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Preparation and Characterization of Polymer Concrete with recycled additives

A Thesis

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By

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قال الله تعالى :

﴿ يَرْفَعُ اللَّهُ الَّذِينَ ءَامَنُوا مِنكُمْ وَالَّذِينَ أُوتُوا
الْعِلْمَ دَرَجَاتٍ ۗ وَاللَّهُ بِمَا تَعْمَلُونَ خَبِيرٌ ﴾

سورة المجادلة

Dedication

To my Mom;

The reason of what I become today. Thanks for your great support and conditions care through my life.

To my husband;

Mahdi

If all men could be as generous and loving as you are, this world would be a happier place.

I appreciate your care and support all the time

To my little baby;

Asser

I hope you are proud of me

With Respect

Zainab jawad

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I would like to express my deepest sense of gratitude to my supervisor, *Prof. Dr. Ahmed fadhil* for his continuous advice and encouragement throughout the course of this work.

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zainab 2022

الخلاصة

الخرسانة البوليمرية هي مادة مركبة تتكون من الركام (الرمال والحصى) والراتنج حيث يعمل الراتنج على ربط الركام معا بدلا من الاسمنت والماء المستخدم عادة في الخرسانة التقليدية. ومن اجل تطبيق مفهوم الاستدامة في مجال البناء والانشاء فإن الامر يتطلب ايجاد مواد بديلة عن المواد المسببة للتلوث البيئي واستهلاك المواد الاولية الطبيعية. يهدف ذلك الى صناعة خرسانة خضراء قائمة على إعادة التدوير باستخدام مواد النفايات. تم استخدام الرماد المتطاير و خرده المطاط الناتجه من إطارات السيارات كمواد مستدامة.

في هذه الدراسة تم استخدام مادة البولي استر كبديل للاسمنت مع ثلاث أنواع من الإضافات : الرماد المتطاير ، خرده المطاط ومطاط السليكون . حيث تم اضافة الرماد وخرده المطاط كجزء من الرمل اما بالنسبة لمطاط السليكون تمت اضافته كجزء من البولي استر بثلاث نسب مختلفة (٥ ، ١٠ ، ١٥) % . علما أن المواد المضافة بنسب وزنية .

أجريت العديد من الفحوصات التي تعتبر مهمة في مجال البناء مثل مقاومة الانضغاط ، مقاومه الشد الانزلاقي ، الكثافة والاهتزاز الحر.

أظهرت نتائج مقاومة الانضغاط ، زيادة مقاومه الانضغاط مع زياده نسبه اضافة الرماد ولكن تقل مع زيادة نسبه إضافة المطاط . العينة التي تضمنت ١٥% رماد لديها أعلى مقاومه انضغاط ٦٩,٤ ميكا باسكال بينما العينة التي تضمنت ١٥% خرده المطاط لديها اقل مقاومه انضغاط ١٢,٥ ميكا باسكال .

أظهرت نتائج مقاومة الشد الانزلاقي ، زيادة مقاومه الشد مع زياده نسبه اضافة الرماد ولكن تقل مع زيادة نسبه إضافة المطاط . العينة التي تضمنت ٥% مطاط السيليكون لديها أعلى مقاومه شد ١٠,٣ ميكا باسكال بينما العينة التي تضمنت ١٥% خرده المطاط لديها اقل مقاومه شد ٣,٦ ميكا باسكال .

أظهرت نتائج الاختبار الحركي (الاهتزاز الحر) ، زيادة خواص التخميد مع زياده نسبه اضافة المطاط ولكن تقل مع زيادة نسبه إضافة الرماد . العينة التي تضمنت ١٥% سيليكون مطاط لديها أعلى نسبة تخميد ٨% .

تظهر نتائج هذه الدراسة مع زياده نسب الإضافات (رماد ، خرده المطاط ، مطاط السليكون) تقل كثافة الخرسانة البوليمرية . العينة التي تضمنت ١٥% خرده المطاط لديها أقل كثافه ١٩٠٠ كغم/م³ .

أثبتت نتائج هذه الدراسة بالإمكان استخدام الخرسانه البوليمريه كبديل للخرسانه التقليديه في العديد من التطبيقات التي تتطلب خواص ميكانيكيه و خواص تخميد عاليه .

Abstract

Polymer concrete is a composite material consisting of aggregates (sand and gravel) and resin. The resin binds the aggregates together instead of the cement and water usually used in conventional concrete. In order to implement the concept of sustainability in the field of building and construction, it is required to find alternative materials for the materials that cause environmental pollution and the consumption of natural raw materials. This aims to manufacture green concrete used recycled waste materials. Fly ash and crumb rubber of car tires were used as a sustainable material.

In this study, polyester was used as a substitute for cement with three types of additives: fly ash, crumb rubber and silicon rubber. Fly ash and crumb rubber were added as part of the sand. silicone rubber was added as part of polyester in three different proportions (5, 10, 15) wt.%.

Many tests were carried out that are important in the field of construction such as compressive strength, splitting tensile strength, density and free vibration.

The results of compressive strength test revealed that the material's compressive strength improved along with an increase of fly ash, but it decreased with the increase rubber. The sample that contained 15 wt.% fly ash had the highest compressive strength of 69.4 MPa while the sample that contained 15 wt.% crumb rubber had the lowest compressive strength of 12.5 MPa.

The results of splitting tensile strength showed an increase in tensile strength with an increase in fly ash addition, but it decreases with an increase in rubber. The sample that contained 5 wt.% silicone rubber had the highest tensile strength of 10.3 MPa, while the sample that contained 15 wt.% crumb rubber had the lowest tensile strength of 3.6 MPa.

The results of the dynamic test, which included free vibration, demonstrated that the damping properties improved along with an increase in rubber, but it decreased with increase fly ash. The sample containing 15 wt.% silicone rubber has the highest damping rate of 8%.

The results of this study show that with the increase in the percentage of additives (ash, crumb rubber, silicon rubber), the density of polymeric concrete decreases. The sample that contained 15 wt.% crumb rubber had a minimum density of 1900 kg/m³.

The results of this study show that polymeric concrete can be substituted for conventional concrete in numerous applications that require high mechanical and damping properties.

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List of Symbols

Symbols	Meaning	Unit
A	Cross-sectional area	mm ²
σ	Compressive strength	MPa
P,F	load	N
ζ	Damping ratio	%
fn	fundamental frequency	HZ
frt	splitting tensile Strength	N/mm ²
D	Cylinder diameter	mm
L	Cylinder length	mm

List of Abbreviations

Abbreviation	Meaning
ASTM	American Society For Testing Materials
PC	Polymer Concrete
PIC	Polymer Impregnated Concrete
PMC	Polymer Modified Concrete
FTIR	Fourier Transform Infrared
IQS	Iraqi Standard Specifications

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Examining Committee Certificate

We certify that we had read this dissertation entitled (**Preparation and Characterization of Polymer Concrete with recycled additives**) in its contents and in what it its connected with, and in our opinion, it meets the requirements to have the master degree in Materials Engineering/ Polymers and petrochemicals Industries Engineering.

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1.1 Introduction

Polymer concrete (PC) is a composite material in which the binder consists entirely of a synthetic organic polymer. It is also known as synthetic resin concrete, plastic resin concrete, or simply resin concrete. Because the use of a polymer instead of Portland cement represents a substantial increase in cost, polymer should be used only in applications in which the higher cost can be justified by superior properties, low labor cost, or low energy requirements during processing and handling. It is therefore important that architects and engineers have some knowledge of the capabilities and limitations of PC materials in order to select the most appropriate and economic product for a specific application [1]. The fast curing, excellent strength and durability, excellent damping properties, and wide range of elastic moduli available have made PC a very versatile material with many applications. Its primary disadvantages are high cost (binder cost ranges from less than \$1 per pound to many dollars per pound); sensitivity of properties to temperature; volatility and flammability of monomers and resins; and lack of experience with PC by many users [2] [3].

1.2 Literatures Review

- **K. S., et al. (2004)** studied The use of fly ash as a replacement for sand in polymer concrete (PC). It was discovered that a replacement of 15 wt.% of sand with fly ash improves the compressive strength of unreinforced PC cylinders by about 30% and the flexural strength of steel-reinforced PC beams by about 15% [3].

- **J.M.L., et al. (2004)** utilized epoxy resin and silica sand as aggregate. The chopped carbon and glass fibers used were 6 mm long. The glass fibers were also pre-treated with Silane to improve the adhesion between fibers and resin and fracture properties. In general, addition of fibers increases flexural strength and fracture properties. The fracture toughness of carbon fiber reinforced polymer concrete can increase up to 29% while glass fiber polymer concrete can increase up to 13% when comparing with epoxy non reinforced polymer concrete. The object of this research work is to evaluate the influence of fibers on the mechanical and fracture properties of polymer concrete[4] .

- **Marinela et al. (2010)** utilized a solid waste, fly ash and silica fume, in polymer concrete. The results show the influence of fly ash and silica fume content on the mechanical properties of polymer concrete with epoxy resin. The fillers improved the mechanical characteristics of polymer concrete compared to that of polymer concrete without filler: the compressive strength of polymer concrete with fly ash content was favorably influenced by the filler compound to polymer concrete with silica fume [5].

- **Weena Lokuge et al. (2013)** studied the effect of fly ash on the mechanical properties of polymer concrete by using different types and percentages of resin combined with sand, fly ash and coarse aggregate. They concluded that the addition of fly ash into the polymer concrete mix increased the strength of the concrete in compression and also the modulus of elasticity. When fly ash is further increased, there is a point where there is excess fly ash and the resin will no longer properly bound with the aggregates [6].

- **Marinela et al. (2016)** obtained the polymer concrete by adding different types of wastes such as argillaceous powder, calcareous powder, marble powder and fly ash to a witness mix obtained by mixing epoxy resin and aggregates in two sorts (0-4 mm and 4-8 mm). The mechanical properties (compressive strength, flexural strength, split tensile strength) were experimentally determined. Calcareous powder and fly ash improved the mechanical properties while argillaceous powder addition decreased the values of mechanical strengths in comparison with witness[7] .

- **H. Alperen et al. (2017)** studied the effects of electronic plastic waste (e-plastic) on the mechanical properties. E-plastic was used as a part of the filling materials (quartz sand and gravel) to obtain polymer concrete in this study. Unsaturated polyester resin material used as binder. 28-day of axial compressive, flexural and splitting tensile strength values of the test samples were evaluated. Experimental study shows that ideal resin ratio and ideal e-plastic ratio values are (15 and 5)wt.%, respectively[8] .

- **Gavril et al. (2018)** prepared of polymer concrete with natural aggregates and fly ash as filler. Fly ash was added as filler and aggregate sort 0-4 in different dosages by saw dust and chopped PET bottles. The influence of waste as substitution of aggregate on density, workability and compressive strength was analyzed and compared with a control mix of polymer concrete prepared with natural aggregates and fly ash as filler. The wastes used as aggregate substitution decreased the density of polymer concrete, indicating a lightweight concrete for all mixes. The compressive strength for polymer concrete with wastes as aggregates substitution were closed as values to the

control mix, enhancement in compressive strength up to 18% of CPC for addition 25 vol.% of saw dust in PC [9].

-Awham M. et al. (2019) produced polymer concrete (PC) has high mechanical and physical characteristics. This PC was prepared by using the waste of aggregates from demolitions and construction materials with low cost as compared as cement concrete. Unsaturated polyester resin was used as cement replacement. Physical test such as density and mechanical tests such as compressive strength, flexural strength, splitting tensile strength and Schmidt hammer were performed. The results proved that all the mechanical properties of all prepared mortars were increased with increasing the weight percentage of polymer added while the density was decreased [10].

- Gonzalo et al. (2019) utilized a polyester resin, recycled tire fibers and silica sand in polymer concrete. Silica sand was partially replaced by recycled tire fibers (0.3, 0.6, 0.9 and 1.2 vol%) and gamma irradiation (50 and 100 kGy) was applied. Mechanical properties were determined in compression and flexion. Significant improvements on the mechanical properties were obtained and related to morphological and structural changes of the recycled tire fibers [11].

-Norbert Kepczak (2019) investigated the influence of the addition of styrene-butadiene rubber on the dynamic properties of polymer concrete. used for the tests 10% volume addition of styrene-butadiene rubber granulate with three different grain gradations was used for the tests. The modal study was carried out in the 0 to 2000Hz frequency range. The best results were obtained for a sample made with a 10% styrene-butadiene rubber volume

addition with grain sizes from 0.6 to 2 mm. In this case, the biggest decrease of the amplitude of the transfer function value was 76%, while the biggest increase of the damping ratio was 431.5%, in comparison with the clear polymer concrete sample. The worst results were obtained for a sample made with a 10% styrene-butadiene rubber volume addition with grain sizes from 2.5 to 6 mm [12].

-P. Torkittikul et al. (2020) investigated the properties of polyester resin polymer concrete containing various amount of aggregate. The mixtures were prepared with three different aggregate to binder ratio of (70-30) wt.%, (75-25) wt.% and (80-20) wt.%. After mixing, all samples were cast in the standard molds and left to harden at room temperature until testing. The results show that the final setting time of binder was 50 minutes. Further, the polyester resin polymer concrete with 70, 75 and 80% aggregate achieved compressive strength of around 422-447 kg/cm² within 24 hours after mixing and achieved compressive strength of approximately 572, 540 and 525 kg/cm² respectively at 7 days of curing [13].

- Kinga et al. (2021) studied the influence of doping polymer concrete with styrene-butadiene rubber (SBR) on its dynamic and mechanical properties. The research was divided into two stages. First, experimental modal analysis was carried out in the time and frequency domain from 0 to 2000 Hz to elaborate on the dynamic properties of the polymer. The results indicated that increasing the amount of rubber granulate (SBR) in the polymer concrete improved the damping ratio and reduced the vibration amplitude [14].

1.3 Conclusion Remarks

Based on the critical review of the available literature on polymer concrete, following conclusions can be drawn:

1- Polymer concrete has been initially developed as an alternative material in the domain of civil engineering, but over the period of time, owing to its superior properties have found favour as a replacement material in machine building applications. Rapid curing, high compressive strength, high specific stiffness and strength, resistance to chemicals and corrosion, ability to form complex shapes, excellent vibration damping properties are chiefly responsible for its use in these areas.

2- An increase in the rubber content of the polymer concrete results in lower resonance frequencies. The increase in rubber content in the sample results in a significant increase of the damping coefficient and decreased amplitude. It is not recommended doping the mineral cast with more than 20% of rubber granulate by volume. In excess of this value, the rise in damping properties is not so pronounced, while the mechanical properties drastically decrease.

3- Use of various types of thermoplastic and thermosetting resins has been reported in the literature. Most of the studies on polymer concrete have been reported on polyester and epoxy resins. Few studies are reported on the use of Methacrylate, vinylester and furan resins also. Comparative studies between epoxy and polyester resins reported that epoxy polymer concrete has far superior mechanical properties and durability.

4- Various types of aggregate materials have been used by the researchers most of them based upon the choice of locally available materials to reduce the cost. River sand, foundry sand, crushed stone, quartz, granite and gravel are some of the materials reported by the authors.

5- The resin dosage reported by various authors mostly lies in the range of 10 to 20% by weight of polymer concrete. Higher resin dosage is recommended when using fine aggregate, because of the large surface area of these materials. A few studies have been reported in the literature to find out the optimum resin content based upon the minimum void content of the aggregate mix.

6- Various curing regimes have been reported by researchers one of them is room temperature curing. Curing time studies on polymer concrete have established that it achieves around 70% of its strength after a curing of one day at room temperature. A number of researchers have used 7, 14 and 28 days' room temperature criterion in their research work.

7- Various types of micro fillers like fly ash, silica fume, calcium carbonate etc. have been incorporated in polymer concrete to improve the compressive strength of polymer concrete. Addition of fly ash has been reported by a number of researchers which not only results in improvement in the workability of the polymer concrete mix but also has a significant effect on the mechanical properties. Enhancement in compressive strength upto 30% has been reported for addition of 15% fly ash in polymer concrete.

8- Polymer concrete is being used in machine buildings since last few decades and it is proven to have better damping than traditional materials of machine building.

1.4 Aim of the current work:

Manufacture of polymeric concrete with high static and dynamic properties for high damping structure applications. At the same time reducing the negative effect of waste materials on environment such as fly ash and rubber.

2.1 Introduction

Polymer concrete (PC) is a composite material in which aggregates are bonded together with resins in a polymer matrix. Performance of PC is strongly dependent on various types and the mixed proportions of aggregates and resins [15]. Polymer concrete is becoming increasingly popular due to many advantages that it possesses. It is very strong, durable and cures very rapidly, an important factor in most of the civil engineering applications such as transportation, utility, marine and building components [16, 17].

It has superior physical and chemical properties such as a short curing time, impact resistance, chemical resistance, electrical insulation, waterproofness, and freeze–thaw durability [18,19].

The polymer concretes are distinguished by the nature of the binder; e.g., furan, polyester, epoxy, phenol formaldehyde, carbamide, and so on. The classification of the main types of polymer concrete according to the kind of synthetic resins involved is shown in Figure (2.1) [20]. A variety of aggregate types have been used in PC silicates such as gravel, limestone, calcareous rock, granite, clay, quartz, crushed stone, silica sand or calcium carbonate (CaCO_3), as well as fine fly ash, phosphor-gypsum, cinder, and silica fume. Several silica sands have been used in the foundry industry [21].

Aggregates used must be usually dry and free of dirt to get the best bond between aggregates and resin. Figure (2.2) shows some aggregate systems used in PC mixtures. The mix design of PC typically uses an aggregate size gradation to provide the lowest possible void volume and require the least polymeric binder necessary to coat the aggregates [22].

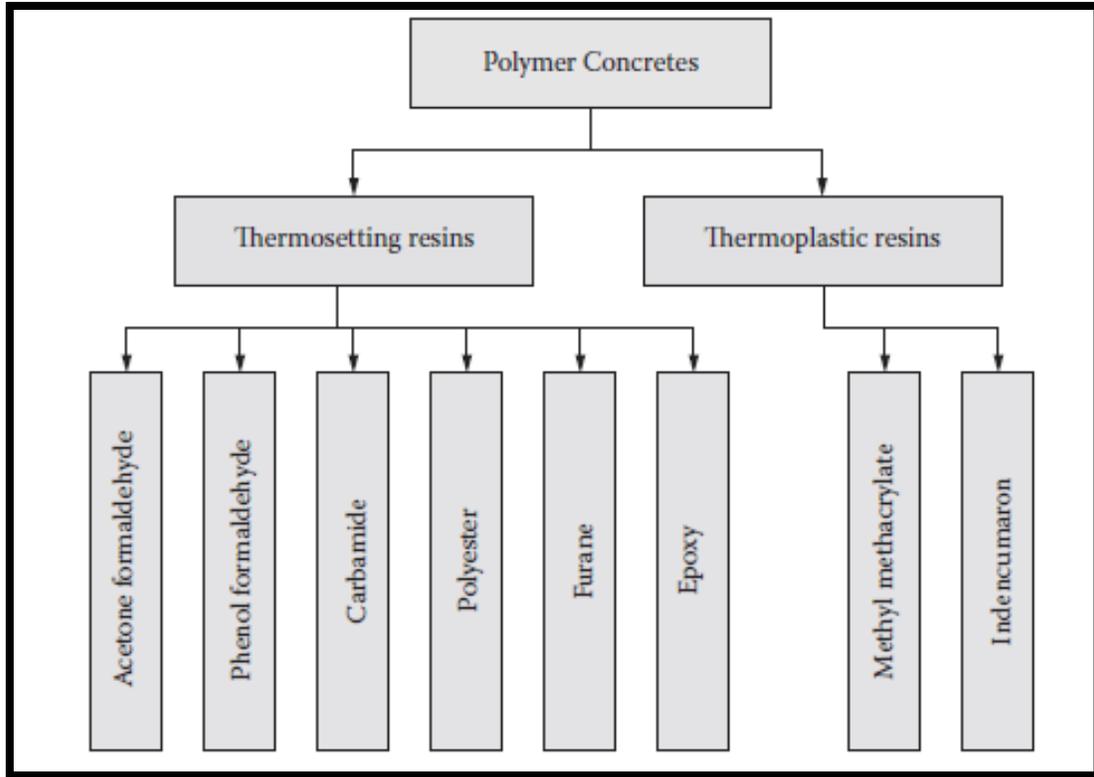


Fig. (2.1) Classification of polymer concretes [20].

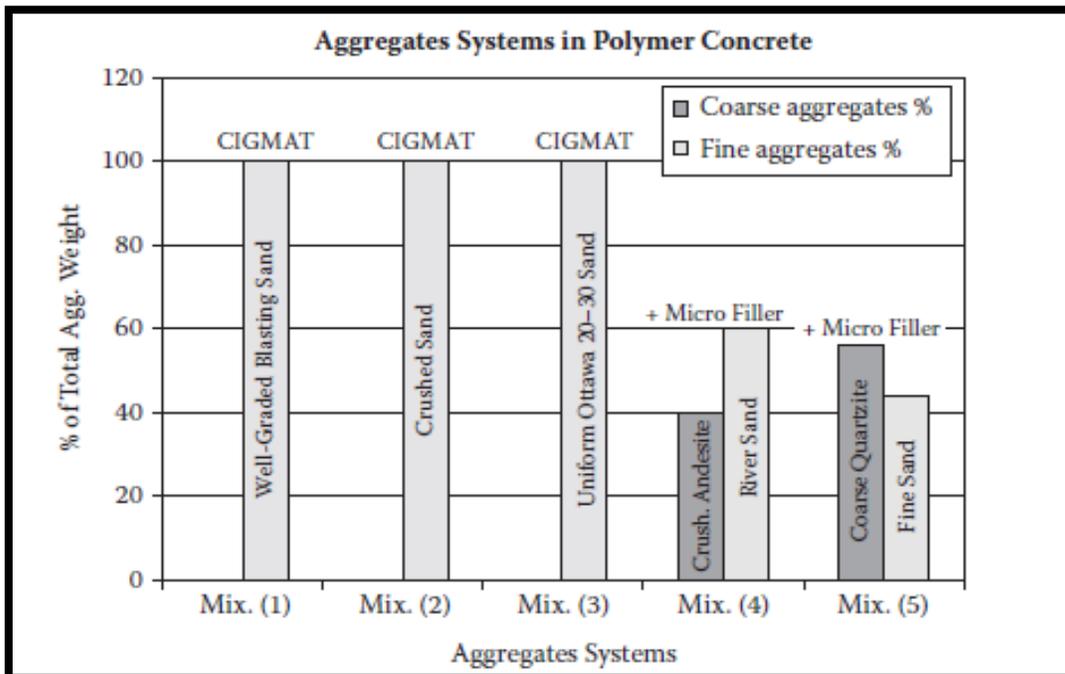


Fig. (2.2) Most common aggregate systems used in PC [22].

2.2 Types of polymer in concrete

The polymer in concrete has three types of polymer impregnated concrete (PIC), polymer concrete (PC) & polymer modified concrete (PMC). This thesis is mainly focused on polymer concrete.

2.2.1 Polymer impregnated concrete (PIC)

In polymer composition most famous is PIC (polymer impregnated concrete) because of its durability and mainly utilized in marine structures, precast concrete and repairing works. For making polymer impregnated concrete the normal concrete is dry and dipped on the monomer for 4–5 h in which the concrete soaks monomer and filled in the void of the concrete. After this process polymerization takes place this has various methods for polymerization like thermal catalytic method, radiation method so, finally produced PIC. The impregnation processes the monomer is penetrated up to 20 mm–50 mm on the surface of the concrete. The compression strength of PIC increased 3–4 times as comparing with normal concrete [23].

2.2.2 Polymer modified concrete (PMC)

Polymer-modified concrete (PMC), or polymer Portland cement concrete (PPCC or PCC), is normal Portland cement concrete with a polymer admixture. The polymer and the cement hydration products comingle and create two interpenetrating matrices, which work together, resulting in an improvement in the material properties of PCC alone. PMC is the term for such concrete with lower dosages of polymers, typically 5% or less, and PPCC or PCC generally is the term for composites with more than 5% polymer by weight of concrete. Current applications of PMC are primarily as overlays on

roadways and bridges, both as new construction and as repairs of existing deteriorated structures. PMC is also being used in flooring, water tanks, swimming pools, septic tanks, silos, drains, pipes, and ship decks [24].

2.2.3 Polymer concrete (PC)

Polymer concrete consists of aggregates bonded together by a resin instead of a cement. The most commonly used resins are epoxy, polyester and vinyl-ester.

2.2.3.1 Types of polymers used in concrete

A wide variety of monomers are used to produce PC. The polymers most frequently used are based on five types of monomers:

1- Epoxy Polymer Concrete

Epoxy binder is a thermosetting polymer. The epoxy polymer can be hardened with a variety of curing agents, the most frequently used being polyamines (e.g., tertiary polyamines). The use of polyamine hardeners (curing agents) results in PC products with the highest chemical resistance. Other curing agents are polyamides and Polysulfide polymers.

Epoxy PC products cured with polyamides have greater flexibility, better heat resistance, and reduced chalking tendency in outdoor exposure, but their solvent and chemical resistance is lower than for similar products cured with polyamines. The adding of polysulfide polymers produces an epoxy PC with greater flexibility.

Epoxy PC exhibits high adhesion strength to most materials, low shrinkage, high acid- and alkali-resistance (but nondurable in oxidizing medium), and

good fatigue and creep resistance. Because they are relatively expensive, epoxy polymers have not been used very widely as binders in PC products. Therefore, epoxy PC is used for special applications, in situations in which the higher cost can easily be justified, such as mortar for industrial flooring to provide physical and chemical resistance, skid-resistant overlays (filled with sand, emery, pumice, quartz) in highways, epoxy plaster for exterior walls (e.g., in exposed aggregate panels), and resurfacing material for deteriorated areas (e.g., in flooring). Epoxy PC reinforced with glass, carbon, or boron fibers is used in the fabrication of translucent panels, boat hulls, and automobile bodies [25,26].

Dilution of epoxy resins is achieved by introducing solvents. In this case, the viscosity is much reduced and the pot life is increased. However, the use of volatile solvents leads to formation of pores and capillaries in the binder, and hence to a reduction in polymer density [20].

It was concluded that the amount of resin and filler in the chemical composition of the fabricated epoxy PCs had a great influence on identification of the maximum physical strength. The PC specimen with 15% resin and 200% filler resulted in maximum compressive and flexural strength. The tensile strength was maximized with 20% resin and 200% filler. The mechanical strength of fabricated PCs was 4- to 5-fold higher than Portland cement concrete [15].

2- Carbamide Polymer Concrete

Carbamide (urea-formaldehyde) resin is prepared by the poly condensation reaction of urea and formaldehyde in aqueous or aqueous-alcoholic medium

Polymer concretes based on carbamide resins have a low toxicity and are favorable in manufacturing. However, the content of the polymer matrix in these PCs is high (up to 30%) and their physical and mechanical properties are low in comparison to other types of polymer concretes.

It should be noted that carbamide resins contain a large amount of free water (30%–40%), which leads to more shrinkage during curing of the composition. In some cases, this leads to cracking of the material [20].

3- Acryl Polymer Concrete

The most common acrylic polymer is polymethyl methacrylate, which is obtained by polymerization of methyl methacrylate (MMA). The material consists of a highway- grade aggregate and a matrix produced by cross-linking MMA with trimethylol propane trimethacrylate or other polyfunctional acrylic oligomers.

PC made with this acrylic polymer as a binder is a versatile material, has excellent weathering resistance, good waterproofing properties, good chemical resistance, and relatively low setting shrinkage (0.01% to 0.1%); its coefficient of thermal expansion is equivalent to that of Portland cement concrete. Because of a very low tendency to absorb water, acrylic PC has a very high freeze–thaw resistance. The low flash point (11°C) of the MMA monomer is a disadvantage, however, as it constitutes a safety problem.

Although the MMA monomer is more expensive than the prepolymer monomer used in the more popular polyester PC, its unique properties account for its use in a great many diverse applications, including the manufacture of stair units, sanitary products, curbstones, and facades. The low temperature capability and long-term durability make the material ideal for emergency

repairs that must be accomplished when standard concrete repair materials cannot be used. A highly successful development has been its use as a rapidly curing, structural patching material for repairing large holes in bridge decks, spall repairs, emergency full-depth repairs, bridge expansion joint headers, bearing pads, closure pours, and concrete structural beam repairs. The MMA polymer concrete can be applied at any time after the primer has cured, which allows for preparation of many areas ahead of time making placement more efficient [25,26,27].

4- Furan Polymer Concrete

Furan polymers are based on furfuryl alcohol, which is derived from agricultural residues such as corncobs, rice hulls, oat hulls, or sugar cane bagasse. The furan prepolymer is usually cross-linked with furfuryl alcohol, furfuraldehyde, or formaldehyde to yield thermosetting polymers, highly resistant to most aqueous acidic or basic solutions and strong solvents such as ketones, aromatics, and chlorinated compounds.

The important characteristic of furan resins is their ability to be stored for long periods of time (up to 5 years), even at low temperatures. However, short-term pot life and toxicity in the uncured state hamper the use of these resins, and high self-heating temperature causes significant thermal stresses, which adversely affect the strength characteristics of furan PC. It was found that the State of the Art in Polymer Concrete 7 degradation of furan polymers due to aging leads to a decrease in the mechanical properties of the composite. The furan polymers are used as binders in mortars and grouts to achieve chemically resistant brick floors (e.g., carbon brick and red shale brick) and linings. In addition to exhibiting superior chemical resistance, these floors

have excellent resistance to elevated temperatures and extreme thermal shock [20,25,26].

5- Polyester Polymer Concrete

Polyester resins like epoxy are a type of thermosetting resins, obtained by polycondensation. They have a low viscosity, and materials that are based on them have high mechanical and electrical insulating properties and high resistance to acids, gasoline, oils. Because of low cost, the most widely used unsaturated polyester polymer is in the form of 60% to 80% solutions of the prepolymer in copolymerizable monomers such as styrene and a mix of styrene with methyl methacrylate. During hardening, the polyester prepolymer and the monomer react through their unsaturated groups (double bonds).

It should be added that polyester resins are toxic, and with poor stirring of the mixture components the probability of stratification and level-by-level curing of the composition is high. Polyester PC has high mechanical, cohesion and adhesion strength, and good chemical and freeze–thaw resistance. Polyester PC is used in various precast and cast-in-place applications in construction works, public and commercial buildings, for the manufacture of sanitary engineering, cladding of composite pipes in bathrooms and toilets, stairs, and chemical-resistant floors [20,25,26].

2.2.3.2 Properties of polymers concrete

Using synthetic resins instead of traditional Portland cement binder allows concrete to be created with a series of interesting properties such as high chemical resistance to many corrosive environments or high mechanical

strength. In ordinary concrete, the strength properties of cured cement paste are at least several times lower than the corresponding features of the mother rocks of the aggregate, and the adhesion of binder and aggregate is relatively low. The situation is different in resin concretes: the tensile strength of hardened resin binder is much higher, and the compressive strength is similar to the strength of the rocks from which the aggregate was obtained.

Polymer concrete composites have generally good resistance to attack by chemicals and other corrosive mediums, have very low water sorption properties, good resistance to abrasion, and marked freeze–thaw stability. Also, the greater strength of polymer concrete in comparison to that of Portland cement concrete permits the use of up to 50% less material. This puts polymer concrete on a competitive basis with cement concrete in certain special applications. The chemical resistance and physical properties are generally determined by the nature of the polymer binder to a greater extent than by the type and the amount of filler. In turn, the properties of the matrix polymer are highly dependent on time and the temperature in which it is exposed.

The viscoelastic properties of the polymer binder give rise to high creep values. This is a factor in the restricted use of PC in structural applications. Its deformation response is highly variable depending on the formulation, and the elastic module may range from 20 to about 50 GPa, tensile failure strain being usually 1%. Shrinkage strains vary with the polymer used (high for polyester and low for epoxy based binder) and must be taken into account in an application [26,27,28].

Other advantages of polymer concrete should be mentioned as well [28]:

1. Impervious to liquids, small number of pores, absolute lightness.

2. High freeze–thaw resistance resulting from non-moisture-absorbing property; good electric insulation.
3. High resistance to corrosive chemical substances, including acids and bases.
4. High resistance to scratches; it does not peel, does not splinter, does not require any maintenance, and experiences no erosion, which reduces costs of maintenance and exploitation.
5. Increased flexural, compressive, and tensile strengths; fast setting times (curing within 1 or 2 hours); good durability.
6. May be applied for any load class.
7. Due to the properties of polymer concrete, products made of this material are durable and strong and are characterized by higher mechanical resistance to loads than traditional concrete, which means that the cross-section area for
8. comparable load classes are smaller in polymer concrete products— thus they are lighter than concrete products, which results in easier and quicker installation.
9. Due to natural components, it is an environment-friendly material, debris may be reused (aggregate can be returned to the production process)
10. Good adhesion to essential construction materials (steel, traditional concrete)
11. Good ability to dampen vibrations due to resins contained in the material 11- Possibility to obtain very smooth surfaces, guaranteeing many practical applications.
12. Resistance to changing weather conditions and atmospheric factors.
13. Very short time to achieve installation and usage efficiency.

14. Easy drilling and cutting with diamond bits and saw blades.

15. High abrasion resistance (comparable to granite).

The advantages of polymer concrete are particularly noticeable when comparing its individual properties to traditional B30 class concrete (Table 1.2).

Table (1.2). Physical–Mechanical Properties of Polymer Concretes [29].

Indicator	Unit	Kind of Polymer Concrete						Portland Cement Concrete (B30)
		Epoxy	Furan	Furan-epoxy	Polyester	Carbamide	acrylate	
Average density	10 ² Kg/m ³	22-24	22-24	22-24	22-24	22-24	22-24	19-25
Compression strength	MPa	50-150	70-90	90-110	80-100	40-70	70-90	13-35
Tension strength	MPa	10-40	5-8	9-11	7-9	3-7	10-13	1.5-3.5
Flexural strength	MPa	15-50	---	---	15-45	---	30-33	2-8
Modulus of elasticity	10 ⁴ MPa	3-4	2-3.2	3.2-3.8	1.8-3.6	1-1.5	1-1.5	2-3
Poisson's ratio	---	0.24-0.29	0.32	0.27	0.2-0.23	0.22-0.26	0.27	0.15-0.2
Shrinkage at hardening	%	0.005-0.09	0.1	0.05-0.08	0.08-0.1	0.2-0.25	0.15-0.2	0.015-0.3
Water sorption	%	---	0.05-0.9	0.01	0.05-0.1	0.2-0.3	0.01	5-8
Heat resistance	C°	120-130	120-140	120	80	100-110	60	200-400
Wear resistance	Kg/m ²	0.05-0.1	0.18-0.21	0.05-0.1	0.15-0.25	0.2-0.3	---	0.85
Freeze resistance	Number of cycles	500	300	500	300	200	500	1000
Toughness	J/cm ²	3-10	0.15-0.25	0.16-0.25	0.2-0.25	0.15-0.25	---	0.5

2.2.3.3 Factors affecting on properties of polymer concrete

There are many factors which influence the mechanical properties of polymer concrete such as resin type and content, aggregate type and mix

design, fiber reinforcements, micro filler type and content, curing conditions, silane coupling agents, moisture content of aggregates etc.

1-Resin type and content

The choice of particular type of resin depends upon factors like cost, desired properties, chemical/weather resistance required. Epoxy resins are preferred over polyester because of their better mechanical properties as well as better durability when subjected to harsh environmental factors, but higher cost is a deterrent in their wide spread acceptance. A comparative study on the properties of epoxy and polymer concrete states that traditionally epoxy concrete has better properties than polyester concrete, but the properties of polyester concrete can be enhanced upto the same level by addition of micro fillers and silane coupling agents [30].

MMA has got a limited application because of its higher flammability and disagreeable odour, however it has received some attention because of its good workability and low temperature curability [31].

The compressive strength and flexural strength increase with increase in polymer content. It is observed that both flexural and compressive strength attain the maximum value between 14-16% resin content by weight [32]. Further studies in this area have also provided the similar results. Variation of compressive strength of polymer concrete for various types of resins and their dosage has been reported in literature [33]. It was observed that highest strength was obtained in all types of resins at a resin dosage of 12 wt.%.

2- Microfillers

A microfiller is also often added to polymer concrete mix to reduce the void content in aggregate mixture and thereby increase the strength of polymer concrete. The microfiller is a fine powder with a particle size less than 80 microns. Use of Calcium Carbonate, Fly ash and silica fume have been reported in literature. Fly ash is a byproduct of the coal burning in power plants and is used as a filler because of its easy availability and because its usage in polymer concrete is reported to yield better mechanical properties as well as reduced water absorption [34].

Addition of fly ash also improves the workability of fresh polymer concrete mix resulting in products with excellent surface finish [35]. Addition of fly ash has been reported by a number of researchers which results not only in improvement in the workability of the polymer concrete mix but also has a significant effect on the mechanical properties. Enhancement in compressive strength upto 30% has been reported by addition of 15% fly ash in polymer concrete [36].

3- Moisture content of aggregate

Heat assisted drying of the aggregates before mixing with resin has been suggested by most of the researchers. It has been reported that water content of the aggregate has a remarkable influence on the strength of polymer concrete, and therefore the water content shall be limited to 0.1% [37]. It has been recommended that the moisture content of the aggregate shall not exceed from 0.1% to 0.5% for better mechanical properties [36,37].

4- Curing conditions

Polymer Concrete achieves more than 80% of its 28-day strength in one day. Conversely, normal Portland cement concrete usually achieves about 20% of its 28-day strength in one day. The early strength gain is important in precast applications because it permits the structures to resist higher stresses early due to form-stripping, handling, transportation and erection operations [38,39].

5-Fibre reinforcement

A large number of studies have been reported regarding the effect of reinforcement of polymer concrete by addition of various types of fibers. Steel fibers, glass fibers, carbon fibers and polyester fibers have been added in polymer concrete in varying quantities for enhancement of its properties. Earlier studies on addition of steel fibers in epoxy concrete using sand as an aggregate reported an increase of 40% in the flexural strength with addition of 3.5% steel fibers [40]. Presenting somewhat contrasting results, it was reported that addition of steel fibers increases the compressive strength whereas addition of glass fibers decreases the compressive strength [41]. Longer fibers are reported to have better effect on compressive strength [42]. Ductility of polymer concrete also improved with addition of fibers [43].

Addition of copper coated stainless steel fibers in polyester concrete having granite as aggregate improved the compressive strength of the resulting material [44].

It is observed that there is an increase in the compressive and flexural strength and stiffness due to glass fiber reinforcement. The area under the stress-strain curve is taken as a measure of toughness and it can be seen that

glass fibers enhance the toughness of polymer concrete. Change in properties is approximately proportional to the volume fraction of fibers. Further silane treatment of glass fibers before their use in polymer concrete report an enhancement in mechanical properties up to the extent of 25% [45].

6- silane coupling agents

The use of silane coupling agents, which may provide chemical bonding between the two phases considerably improves the interfacial adhesion and therefore enhance the mechanical properties of these materials. The bonding mechanism of the resin and inorganic aggregate through silane is provided below in Figure (2- 3) through a possible mechanism based upon reaction between the silane, polymer resin and aggregate. Effect of silane coupling agents on compressive strength of polymer concrete has also been reported. It was reported that use of silane coupling agents which may provide chemical bonding between the two phases, improves the interfacial adhesion [46].

Effect of different types of silane coupling agents i.e. γ -methacryloxy propyltrimethoxy silane and γ -aminopropyltriethoxy silane on polyester resin concrete containing 12% resin is reported in literature [47]. Silane coupling agents were used as integral blend additive by mixing 1% coupling agent (by weight of resin) during the mixing of resin. Addition of γ methacryloxy propyltrimethoxy silane was reported to have better enhancement of properties than γ - aminopropyltriethoxy silane.

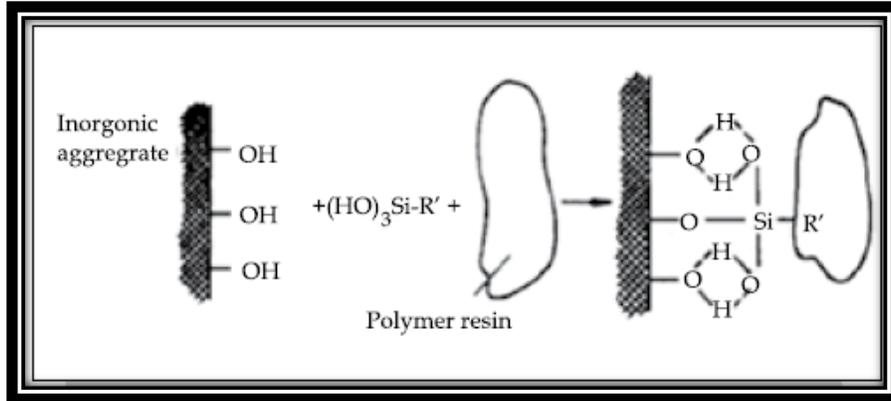


Figure (2- 3) Schematic representation of bonding through silane coupling agent [46].

2.2.3.4 Applications of polymer concrete

Polymer concrete is usually used in severe conditions in industrial and public buildings as well as in transportation and hydraulic structures. The main uses are repair/strengthening, and corrosion protection of concrete structures.

The main advantages of polymer concrete over ordinary concrete are improved mechanical strength, low permeability, and improved chemical resistance. A highly successful development has been its use as a rapid-setting, structural patching material for repairing large holes in bridge decks [3].

One of the advantages of polymer concrete is its ability to dampen vibrations. It had been used mainly in foundations that support high frequency equipment, but now it is being used for building structures undergoing dynamic loads [48].

Precast PC has been widely used for flooring, utility boxes, manholes, drains, wall panels, and machine bases. Precast PC can be produced quickly, as compared to precast concrete or machined cast iron, has a high strength-to-weight ratio, and can be produced with cast inserts. However, the limited pot life of polymeric binder mix makes it difficult to obtain high-quality large products and structures made from epoxy, polyester, furan, and carbamide polymer concretes.

The main limitation of the wide application of PCs is their relatively high material cost. This is why it is important to find the optimum technical-economic compromise [3].

Due to its properties, polymer concrete is currently used in many applications [3,49,50].

1. In highway pavements.
2. As underground wastewater pipes.
3. For manufacturing thin overlays.
4. As precast components for bridge panels, overlay bridge decks, bridge drainage systems (bridge edge beams, bridge curbs, bridge drainage inlets, gutters), for linear drainage systems (channels, linear drainage channels, linear drainage silt boxes), parking garage decks, industrial floors and dams, buildings, machine bases, and transportation components, as well as for hydraulic structures such as dams, dikes, reservoirs, and piers (where PC creates a highly abrasion-resistant surface).
5. For production of industrial tanks intended for electrolysis of nonferrous metals, production of catch basins and channels to drain aggressive industrial wastewater, water meter chambers, sewage pump

stations, production of storage tanks to store corrosive substances such as acids and bases.

6. For repair of structures and for coatings, due to its strong bonding with PCC (there must be no sealants, curing compounds, or any other material covering the concrete, as it will interfere with the adhesion of PC).

2.2.3.5 Limitations of polymer concrete

There are some limitations to the use of polymer in concrete [51].

1. the primary limitation of concrete-polymer materials is cost; the cost of polymers can range from 10 to 100 times that of Portland cement.
2. Another limitation is its inability to withstand high temperatures, particularly fires, and therefore the materials cannot be used as the structure for buildings housing people.
3. A third limitation is the odor and/or toxicity and/or flammability of many of the monomers and resins during construction or fabrication. While these limitations only exist for the relatively short time until curing occurs.

2.3 The used materials

1- Unsaturated polyester resin (UP)

Unsaturated polyester resin (UP) is a linear polymer having an ester bond and an unsaturated double bond formed by polycondensation of unsaturated dibasic acids with diols or by saturated dibasic acids and unsaturated diols [52].

The C=C bond of the resin molecular chain and styrene (ST)-unsaturated polyester (PES) can crosslink copolymerization reaction to form four possible structures: (I) intermolecular crosslinking with or without linking through styrene monomers; (II) intramolecular crosslinking with or without linking through styrene monomers; (III) branching on the polyester molecule by styrene; and (IV) free styrene homopolymerization [53].

The curing mechanism of the unsaturated polyester resin is radical curing, including different stages of chain initiation, chain growth, and chain termination, as well as chain transfer [54,55]. Although there are many ways to initiate free radicals, such as heat, light, electron beam, ultrasonic waves, etc., in the practical application, the use of free radical initiators is mostly. According to the temperature of the free radical initiator and the initiation conditions, the unsaturated polyester resin initiating system can be composed of a normal temperature high-temperature initiation system, a high-temperature initiation system, a photoinitiation system, a radiation initiation system or other initiation systems.

2- Aggregates

Aggregates generally occupy 70 to 80 percent of the volume of concrete and therefore can be expected to have an important influence on its properties [56]. Aggregate is not simply an inert filler in concrete, and its properties deserve careful consideration. Aggregates are granular materials, usually natural rock (crushed rock or natural gravels) and sands.

Aggregates are classified as normal weight, heavyweight, and lightweight, based on specific gravity. Aggregate properties that affect concrete pavement performance include shape and texture, size gradation, absorption and surface

moisture, specific gravity, unit weight, physical durability, chemical durability, and strength. Strength of the aggregate particles rarely governs concrete strength, because the lower strength of the paste or the aggregate-paste bond is likely to govern instead [56].

Aggregate shapes may be rounded or angular, with rounded materials occurring naturally and angular materials produced by crushing and processing. Within those two main divisions, aggregate shapes may be further classified as spherical, irregular, highly irregular, flat or oblate/flaky, and elongated.

Textures may be glassy, smooth, granular, rough, crystalline, or honeycombed. Rounded aggregates are more workable, but angular particles may develop higher strength, which is important for pavements [57].

3- Fly ash

Fly ash, the most widely used supplementary cementitious material in concrete, is a by-product of the combustion of pulverized coal in electric power-generating plants. It produces spherical glassy particles that are finer than portland cement.

Two types of fly ash are available, depending on the type of coal that was burned to make the ash. Class F fly ash has pozzolanic properties, and class C fly ash has both pozzolanic and cementitious properties. Class F fly ash is typically used at 15–25% by mass of the cementitious material, and class C at 15–40% by mass. Requirements for class C and F fly ash are provided in ASTM C618-12 [56].

Fly ash particles less than 50 μm are generally spherical and the larger sizes tend to be more irregular. The spherical particles confer significant benefits to the fluidity of the concrete in a plastic state by optimizing the packing of particles. The fly ash spheres appear to act as 'ball bearings' within the concrete reducing the amount of water required for a given workability. In general, the finer a fly ash the greater the water reducing effect. Visually fly ash concrete may appear to be very cohesive, until some form of compactive effort is applied. Any reduction in water content reduces bleeding and drying shrinkage [59].

4- Silicone rubber

Silicone rubber is an elastomer (rubber-like material) composed of silicone itself a polymer containing silicon together with carbon, hydrogen, and oxygen. The name silicone was given in 1901 by Kipping to describe new compounds of the generic formula R_2SiO . These were rapidly identified as being polymeric and actually corresponding to polydialkylsiloxanes, with the Formulation, Where R represents methyl or phenyl or vinyl or trifluoropropyl. Structure of Silicone rubber is shown in Figure (2.5) [60].

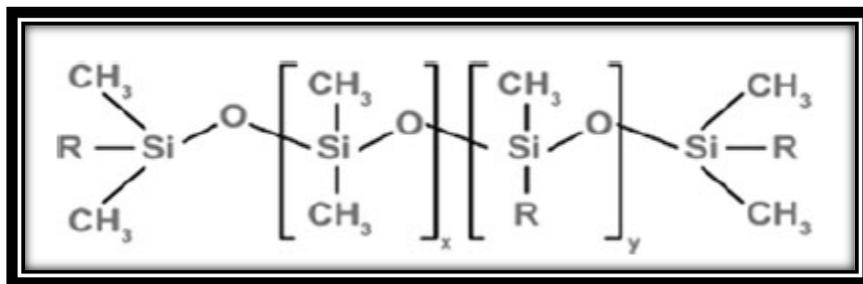


Figure (2.5) Silicone rubber structure [17].

5- Crumb rubber

Crumb rubber is a waste tire in which the size of the whole tire is reduced and grinded into smaller particle ranging from 4.75 mm to 75 μ m [61]. It is produced in a special mill through grinding of the waste tire to granular sizes between 0.425 mm to 4.75 mm, with different sizes produced based on the properties and temperature of the milling machine generated [62]. It can be used as a partial replacement of fine aggregate in concrete or mortar [61, 62].

Crumb rubber is being used in concrete as a partial replacement to fine aggregate to produce rubbercrete [63]. In comparison to fine aggregate it has lower specific gravity ranging from 0.51 to 1.2, bulk density ranging from 524 kg/m³ to 1273 kg/m³, lower water adsorption, strength and stiffness [64].

Crumb rubber is hydrophobic and non-polar material which repels water and entraps air into its surface [65]. It also has a different gradation compared to fine aggregate which falls below the lower limit of the curve in particle size analysis. Therefore, when it partially replaced fine aggregate in rubbercrete, it changes the grading to a non-continuous aggregate gradation. Partial replacement of fine aggregate with crumb rubber in rubbercrete is normally done by volume of the materials due to the lower specific gravity of crumb rubber compared to fine aggregate [66].

3.1 Introduction

This chapter includes a brief description to the used materials which are unsaturated polyester, silicone rubber, aggregates, fly ash and crumb rubber. Preparation of polymer concrete and characterization techniques used such as splitting tensile strength, FTIR, compressive strength, dynamic response and density. Figure (3-1) shows a brief description to the process of preparation and characterization of PC.

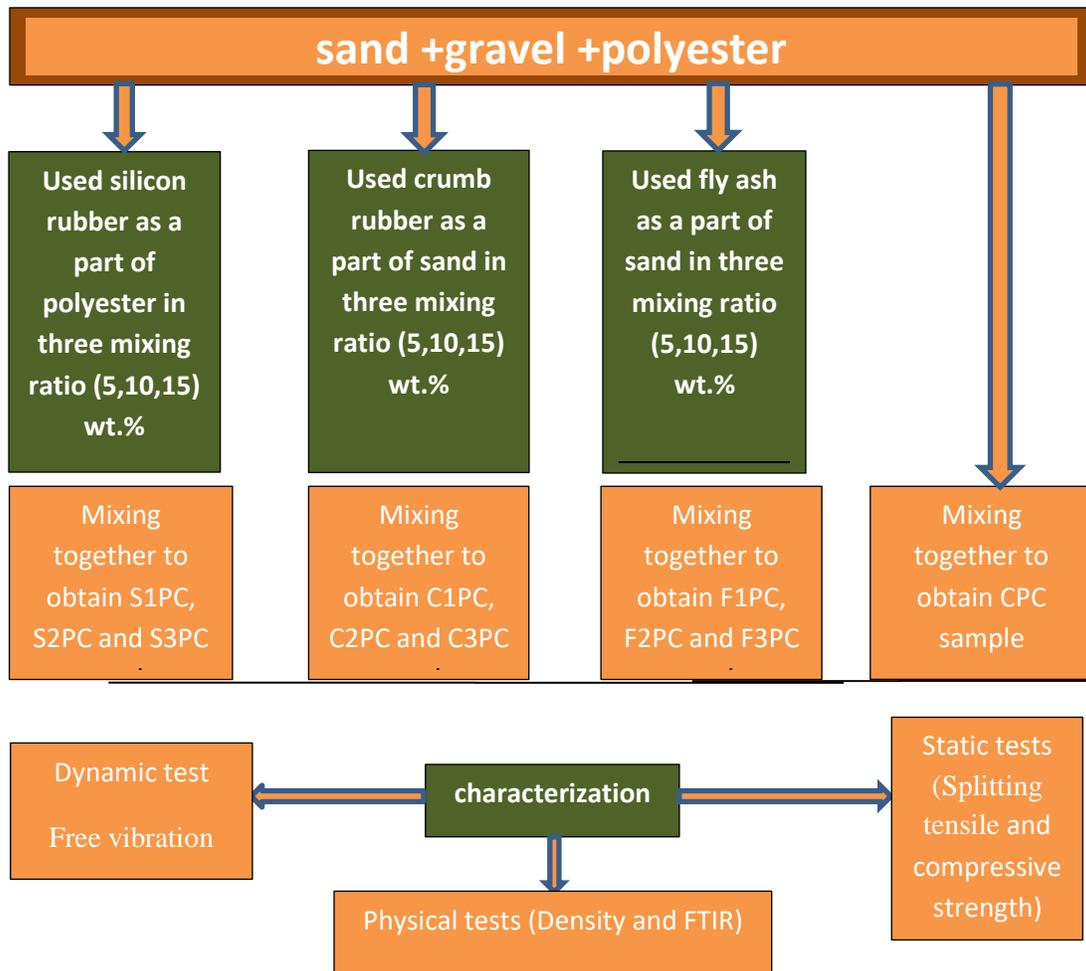


Fig. (3-1). Flow chart for producing and characterization of polymer concrete.

3.2 Materials

3.2.1 Unsaturated polyester

Unsaturated polyester resin used as a binder material and employed in production of polymer concrete samples in this study. It has been brought from Saudi Industrial Resins Factory, Jeddah. The properties maintain in Table (3-1).

Table (3-1): Properties of the used unsaturated polyester *.

Property	Data	Unit
Density	1300	kg/m ³
Appearance	Clear ,yellowish	-----
Viscosity	450 – 700	cps
Water absorption	1	%
Specific Gravity	1.04 ± 0.2	-----
Tensile strength	33.5 - 70	MPa
Elastic modulus	3.102 – 10.6	GPa
Elongation at break	0.5 – 5	%
Flexural strength	76 – 120	MPa

**according to manufacturer*

3.2.2 Silicone rubber

Silicone rubber is an elastomer (rubber-like material) in liquid state. It is containing silicon together with carbon, hydrogen, and oxygen. It is generally nonreactive, stable, and resistant to extreme environments and temperatures.

Silicone has been brought from Iraqi rubber company, the properties maintain in Table (3-2).

Table (3-2): Properties of the used Silicone rubber *.

Property	Data	Unit
Viscosity	3000 \pm 500	cps
Density	1500	kg/m ³
Hardness	61	Shore A
Elongation	550 \pm 50	%
Shrinkage Rate	0.1	%
Tensile Strength	9.77 – 10.14	MPa
Elastic modulus	0.05	GPa

*According to manufacturer

3.2.3 Sand

Al-Ukhaidher natural sand was used in the concrete mixes of this study. The grading and sulfate salts content of the fine aggregates conform to the Iraqi standard specification (I.O.S.) No.45/ 1984 [67] as shown in Tables (3-3) and (3-4), the dry density of fine aggregate is (1750) kg/m³. the grading test employed for this work is located in ceramic and building materials department at university of Babylon as shown in Figure (3-2).

Table (3-3): Sieve analysis of sand.

Sieve number	Sieve Size (mm)	Passing %	IQS 45-1984 [68] zone 3
1	9.5	100	100
2	4.75	98	100-90
3	2.36	93	100-85
4	1.18	89	100-75
5	0.6	72	79-60
6	0.3	27	40-12
7	0.15	7	10-0

Table (3-4): Sand sulfate salts content result.

SO ₃ % content	The allowable percentage limit	The test result
% 0.3818	% 0.5	Acceptable according to IQS 45-1984 requirement



Fig. (3-2). Sand grading test.

3.2.4 Gravel

In this investigation used Al-Nebae natural crushed gravel, the gravel cleaned and washed by municipal water several times and allowed to dry in the air. Tables (3-5) and (3-6) show the sulfate salts content and grading of the coarse aggregate according to the Iraqi standard specification (I.Q.S.) No.45/ 1984 [67], the dry density of coarse aggregate that was used in the experiment is (1650) kg/m³. In this research used only gravel with sieve size (5 and 10) mm. the grading test employed for this work is located in ceramic and building materials department at university of Babylon as shown in Figure (3-3).

Table (3- 5): Sieve analysis of gravel.

Sieve NO.	Sieve size (mm)	Passing %	IQS 45-1984 [68]
1	37.5	100	100-95
2	20	65	70-35
3	10	15	40-10
4	5	0	5-0

Table (3- 6): Sulfate salts content result.

SO ₃ % content	The allowable percentage limit	The test result
% 0.03	% 0.1	Acceptable according to IQS 45-1984 requirement



Fig. (3-3). gravel grading test.

3.2.5 Fillers

3.2.5.1 Fly ash

Fly ash obtained locally from the residuals of burning coal. The particle size distribution was obtained using particle size analyzer device as shown Figure (3-4), it can be observed that the fly ash had a minimum particle size of about $10\ \mu\text{m}$ with a maximum of $90\ \mu\text{m}$. The true density of fly ash is $0.0367\ (\text{g}/\text{cm}^3)$ was measured using high precision density tester GP-120S.

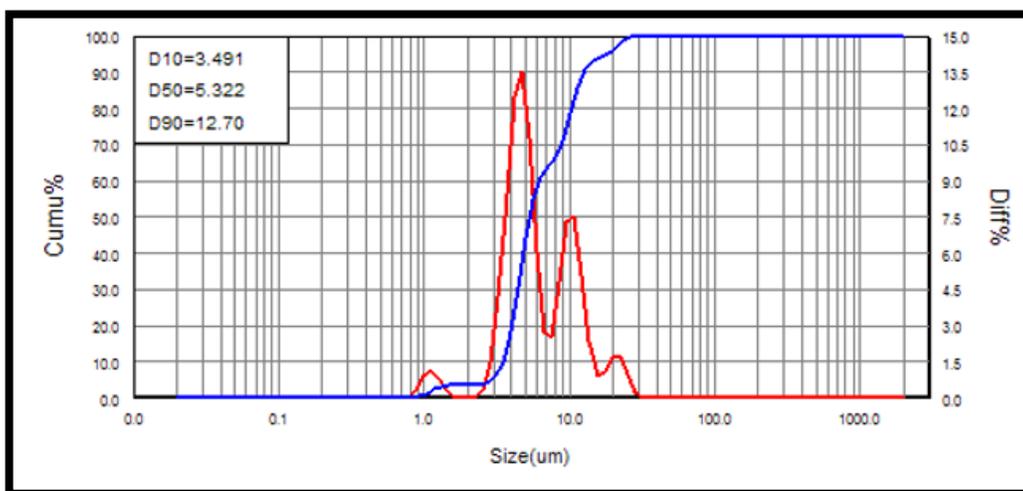


Fig. (3-4). Particles size distributions for fly ash.

3.2.5.2 Crumb rubber

Crumb rubber obtained from tire factory in Babylon. From sieve analysis, the particle size of crumb rubber is 200 μm . The true density of crumb is 0.3641 (g/cm^3) measured using high precision density tester GP-120S. Rubber treatments with NaOH to improve rubber adherence to polyester resin. In rubber treatment, a mixing ratio of (1:30 w/v) was used. For every 30 ml of distilled water, 1 g of sodium hydroxide is added, then the rubber is immersed in the solution for 24 hours before being rinsed numerous times with distilled water until the pH reaches 7. The effects of the treatments on rubber crumb surfaces were studied using Fourier transform infrared spectroscopy (FTIR). Rubber crumbs with a surface treatment are capable of increasing surface energy and thus improving the wettability of the polyester matrix on the rubber. Surface treatment with NaOH resulted in oxidation and sulphonation of the rubber, as well as an aging effect. On the rubber surface, oxidation, sulphonation, and aging introduced functional groups containing oxygen, such as carbonyl, carboxyl, and hydroxyl. The extent to which polyester may spread over a rubber solid surface is known as wettability. The interfacial adhesion between the polyester and the rubber might be poor or strong depending on the surface morphology, surface energy, and contact angle between them. Rubber is normally hydrophobic and has a low surface energy without any treatment.

3.3 Samples Preparation

3.3.1 Molds Preparation

For compressive strength test, cube samples are used. The size of cubical mold was (70.7 X 70.7 X 70.7) mm. The mold is made of steel and is located

in the laboratories of the Faculty of Materials Engineering as shown in Figure (3-5).



Fig. (3-5). cubical mold of compressive strength test.

For splitting tensile strength test, cylindrical samples are used. Cylindrical mold used in diameter 50 mm and height 100 mm. The mold is a tube made of a polymeric material that has been cut according to the required dimensions as shown in Figure (3-6).

For dynamic response test, beam samples were used. The size of mold was 250 mm long, width 25 mm and the thickness 15 mm. The mold made of PMMA polymeric material that has been cut according to the required dimensions as shown in Figure (3-7).



Fig. (3-6). Cylindrical mold of splitting tensile strength test.



Fig. (3-7). mold of dynamic response test.

3.3.2 Mixing of samples

It is important to use the correct mixing ratios to produce a tough, long life, and durable concrete. PC mix ratio is an important factor in determining the compressive strength of the concrete mixture.

Various mixing ratios were used to obtain control mix of polymer concrete as shown in Table (3- 7) and Figure (3-8). The control mixing ratio is (1:2:2). The control mix of polymer concrete (CPC) was prepared with unsaturated polyester resin in a dosage of 20 wt.%, sand 40 wt.% and gravel 40 wt. %.

Table (3- 7): Various mixing ratio of polymer concrete.

Grade of concrete	Mixing ratio (Resin :Sand: Gravel) wt.%
M1	1: 0.5 : 0.5
M2	1: 1: 1
M3	1: 2 : 1
M4	1: 2: 4
M5	1: 2 : 2

The following is a description of PC production as shown in Figure (3-9). Firstly, gravel and sand are mixed together in dry state. After that, at room temperature, the resin is blended with gravel and sand. Then, the hardener is added to begin the process of curing. The hardener initiates and accelerates the polymerization reaction. Curing occurs when styrene reacts polyester chains' reactive double bonds. The ratio of hardener is 1 wt. % of polyester.



Fig. (3-8). Various mixing ratio of PC.



Fig. (3-9). The steps of production PC.

Table (3-8) shows nine PC mixtures made with various additives (fly ash, silicone rubber, and crumb rubber).

Fly ash and crumb rubber were used as part of the sand in polymer concrete PC, while silicone rubber was used as part of the unsaturated polyester resin. The material's densities were used to convert these proportions to weighted percentages.

Table (3-8).: Mixing ratio of polymer concrete.

Sample item	Resin (Wt. %)	Sand (Wt. %)	Gravel (Wt. %)	Additive (Wt. %)
CPC	20	40	40	-----
Sample item	Resin (Wt. %)	Sand (Wt. %)	Gravel (Wt. %)	Fly Ash (Wt. %)
F1PC	20	35	40	5
F2PC	20	30	40	10
F3PC	20	25	40	15
Sample item	Resin (Wt. %)	Sand (Wt. %)	Gravel (Wt. %)	Crumb Rubber (Wt. %)
C1PC	20	35	40	5
C2PC	20	30	40	10
C3PC	20	25	40	15
Sample item	Resin (Wt. %)	Sand (Wt. %)	Gravel (Wt. %)	Silicon Rubber (Wt. %)
S1PC	15	40	40	5
S2PC	10	40	40	10
S3PC	5	40	40	15

3.3.3 Casting of samples

Before casting, the molds were carefully oiled to be ready for casting fresh PC. The mixture was added to mold and allowed to cure at room temperature as shown in Figure (3-10). Then, the sample removed from the molds and kept at room temperature for seven days until taken to the test as shown in Figure (3-11).



Fig. (3-10). casting of mixture into molds.



Fig. (3-11). samples after removed the molds.

3.4 Characteristic of polymer concrete

3.4.1 Compressive Strength

According to ASTM C579-12 specification [68]. The cubes samples were examined with an age of (7 days) with a compression testing machine located in ceramic and building materials department at university of Babylon, which is a destructive test device with a rate of loading 41 MPa/min and 2000 kN capacity as shown in Figure (3-12). Three samples were examined and the strength of three cubes in each type of mixture were taken. The compressive strength is calculated from the following equation:

$$\sigma_c = \frac{F_{\max} \times 1000(N)}{A(mm^2)} \dots\dots\dots (3- 1)$$

Where: σ : Compressive Strength (N/mm²) F: Maximum load (N) A: Area of the cube (mm²).



Fig. (3-12). compressive strength test devise.

3.4.2 Infrared Fourier Transform Spectrometer (FTIR)

Fourier transforms infrared technique used to characterize the prepared samples using instrument type (IR Affinity-1) made in (Kyoto Japan) located in Polymer and Petrochemicals Department as shown in Figure (3-13). In order to measure a sample, calibrate the device using the KBr, and then prepare a powder of the sample to be examined, and mixed with KBr (mixing ratio 99% KBr). FTIR spectrum provides a diagram between the permeability or absorption and the number of waves that show the chemical composition of the material. This test carried out according to ASTM E1252 [69].



Fig. (3-13). Infrared Fourier Transform Spectrometer.

3.4.3 Splitting Tensile Strength

According to ASTM C496-17 specification [70], the cylindrical test sample is placed in a horizontal position on its side, and the sample fracture is the

result of the side tension effect associated with carrying the pressure affected by the test machine on the sample, compression testing machine located in ceramic and building materials department at university of Babylon, which is a destructive test device with a rate of loading (0.7-1.4) MPa/min. Figure (3-14) shows the device for this test. The splitting tensile strength is calculated from the following equation:

$$f_{rt} = \frac{2 \times P}{\pi \times D \times L} \dots\dots\dots (3-2)$$

Where: f_{rt} : splitting tensile Strength (N/mm^2) P: Maximum load (N) D: Cylinder diameter (mm) L: Cylinder length (mm)



Fig. (3- 14). Splitting tensile strength test device.

3.4.4 Density

Figure (3-15) shows the high precision density tester, that the specification of this machine is digital accuracy = $\pm 0.0001 \text{ g/cm}^3$, type GP-120 S, which work according to ASTM D-792 [71], made in Matsu Haku, China. Where the Liquid density mode GP-120S device was used to measure the density of the sample. In this test, samples from any previously performed test have been measured their density, this method can be used with sheet, rod, tube and molded articles also powders, the specimen was weighed in the air then in distilled water at 23°C using a sinker and wire to hold the specimen completely submerged as required.

$$\text{Density} = W_{\text{body in air}} / (W_{\text{body in air}} - W_{\text{body in water}}) * \text{fluid density} \dots\dots\dots (3-3)$$



Fig. (3-15). Density device.

3.4.5 Fundamental Natural Frequency and Damping Factor

Vibration characteristics such as the fundamental natural frequency (f_n) and damping factor (ζ) were measured using ceramic shear accelerometer model 352C22 from PCB Piezotronics. The accelerometer dynamic signal was acquired using National Instruments (NI) Data Acquisition (DAQ). These characteristics were measured by attaching an accelerometer at the free end of a cantilever composite beam as shown in Figure (3-16), this test is located in mechanical engineering at university of Babylon as shown in Figure (3-17).

The acceleration data was analyzed using LabVIEW software. The acceleration-time domain was transferred to the amplitude-frequency domain to the natural frequency of the composite samples.

Damping ratio (ζ) and quality factor (Q) were determined from the frequency domain using half-power bandwidth method as shown in Figure (3-18). The test was repeated three times for each specimen and the average values have been considered.

The plateau in the amplitude-frequency domain represents the fundamental frequency. The damping ratio corresponding to this peak could be determined using equation (3.4)

$$\zeta = \frac{f_2 - f_1}{2 f_n} \quad \dots\dots\dots (3-4)$$

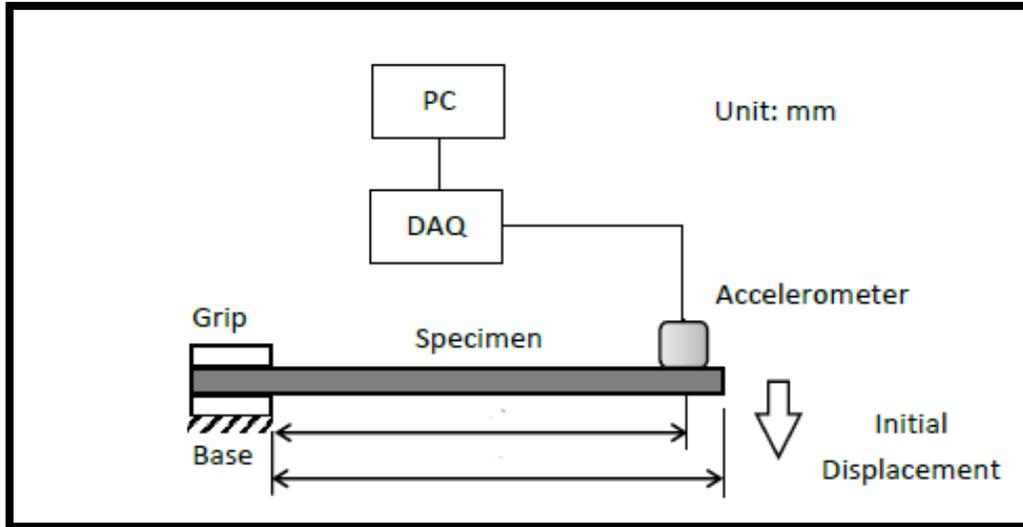


Fig. (3-16). Schematic diagram of damping test.

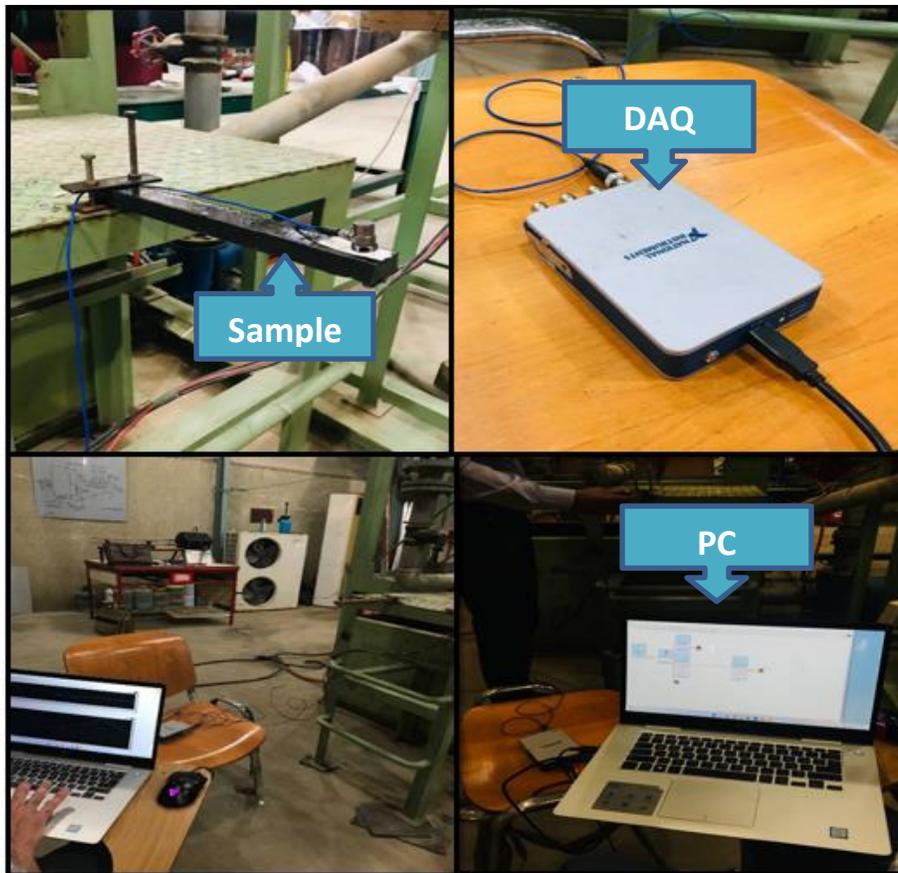


Fig. (3-17). The specimen and testing setting of dynamic properties.

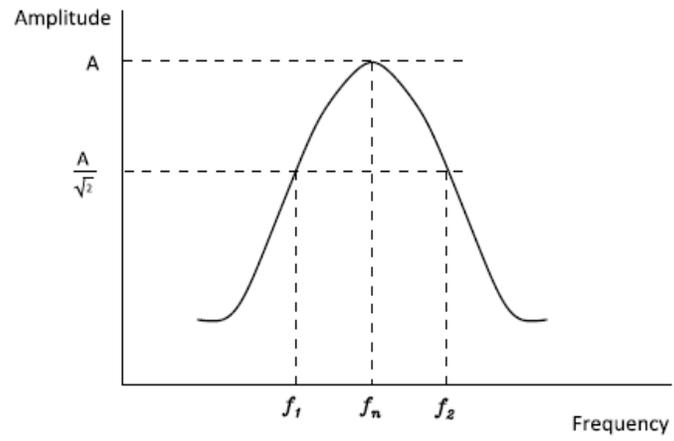


Fig. (3-18). Half-power band method.

4.1 Introduction

This chapter discusses all the experimental results obtained from the physical, static and dynamic tests. In addition, compares the results of different additives with control polymer concrete (CPC) sample to evaluate the performance of polymer concrete and known the effect of additives on the properties of concrete.

4.2 Results of Physical tests

4.2.1 Density

The true density (g/cm^3) was measured using a high precision density tester (GP 120S). According to Figure (4-1), the density of PC was decreased with increase in fly ash content because fly ash added to PC as part of sand has low density $36.7 (\text{kg/m}^3)$ compared to the density of sand $1750 (\text{kg/m}^3)$.

The density varied between 2040 and 1900 kg/m^3 for the mix with crumb rubber as shown in Figure (4-1). The decrease in density of PC with increasing crumb rubber is due to the lower density of the crumb (364.1 kg/m^3) compared to sand (1750 kg/m^3).

The slight decrease in density as shown in Figure (4-1) due to the value of silicone rubber density (1500 kg/m^3) is closer to the density of polyester (1300 kg/m^3) and the high porosity of silicone.

The density of all mixes was smaller than that of control mix, which had a density of 2240 kg/m^3 . It also shows a significant decrease in the weight and density of concrete due to the low density used materials.

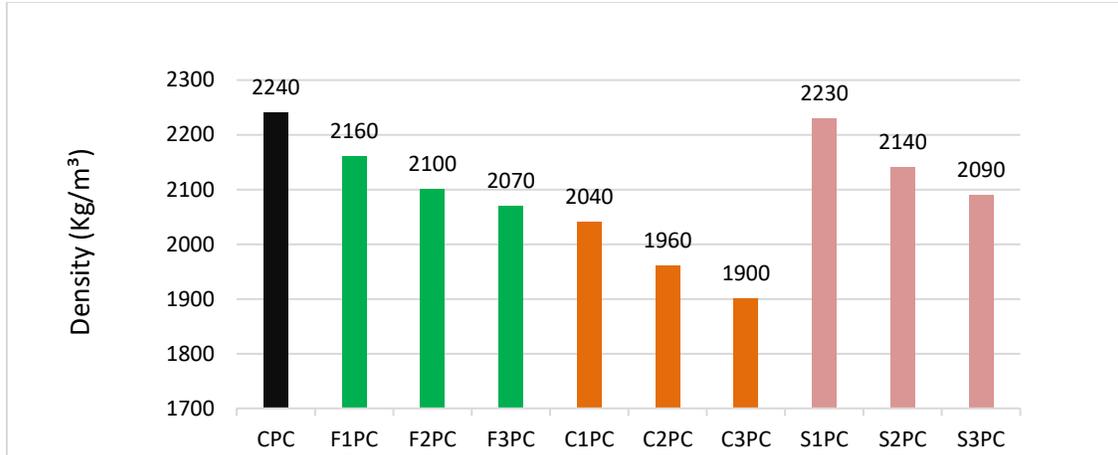


Fig. (4-1). Densities of different types of polymer concrete mixture.

4.2.2 Fourier Transform Infrared Spectroscopy Analysis (FTIR)

Figure (4-2) shows the study of the FTIR spectra, surface alteration on the rubber surface and changing the polarity of the surface. More polar groups on the surface result from surface changes. Higher polarity is expected to increase the surface energy of the rubber surface and initiate more interactions with the polyester polar groups. Improved rubber hydrophilicity and greater adhesion between rubber and polyester improved composite tensile strength.

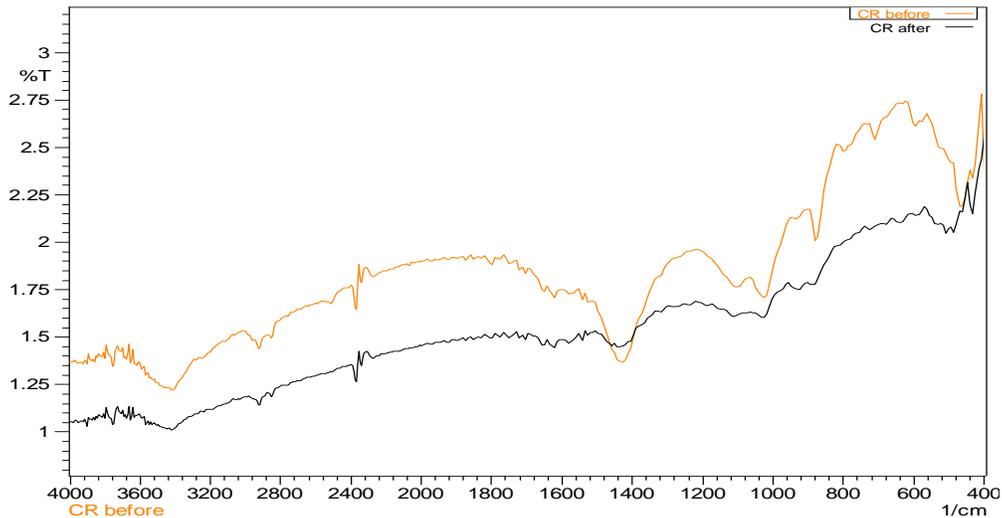


Fig. (4-2). Crumb rubber before and after treatment.

4.3 Results of static tests

4.3.1 Compressive Strength

The compressive strength of cubic samples from the compressive strength measurement instrument by applying Equation (3- 1), at 7 days of age. Figure (4-3) shown when (5,10,15) wt.% of sand is replaced with fly ash, compressive strength is typically increased as agreed with [72,73]. The reason for this occurrence could be that fly ash is more workable than sand. The fine and spherical fly ash particles improve the lubricating properties of the fresh polymer concrete mix, increasing its plasticity and cohesiveness. When employing a significant amount of fly ash, caution should be taken because the material's high surface area can make the mix overly sticky and unworkable.

As the percentage of crumb rubber increases, the compressive properties of the concrete decrease as shown in Figure (4-3). The reduction in strength is primarily due to the relatively low strength and elastic modulus of the crumb rubber. In addition, it was reported that the interaction between polyester and crumb particles was weaker than that in the case of polyester resin and sand. The stiffness difference between rubber and normal fine aggregates is the main reason for the strength reduction. The result has shown that with increasing content of rubber in the PC mix, the compressive strength of the material decreases drastically as agreed with [74]. These results also demonstrate that the surface treatment with NaOH solution can enhance the bonding strength between the resin and rubber. However, the strength still decreases with increasing NaOH-treated particles in agreement with [75].

The highest value of the compressive strength 57.95 N/mm^2 in the case of PC with silicone rubber was obtained for the mixture S1PC as shown in Figure (4-3). Because polyester is amorphous polymers, their molecular chains are random and contain voids. Therefore, when rubber is added to it, the rubber fills the voids, and thus the mechanical properties increase. Increased silicone rubber content in PC leads in a decrease in compressive strength due to high porosity and weak adhesion to resin. Figure (4-4) shows the failure sample after applied compressive stress.

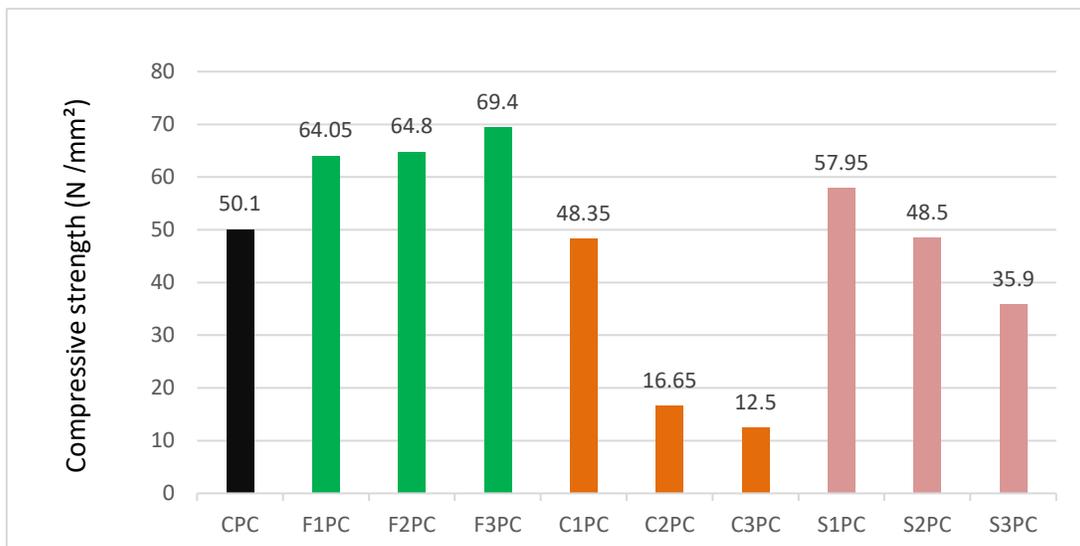


Fig. (4-3). Compressive strength of different types of PC mixture.



Fig. (4-4). Failure of compressive strength samples.

4.3.2 Splitting Tensile Strength

Figure (4-5) shows the average of splitting tensile strength of the cylinder samples from the compressive strength device at the age of 7 days, by applying the Eq. (3-2). Fly ash provide a highly adhesive interfacial bonding between the polymeric matrix and the aggregate lead to increase the value of splitting tensile strength when increase the wt.% of fly ash.

The decrease in split tensile strength with an increase in silicone rubber may be due to the lower adhesion of resin to rubber compared to resin to aggregate in polymeric concrete and a higher level of porosity of the material. The highest value of the split tensile strength 10.3 N/mm² in the case of PC with silicone rubber was obtained for the mixture S1PC as shown in Figure (4-5). Because polyester is amorphous polymers, their molecular chains are random and contain voids. Therefore, when rubber is added to it, the rubber fills the voids, and thus the mechanical properties increase.

Crumb rubber has less surface energy and a rougher surface compared to fly ash, which may lead to less adhesion and a reduction in splitting tensile strength as a greed in previous work [74] as shown in figure (4-5). The tensile strength of the crumb rubber -unsaturated polyester composite decreased with increased rubber crumbs content. The decrement of tensile strength was caused by weak filler-matrix interfacial adhesion between rubber crumbs and polyester. Weak interfacial adhesion causes inefficient stress transfer between fillers and matrix so that lower load is needed to cause the composite failure. Poor interfacial rubber-polyester adhesion is also caused by hydrophobic nature of rubber. Hydrophobic behavior causes the inhomogeneous distribution of rubber crumbs within polyester and insufficient matrix to hold

the fillers. The high tensile stress is responsible to cause microcracking at the interfacial transition zone. The tensile capacity of polymer matrix is significantly high as agreed with [77]. Figure (4-6) shows the failure sample after applied splitting tensile stress.

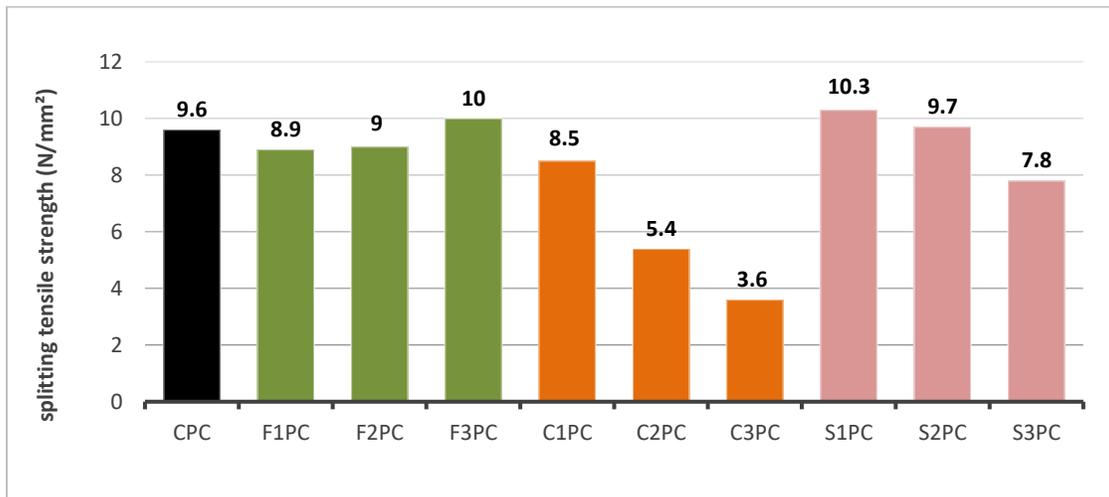


Fig. (4-5). splitting tensile strength of different types of PC mixtures.



Fig. (4-6). Failure of splitting tensile strength sample.

4.4 Results of dynamic test

4.4.1 Fundamental natural frequency and damping factor

A variety of methods can be applied to measure the damping ratio, including the free vibration method, resonant frequency method, semi-power method and duplicate rigidity method.

The Figures below obtained from free vibration device represent the frequency of all polymer concrete mixtures. It can be said that decreasing resonance frequencies were observed along with increasing amounts of rubber in the composite as agreed with [76].

The lowering of the natural frequency resulted directly from the lowering of the static stiffness of the samples. In the case of sample C1PC and S1PC, in which the amount of rubber in the samples was the smallest, the frequency reduction was also the smallest, because the stiffness of these samples was the highest compared to sample C3PC and sample S3PC as shown in figures (4-5) and (4-6). The highest amplitudes for resonance vibrations were noticed for the (C1PC) sample as shown in Figure (4-5). The tests indicate that as the amount of rubber in the material increases, the amplitude decreases as shown in figures (4-5) and (4-6).

It can be seen in figure (4-7), that the amplitude slightly increased with increase in fly ash ratio. This is due to the strong adhesion between fly ash and resin.

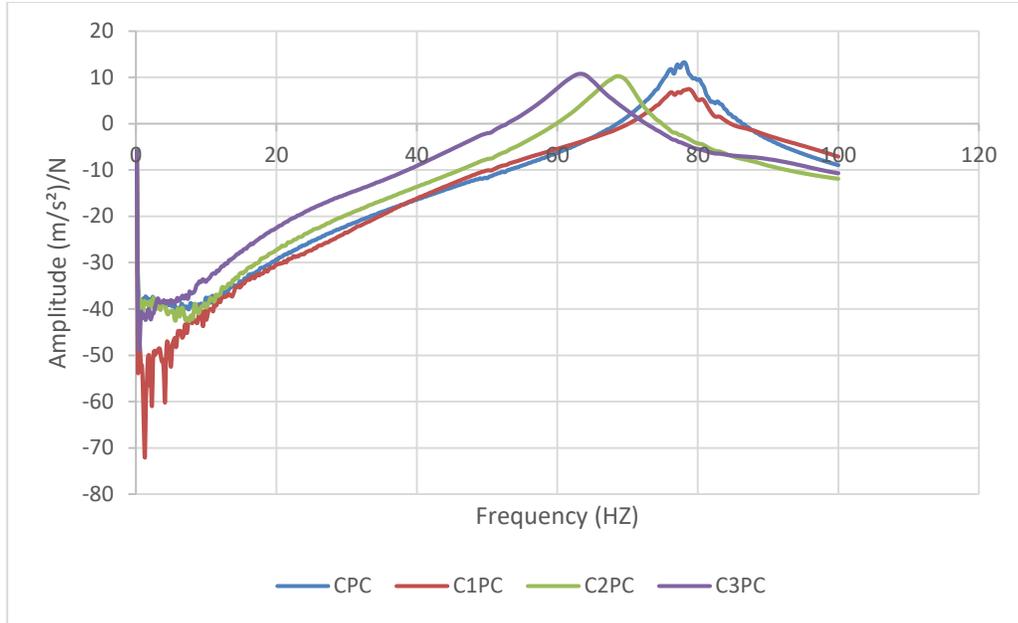


Fig. (4-7). Fundamental natural frequency of PC with crumb rubber additive.

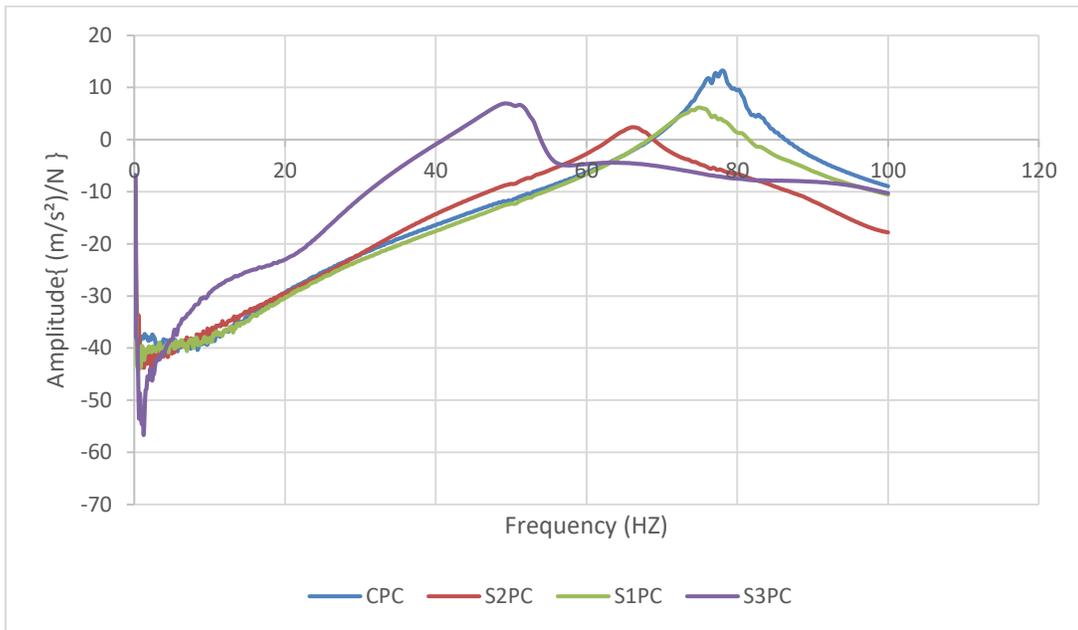


Fig. (4-8). Fundamental natural frequency of PC with silicone rubber additive

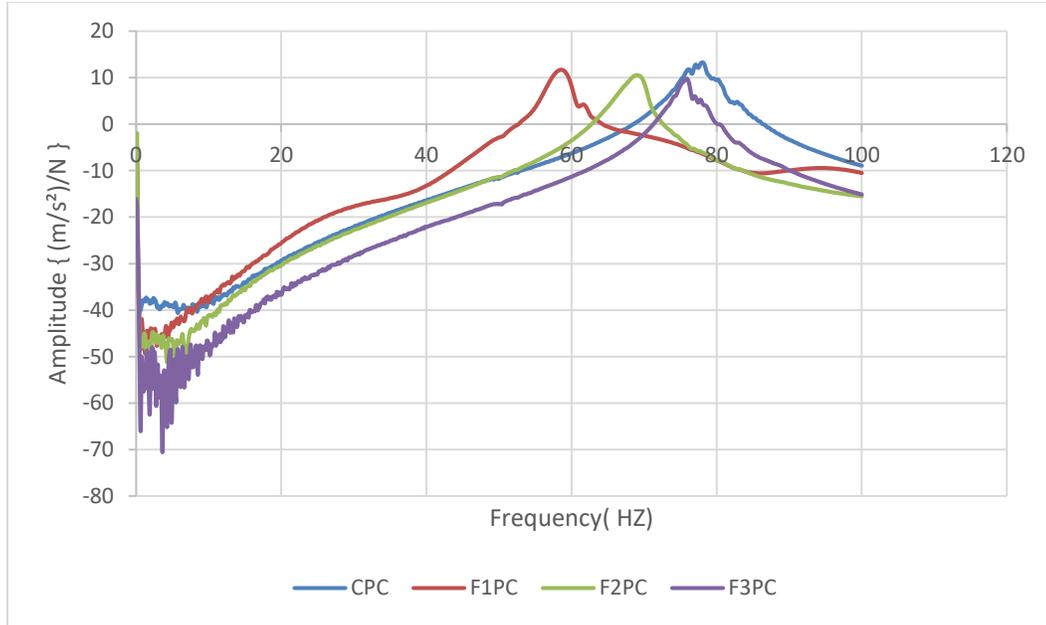


Fig. (4-9). Fundamental natural frequency of PC with fly ash additive.

The classical method of determining the damping at a resonance, using a frequency analyzer, is to identify the half power (-3 dB) points of the magnitude of the frequency response function. Eq. (3-4) can be used to compute the damping ratio.

It was also clearly displayed in Figure (4-8), that the damping ratio was remarkably increased with the increase in rubber dosage, which was expected to be related to the elasticity of the chains and their ability to dissipate energy.

Damping ratio of polymer concrete that contain fly ash is significantly lower than the control concrete sample (CPC) as shown in figure (4-24). This is probably due to the low elastic modules of fly ash in polymer concrete. The combination of rubber and polymer concrete allows a material with even better dynamic properties to be obtained.

The sample that included 15% silicone rubber had the highest damping ratio 8%. Damping ratio of the sample containing 15% fly ash was at least doubled. According to Figure (4- 8), rubber improves the damping ratios of polymer concrete as agreed with previous work [76]. Samples with the greatest amount of rubber experienced the most significant increase. The best results of different additives of PC maintained in Table (4-1).

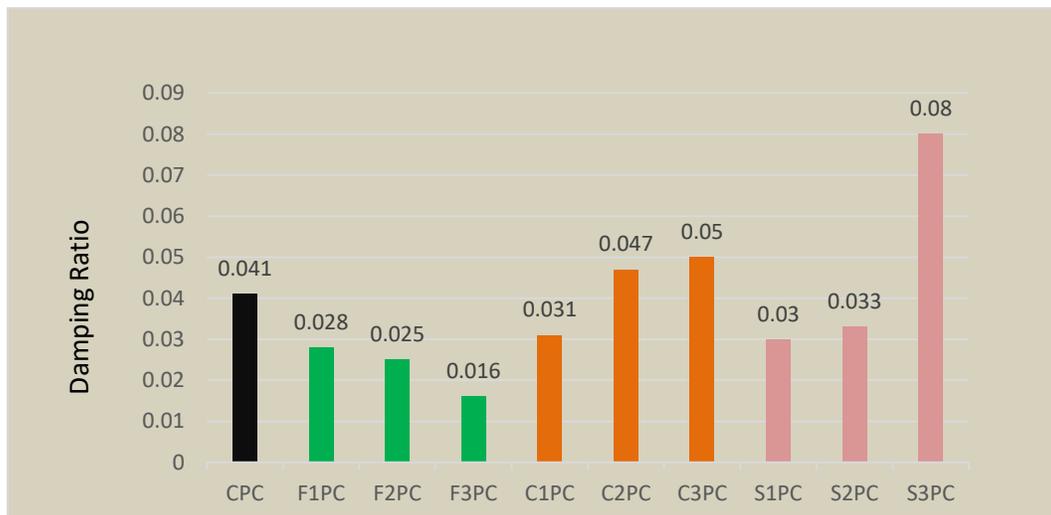


Fig. (4-10). Damping ratios for samples.

Table (4-1): The best result for every additive.

property	C1PC	C2PC	C3PC	S1PC	S2PC	S3PC	F1PC	F2PC	F3PC
Compressive strength	✓	-	-	✓	-	-	-	-	✓
Splitting tensile strength	✓	-	-	✓	-	-	-	-	✓
Damping	-	-	✓	-	-	✓	✓	-	-

5.1 Conclusions

The following are the conclusions that may be derived from this work:

1. To generate a homogenous and workable PC mix with a uniform distribution of aggregates, the ideal resin-to-aggregates ratio is 20:80.
2. Increased rubber content in PC leads in a notable improvement in dynamic characteristics. The damping enhanced by 95% of CPC for 15% silicone rubber resin replacement.
3. Addition of fly ash has a significant effect on the mechanical properties. Enhancement in compressive strength is up to 38% of CPC for 15 wt.% fly ash replacement.
4. The significant drop in mechanical characteristics of the PC doped with rubber may be due to the weaker adherence of resin to rubber compared to adhesion of resin to aggregates in polymer concrete, as well as a higher level of material porosity.

5.2 Recommendations

There are recommendations that may be useful for further work in this field, which are:

1. Prepare polymer concrete with another thermoset resin like epoxy.
2. Use other additives like (silica fume, waste of plastic) and study the effect of additives on mechanical properties.
3. Study of other properties of concrete such as fatigue strength, flexural strength, impact resistance.

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