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Strength Properties of Polymer Reactive Powder Concrete with Waste Materials

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Abstract

Reactive powder concrete, or RPC, outperforms conventional or even high-performance concrete in terms of ultra-high strength and better durability. Several buildings were destroyed in Iraq, and recycling the garbage from these buildings can significantly help reduce waste and environmental pollution as well as serve as a source of aggregate for use in new construction. Reusing garbage and using sustainable building materials are now crucial environmental challenges, so this study aimed to replace the natural fine aggregate, NFA, used in preparations of polymer reactive powder concreter, "PRPC" with recycled aggregates, or RA, from crushed old concrete, COC, in order to make PRPC production more environmentally and sustainably friendly. In this study, RPC is modified by adding styrene butadiene rubber (SBR), a polymer, to the original mixture at a ratio of 13% by weight of cement. This study sought to determine the effect of using COC as recycled fine aggregate (RFA) on the compressive, splitting, and flexural strengths of PRPC. The main objective of this investigation is to study the effect of oil (water, new oil, and waste engine oil) on the compressive and tensile strengths of PRPC with COC and to compare the behavior with that of a control mix (PRPC with NFA). The mixtures were prepared using six different percentages of RFA, replacing 0, 20, 40, 60, 80, and 100% NfA. After 28 days, the six mixes were divided into three groups. The first was still being cured in water, W; the second in waste engine oil, WEO; and the third in kerosene oil, KO. The results showed that using COC as RFA in PRPC was viable, and according to this investigation, the mix with 40% COC replacement with NFA provides the highest values of compressive strength, tensile strength, and flexural strength before and after exposure to liquids (water, new oil, and waste engine oil).

Keywords: Used Engine Oil; Modified Reactive Powder Concrete; Recycle Fine Aggregates; Garbage; Crushed Concrete; Kerosene.

1. Introduction

Concrete is a key component of many different building types and is widely used in construction and engineering [1]. One of concrete's most crucial characteristics and a key determinant of its success in the future is its durability. Conventional concrete in direct contact with oil products (OPs) has a variety of problems, including a loss of strength, a rise in permeability with aging, cracks, and corrosion of the reinforcement steel bars [2]. Reactive powder concrete (RPC) is a type of concrete that has gained popularity over the past few decades and is marked by extraordinarily high mechanical properties and excellent durability [3, 4]. Ordinary reactive powder concrete (ORPC) is an advanced mechanical material with ultra-high strength and performance. In the early 1990s, scientists at the Bouygues laboratory in France developed RPC for the first time. The idea was first proposed by Richard & Cheyrezy [5]. Portland cement, sand, and silica fume are very fine powders that are used to create reactive, powdered concrete. Superplasticizers are always used to lower the water-to-cement ratio (w/c) to less than 0.2 and increase the workability of the RPC, and steel fibers are occasionally used [6, 7].

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When stresses are applied, the numerous microcracks in traditional concrete soon form. This material's low tensile and flexural strengths are caused by these fissures. As a result, durability requires the creation of concrete with high strength and low permeability [1, 8]. An innovative class of polymer-reactive powder concrete, or PRPC, is being developed in an effort to construct such ORPC. A new type of concrete known as "polymer concrete" has been created as a result of ongoing study by concrete technologists to comprehend, enhance, and develop the qualities of concrete [8].

Polymer has been increasingly used as a construction material in recent years due to its increased features of high strength, extensibility, waterproofness, adhesion, and durability [9]. According to ACI 548.1R-86, polymer Portland cement concrete (PPCC) mixtures are normal Portland cement concrete blends that have an emulsified or water-soluble polymer added [10]. Typically, latex materials like polyvinyl esters or styrene butadiene rubber (SBR) were used to prepare PPCC [11]. Many polymer-concrete materials have the following characteristics: high strengths, good cohesiveness, appropriate durability, and resistance to water, acid, and oils, among other things. In order to repair damaged concrete constructions, such as roads, bridges, railroads, river and sea banks, pavement, and various other cement concrete structures, and these materials can be employed. Moreover, this material can be employed as a corrosion-resistant material in harsh environments [12, 13]. SBR emulsions are increasingly being used in concrete during construction and maintenance projects because of the benefits they provide in terms of flexure strength, adhesion, and impermeability [14]. The permeability of concrete, which affects how quickly aggressive liquids may be transferred into or through the materials, governs how durable concrete is against many types of environmental attack. So, when SBR is combined with pozzolanic elements, the concrete's microstructure is altered and its permeability is decreased, which minimizes or eliminates liquid penetration into the concrete [15].

Due to its distinct economic and operational qualities, oil has emerged as one of the most important energy resources since the turn of the previous century. Concrete or steel tanks can be used to store liquid petroleum products above or below ground [16]. When designing industrial and liquid storage concrete structures, such as oil tanks, the permeability of the concrete becomes a top concern. For this reason, it is essential to produce concrete with outstanding mechanical qualities and high endurance for structures used for oil storage. Modifying concrete using a polymer enables the creation of such concrete. Moreover, the addition of polymers to ORPC will provide ultra-high-strength concrete with longevity that is appropriate for vital structures [17].

Buildings made of concrete are frequently torn down over time to make way for newer construction or, in some cases, because of extreme damage from natural disasters. The usual method for handling demolition garbage is to dispose of it in landfills, which is not a sustainable solution. Concrete recycling has grown in acceptance and popularity as a substitute for other aggregate sources in recent years. Recycling demolition debris aims to decrease reliance on imported raw materials, which will lower CO_2 emissions from both material extraction and transportation [18, 19].

Using recycled aggregate (RA) is unquestionably a vital step toward the management of building waste and sustainable development in the concrete industry. Natural aggregate NA can be replaced with RA, which benefits environmental preservation [18]. The utilization of RA from crushed old concrete generally reduces the environmental effects of construction and demolition waste, decreasing the need for rock mining and landfilling, and, in practical terms, this method offers a new raw material for producing concrete [19, 20]. Reduced strength due to a decrease in the bond strength of the interfacial transition zone (ITZ) has been identified as the main difference between natural and recycled aggregate [21, 22].

Due to the evident economic and environmental advantages, researchers have recently shown a greater interest in the reuse of recycled concrete aggregate produced by building demolitions [23–26]. For instance, Dabiri et al. [25] evaluated the impact of replacing natural fine and coarse aggregate on the compressive strengths of concrete. The results showed that adding recycled aggregate could only slightly lower compressive strength, and concrete containing recycled fine aggregate loses strength over time less than concrete containing coarse aggregate or both fine and coarse aggregate. In a study by Onyelowe et al. [24], the compressive strength of concrete created from recycled aggregate was investigated, and a clever prediction was made using a novel artificial neural network (ANN). This ANN makes use of a sigmoid function and allows the suggestion of closed-form equations. In general, the closed-form equation has demonstrated its potential to be used in recycled aggregate concrete design and construction activities for an evaluation of the sustainable performance of recycled aggregate concrete, performing at an average accuracy of 97.5% with an internal consistency of 99%.

The purpose of Naouaoui & Cherradi's [26] article was to characterize recycled aggregate concrete and compare it to various international studies. Compressive strength was the primary mechanical property examined in the study. The study's methodology involved breaking down concrete from demolished buildings to create aggregates that are then utilized to create experimental samples of RAC with varying percentages of natural aggregates (NA) replaced by recycled aggregates. Test results demonstrate that recycled aggregates (RA) cannot replace natural aggregates at high replacement levels since the compression is significantly reduced.

Mi et al. [27] investigated the effects of the slump and compressive strength of recycled aggregate concrete on the compressive strength ratio between original concrete and recycled aggregate concrete. According to the findings, modifying the compressive strength ratio can produce a range of slump and compressive strength while also minimizing mortar inhomogeneities. Therefore, by modifying the compressive strength ratio in accordance with the needs of various projects, construction companies can employ more recycled concrete. Additionally, rather than combining waste concretes from various sites and then using them directly in projects, the companies that handle construction debris should classify the waste concretes from different sites.

Naderpour & Mirrashid [28] have undertaken numerous laboratory tests on the behavior and durability of eco-friendly recycled aggregate concrete. The results of 138 eco-friendly concrete samples were used to present a highly effective framework for forecasting the compressive strength of this type of concrete. According to the results of the suggested model, increasing the amount of recycled aggregates in the concrete admixture up to a maximum of 1000 kg/m^3 could increase the compressive strength. The model suggested can be considered a strong strategy for use in future codes due to the increased demand for sustainable development and the usage of eco-friendly concrete in buildings.

There isn't any research that is relevant to the performance of RPC formed from recycled aggregate exposed to waste oil, as most studies on RPC exposed to oil have been on RPC modified by polymer and exposed to new oil. For assessing the impact of waste and new oil on the performance of RPC when exposed to oil products, the same modification described by Al-Attar et al. [29] has been applied in the current work. Additionally, recycled material was employed as fine aggregate rather than normal aggregate, and butadiene styrene rubber was used as an ultra-high-range water reducer.

2. Problem Statement

Nowadays, in Iraq, there is an increase in the use of electrical generators due to the limitations of electrical power outside and at the centers of the cities, and the oils of these engines will cause the deterioration of surrounding concrete as shown in Figure 1.

(a) (b) (c)

Figure 1. (a) Electrical generator. (b) Metal tanks used for oils. (c) The deterioration of concrete by new and waste oil products

Furthermore, it takes a lot of labor to manage the crushed concrete produced by demolitions and crushed buildings, and it takes up a lot of room in landfills. So, concrete manufactured from recycled aggregate helps numerous sustainability programs. However, the use of recycled fine aggregate concrete (RFAC) is still relatively small due to poor development in the area of testing and criteria concerning PRPC or concrete manufactured with RFAC. This highlights the need for additional study and advancements in the area regarding this type of concrete. Therefore, the authors find it significant to study the feasibility of using crushed old concrete (COC) as RFA instead of normal fine aggregate (NFA) for producing PRPC and using waste engine oils (WEO) instead of common oil (Al-Dora kerosine oil). The study is directed at studying the effect of this material on concrete after exposure to it. The current study compares the behavior of PRPC developed with RFAC to that produced with ordinary aggregate in order to determine the influence of oil (kerosene, waste engine oil) on the strength characteristics of this kind of concrete when it will be in contact with oils. A flowchart for the experimental work schedule is shown in Figure 2.

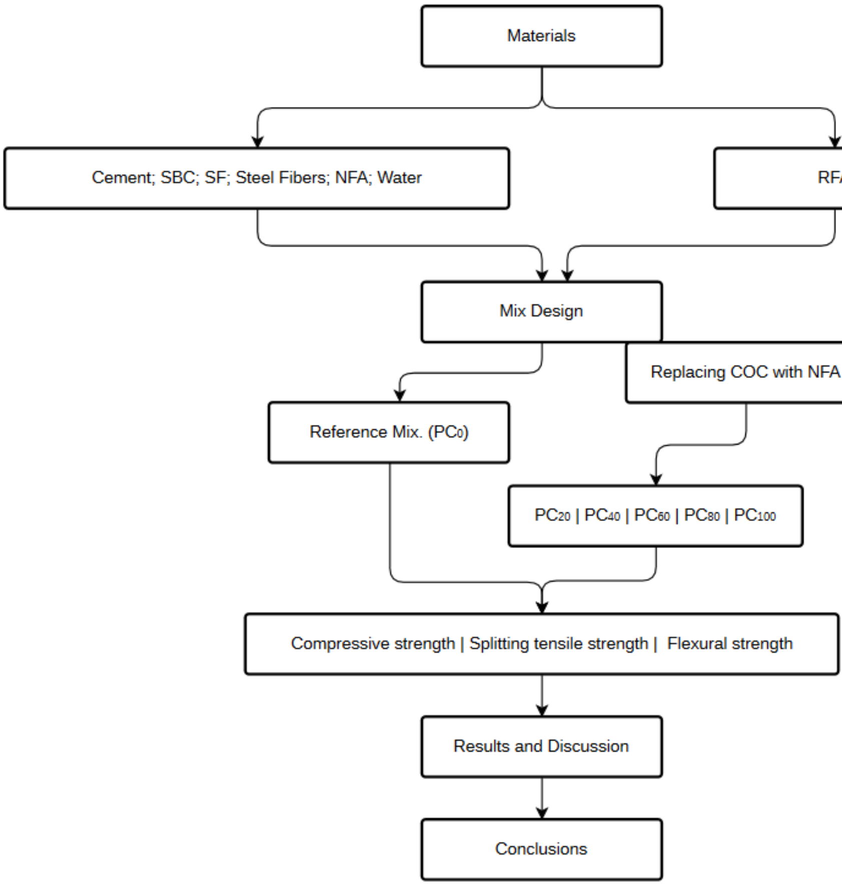


Figure 2. A flowchart for the experimental work

3. Materials and Testing Procedures

3.1. Mix Composition

In this study, Type-I Portland cement with the brand name "MASS", manufactured by Bazain Cement Factory, was used. According to the findings, the adopted PC complied with Iraqi specification No. 5/1984 [30]. Natural sand that had been carried from the Al-Ukhaider area west of Baghdad was used in this experiment. The second grading zone is indicated by the test results, which show that the grading and sulfate content are both in compliance with Iraqi specification No. 45/1984 [31], as shown in Figure 3. Steel fibers (Sf) with dimensions of 30 mm in length, 0.375 mm in diameter, and a tensile strength Ts of 1130 MPa were employed. In order to comply with ASTM C1240-05, a gray-colored densified silica fume (SF) is utilized. The specific density and surface of SF are, respectively, 1780 kg/m^3 and 23800 m^2/kg. In this study, styrene butadiene rubber (SBR) emulsion was employed as a polymer admixture to create RPC with a polymer modification, or PRPC. All types of cement can be used with this polymer. Table 1 lists the SBR characteristics. All mixes were mixed and cured using potable water.

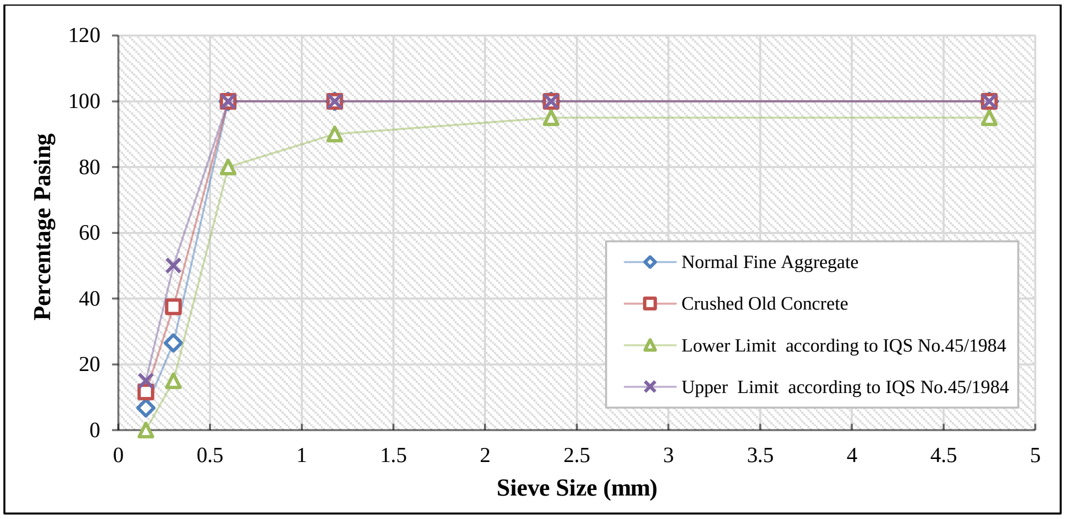


Figure 3. Grading curve of the normal and recycled, fine aggregate

Table 1. Properties of SBR emulsion*

Appearance	Specific Gravity	Ph - Value	Chloride Content	Butadiene	Styrene
White Emulsion	1.03 ± 0.02 @25C^0	9 ± 2	Nil	40 (%By Weight)	60 (%By Weight)

* Properties were obtained from the product data sheet.

3.2. Recycled Aggregate

The recycled aggregate came from old structures that were destroyed in Al-Ramady, west of Baghdad. The building's age is unknown; however, most of the old houses in the area date from approximately 50 years ago. A sample of the crushed old concrete before crushing is shown in Figure 4-a. The old concrete was initially broken by a drill (Figures 4-b and 4-c), then it was reduced to smaller pieces by hand using a sledgehammer, and finally the crushed particles were taken to a mill (Figure 4-d) to make them fine and produce fine recycled concrete aggregate. The fine particles were then sieved using a 600 µm standard sieve to obtain grading similar to normal sand.

(a) (b) (c) (d)

Figure 4. (a) A destroyed old house (b) Crushed concrete (c) A drill that is used to destroy structures (d) A mill is used to change crushed concrete into fine particles

3.3. Oil Products

WEO came from electrical generating plants, and kerosene oil, or KO, was delivered by the Al-Daura Refinery in Baghdad city. Used engine oil, or UEO, was collected from tiny electrical generation stations in and around Al-Ramady city that provided electrical current to homes and markets in this city.

3.4. PRPC Mixtures

Six mixes were examined in order to carry out the objectives of this study, as shown in Table 2. The reference concrete mixture "PC0" was created with a flow table of 150 ± 5 mm and a target compressive strength (Cs) of (140 ± 10 MPa) for 28 days. According to Richard & Cheyrezy [5] and Ali [32], the design was created. Table 2 shows the ideal mixing ratio (reference mix) and different mixtures with recycled aggregate (RA).

Table 2. Composition of original PMRPC and PMRPC with crushed concrete

Mixes Title	PC0	PC20	PC40	PC60	PC80	PC100
Portland Cement (PC) (kg/m^3)	930	930	930	930	930	930
Silica Fume (SF) (kg/m^3)	205	205	205	205	205	205
Normal Fine Sand (NFS) (kg/m^3)	990	792	594	396	198	0
Crushed concrete (CC) (kg/m^3)	0	198	396	594	792	990
Styrene Butadiene (SB)	13% by weight of cement					
Steel Fiber (S_f) (kg/m^3)	2% by volume for all mixes					
Water (W) (kg/m^3)	2016	205	211	215	220	224
% of Replacement	0	20	40	60	80	100
W/C %	0.21	0.22	0.226	0.231	0.236	0.24
Flow (mm)	153	150	151	152	150	148

3.5. Mixing of PRPC

Materials are weighed out and blended in a 0.1 m^3 capacity rotary mixer. The required amount of cement was combined in dry form with the required amount of SF. 15 minutes were spent on this process to make sure the SF powder was evenly distributed among the cement particles. Next, after the components had been mixed for 1.5 minutes to achieve a homogenous mixture, the polymer was added, and the W was added after the polymer had been thoroughly mixed into all of the materials. This process is comparable to Ohama's approach [33].

3.6. Casting and Pressing of Test Specimens

Before use, the molds were lightly coated with mineral oil. The materials were then cast into steel molds, and the specimens were then crushed using a vibrating machine to eliminate as much of the trapped air as possible. This was accomplished within 10 to 15 seconds. The concrete surface was prepped for pressing after casting. In order to compact the specimens, 15 MPa of pressure was applied for one day. The specimens are pressed in order to release some of the mixing water. According to the Al-Wahili [34] approach, the water/binder ratio will be lowered by roughly 4% during the curing of test specimens.

3.7. Curing of Test Specimens

After a preliminary curing at room temperature at "20 ^{0}C" for 24 hours, the specimens were moist cured at "90 ^{0}C" for two days, and then the water curing was conducted at "20 ^{0}C "for up to 28 days, as shown in Figure 5. All specimens were exposed to liquids (W, UEO, and KO) three times: one, three, and six months after the curing period.

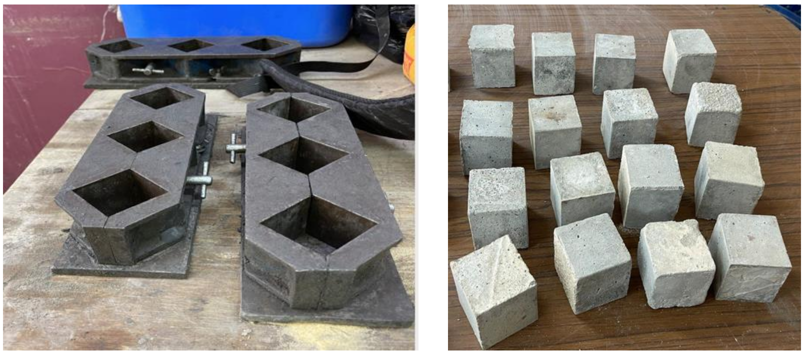
(a) (b) (c)

Figure 5. Curing of polymer reactive powder concrete. (a) Curing of specimens in air. (b) Curing of specimens in water. (c) Curing of specimens in oil

4. Results and Discussion

4.1. Compressive Strength (Cs)

B.S. 1881, Part 116 [35] was used to determine the Cs test. Three cubes on average were taken from the 50 mm test set at each testing age (7, 14, and 28 days), as well as at (30, 90, and 180 days), for various exposure settings as shown in Figure 6. The test results for the original PRPC (PC_0) and the PRPC with RFA (PC_{20}, PC_{40}, PC_{60}, PC_{80}, PC_{100}) subjected to oil products for up to 180 days of exposure for compressive strength are shown in Tables 3 to 5 and Figures 7 to 10.



(a) (b)

Figure 6. (a) Molds of compressive strength. (b) Cubic specimens after casting of PRPC

Table 3. Average compressive strength results (MPa) of the tested specimens that were exposed to water

Mixes title.	Age (days)	PC_0	PC_{20}	PC_{40}	PC_{60}	PC_{80}	PC_{100}
	7	102.3	100.2	98.9	96.6	77.6	71.3
Moist and air curing	14	130.1	130.7	129.5	129.2	105.6	100.3
	28	148.3	148.9	150.6	149.8	146.5	130.3
	30	154.2	153.9	151.8	148.4	140.8	134.5
Exposure liquids (Water)	90	160. 8	161.1	159.3	158.1	145.3	139.2
	180	173.2	173.9	174.1	173.9	159.9	149.3

Table 4. Average compressive strength results (MPa) of the tested specimens before and after exposure to used engine oil

Mixes title.	Age (days)	PC_0	PC_{20}	PC_{40}	PC_{60}	PC_{80}	PC_{100}
	7	102.3	100.2	98.9	96.6	77.6	71.3
Moist and air curing	14	130.1	130.7	129.5	129.2	105.6	100.3
	28	148.3	148.9	150.6	149.8	146.5	130.3
	30	160.8	159.1	156.9	156.6	146.7	140.9
Exposure liquids (Used Engine Oil)	90	165.7	164.9	166.7	164.0	154.9	148.5
	180	178.6	179.0	179.3	179.1	166.7	163.2

Table 5. Average compressive strength results (MPa) of the tested specimens before and after exposure to kerosene

Mixes title.	Age (days)	PC_0	PC_{20}	PC_{40}	PC_{60}	PC_{80}	PC_{100}
	7	102.3	100.2	98.9	96.6	77.6	71.3
Moist and air curing	14	130.1	130.7	129.5	129.2	105.6	100.3
	28	148.3	148.9	150.6	149.8	146.5	130.3
	30	162.7	161.5	158.7	159.3	148.5	142.9
Exposure liquids (Kerosene)	90	167.9	166.3	165.9	165.2	158.8	148.2
	180	180.3	180.9	181.6	181.0	170.6	164.6

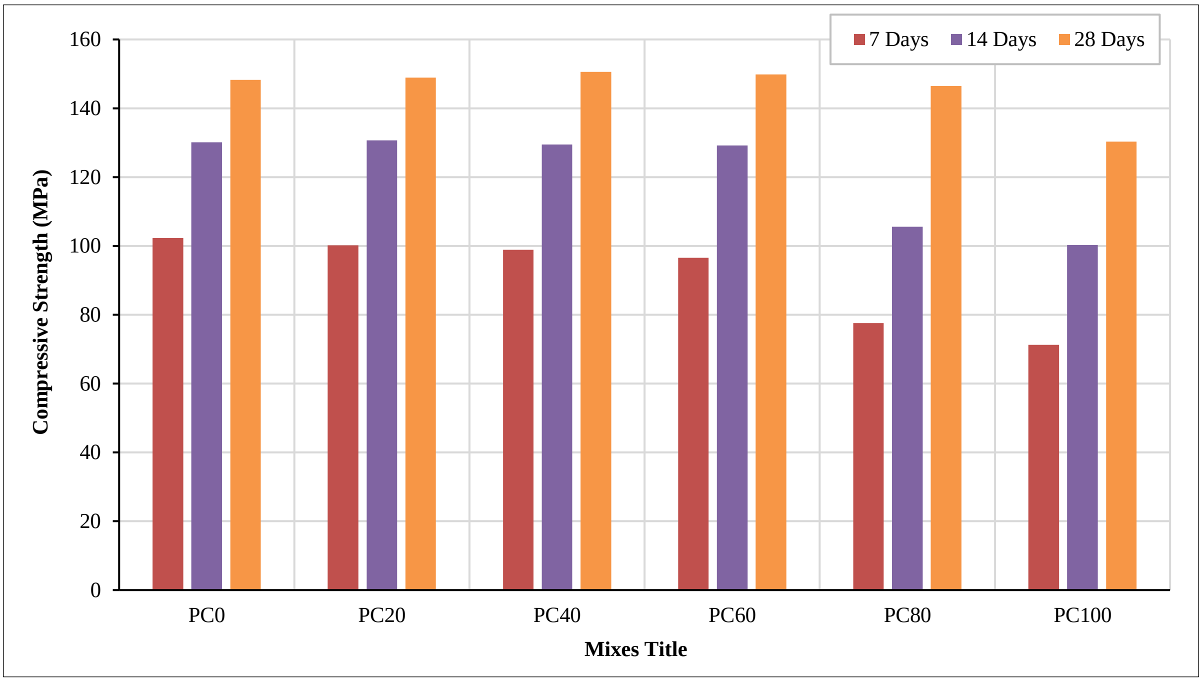


Figure 7. Compressive strength of all mixes at different ages before exposure to oil

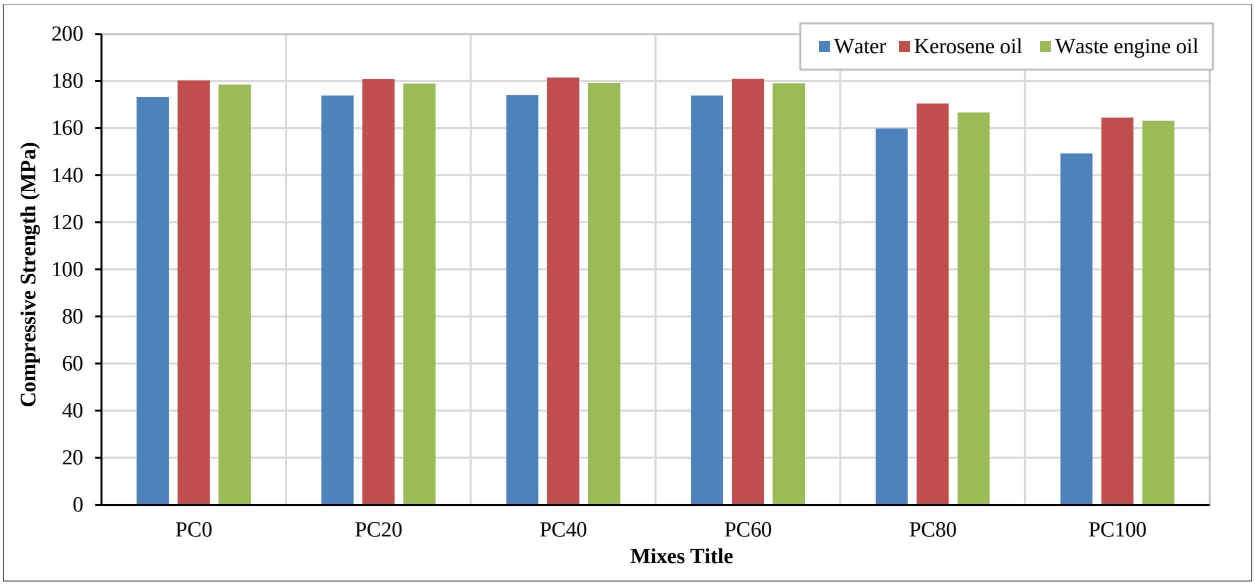


Figure 8. Compressive strength of all mixes after 180 days exposure

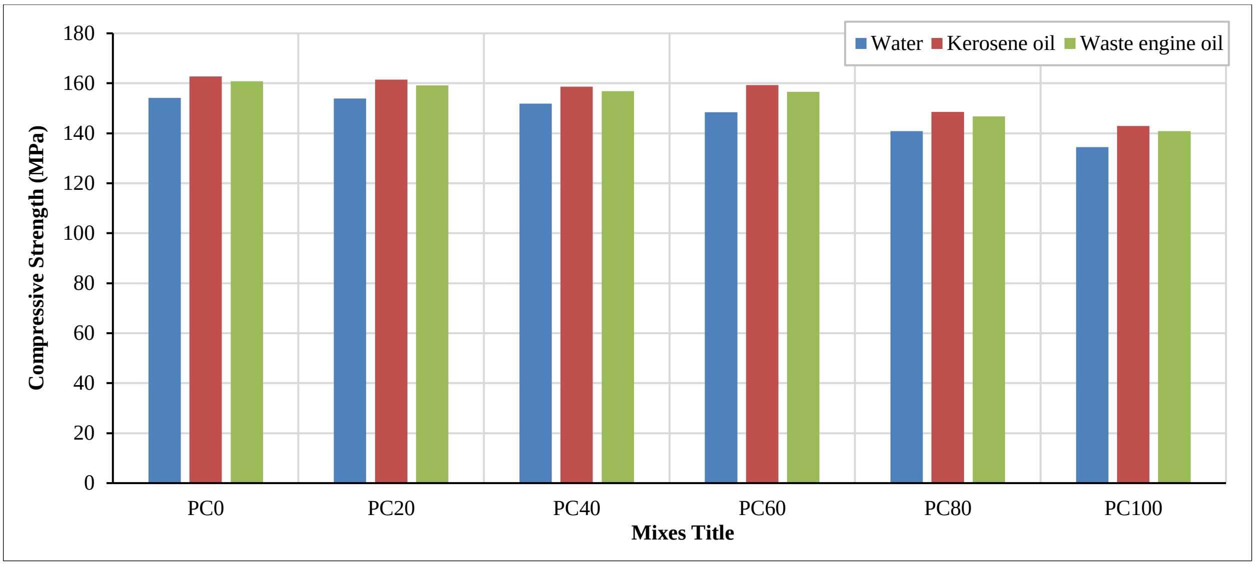


Figure 9. Compressive strength of all mixes after 30 days exposure

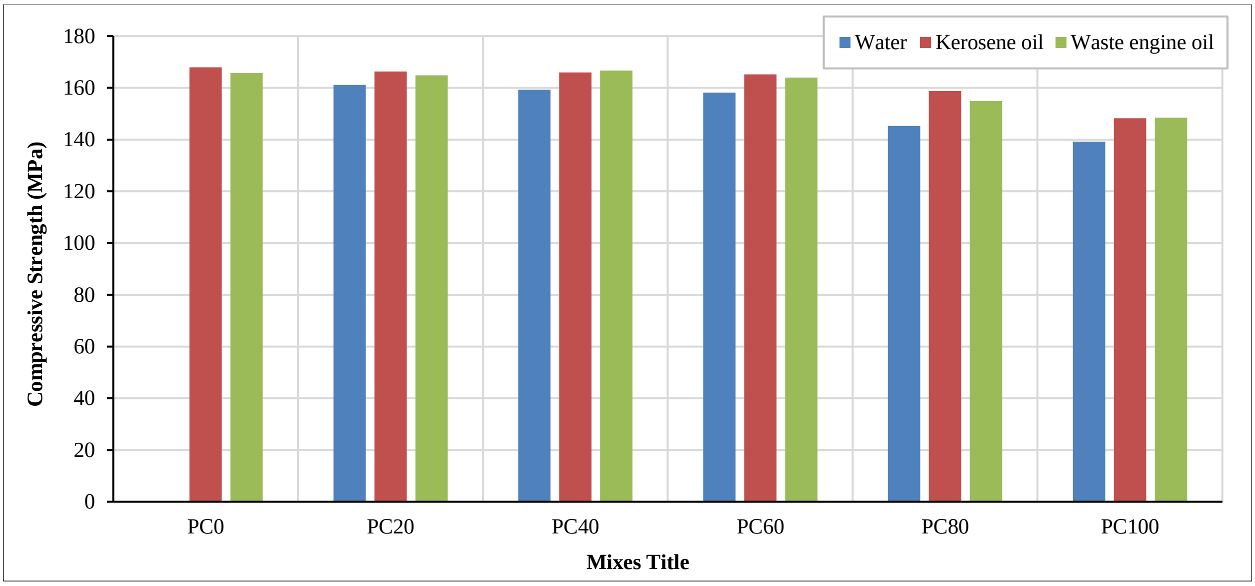


Figure 10. Compressive strength of all mixes after 90 days exposure

The following findings are drawn from the compressive strength results:

1. The Cs of the water-cured specimens continued to rise up to 180 days of age. The constant hydration of cement is the reason for this behavior [36].

2. All the specimens showed a consistent rise in strength with age when stored for two days in W at "90 ^{0}C" after demolding and then in air and moist curing up to the age of the test. There are three possible explanations for this rise in Cs. As SBR emulsion functions as a superplasticizer, SP, first, and PRPC have lower w/c ratios, which offer better strength [33]. The second is that, as a result of the SBR's strong binding properties, the formation of a three-dimensional network of polymer molecules through concrete strengthens the binder system. The final fact is that pores can be partially filled with polymer to reduce porosity and hence increase Cs [32, 37].

3. As seen in the data, (70–75%) of the improvement in compressive strength happened in the first 28 days. This is because:

   - The addition of SBR emulsion, which acts as a SP, is compatible with cement, has the potential to decrease in W use by more than 40%. The most closely-grained preparation is made from fine sand with a grain size of 600 µm. In the process of arranging size between cementitious characteristics and aggregate, they also generate discontinuous preparation, but the improvement was due to the denser microstructure of the cement matrix.

   - Particularly for the heat treated mixtures, the PC hydration process increased during this time. This pattern is consistent with the findings of many researchers [6, 13, 32, 38, 39].

   - Concrete with extremely high compressive strength growth, which was demonstrated to occur more quickly in the first seven days, can be produced by applying sufficient pressure during early setting to remove all available water and air from the fresh mixture. It is evident that pressurization increases component interlocking, resulting in an extremely dense microstructure with fewer capillary pores [32, 36, 39].

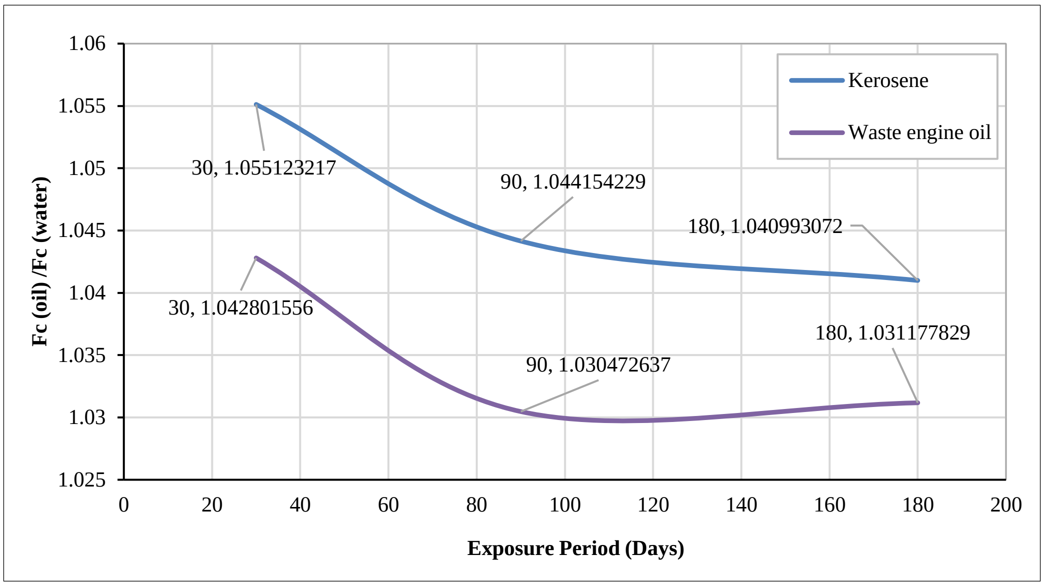
4. As shown in figures 5 to 8, concrete specimens exposed to oil products gradually lose some of their strength. The greatest reduction values for the specimens exposed to oil products were up to 9.8% and 9.2% for the specimens subjected to waste engine oil and kerosene for 180 days, respectively. It is obvious from figure 9 that the original PRPC and PRPC with recycled aggregate are affected very little after exposure to OP_s at the latest ages. The style of curing of these mixes enables them to gain reasonable strength at an early age, as the hydration operation responsible for this strength [32].

5. Original PRPC and PRPC with RFA perform better in terms of higher compressive strengths. The reduction in compressive strength in the mix with 60% crushed old concrete as recycled fine aggregate relative to the original PRPC (reference mix), was negligible because it is very low. These findings corroborated those of earlier studies [1, 3, 38]. Results of this study generally compared favorably with earlier research [1, 6, 26] on RPC or high strength concrete with recycled material

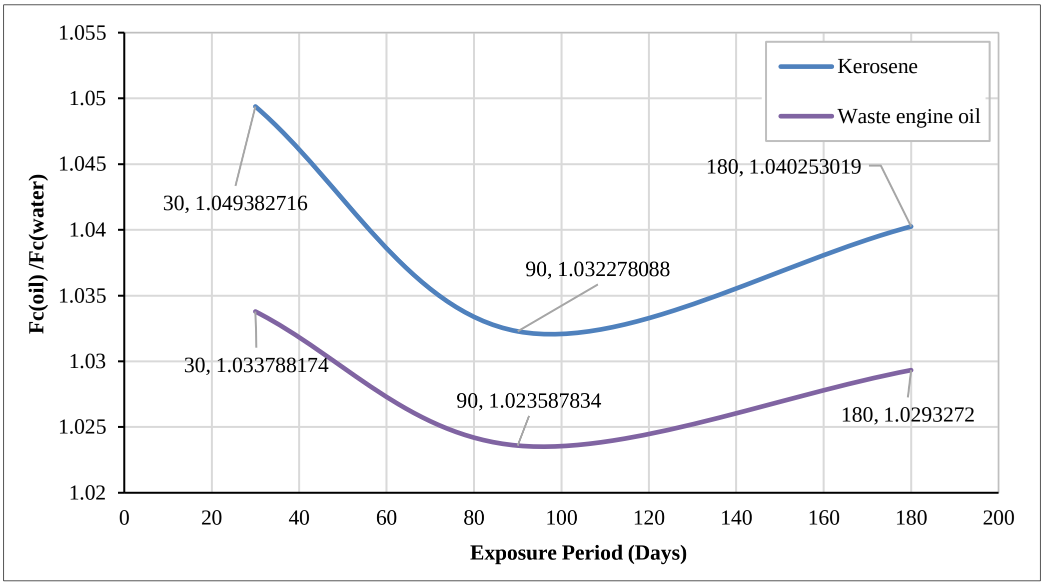
6. When compared to the original PRPC (reference mix), the Cs drop in mixes ($PC_{80,}$ PC_{100}) including 80, 100 % RA from CC was very small. In general, the outcomes have demonstrated its potential for use in recycled fine aggregate concrete design and construction tasks for a sustainable performance assessment of recycled aggregate concrete [27, 38]

7. The experimental results showed that, the PRPC mixes exhibited superior performance in all tested properties compared to the original RPC, especially when exposed to oil products. This behavior could be related to the role of the polymer in filling the pores and cracks and thus improving the surface condition [29]. Additionally, it was determined that using recycled aggregate might only slightly decrease compressive strength [25].

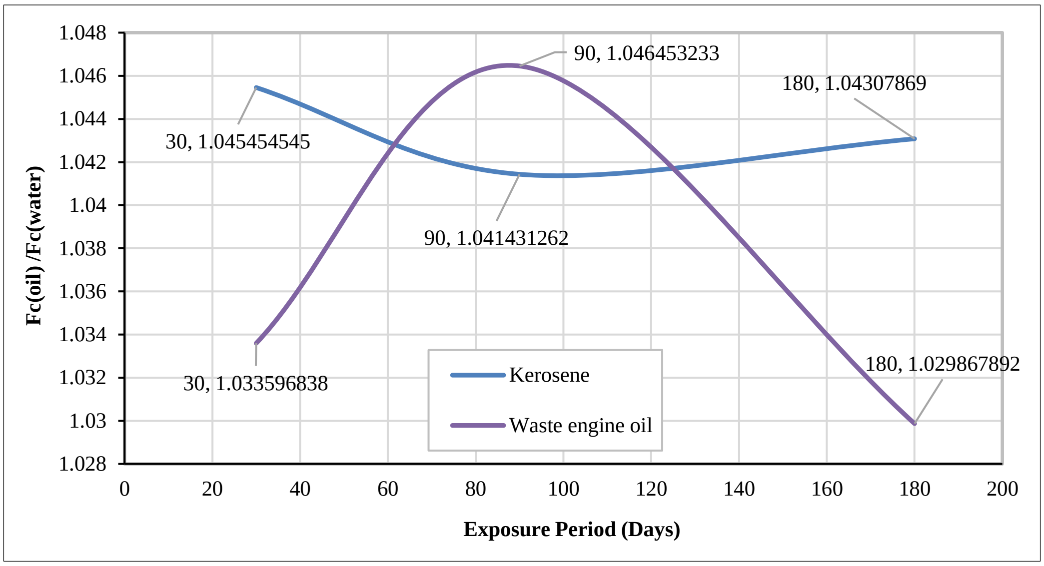
8. The strength values for specimens soaked in oil products were compared to those reached by specimens cured in water for the same amount of time in order to demonstrate the impact of exposure to new and waste oil on the development of compressive strength in PRPC mixtures. The ratios of fc (oil)/fc (water) with curing age are shown in Figure 11. Up until the ages of 120–150 days, curing with new and used oil has a good influence on strength gain. After that, water curing took control and produced greater results. Such behavior might be explained by the concrete being denser as a result of the entry of oil products, which have a lower viscosity than water [13, 29].



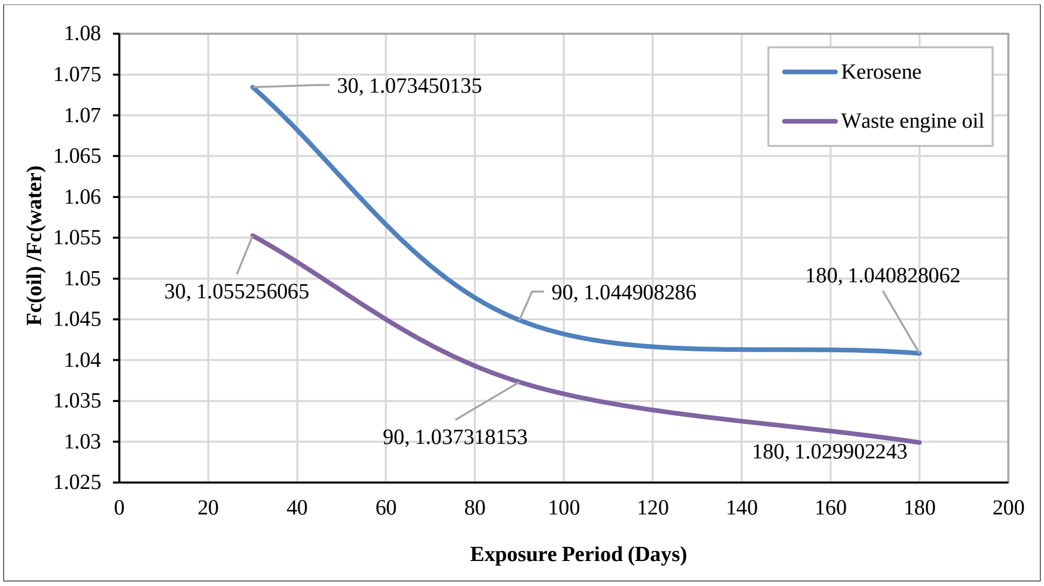
(a) Mix PC_0 (Reference Mix)



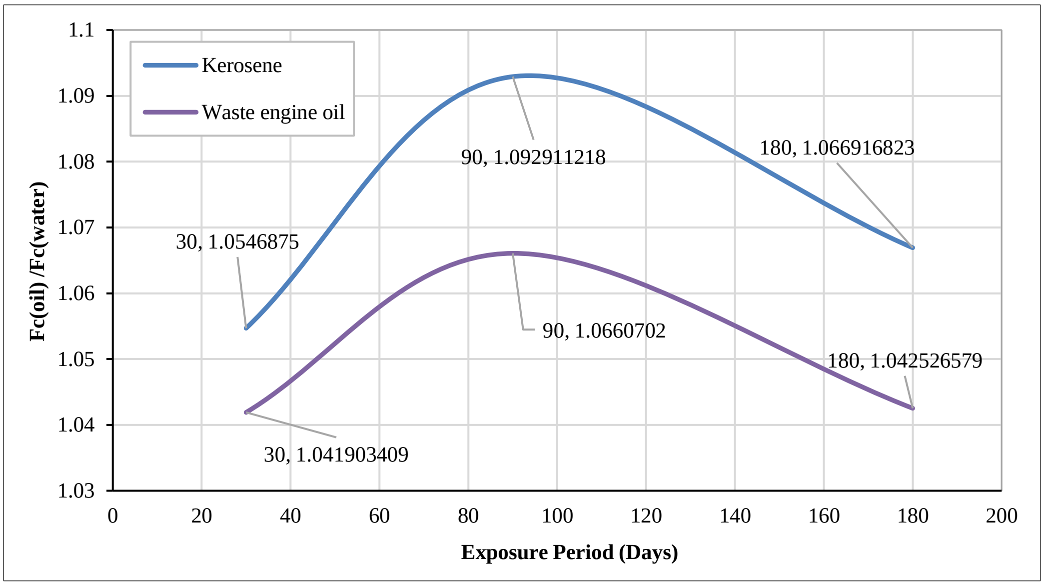
(b) Mix PC_{20}



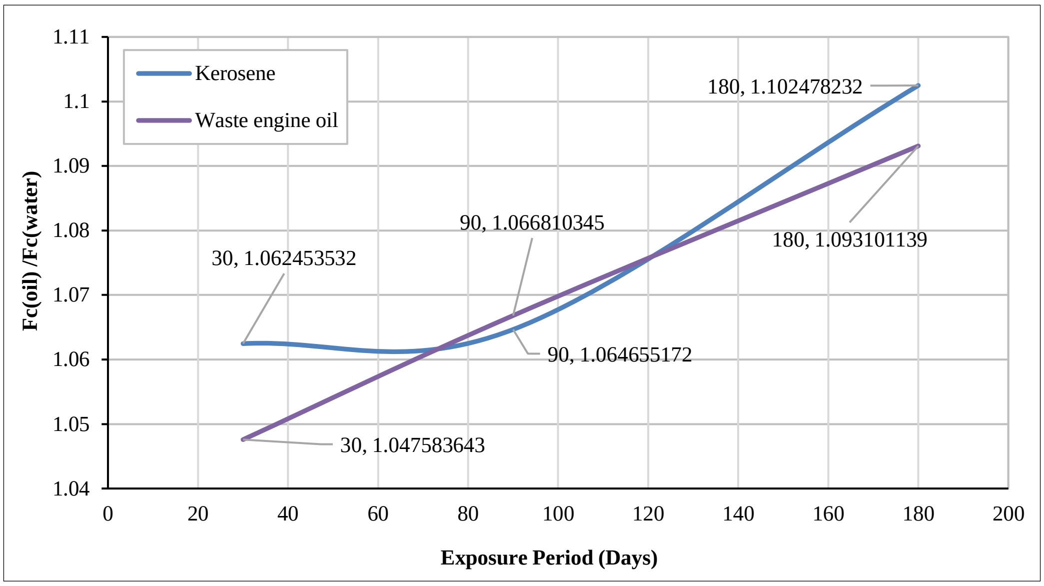
(c) Mix PC_{40}



(d) MixPC60



(e) Mix PC_{80}



(f) Mix PC_{100}

Figure 11. Relative change in compressive strength of mixes exposed to oil products with time

4.2. Splitting Tensile Strength

ASTM C496-96 was used to measure the splitting tensile strength (STs) [40]. A cylinder (100×200) mm in size was used. For all mixtures and curing circumstances, the average splitting tensile strength of the three cylinders was recorded. Tables 6 to 8 and Figures 12 to 15 show the relative variation of splitting tensile strength of the specimens exposed to different oil products compared with those cured in water at the same age, illustrating the impact of time of water curing or exposure to oil products on the splitting tensile strength for various types of concrete mixes.

Table 6. Average splitting tensile strength results (MPa) of the tested specimens that were exposed to water

Mixes title	Age (days)	PC_0	PC_{20}	PC_{40}	PC_{60}	PC_{80}	PC_{100}
Moist and air curing	14	9.21	9.2	8.43	8.2	7.2	6.93
	28	10.32	10.21	9.86	9.3	9.0	8.43
Exposure liquids (Water)	30	10.83	10.83	10.18	9.71	9.18	8.95
	90	12.73	12.72	11.87	11.21	10.83	9.92
	180	13.38	13.39	13.42	13.37	12.69	12.33

Table 7. Average splitting tensile strength results (MPa) of the tested specimens before and after exposure to used engine oil

Mixes title	Age (days)	PC_0	PC_{20}	PC_{40}	PC_{60}	PC_{80}	PC_{100}
Moist and air curing	14	9.21	9.2	8.43	8.2	7.2	6.93
	28	10.32	10.21	9.86	9.3	9.0	8.43
Exposure liquids (waste engine oil)	30	9.9	9.89	8.97	8.16	8.02	8.09
	90	12.8	11.98	11.34	10.82	10.08	9.12
	180	13.40	13.41	13.44	13.40	12.73	11.42

Table 8. Average splitting tensile strength results (MPa) of the tested specimens before and after exposure to kerosene

Mixes title	Age (days)	PC_0	PC_{20}	PC_{40}	PC_{60}	PC_{80}	PC_{100}
Moist and air curing	14	9.21	9.2	8.43	8.2	7.2	6.93
	28	10.32	10.21	9.86	9.3	9.0	8.43
Exposure liquids (Kerosene)	30	10.19	10.01	9.21	8.76	8.27	8.19
	90	12.9	12.0	11.77	11.10	10.39	10.05
	180	13.41	13.42	13.45	13.40	12.75	12.51

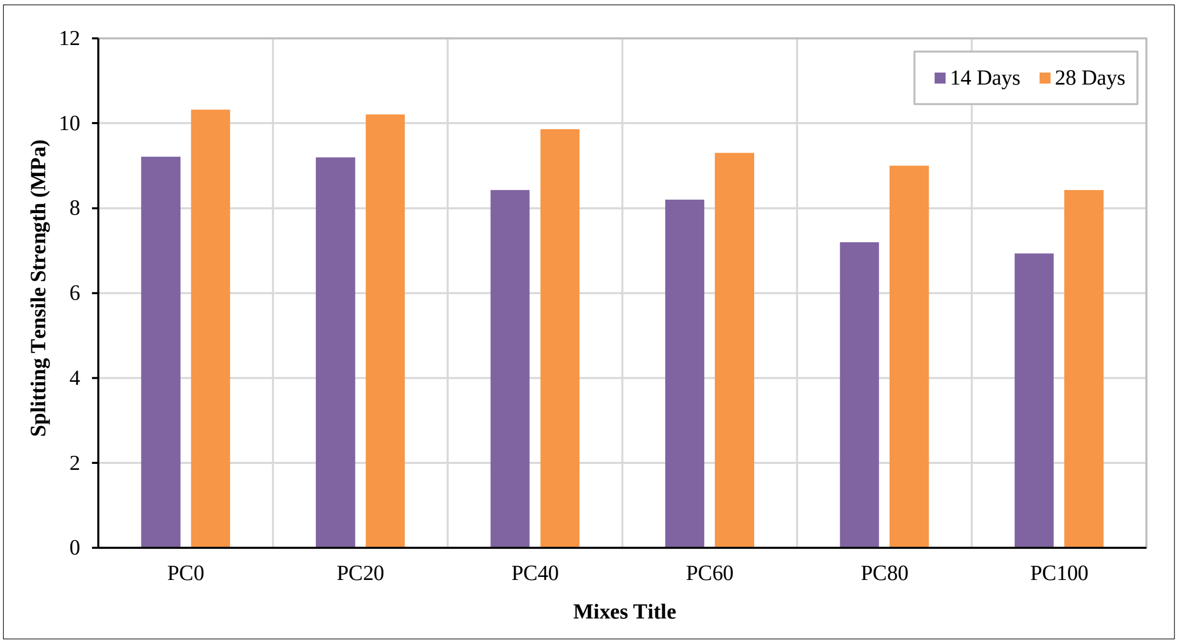


Figure 12. Splitting tensile strength of all mixes at different ages before exposure

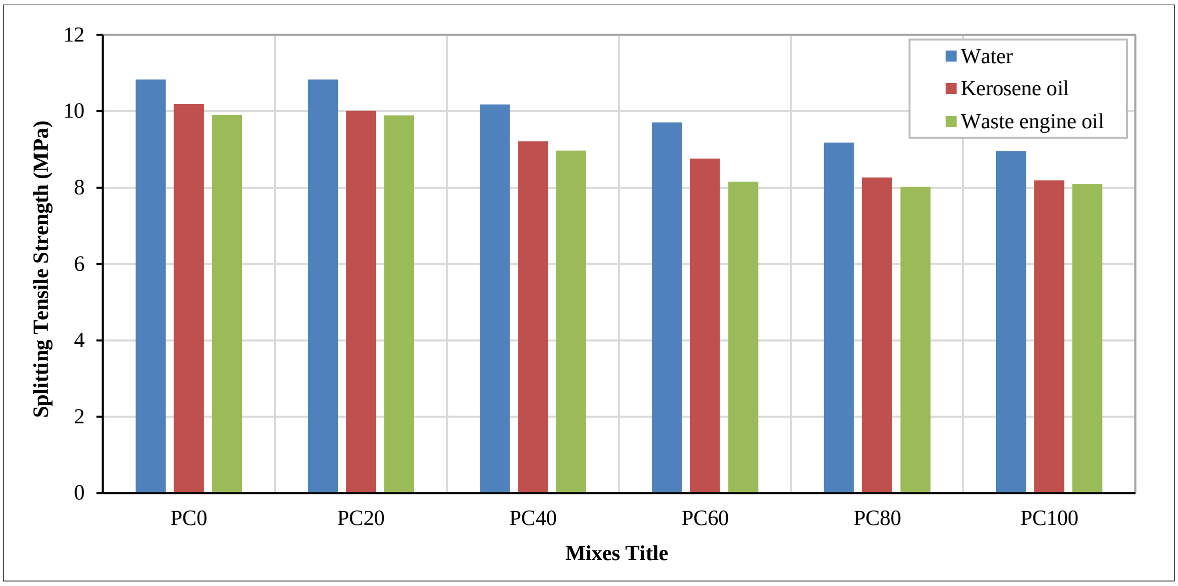


Figure 13. Splitting tensile strength of all mixes after 30 days exposure.

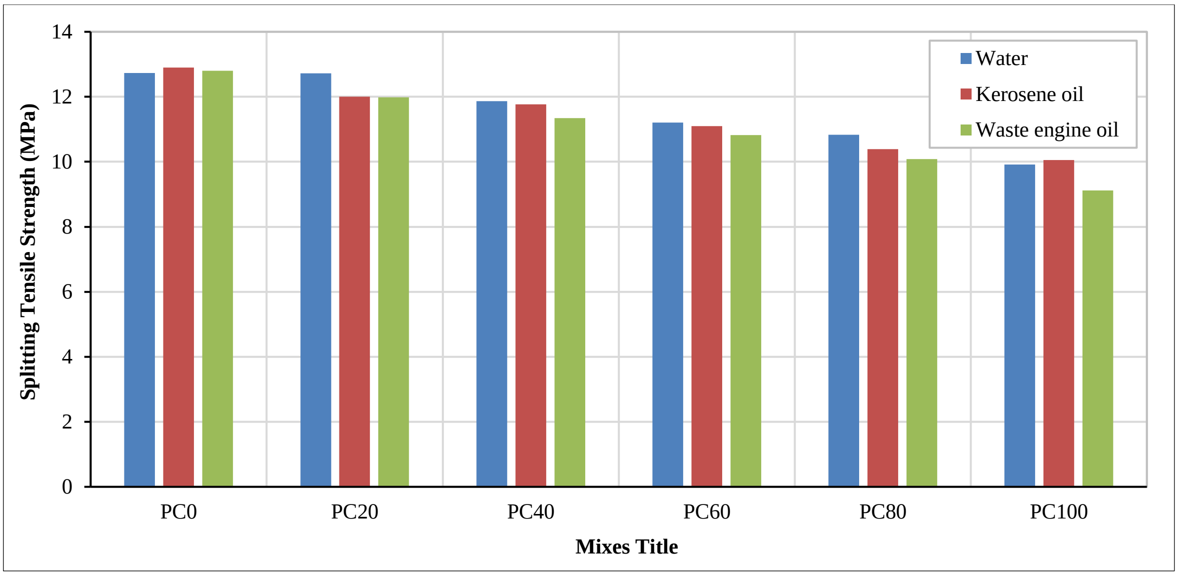


Figure 14. Splitting tensile strength of all mixes after 90 days exposure

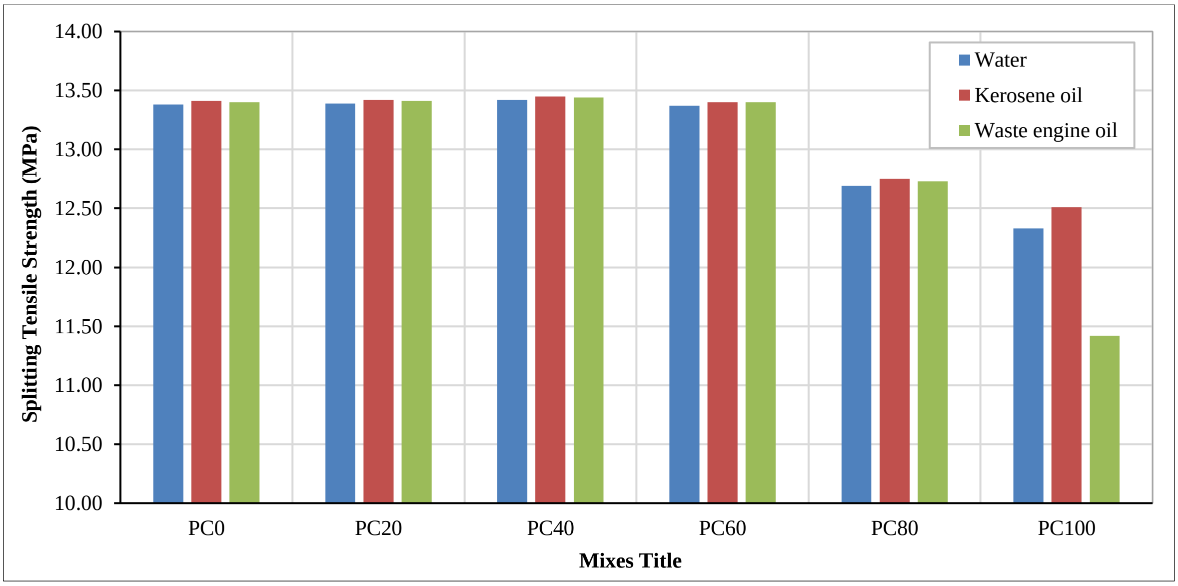


Figure 15. Splitting tensile strength of all mixes at after180 days exposure

Findings show that specimens that were cured in water significantly increased the splitting tensile strength for all different types of PRPC mixes at all testing periods. The continuing cement hydration process is the reason for this increase [41]. However, when the specimens were exposed to oil products, the splitting tensile strength increased for all mixes at all testing ages.

Reference PRPC and PRPC with recycled fine aggregate cured in water or exposed to oil products showed a significant development in splitting tensile strength for all testing periods, reaching the reference mix (12.38, 13.2, 13.21) MPa for the specimens exposed to water, waste engine oil, and kerosene oil, respectively. This improvement may be due to the matrix's superior dispersion and homogeneity, which strengthen the link between the steel fibers and matrix and, in turn, strengthen the tensile strength [2]. This may be related to recycled aggregate's superior qualities, such as its low porosity and strong adhesion to existing mortar [28, 39].

Higher tensile splitting strengths can be obtained by using original PRPC and PRPC with recycled fine aggregate. When compared to the original PRPC (reference mix), the splitting tensile strength of the mixture with 60% RFA from crushed old concrete was barely affected. The reduction in splitting tensile strength in mixtures (PC80, PC100) including 80 or 100% recycled aggregate from crushed concrete was minimal when compared to the original PRPC (reference mix). Many studies [1, 29, 37] have noted that the tensile strength of RPC is more sensitive to micro-cracking than the compressive strength, which might be explained by the effect of recycled aggregate surfaces on the binding strength between recycled aggregate and mortar.

4.3. Relationship Between Compressive and Splitting Tensile Strength after Exposure to Liquid

Figures 16 to 18 present the relationship between Ts and Cs in the three cases after 180 days of exposure to water, waste engine oil, and kerosene oil. The relationship between tensile and Cs is determined by a regression analysis. These figures show the correlation coefficient value, or (R^2), between compressive strength and tensile strength in the case of water exposure, the value of (R^2) (0.9924), and a correlation coefficient between Cs and Ts in the case of waste engine oil and kerosene oil of (0.8559), (0.9913), respectively. In other words, these outcomes are statistically significant. When the compressive strength of the polymer reactive powder concrete is specified, the tensile strength can be estimated with reasonable accuracy using the regression equation. It can also be seen from these figures that the increase in compressive strength leads to an increase in splitting tensile strength. The results indicated that the compressive and splitting tensile strengths of polymer reactive powder concrete with recycled fine aggregate are related to each other, when the compressive strength increases the splitting tensile strength also increases at a certain rate depending on the curing time, type of oil, percentage of replacement, and other factors. In this work, the factors are: liquid exposure type and percentage of replacement.

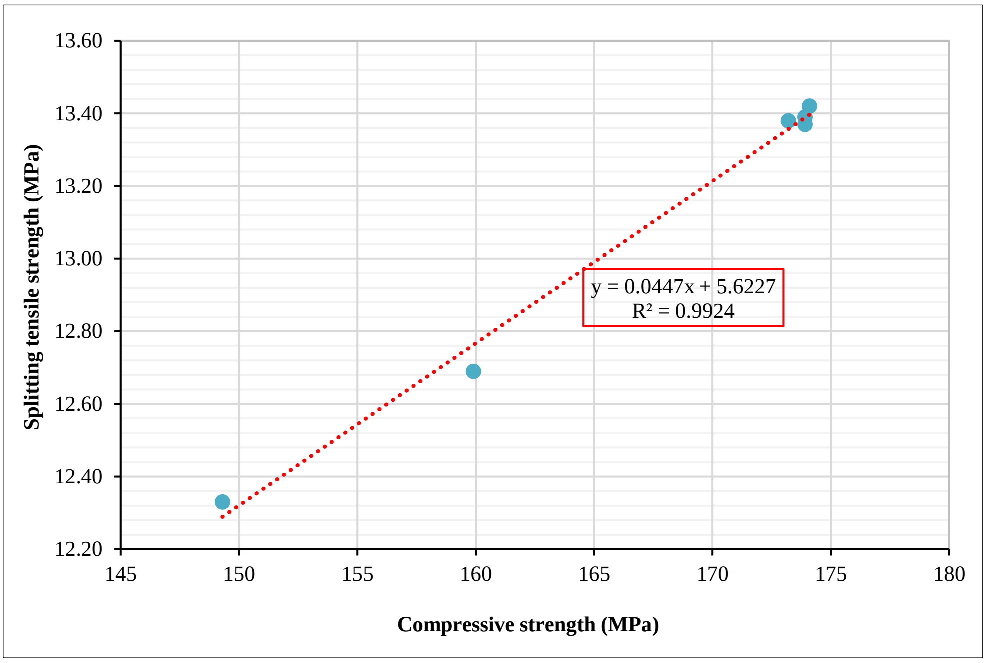


Figure 16. Relationship between Cs and Ts after 180 days exposure to water

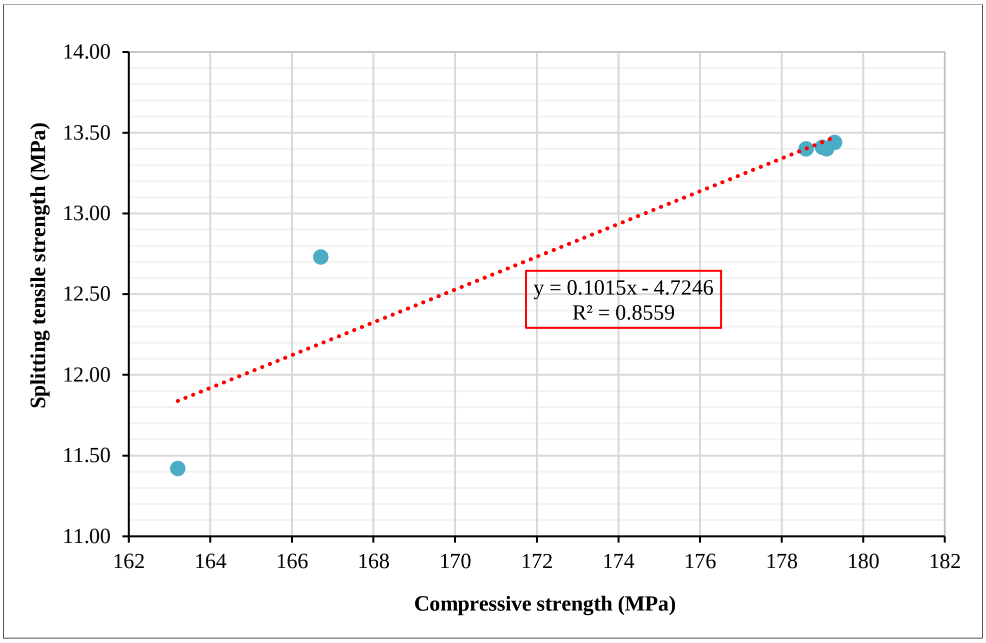


Figure 17. Relationship between Cs and Ts after 180 days exposure to waste engine oil

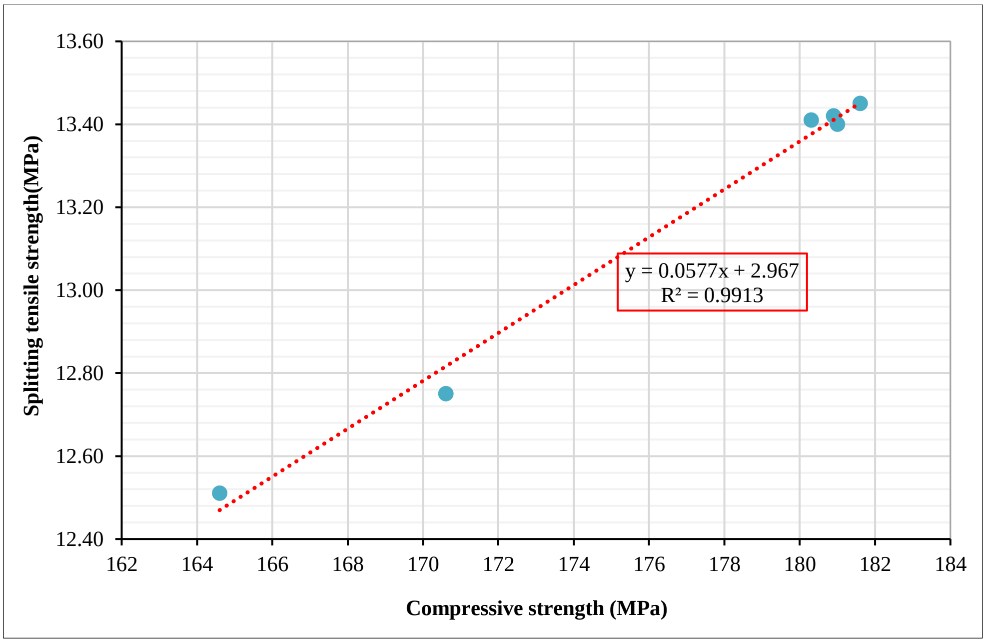


Figure 18. Relationship between Cs and Ts after 180 days exposure to kerosene oil

4.4. Flexural Strength

The flexural strength of (40 × 40 × 160) Prism specimens was evaluated in accordance with ASTM C293/C293M-16 [41] utilizing a simple beam with center point loading. The flexural strengths for concrete of various types of mixes are illustrated in Table 5, for all tested specimens. Figures 19 to 22 show the relative change in flexural strength of the specimens exposed to oil products compared with that of those cured in water, as a function of age (see Table 9 to 11).

Table 9. Average splitting tensile strength results (MPa) of the tested specimens that were exposed to water

Mixes title	Age (days)	PC_0	PC_{20}	PC_{40}	PC_{60}	PC_{80}	PC_{100}
Moist and air curing	14	9.21	9.2	8.42	8.12	7.2	5.99
	28	12.32	12.31	12.1	11.91	10.95	10.33
Exposure liquids (Water)	30	13.83	13.29	13.11	12.09	11.18	10.45
	90	15.72	15.54	14.72	13.61	12.83	11.92
	180	16.33	16.34	16.78	16.28	15.89	15.63

Table 10. Average splitting tensile strength results (MPa) of the tested specimens before and after exposure to waste engine oil

Mixes title	Age (days)	PC_0	PC_{20}	PC_{40}	PC_{60}	PC_{80}	PC_{100}
Moist and air curing	14	9.21	9.2	8.42	8.12	7.2	5.99
	28	12.32	12.31	12.1	11.91	10.95	10.33
Exposure liquids (waste engine oil)	30	16.31	15.99	15.31	14.06	13.97	12.19
	90	16.91	16.20	16.17	15.10	14.79	13.05
	180	18. 63	18. 64	18.86	18.55	17. 39	17. 16

Table 11. Average splitting tensile strength results (MPa) of the tested specimens before and after exposure to kerosene

Mixes title	Age (days)	PC_0	PC_{20}	PC_{40}	PC_{60}	PC_{80}	PC_{100}
Moist and air curing	14	9.21	9.2	8.42	8.12	7.2	5.99
	28	12.32	12.31	12.1	11.91	10.95	10.33
Exposure liquids (Kerosene)	30	15.38	15.19	15.15	14.83	13.85	12.98
	90	16.72	16.38	15.84	15.2	14.48	13.82
	180	18. 82	18. 85	18.88	18.79	17. 67	17. 32

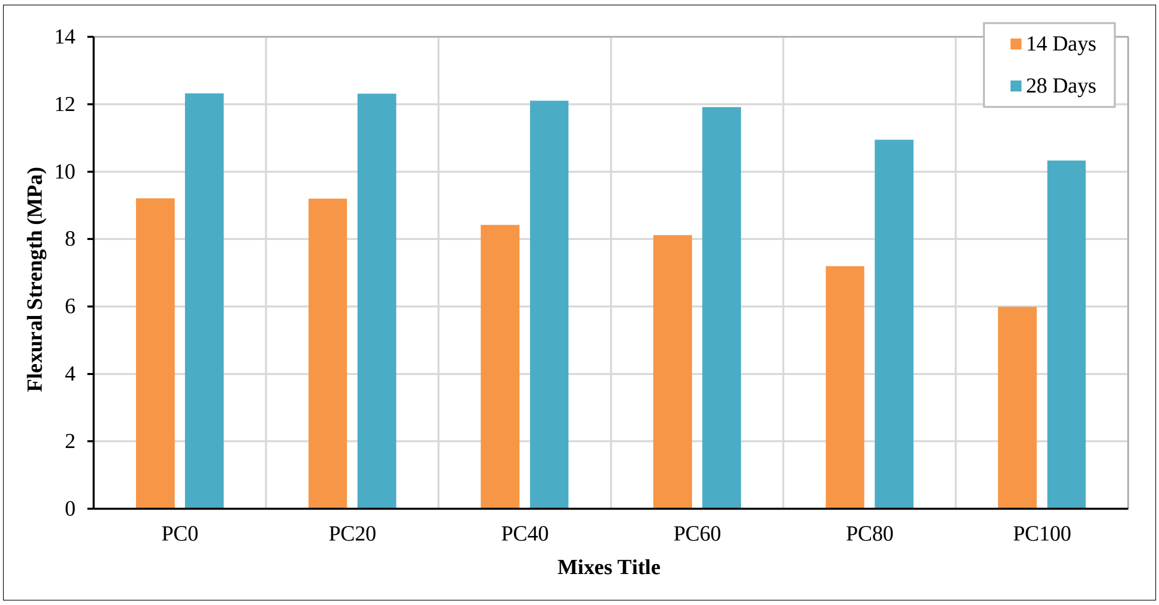


Figure 19. Flexural strength of all mixes at different ages before exposure

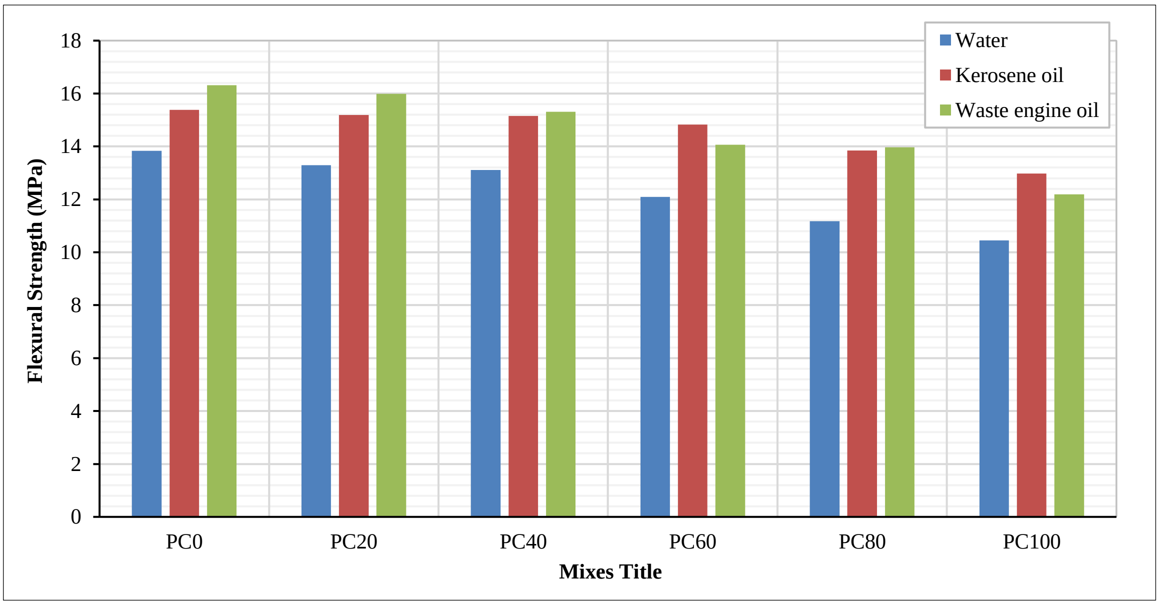


Figure 20. Flexural strength of all mixes after 30 days exposure

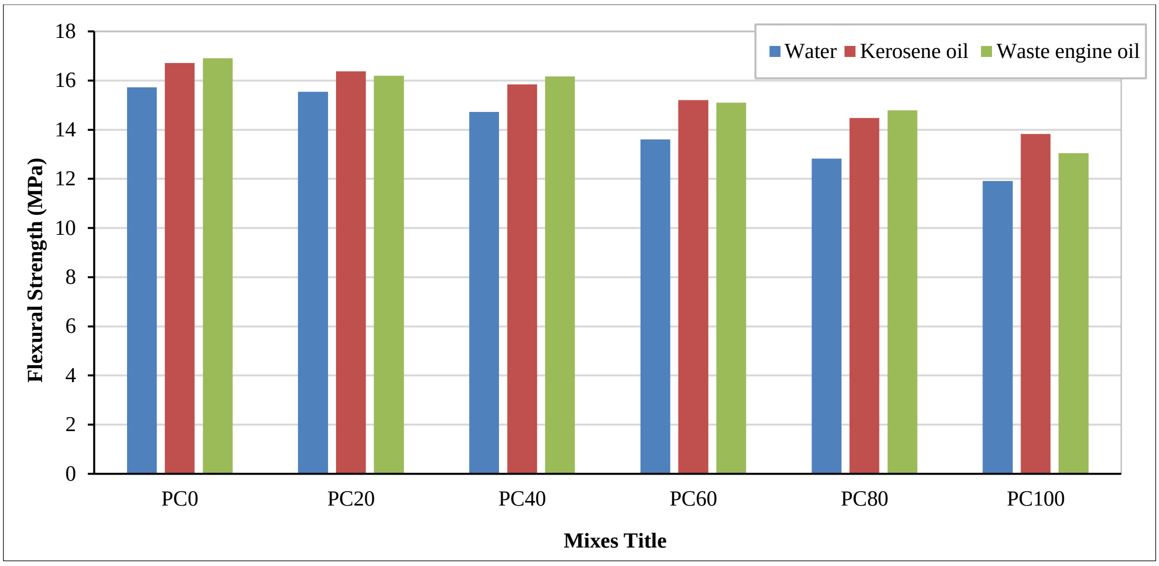


Figure 21. Flexural strength of all mixes after 90 days exposure

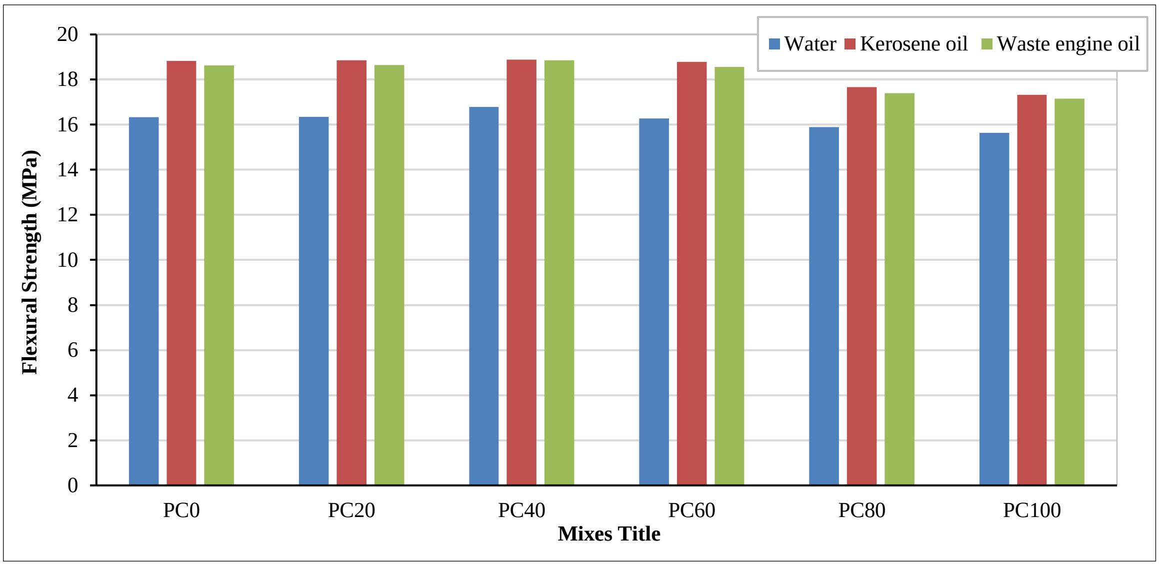


Figure 22. Flexural strength of all mixes at after180 days exposure

The flexural strength of the specimens continuously exposed to water increased significantly with time. The considerable increase in flexural strength is attributed to the effect of steel fiber, pressurization and the heat treatment which produces more hydrates and fewer capillary pores, thereby increasing the strength of the microstructure and reducing the micro cracking [32]. Original PRPC and PRPC with recycled fine aggregate can both produce materials with higher flexural strengths. The flexural strength of the mixture with 60% recycled fine aggregate from crushed old concrete was hardly impacted as compared to the original PRPC (reference mix). When compared to the original PRPC (reference mix), the drop in flexural strength in mixtures (PC_{80}, PC_{100}) incorporating 80 or 100% recycled aggregate from crushed concrete was insignificant. While some researchers believe that the use of RCA affects the characteristics of concrete, others have generated RCA concrete that performs as well as normal concrete (NC) [20, 21]

4.5. Relationship Between Compressive Strength and Flexural Strength after Exposure to Liquid

Figures 23 to 25 present the relationship between flexural strength and compressive strength in the three cases after 180 days of exposure to water, waste engine oil, and kerosene oil. The relationship between Fs and Cs is determined by a regression analysis. These figures show the correlation coefficient value, or R^2, between Cs and Fs in the case of water exposure the value of (R^2) 0.8005, and a correlation coefficient between Cs and Fs in the case of waste engine oil and kerosene oil of (0.9812), (0.9857), respectively. Thus, these findings are statistically significant. When the compressive strength of the polymer reactive powder concrete concrete is specified, the flexural strength can be estimated with reasonable accuracy using the regression equation. It can be seen also from these figures that the increase in compressive strength leads to an increase in the flexural strength. The results indicated that the Cs and Fs of PRPC with recycled fine aggregate related to each other, when the compressive strength increase the flexural strength also increase at the certain rate depending on the curing time, type of oil, percentage of replacement, and other factors.in this work the factors are: liquid exposure type and percentage of replacement.

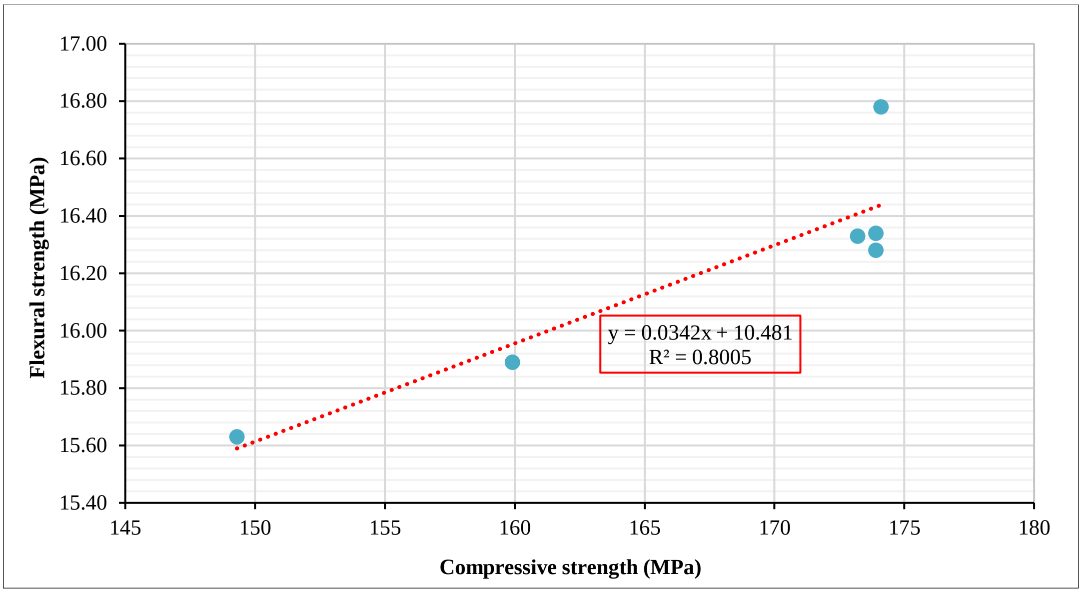


Figure 23. Relationship between Cs and Fs after 180 days exposure to water

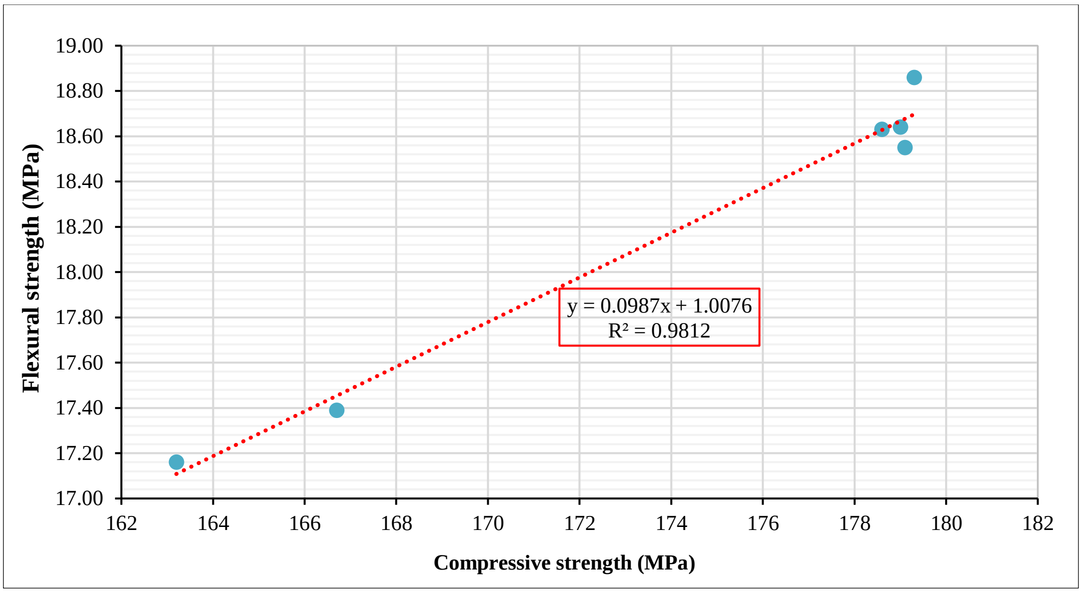


Figure 24. Relationship between Cs and Fs after 180 days exposure to waste engine oil

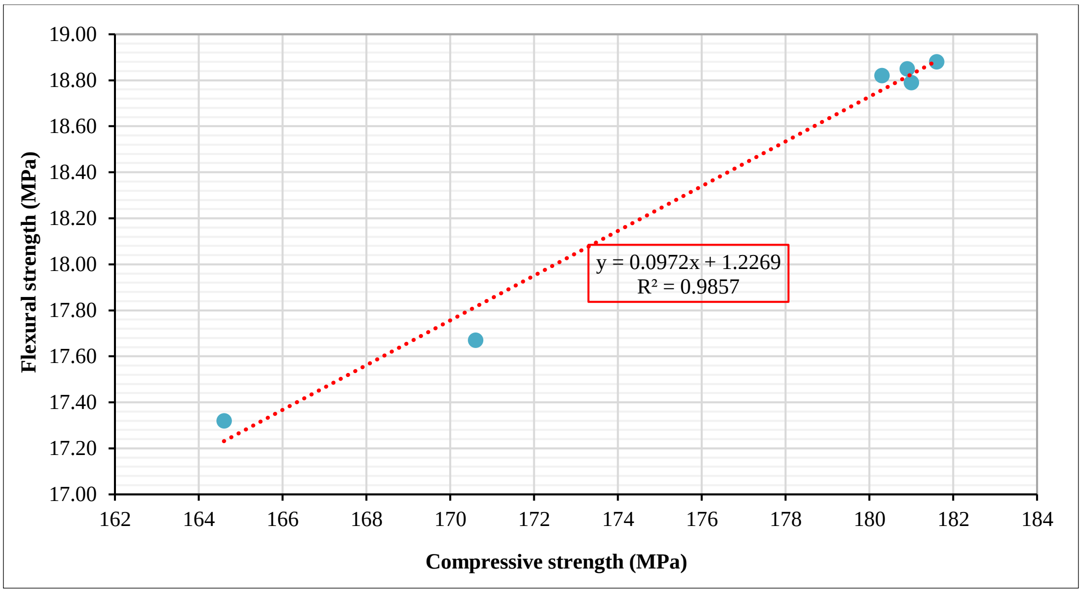


Figure 25. Relationship between Cs and Fs after 180 days exposure to kerosene

5. Conclusions

In this study, PRPC samples with recycled fine aggregates from crushed old concrete were examined to see how they affected PRPC's strength characteristics when exposed to oil. The following were the primary findings:

- The proportion decrease in compressive strength value because of the use of RFA was more significant in PRPC mixtures exposed to kerosene than in PRPC mixtures exposed to waste engine oil, so according to this study, waste crushed concrete could be used as recycled sand in polymer reactive powder concrete (PRPC) up to 60% of normal sand replacement without any appreciable strength loss.
- Increasing the proportion of recycled aggregates in the RPC by up to 40% could boost its strength both before and after exposure to oil. The study can be viewed as a solid methodology for use in future studies given the rising demand for sustainable development and the usage of eco-friendly concrete in building. There are numerous benefits, both financial and environmental, to using RA in concrete, so this study urges us to employ this kind of polymer-reactive powder concrete in a variety of applications, such as oil tanks for new or used oil, as well as concrete that will come into contact with oil.

Although this research only discusses the impact of RFA on the strength characteristics of PRPC, future work will need to examine additional findings about the impacts of using RFA on PRPC durability, such as absorption and shrinking.

6. Declarations

6.1. Author Contributions

Conceptualization, S.H. and M.F.; methodology, S.H.; software, S.H.; validation, S.H. and M.F.; formal analysis, S.H.; investigation, S.H.; resources, M.F.; data curation, S.H.; writing—original draft preparation, S.H.; writing—review and editing, M.F.; visualization, S.H.; supervision, M.F.; project administration, S.H.; funding acquisition, S.H. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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