013**.Polyethylene Terephthalate (PET) is one of the most common consumer plastics used and is widely employed as a raw material to realize products such as blow bottles for soft-drink use and to containers for the packaging of food and other consumer goods, **Afroz, et al., 2013**.

Total plastic consumption has been increasing in recent years and so contributing to an ever-growing volume in the plastic waste stream .This is considered a serious environmental threat, especially in Asia , where demand has been growing in China and India . The estimated production of plastic bottles in India alone was about 20,000 million between 2005 and 2006 . Western Europe consumes about 60 million tonnes of plastics a year, resulting in about 23 million tonnes of plastics waste , **Silva, et al., 2013** .

In 2007 it is reported a world’s annual consumption of PET drink covers of approximately 10 million tons, which presents perhaps 250 milliards bottles. This number grows about up to 15% every year , **Afroz, et al., 2013**.

The use of waste materials as aggregate in concrete preparation can consume vast amounts of waste materials. This can solve problems of lack of aggregate on construction sites and reduce environmental problems related to aggregate mining and waste disposal , **Saikia , and Brito, 2014**.

1.1 Objective of the Study

The objective of this study is to offer an attractive low-cost material with consistent properties , and improve the sustainability in concrete industry by using PET waste as an aggregate in HPC , which have benefits such as decreasing the usage of natural resources, the wastes consumption, avoiding the environmental pollution and economizing energy .

2. MATERIALS AND EXPERIMENTAL WORK

2.1 Materials

2.1.1 Cement

Iraqi Ordinary Portland cement manufactured in the north of Iraq with trade mark of (Al-Mass) was used in casting all specimens throughout the experimental work. **Tables (1) and (2)** show the physical properties and chemical analysis respectively. The results indicate that the cement confirms to the Iraqi Specifications **I.Q.S. 5/1984**.

2.1.2 Fine aggregate

Natural sand supplied from (Al-Ukhaydir) area was used for preparing mixes , with maximum aggregate size of 4.75mm. The sieve analysis and physical properties of this aggregate are shown in **Table (3)**. It conforms to the Iraqi Specifications **I.Q.S. No.45/1984** Zone 2.

2.1.3 Coarse aggregate

Crushed gravel supplied from (Al-Nibaee) region in Baghdad City was used for preparing mixes. It has nominal maximum aggregate size 14mm . The sieve analysis and physical properties of this aggregate are shown in **Table (4)** . It conforms to the Iraqis specifications **I.Q.S. No.45/1984**.

2.1.4 Water

The water used for both mixing and curing was potable water from the water-supply network system (tap water) .

2.1.5 Silica fume

Silica fume of Jordanian origin densified type was used throughout this work as a partial replacement of cement . **Tables (5) and (6)** show the physical properties and chemical analysis of silica fume respectively. The results indicate that the properties of silica fume used are comply with **ASTM C1240-05** standard specification.

2.1.6 Superplasticizer

A high range water reducing admixture (superplasticizer) commercially known as Hyperplast PC260 , which complies with **ASTM C494-10 Type F**, was used in this research .

2.1.7 Waste plastic (PET-aggregate)

2.1.7.1 Preparation of plastic PET- aggregate

In this study, PET particles as shown in **Plate (1)** are provided by grinding waste PET bottles and used as fine aggregates in concrete. These PET particles were produced as shown in the following steps:

- Collecting the PET bottles needed for research from disposal area .
- Removing the cover and trade label .
- Washing the bottles and spreading them to dry out .
- Shredding and grinding the bottles to smaller size as that of sand by plastic granulator machine (blade mill) as shown in **Plate (2)** , used for plastic manufacturing plant located in Hit city west of Iraq .

- Then ,the obtained particles were separated ,through sieves and subsequently reassembled according to the sieve size (10 mm) ; the particles passed this sieve were used as fine aggregate , while the coarser one were re-grinded again .

2.1.7.2 Physical and mechanical properties of PET-aggregate

After production of PET-aggregate , it was analyzed in terms of some physical properties such as density and sieve analysis. **Table (7)** and **Table (8)** present the sieve analysis, measured physical and mechanical properties of PET particles , respectively . It can noted from **Table (7)** the sieve analysis of PET-aggregate do not comply with natural sand grading as shown in **Table (3)** due to character of plastic texture and shape of plastic pieces which it is usually be flaky , irregular , sharp edge and angular particle , while the natural fine aggregate is usually be spherical and granulated particles . Moreover it is important to focusing on sustainability of natural sources, negative environmental impact of plastic waste and reduce the coast of construction .

2.2 Experimental Work

2.2.1 Mix design and proportions of HPC

The mix design was made according to the American method (**ACI 211.4R-08**). The reference concrete mixture was designed to obtain the required compressive strength of cube equals to (60 MPa) at 28 day. The cementitious content (cement + silica fume) is (510 kg/m^3) with partial replacement of cement weight by(10%) silica fume , the water to cementitious materials (w/cm) ratio is (0.29) , coarse aggregate is (1160 kg/m^3) and fine aggregate is (660 kg/m^3) , the dosage of superplasticizer which was (0.8 L/100Kg of cementitious materials) in order to have a required slump (175mm) for reference mix only . Finally , the waste plastic (PET-aggregate) was used as partial replacement of natural sand in three volume percentage (2.5 , 5 , 7.5)% .The details of the mixes used throughout this study are given in **Table (9)** .

2.2.2 Procedure of concrete mixing

An electrical rotary mixer was used to batch all specimens with 0.1 m3 capacities. The coarse and fine aggregate wetted to be in saturated surface dry (SSD) conditions .The ingredients were initially mixed by hand in dry condition (cement + silica fume) , and (fine aggregate + PET-aggregate). Firstly, the coarse aggregate and some of the mixing water were added to the mixer and mixed thoroughly. While the mixer was running , the fine aggregate and PET- aggregate were added with the remaining water. Without stopping the mixer the cementitious materials (cement + silica fume) were added and the solution of (water + SP) was added gradually. The concrete was mixed, after all ingredients were in the mixer, for (3-4) min , followed by a 2 minutes stop, and the mixing was manually continued, especially for the portions not reached by the blades of the mixer. Then the mixer was operated for 2 minute to attain homogeneous, uniform in color and consistency concrete .

2.2.3 Preparation of specimens

The molds were well cleaned and the internal surfaces were oiled to prevent adhesion with concrete after hardening. The molds were filled with concrete in layers of (50) mm depth , and each layer was compacted by a vibrating table for a sufficient period to remove any entrapped air as possible. After completing consolidation, the surfaces of the specimens have been leveled by hand trawling. The specimens are covered with Nylon sheets to prevent evaporation of mixing water from concrete, and they have been left about 24hours in the laboratory. After remolding the specimens curing process was done by completely immersion the specimens in water storage tank until the time of testing.

2.3 Testing Hardened Concrete

2.3.1 Compressive strength test

The compressive strength test was determined according to (**B.S.1881: part 116)**, using 100 mm cubes. The compressive strength cubes were tested using a standard testing machine (TINIUS OLSEN). The average compressive strength value of three cubes was recorded for each testing age (7, 28 , 56 and 91 days).

2.3.2 Splitting tensile strength

Splitting tensile strength was conducted on cylinders of (100mm diameter and 200mm height according to **ASTM C496-04** . The average of three cylinders was recorded for each testing age (7, 28 , 56 and 91) days respectively for splitting tensile strength.

2.3.3 Flexural strength (modulus of rapture)

Flexural strength of concrete was measured on (100×100×400 mm) prism specimens in conformity with **ASTM C293-10**, at ages of (7 , 28 ,56 and 91 days) . The prisms were subjected to center-point loading using the testing machine (SANS Testing Machine), and the average value of three specimens in each mix was taken .

2.3.4 Static modulus of elasticity

The static modulus of elasticity was performed according to the **ASTM C469-02** , The test was carried out at age of 28, and 91 days using cylinders of (150×300) mm , and the cylinder specimens were grinding top surface to be smooth and level. The average value of three cylinders was calculated at each result.

3. RESULTS AND DISCUSSTION

3.1 Compressive Strength

The effect of PET-aggregate content as partial replacement of sand on the compressive strength in comparison to concrete without plastic aggregate illustrated in **Fig.(1)** , the results indicate that the compressive strength decreases with the increase of PET-aggregate content . This trend can be attributed to the reduction in adhesive strength between the surface of the PET- aggregate and the cement paste. Another factor is the mismatch of particle size and shape between natural and plastic waste aggregates, , **Saikia , and Brito, 2014**. Additionally, PET-aggregate is considered to be a hydrophobic material, so this property may restrict the water movement necessary for cement hydration from entering through the structure of the concrete specimens during the curing period, **Ismail, and AL-Hashmi, 2008**.

On the other hand , It is observed from **Table (10)** and **Fig.(2)** , that the all specimens exhibit an increase in compressive strength with the progress of age. This increase in compressive strength is due to the continuity of cement hydration process which forms a new hydration product within the concrete matrix .

3.2 Static Modulus of Elasticity

The **Fig.(3)** indicated that the value of modulus of elasticity decreased with the increase in plastic aggregate content , and the minimum value was (40.53 , 42.16 GPa) for mix(M7.5) at 28 and 91 days respectively. The values of modulus of elasticity for all HPC mixes shown in **Table (11)** . The reduction in modulus of elasticity can be attributed to the small modulus of elasticity of PET particles; the poor bond between the matrix and plastic aggregates can also contribute to this drop and can be nominated as another reason for this phenomenon, **Rahmani, et al., 2013** .

3.3 Splitting Tensile Strength

The results of splitting tensile strength for various types of HPC specimens at age (7, 28, 56 and 91) days are presented in **Table (12)** . The relationship between splitting tensile strength and various ratios of waste plastic aggregate is shown in **Fig.(4)** . Generally while the rate of sand replacement with PET-aggregate particles increases, the splitting strength have an increasing tendency at first, but it declines after a while . As shown in **Fig.(4)** , the 2.5% replacement of sand volume with PET particles, leads to increases in splitting strength with compared to (M0), while the substitution of (5% and 7.5%) of the sand volume with PET particles caused sharply reduction in splitting tensile strength. In fact , for (M2.5) with low percentages of PET-aggregate content, when the load reaches to its maximum the probability of inter locking between the PET-aggregate on the fractured surfaces increases due to the special shape of the PET particles and their flexibility **.** But when the PET-aggregate percentage increases, because of the weak cohesion between the texture and the PET particles, the smooth surface of the plastic particles and the fact that the strength of the PET-aggregate is lower than that of the natural aggregate , cause a weaker bonding between these particles and the cement paste. As a result, the splitting tensile strength decreases gradually, **(Yadav,2008. Rahmani, et al., 2013 . Brito, and Saikia, 2013 . Saikia , and Brito, 2014.)**

3.4 Flexural Tensile strength

The results of the flexural strength tests for the all HPC mixtures M0 ,M2.5, M5, and M7.5 are illustrated in **Fig.(5)**. As shown in **Fig.(5)** and **Table (13)** , the maximum values of flexural strength was for mix (M2.5), then the strength of flexural trend to drops for mixes (M5 and M7.5) , but still in values higher than control HPC (M0) . This behavior is mainly attributed to the fibro-form, flaky shape and particles size of PET-aggregate , which acts as a fibers role in concrete by the increase in crack resistance of the composite and ability of fibers to resist forces after the concrete matrix has cracked. Furthermore , The plastic PET-aggregates can delay crack initiation and prolong the crack propagation interval thereby increasing structural strength, **Brito, and Saikia, 2013** .

4 . CONCLUSIONS

The main conclusions that can be drawn from this study are:

- The compressive strength values of all waste plastic HPC mixtures tend to decrease below the values for the reference concrete mixtures with increasing the PET-aggregate ratio at all curing ages. The percentage of decreasing in compressive strength for plastic

HPC were (12.49, 17.49 and 27.02) % for M2.5 , M5 and M7.5 respectively compared with M0 at 28 days .

- Regardless of the percentage content of PET-aggregate and curing time, the modulus of elasticity of HPC containing PET-aggregate are lower than those of the reference concrete. This property decrease as the content of PET-aggregate increases. The minimum values were (40.53 , 42.16 GPa) for mix (M7.5) at 28 and 91 days , respectively.
- The HPC specimens containing various amounts of PET particles , exhibited different behaviors in splitting tensile strength. So that 2.5% replacement of fine aggregates with PET particles yielded the optimum splitting tensile strength (4.01 MPa) at 28 days . On the other hand, with further increase of PET-aggregate contents, the splitting tensile strengths were decreased by (11.6 and 13.17)% for M5 and M7.5 at 28 days respectively.
- HPC containing PET-aggregate gives better modulus of rapture at all ages of curing , as compared with reference concrete specimens. The maximum increase was (20.85)% for M2.5 at 28 days with respect to M0 , while the flexural strength for mixes (M5 and M7.5) decrease below M2.5 , but were still higher than (M0) by (11.36 and 10.42) % .

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List of Abbreviations

M0	High performance concrete content (0)% PET-aggregate replacement of sand by volume
M2.5	High performance concrete content (2.5)% PET-aggregate replacement of sand by volume
M5	High performance concrete content (5)% PET-aggregate replacement of sand by volume
M7.5	High performance concrete content (7.5)% PET-aggregate replacement of sand by volume

Table 1. Physical properties of cement used throughout this work.

Physical properties	Test result	Limits of Iraqi spec. No.5/1984
Specific surface area, Blaine Method, (m^2/kg).	300	> 230
Setting time : -Initial setting (hrs: min) -Final setting (hrs: min)	 1:40 4:00	 ≥ 45 min ≤ 10 hrs
Compressive strength of mortar (MPa): 3-days 7-days	 21 27	 ≥ 15 ≥ 23
Soundness % (Autoclave)	0.02	≤ 0.8

Table 2. Chemical composition and main compounds of ordinary portland cement.

Oxide composition	Abbreviation	by weight%	Limits of Iraqi spec. No.5/1984
Lime	CaO	61	-
Silica	SiO_2	19.84	-
Alumina	Al_2O_3	5.28	-
Iron oxide	Fe_2O_3	4.2	-
Magnesia	MgO	2.49	≤ 5%
Sulphate	SO_3	2.48	≤ 2.8% , when C_3A more than 5%
Loss on Ignition	L.O.I.	3.8	≤ 4%
Lime saturation Factor	L.S.F.	0.92	0.66-1.02
Insoluble residue	I.R.	1.13	≤ 1.5% **
Main compounds (Bogues eq.)		**by weight of cement%**	
Tricalcium silicate (C_3S)		48.9	
Dicalcium silicate (C_2S)		20.26	
Tricalcium aluminate (C_3A)		6.89	
Tetracalcium aluminoferrite (C_4AF)		12.77	

Table 3. Grading and physical properties of fine aggregate.

Sieve size (mm)	Passing%	Limits of Iraqi spec. No.45/1984/Zone 2
10	100	100
4.75	94	90-100
2.36	79.4	75-100
1.18	65.4	55-90
0.6	51.5	35-59
0.3	19	8-30
0.15	3.7	0-10
Physical properties		**Limits of Iraqi spec. No.45/1984**
Fineness modulus : 2.87		-
Specific gravity: 2.68		-
Absorption : 1.66%		-
Dry rodded density: 1800 kg/m³		-
Sulfate Content		**Limits of Iraqi spec. No.45/1984**
SO_3: 0.2 %		≤ 0.5%

Table 4. Grading and physical properties of coarse aggregate.

Sieve size (mm)	Passing%	Limits of Iraqi spec. No.45/1984 Nominal size (5-14)mm
20	100	100
14	99.9	90-100
10	72	50-85
5	8.5	0-10
Physical properties		**Limits of Iraqi spec. No.45/1984**
Specific gravity: 2.76		-
Absorption : 0.23 %		-
Dry rodded density: 1650 kg/m³		-
Sulfate content		**Limits of Iraqi spec. No.45/1984**
SO3: 0.02 %		≤ 0.1%

Table 5. physical properties of SF.

Physical properties	SF Results	ASTM C1240-05 requirements
Percent retained on 45µm (No. 325) sieve, max, %	7	**≤ 10**
Strength Activity Index with Portland cement at 7 days, min % of control	116	**≥ 105**
Specific surface area (m^2/g)	20	**≥ 15**
Bulk density (kg/m^3)	480	
Moisture content	0.74	≤ 3 %
Physical form and Color	grey to dark grey powder	

Table 6. Chemical analysis of SF.

Oxide Composition	Oxide content %	ASTM C1240-05 Requirements
SiO_2	91.44	Min. 85.0%
Al_2O_3	0.05	-
Fe_2O_3	0.03	-
MgO	0.24	-
CaO	1.04	-
SO_3	0.11	-
L.O.I	4.12	Max. 6.0%

Table 7. Sieve analysis of PET-aggregate.

Sieve size (mm)	Passing%
10	100
4.75	98
2.36	35
1.18	4.2
0.6	1
0.3	0.7
0.15	0.4

Table 8. PET –aggregate particles specification.

Physical properties	Results
Bulk Density (ASTM C29 -09 / Dry Rodded)	447 kg/m^3
Specific gravity	1.285
Water Absorption (24 hr)	0.00%
Thickness	(1 – 0.14) mm
Shape of particles	Flaky and fiberform particles and some pellets pieces with max. size 4.75 mm
Color	crystalline white to blue sky

Table 9. HPC mix proportions used through this work

Items	M0	M2.5	M5	M7.5
Cement kg/m^3	459	459	459	459
Silica fume kg/m^3	51	51	51	51
Water l/m^3	148	148	148	148
SP Liters/100 kg of cementitious materials	0.8	0.8	0.8	0.8
w/cm	0.29	0.29	0.29	0.29
Coarse Aggregate kg/m^3	1160	1160	1160	1160
Fine Aggregate kg/m^3	660	642.8	626.3	609.8
PET-aggregate kg/m^3	0	7.9	15.8	23.7
Average compressive strength at 28 days (MPa)	69	60.38	56.93	50.35

Table 10. Compressive Strength Test Results for all HPC mixes

Mix Symbol	PET-aggregate(%)	Compressive Strength MPa			
		7 days	28 days	56 days	91 days
M 0	0	59.73	69	71.15	74.17
M 2.5	2.5	53.9	60.38	64.1	66.8
M 5	5	49.6	56.93	58.22	62.1
M 7.5	7.5	45.44	50.35	56.1	61.23

Table 11. Static modulus of elasticity for all HPC mixes

Mix Symbol	PET-aggregate(%)	Static Modulus of Elasticity (GPa)	
		28 days	91 days
M 0	0	43.08	46.94
M 2.5	2.5	40.81	43.72
M 5	5	40.77	43.45
M 7.5	7.5	40.53	42.16

Table 12. Splitting tensile strength test results for all HPC mixes

Mix Symbol	PET-aggregate(%)	Splitting Tensile Strength (MPa)			
		7 days	28 days	56 days	91 days
M 0	0	3.74	3.87	3.95	4.08
M 2.5	2.5	3.83	4.01	4.12	4.2
M 5	5	3.23	3.42	3.78	3.95
M 7.5	7.5	3.18	3.36	3.52	3.64

Table 13. Flexural tensile strength test results for all HPC mixes

Mix Symbol	PET-aggregate(%)	Flexural Tensile Strength (MPa)			
		7 days	28 days	56 days	91 days
M 0	0	8.62	9.11	10.48	11.38
M 2.5	2.5	10.64	11.51	11.87	12.04
M 5	5	10.17	10.31	10.89	11.65
M 7.5	7.5	10.03	10.17	10.62	11.57

Plate 1. Sample of (PET- aggregate).

Plate 2. Plastic granulator machine.

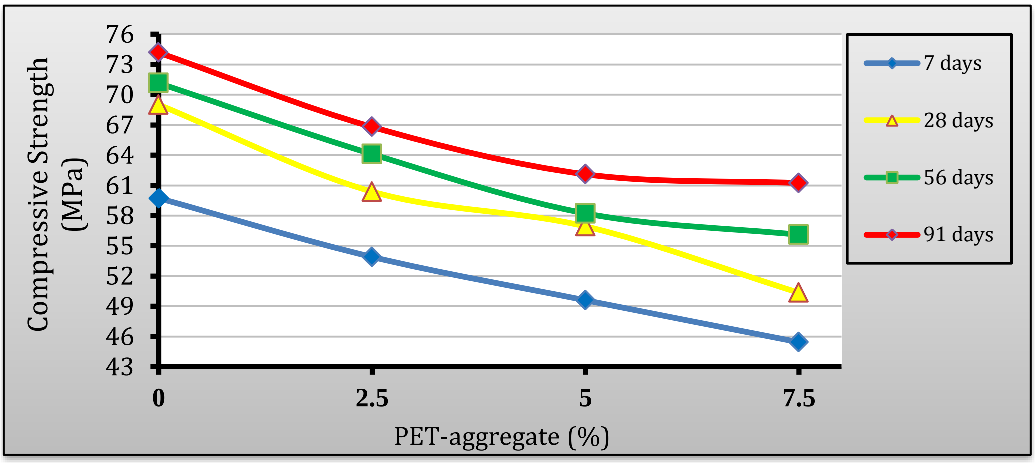

Figure 1. The effect of PET-aggregate content on compressive strength of HPC at different curing ages.

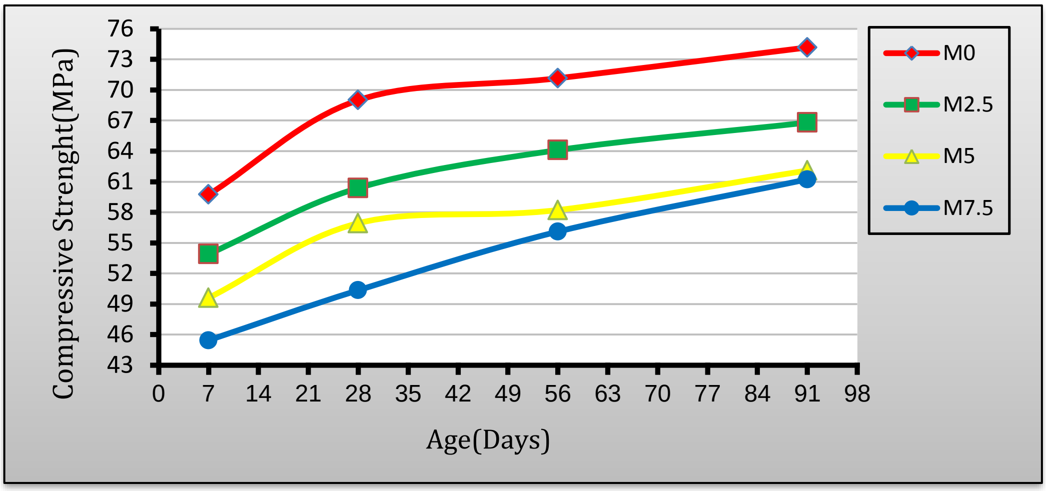

Figure2.: Compressive strength development at different curing ages for all types of HPC.

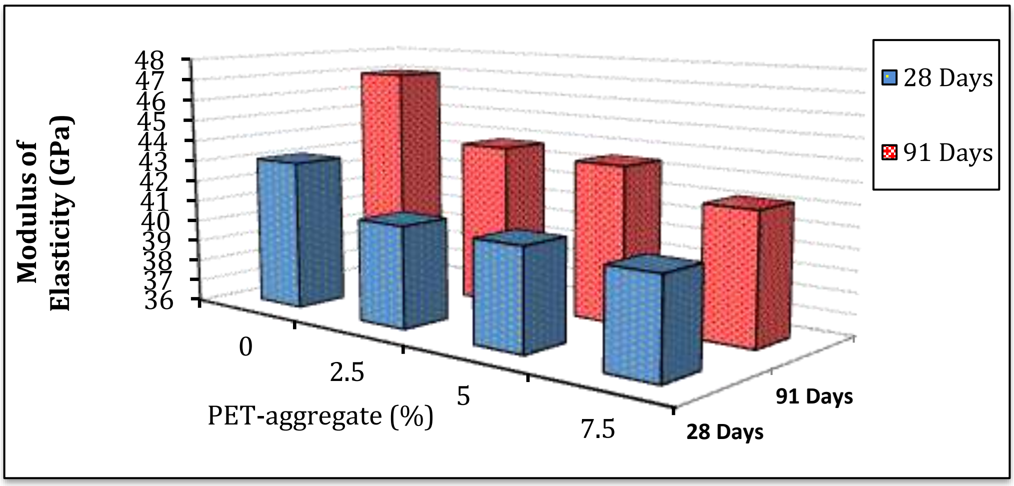

Figure 3. Effect of PET-aggregate on static modulus of elasticity at different curing ages.

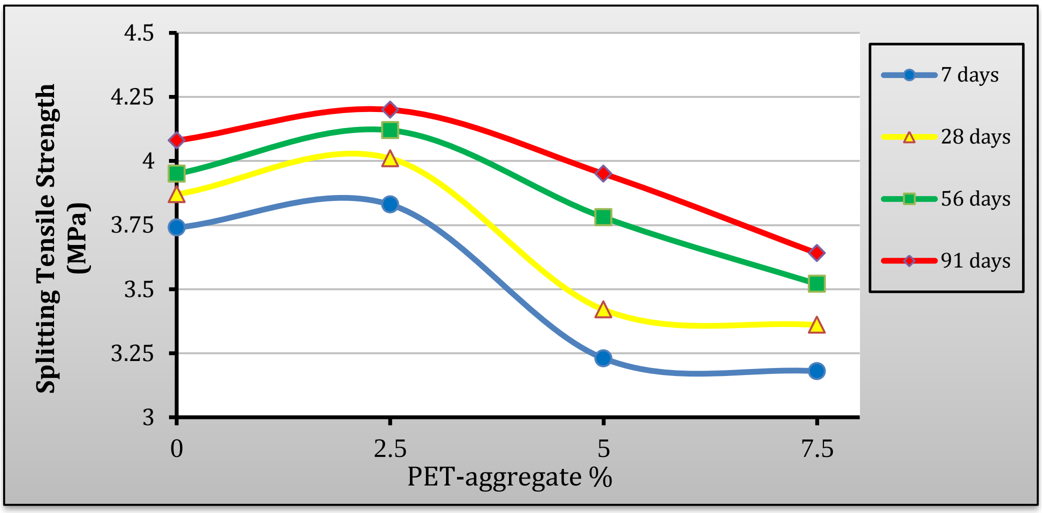

Figure 4. Relationship between splitting tensile strength and PET-aggregate content at different curing ages.

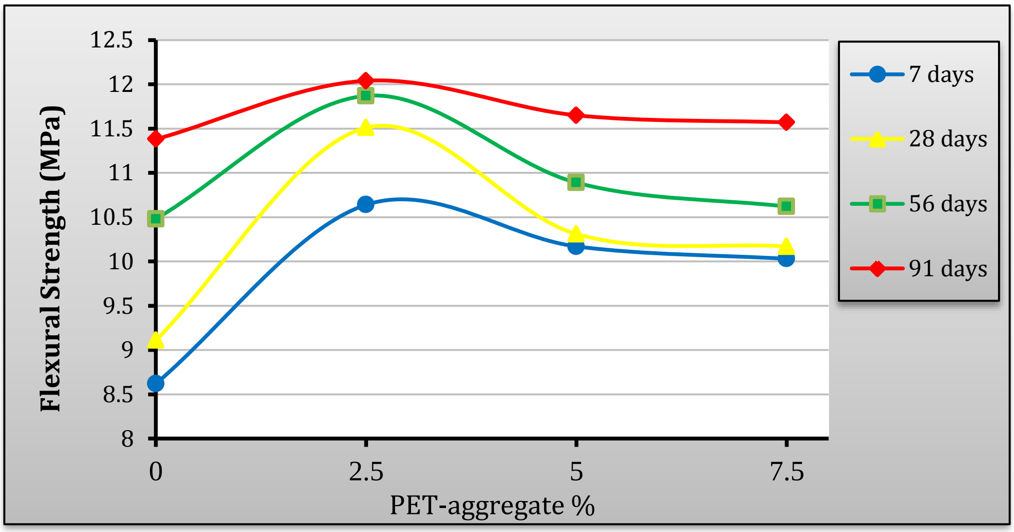

Figure 5. Relationship between flexural strength and PET-aggregate content at different curing ages.