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Review Article

Mechanical Properties of Polymer Concrete

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Polymer concrete was introduced in the late 1950s and became well known in the 1970s for its use in repair, thin overlays and floors, and precast components. Because of its properties like high compressive strength, fast curing, high specific strength, and resistance to chemical attacks polymer concrete has found application in very specialized domains. Simultaneously these materials have been used in machine construction also where the vibration damping property of polymer concrete has been exploited. This review deals with the efforts of various researchers in selection of ingredients, processing parameters, curing conditions, and their effects on the mechanical properties of the resulting material.

1. Introduction

Polymer concrete is a composite material which results from polymerization of a monomer/aggregate mixture. The polymerized monomer acts as binder for the aggregates and the resulting composite is called "Concrete." The developments in the field of polymer concrete date back to the late 1950s when these materials were developed as replacement of cement concrete in some specific applications. Early usage of polymer concrete has been reported for building cladding and so forth. Later on because of rapid curing, excellent bond to cement concrete and steel reinforcement, high strength, and durability, it was extensively used as repair material [1]. Precast polymer concrete has been used to produce a variety of products like acid tanks, manholes, drains, highway median barriers, and so forth.

The properties of polymer concrete differ greatly depending on the conditions of preparation. For a given type of polymer concrete, the properties are dependent upon binder content, aggregate size distribution, nature and content of the microfiller, curing conditions, and so forth [2]. The most commonly used resins for polymer concrete are unsaturated polyester resin, methyl methacrylate, epoxy resins, furan resins, polyurethane resins, and urea formaldehyde resin [3]. Generally, more than 75–80% volume in polymer concrete is occupied by the aggregates and fillers. The aggregates are normally taken as inert materials dispersed throughout the polymer matrix. Normally aggregates are added in two size groups, that is, coarse aggregates comprising material of more than 5 mm size and fine aggregates having size less than 5 mm. The grading of aggregates in the case of polymer concrete is nonstandardized till date and varies widely from system to system. In addition to the coarse and fine aggregates, microfillers are also added sometimes to the polymer concrete system mainly with an aim to fill the microvoids. Similar to the conventional concrete, polymer concrete can also be reinforced for improving its mechanical properties with different kinds of fibres. The use of steel, glass, polypropylene, and nylon fibres has been reported in the literature.

The importance of research on polymer concrete materials has been recognized as early as in 1971 with the setting up of ACI Committee 548—Polymers in Concrete. The Committee has been responsible for developing a large database on properties of polymer concrete. The Committee has also issued state-of-the-art reports and user guides on polymer concrete. RILEM (International Union of Testing and Research Laboratories for Materials & Structures) with setting up of Technical Committee TC-105-CPC (Concrete Polymer Composites) and TC-113-CPT (Test Methods for Concrete Polymer Composites) has been instrumental in preparing various test methods for these materials. Society of Material Science Japan (JSMS) has also contributed towards the development of polymer concrete materials with the help of Synthetic-Resins-for-Concrete Committee. Society of Material Science Japan has also published design recommendations for polyester concrete structures as well as a mix design guide. Amongst the countries which are using polymer concrete composites, the standardization work on various test methods and applications has been taken up mainly by Japan, United States, United Kingdom, Germany, and erstwhile Soviet Union.

Owing to their superior properties like rapid curing, high compressive strength, high specific stiffness and strength, resistance to chemicals and corrosion, ability to form complex shapes, excellent vibration damping properties, and so forth, polymer concrete materials have also been extensively used for applications other than for which these were originally developed. Use of polymer concrete has been reported in electrical insulation systems [4, 5] as well as machine tool applications since late 70s wherein these have been used to replace traditional materials like cast iron for machine tool bases [6–14]. Lot of research has been carried out in last few decades to develop promising applications of polymer concrete, that is, its use in machine tool structures [15–22]. However, before the potential of these materials as an alternative material can be fully harnessed, a methodology for assessment of the long term properties must be available.

2. Factors Affecting Properties of Polymer Concrete

Polymer concrete is prepared by mixing a polymeric resin with aggregate mixture. Microfillers are also employed sometimes to fill the voids contained in the aggregate mixture.

Polymeric resins that are commonly used in polymer concrete are methacrylate, polyester resin, epoxy resin, vinylester resin, and furan resins. Unsaturated polyester resins are the most commonly used resin systems for polymer concrete because of their low cost, easy availability, and good mechanical properties [23]. Furan resins are also used to a great extent in European countries. 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 [3]. The choice of particular type of resin depends upon factors like cost, desired properties, and 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 widespread 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 up to the same level by addition of microfillers and silane coupling agents [24].

The resin dosage reported by various authors mostly lie in the range of 10 to 20% by weight of polymer concrete. Early studies on polyester resin concrete while taking resin content as a variable reported that compressive strength of polymer concrete is dependent upon the resin content [25]. Both the compressive strength and flexural strength increase with the increase in polymer content. After reaching the peak these either decrease or remain unchanged with further increase in the resin content. The lowest polymer content at which the properties are maximum will represent the optimum resin content for the system under study. It is observed that both flexural and compressive strength attain the maximum value between 14 and 16% resin content by weight. Further studies in this area have also provided similar results. Variation of compressive strength of polymer concrete for various types of resins and their dosage has been reported in the literature [26]. It was observed that the highest strength was obtained in all types of resins at a resin dosage of 12%. For two types of epoxy resins, the strength decreased by increasing the resin content to 15%, whereas, for polyester resin, it almost remained constant. The optimum resin content for a particular polymer concrete system is also dependent upon the nature of aggregate used in the system. Higher resin dosage is recommended when using fine aggregate, because of the large surface area of these materials [27–29].

Various types of aggregate materials have been used by the researchers, most of these based upon the choice of locally available materials to reduce the cost. River sand [30, 31], foundry sand [27, 32, 33], crushed stone [34, 35], quartz, granite [36–38], and gravel are some of the materials reported by various authors.

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 fibres, and polyester fibres have been added in polymer concrete in varying quantities for enhancement of its properties. Most of the studies have reported the addition of glass fibres in the range of 0 to 6% by weight of polymer concrete. It has been reported that addition of glass fibres improves the postpeak behaviour of polymer concrete. The strength and toughness of polymer concrete also increase with addition of fibres. Few studies on silane treatment of glass fibres before their use in polymer concrete report an enhancement in mechanical properties up to the extent of 25% [39]. Table 1 provides the details of the various types of reinforcements and their effect on the properties of polymer concrete as reported by various researchers.

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 has been reported in literature. Fly ash is a by the product 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 [37]. Addition of fly ash also improves the workability of fresh polymer concrete mix resulting in products with excellent surface finish [40]. Studies have shown that small size of spherical particles also contributes to a better packing of the aggregate materials which reduces porosity and hinders the penetration of

Table 1: Fibre reinforcements and their effect on polymer concrete.

Author	Resin	Aggregate	Fibers addition	Properties evaluated	Brief findings
Broniewski et al. [55]	Epoxy resin	Sand	Steel fibers of 0.24 mm diameter and 15 mm length, added in 0 to 3.5% by weight	Flexural strength, creep	Addition of 3.5% steel fibers increases the flexural strength by 40%.
Valore and Naus [56]	Polyester, vinylester, epoxy	—	Nylon, glass, aramid, steel fibers of length 12.7 to 38.1 mm	Compressive strength, Young's modulus, split tensile strength, and density	(i) Compressive strength increases as function of density. (ii) Flexural strength is related to compressive strength (inPsi) as $f_f = 25\sqrt{f_c}$ psi. (iii) Fiber addition increases flexural strength and ductility. (iv) Longer fibers have better effect on compressive strength.
Brockenbrough [57]	Methacrylate		(i) Steel fibres of 0.4 mm diameter, 1–3% (ii) Glass fibres of 12.7 mm length, 1–3%	Compressive strength, flexural strength, and split tensile strength	(i) Addition of steel fibers increases the compressive strength, whereas the addition of glass fibers decreases the compressive strength. (ii) Flexural strength of polymer concrete is observed to increase by addition of both steel and glass fibers.
Vipulanandan et al. [39]	(i) Epoxy (ii) Polyester	Ottawa sand, blasting sand	Glass fibres, 0–4%	Compressive strength, flexural strength, and split tensile strength	(i) Maximum compressive and flexural strength are reported at 14% resin content. (ii) Addition of glass fibers increases the flexural strength, compressive strength. (iii) Silane treatment increases the flexural strength by 25%.
Vipulanandan and Mebarkia [58]	Polyester	Blasting sand	Glass fibres, 0–6%	Flexural strength	(i) Flexural strength increases with increase in resin content. (ii) Addition of glass fibers is reported to enhance the strength and toughness of polymer concrete. (iii) Silane treatment of aggregate and fibers also enhanced the flexural strength.
Mebarkia and Vipulanandan [59]	Polyester	Blasting sand	Glass fibers of 13 mm length, 0–6%	Compressive strength	(i) For 18% resin and 4% glass fiber content, an increase of 33% in compressive strength was reported over unreinforced polymer concrete. (ii) Failure strain and toughness increase with addition of fibers.
Rebeiz [31]	Polyester	Gravel, dried sand	Steel fibers of 0.5 mm diameter and 30 mm length, 0–2% by weight	Compressive strength	(i) An optimum mix having 10% resin, 45% gravel, 32% dried sand, and 13% fly ash was reported. (ii) Polymer concrete achieves around 80% of the 28-day strength in one day. (iii) Addition of steel fibers beyond 1.3% increases the compressive strength of the specimens from 80 MPa to 100 MPa. (iv) Steel fibers also increase the ductility of the polymer concrete which results in a better postpeak behavior.
Sett and Vipulanandan [60]	Polyester	Blasting sand	Glass fibers and carbon fibers, 0–6% by weight	Compressive strength, tensile strength, and damping ratio	(i) Compressive strength and the failure strain are reported to increase by 40% by addition of 6% of glass fibers. (ii) Carbon fibers do not have any significant effect on the compressive properties. (iii) It was further observed that damping ratio of polymer concrete increased with addition of glass fibers and carbon fibers.

Table 1: Continued.

Author	Resin	Aggregate	Fibers addition	Properties evaluated	Brief findings
Laredo Dos Reis [32]	Epoxy	Foundry sand	Glass fibers & carbon fibers, 0–2% by weight	Compressive strength	(i) Addition of fibers increases the compressive strength by 27–45% for glass fibers and 36–55% increase for carbon fibers. (ii) Ductility of polymer concrete improved with addition of fibers.
Jo et al. [43]	Polyester	Pea gravel and siliceous river sand	Nano-MMT particles	Flexural strength, split tensile strength	(i) Polymer concrete mix was obtained using 11% resin content, 45% coarse aggregates, 35% fine aggregates, and 11% $CaCO_3$. (ii) It was found that flexural strength and split tensile strength increase with addition of nanoparticles.
Xu and Yu [61]	Polyester	Granite	Copper coated stainless steel fibers, L/d ratio of 70	Compressive strength	(i) Addition of steel fibers improves the properties of polymer concrete. (ii) Compressive strength of steel fiber reinforced polymer concrete is higher than that of plain polymer concrete.
Bai et al. [38]	Epoxy resin	Granite	Glass fibers of 5–25 mm length, added 1 to 5% by weight	Damping	(i) Granite mix is the most important parameter controlling the damping. (ii) Highest damping is reported for mix containing 16% epoxy resin, 5% glass fibers, and granite mix having high proportion of fine aggregate.

aggressive agents, thus considerably improving the chemical resistance of polymer concrete [23]. 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 up to 30% has been reported by addition of 15% fly ash in polymer concrete [41]. Addition of fly ash is also reported to have better performance enhancement when compared to addition of silica fume as a filler [42]. 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% [30]. It has been recommended by various researchers later on that the moisture content of the aggregate shall not exceed from 0.1% to 0.5% for better mechanical properties [41, 43–45].

Various curing regimes have been reported by researchers like room temperature curing, high temperature curing, water curing, and so forth. Curing time studies on polymer concrete have established that it achieves around 70–75% of its strength after a curing of one day at room temperature [31, 45, 46], whereas 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. It is observed that compressive strength of polymer concrete almost becomes constant after dry curing for a period of 7 days [47].

The influence of the aggregate grading on the properties of polymer concrete has been long known. The coarse and fine aggregate should be proportioned in such a way that aggregate mixture has minimum void content and maximum bulk density. This minimizes the amount of binder required to assure proper bonding of all the aggregate particles. Normally, the binder content ranges from 5% to 15% of the total weight but if the aggregate mix is fine, it may even require up to 20% binder. Very few studies have been reported in the literature regarding the proportioning of the aggregate mix in polymer concrete. Earlier studies in this regard have reported that polymer concrete made with aggregate grading according to Fuller's curve had the highest strength [30, 48]. Further it was reported that use of gap graded aggregate resulted in minimum void content. An empirical relation has also been suggested in the literature, which can be used to determine the proportions of coarse and fine aggregates of least-void content [49]. Later studies suggest the optimum mix composition of aggregate for minimising the void content based on design of experiments approach [50]. The mix composition suggested was again based upon the use of gap graded aggregates.

Since, for the cost considerations, the binder content used in polymer concrete materials is quite low, the adhesion of aggregates takes place through a fine layer of resin around the aggregates. A larger contact area is, therefore, desirable which necessitates a proper space filling of the gaps by smaller aggregates or microfiller particles. Use of a silane coupling agent (which strengthens the adhesion between the resin and the aggregates) improves the adhesion and thus the ultimate strength of the polymer concrete. Adhesion at the interface, in absence of any chemical bonding, may be sufficiently good even when it is due to secondary forces between two phases. The use of silane coupling agents, which may provide chemical bonding between the two phases, considerably improves the interfacial adhesion and therefore enhances the mechanical properties of these materials. A few studies on the use of various types of silane coupling agents have been reported in the literature. Various methods of application of silane agents like integral blend method and surface treatment method have been compared [24, 51, 52]. It has been reported that when using integral blend method of silane addition, 1% silane by the weight of resin gives optimum results [53, 54]. Compressive strength and flexural strength of polymer concrete containing silane coupling agents are 15 to 20% higher than those of normal polymer concrete [53].

2.1. Characterization of Mechanical Properties of Polymer Concrete. There have been a lot of studies reported on characterization of mechanical properties of polymer concrete since early 1970s. Table 2 summarizes the efforts of various authors and the major conclusions drawn based upon these studies.

2.2. Fatigue Studies on Polymer Concrete (PC). Studies on fatigue behaviour of polymer concrete are very scarce in the literature. The two million cycle fatigue endurance limit has been reported as a stress level of 59%, very similar to that of cement concrete [68]. A study to evaluate the effect of frequency of testing concluded that frequency of testing shall be taken as a parameter for fatigue testing of polymer concrete. Fatigue behaviour of polymer concrete has been described based upon *S-N* relationships. These relationships are based upon the basic power law functions. The research has shown that the empirical equations used to predict fatigue behaviour of plain concrete fit well for polymer concrete also [69]. Equation (1) as described for cement concrete was applied to fatigue data of polymer concrete [70]:

$$L = (10)^{-aS^b(\log N)^c}, \quad (1)$$

where L is the probability of survival, S is the stress level, N is number of cycles to failure, and a, b, and c are experimental constants.

Failure probability has been incorporated in the *S-N* relationships for polymer concrete to take care of the stochastic nature of fatigue [71].

3. Discussion

Polymer concrete has initially been developed as an alternative material in the domain of civil engineering but over a period of time, owing to its superior properties, has 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 mould into complex shapes, and excellent vibration damping properties are mainly responsible for its use in these applications. It has been observed that the properties of polymer concrete depend upon various parameters like type and amount of resin/polymer used, type and mix proportioning of aggregate, moisture content of aggregate, nature and content of reinforcing fibers, addition of microfillers, curing conditions, use of silane coupling agents, and so forth.

Epoxy resins provide better mechanical and durability properties than polyester, vinylester, furan, and methacrylate resins, but there is inherent high cost associated with these materials. The properties of polyester concrete can also be enhanced to the level of epoxy concrete by addition of microfillers and silane coupling agents. 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. The studies to find the optimum resin dosage for maximizing the mechanical properties have yielded different results depending upon the specific type of resin and aggregate used. It is observed that initially strength increases with increase in resin dosage, but, after reaching the peak, the same either decreases or remains unchanged with further increase in the resin content. Most of the researchers have reported maximum strength for resin dosage in the range of 12–16% by weight of polymer concrete.

Addition of various types of fibers like glass fibers, steel fibers, and carbon fibers in polymer concrete enhances its mechanical properties such as toughness, compressive strength, flexural strength, and fatigue strength. The usual range of fiber addition in polymer concrete is up to 6% by weight of polymer concrete. It was observed that silane treatment of fibers before addition into polymer concrete further enhances its mechanical properties. Addition of microfillers like fly ash, silica fume, calcium carbonate, and so forth in polymer concrete has been reported not only to enhance the mechanical properties but also to improve the workability of mix. Enhancement in compressive strength up to 30% has been reported with addition of 15% fly ash in polymer concrete.

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. The use of river sand, foundry sand, crushed stone, quartz, granite, and gravel has been reported. Till date no standard mix proportion and aggregate grading criterion are available for polymer concrete and, therefore, a number of optimized mix proportions are reported in the literature. These mixes are based upon various optimization criteria like Fuller's curve, and maximum bulk density, and minimum void content and have been developed for various types of locally available aggregates. Almost all the studies are in agreement that use of gap graded aggregate results in better mechanical properties. A few empirical relations are provided in the literature to determine the proportion of coarse and fine aggregates for obtaining least void content, but their application in various other aggregate types is still to be evaluated. It is recommended that aggregate mix having maximum bulk density and having least void content shall be used along with optimum polymer content for achieving maximum strength. Moisture content in the aggregate has a deleterious effect on

Table 2: Summary of mechanical properties of polymer concrete.

Author	Resin	Aggregate and microfiller used	Variables	Properties evaluated	Brief findings
Compressive strength, flexural strength, and so forth					
Okada et al. [35]	Polyester	Crushed stone, river sand, and calcium carbonate	Resin content, 10–15%; filler content, 10–15%; temperature of test, 5 to 60°	Compressive strength, tensile strength	Compressive strength and tensile strength decrease with temperature.
Kobayashi and Ito [34]	Polyester	Crushed stone, fine sand	Silane treatment, resin content, 9 to 13%	Compressive strength, compressive fatigue	(i) Resin content does not have much effect on compressive strength. (ii) Temperature rise was observed for frequency range of 200–400 Hz. (iii) Addition of 1% silane agent increases the load for withstanding 2 million cycles from 59% to 64% of ultimate strength.
Mani et al. [24]	Epoxy, polyester	Crushed quartzite, siliceous sand, and calcium carbonate	Resin type, silane treatment, and microfiller addition	Compressive strength, flexural strength, and split tensile strength	(i) Epoxy concrete has much superior properties than the polyester concrete. (ii) Compressive strength goes up by 30% for the polyester concrete and 36% for the epoxy concrete by incorporation of a silane coupling agent. (iii) The compressive and flexural strengths of the polyester concrete are greatly improved on incorporation of the microfiller.
Vipulanandan and Dharmarajan [25]	Polyester	Ottawa sand	Temperature, strain rate, void content, method of preparation, and resin content	Compressive strength, flexural strength	(i) Maximum flexural and compression modulus are observed between 14 and 16% resin content by weight. (ii) Strain rate was found to have very limited effect on the flexural behaviour. (iii) Compaction moulding was found to have better results than vibration moulding.
Vipulanandan et al. [39]	Epoxy, polyester	Ottawa sand, blasting sand	Resin content, silane treatment, compaction, and glass fiber content	Compressive strength, flexural strength, and split tensile strength	(i) Maximum compressive and flexural strength were reported at 14% resin content. (ii) Addition of glass fibers increases the flexural strength, compressive strength. (iii) Silane treatment increases the flexural strength by 25%.
Vipulanandan and Paul [62]	(i) Epoxy, (ii) polyester	Ottawa sand, blasting sand	Temperature, strain rate, aggregate type, and curing conditions	Compressive strength, split tensile strength	(i) Compressive strength increases with curing temperature. (ii) Maximum strength was obtained for one-day room temperature curing followed by one-day curing at 80°C. (iii) Use of gap graded aggregate resulted in highest compressive strength.

Table 2: Continued.

Author	Resin	Aggregate and microfiller used	Variables	Properties evaluated	Brief findings
Vipulanandan and Paul [63]	Polyester	Ottawa sand	Curing conditions, silane treatment, and rate of loading	Compressive strength, tensile strength, and stress strain relationship	(i) Maximum compressive strength was obtained for a resin content of 15%. (ii) 1-day room temperature curing followed by 1-day curing at 80°C increased the compressive strength by around 50% as compared to 2-day curing at room temperature. (iii) Compressive strength and modulus increase with increase in strain rate. (iv) Silane treatment of aggregate increases the compressive strength by around 14%.
Varughese and Chaturvedi [37]	Polyester	Granite aggregate confirming to ASTM mesh No-5–50, river sand, and fly ash	Fly ash and river sand contents have been varied in full range of 0–100% of fine aggregate to study the replacement of river sand with fly ash	Flexural strength	(i) Fine aggregates in combination with fly ash and river sand show synergism in strength behaviour and resistance to water absorption up to the level of 75% by weight of fly ash. (ii) At the higher level of fly ash, properties decline as the mix becomes unworkable due to the fact that pure fly ash, because of large surface area, does not mix with resin binder effectively.
Maksimov et al. [36]	Polyester	58% crushed granite, 21.8% sand, and 10.4% calcium carbonate		Compressive strength, flexural strength	Compressive strength in the range of 90–108 MPa has been reported.
Abdel-Fattah and El-Hawary [26]	Epoxy, polyester	56% coarse aggregate and 36% fine aggregate	Resin content	Compressive strength, flexural strength	(i) Maximum compressive strength was achieved at 12% resin content for all types of resins. (ii) Highest modulus of rupture was also obtained at 12% resin content, which was almost 3 times that of cement concrete.
Ferreira [27]	Polyester	Clean sand, foundry sand, and $CaCO_3$	Resin content, microfiller content, mixing method, and type of sand	Three-point bend tests on specimens of 40 × 40 × 160 mm	(i) Best results were obtained for 20% resin content. (ii) Clean sand gives better properties with low resin content as foundry sand has high specific surface.
Ribeiro et al. [29]	Epoxy, polyester	Clean sand, foundry sand, and $CaCO_3$	Resin content, microfiller content, type of sand, and curing cycle (7 days at 23°C and 3 hrs at 80°C)	Three-point bend tests on specimens of 40 × 40 × 160 mm	(i) Curing cycle of 3 hrs at 80°C gives almost the same results as 7 days at 23°C curing. (ii) Epoxy resin gives better properties with foundry sand as aggregate, whereas polyester gives better properties with clean sand because of the higher capacity of epoxy to wet the aggregates.

Table 2: Continued.

Author	Resin	Aggregate and microfiller used	Variables	Properties evaluated	Brief findings
Rebeiz et al. [41]	Polyester	Pea gravel as coarse aggregate and sand as fine aggregate, fly ash	Fly ash content	Compressive strength	(i) Replacing 15% by weight of sand with fly ash results in 30% increase in compressive strength. (ii) Caution should, however, be exercised when using a relatively high loading of fly ash, because the high surface area of the material would make the mix become too sticky and thus unworkable.
Bărbuţă and Lepădatu [64]	Epoxy	River gravel of 0–4 mm size and 4–8 mm size, silica fume (SUF)	Resin content, microfiller content	Compressive strength, flexural strength, and split tensile strength	(i) Compressive strength varies from 43.4 to 65.3 MPa and flexural strength varies from 12.29 to 17.5 MPa. (ii) Resin content of 15.6% was found suitable for almost all the properties of polymer concrete.
Haidar et al. [65]	Epoxy	Gravel of 2–4 mm, gravel to sand ratio of 0.25 used for optimum packing density	Resin content, curing conditions	Compressive strength, flexural strength	(i) Maximum compressive strength and flexural strength were reported for a resin content of 13%. (ii) Maximum compressive and flexural strength were obtained after 3 days of curing.
Mix proportions					
Ohama [30]	Polyester	Andesite, river sand, and calcium carbonate	Mix composition based upon maximum bulk density, curing conditions, and water content of aggregates	Compressive strength	(i) The following optimum mix proportion has been suggested: 11.25% resin, 11.25% calcium carbonate, 29.1% andesite (5–20 mm), 9.6% sand (1.2–5 mm), 38.8% sand (<1.2 mm). (ii) Compressive strength becomes constant after 7-days curing at 20°C. (iii) Strength reduces with increases in water content of aggregate; maximum water content shall be limited to 0.1%.
Kim et al. [66]	Epoxy resin	Sand > mesh no. 6 and pebble < mesh no. 6	Compaction ratio, size of aggregates, and mix composition	Damping factor, and modulus, and compressive strength	An optimum mix was reported as having 50% pebble, 42.5% sand, and 7.5% resin.
Rebeiz [31]	Polyester resin from PET waste	Pea gravel, river sand, and fly ash	Curing time	Compressive strength, flexural strength	(i) Authors proposed an optimized mix based upon their study as that containing 10% resin, 45% pea gravel, 32% sand, and 13% fly ash. (ii) Polymer concrete achieves 80% of its strength after curing of one day, when compared to seven-day curing period.

Table 2: Continued.

Author	Resin	Aggregate and microfiller used	Variables	Properties evaluated	Brief findings
			Damping		
Suh and Lee [67]	Polyester resin	Sand and gravel	Mix composition	Damping	(i) The polymer concrete bed had large damping factors over wide frequency range. (ii) Damping factors found experimentally were higher than those for steel structure and cast iron.
Cortés and Castillo [18]	Epoxy resin	Basalt, quartzite, up to 10 mm size	Test Frequency	Damping, compared with that of cast iron	(i) Damping loss factor of polymer concrete is 65% higher than that of cast iron. (ii) Polymer concrete maintains its damping over a large frequency range.
Bignozzi et al. [15]	Polyester	Silica sand, calcium carbonate	Use of recycled fillers, that is, powdered rubber, tyre rubber, and so forth	Damping, loss modulus	(i) Addition of powdered rubber, tyre rubber, and so forth increases damping over wide temperature. (ii) Polymer concrete containing organic fillers can be used for making machine tool bases.
Orak [19]	Polyester	Quartz, 0.5 mm–8 mm	Mix composition	Damping factor	(i) Damping of polyester concrete is four to seven times higher than that of cast iron. (ii) Damping characteristics were not much influenced by mix composition.

the mechanical properties of polymer concrete and, therefore, it is recommended that moisture content in aggregate shall not exceed 0.5%.

Curing conditions play an important role in the final properties of polymer concrete. For field use and ease of operation, room temperature curing is desirable and advantageous. Fast curing is one of the biggest advantages of the polymer concrete systems, with results showing almost 70% strength development after one day of curing at room temperature. Normal Portland cement concrete, on the other hand, usually achieves about 20% of its 28-day strength in one day. This early strength development is very useful in precast applications of polymer concrete. Although curing at elevated temperatures is observed to accelerate the strength development, it is almost universally accepted that 7-day room temperature curing is optimum period for polymer concrete.

In addition to the above parameters, adhesion at binder aggregate interface also has an influence on the properties of polymer concrete. Adhesion at the interface, in absence of any chemical bonding, may be sufficiently good even when it is due to secondary forces between two phases. Silane coupling agents by providing chemical bonding between the two phases considerably improve the interfacial adhesion and therefore enhance the mechanical properties of these materials. From the research available till date, it can be concluded that integral blend method of adding the silane agent in the polymer concrete mix is easy to implement and yields better mechanical properties. The compressive strength and flexural strength of polymer concrete containing silane coupling agents are 15 to 20% higher than those of normal polymer concrete.

Polymer concrete displays higher compressive strength and flexural strength when compared to Portland cement concrete. Compressive strength ranging from 70 to 120 MPa has been reported by various authors. The discussion in the preceding paragraphs states the governing parameters for the mechanical properties of any particular polymer concrete system and thus explains the large variation in the properties reported.

The study of fatigue behaviour of any material is of immense importance if the same has to be utilised for structures, machine tool parts, and so forth, wherein the cyclic loading is predominant. Unfortunately, fatigue behaviour of polymer concrete has not been studied to a great extent and there have been a few studies in this context and the same has been reported in this paper.

4. Concluding Remarks

Research on characterization of mechanical properties of polymer concrete has been carried out by number of researchers and sufficient data has been generated regarding the effect of various parameters like resin type and content, fiber reinforcements, microfillers, curing conditions, aggregate type and grading, and silane coupling agents on the properties of polymer concrete. Based on the critical review of the available literature on polymer concrete, the following conclusions can be drawn.

(1) Comparative studies between epoxy and polyester resins report that epoxy polymer concrete has far superior mechanical properties and durability.

(2) 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.

(3) 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.

(4) It has been reported that addition of glass fibers improves the post peak behaviour of polymer concrete. The strength and toughness of polymer concrete also increase with addition of fibers.

(5) Seven-day room temperature curing criterion has found widespread usage by researchers in their research work and has been almost universally accepted.

(6) Enhancement in compressive strength up to 30% has been reported for addition of 15% fly ash (microfiller) in polymer concrete.

(7) It has been recommended that the moisture content of the aggregate shall not exceed 0.5% for better mechanical properties.

(8) It is recommended that aggregate mix having maximum bulk density and having least void content shall be used along with optimum polymer content for achieving maximum strength.

(9) Use of silane coupling agents further enhances the mechanical properties of polymer concrete.

It is well known that polymer concrete exhibits far better mechanical properties and durability than ordinary Portland cement concrete. Polymer concrete has proven itself to be a material which holds much promise due to its better mechanical properties and durability. It would be in the interest of polymer concrete industry/researchers if the material is categorised and promoted as a polymer composite.

References

[1] D. W. Fowler, "Polymers in concrete: a vision for the 21st century," *Cement and Concrete Composites*, vol. 21, no. 5-6, pp. 449–452, 1999.

[2] E. Kirlikovali, "Polymer/concrete composites—a review," *Polymer Engineering & Science*, vol. 21, no. 8, pp. 507–509, 1981.

[3] Y. Ohama, "Recent progress in concrete-polymer composites," *Advanced Cement Based Materials*, vol. 5, no. 2, pp. 31–40, 1997.

[4] M. Gunasekaran, "Polymer concrete: a versatile, low-cost material for Asian electrical infrastructure systems," in *Proceedings of the IEEE International Symposium on Electrical Insulation*, pp. 356–361, April 2000.

[5] A. Pratap, "Vinyl ester and acrylic based polymer concrete for electrical applications," *Progress in Crystal Growth and Characterization of Materials*, vol. 45, no. 1-2, pp. 117–125, 2002.

[6] P. Koblischek, "Synthetic resin bound concrete," in *Proceedings of the 1st International Congress on Polymer Concretes—Polymers in Concrete*, pp. 409–419, London, UK, 1975.

[7] P. J. Koblischek, "MOTEMA-acrylic concrete for machine tool frames," *International Journal of Cement Composites and Lightweight Concrete*, vol. 7, no. 1, pp. 55–57, 1985.

[8] P. A. McKeown and G. H. Morgan, "Epoxy granite: a structural material for precision machines," *Precision Engineering*, vol. 1, no. 4, pp. 227–229, 1979.

[9] K. Paderewski, "Use of polymer concretes in machine tool construction," *Przeglad Mechaniczny*, vol. 43, no. 13, pp. 12–15, 1984.

[10] E. Saljé, H. Gerloff, and J. Meyer, "Comparison of machine tool elements made of polymer concrete and cast iron," *CIRP Annals*, vol. 37, no. 1, pp. 381–384, 1988.

[11] H. Schulz and R. G. Nicklau, "Machine tool bases made of polymer concrete," *Werkstatt und Betrieb*, vol. 114, no. 10, pp. 747–752, 1981.

[12] H. Schulz and R.-G. Nicklau, "Design of machine tool frames using polymer concrete," *Werkstatt und Betrieb*, vol. 115, no. 5, pp. 311–317, 1982.

[13] H. Schulz and R.-G. Nicklau, "Designing machine tool structures in polymer concrete," *International Journal of Cement Composites and Lightweight Concrete*, vol. 5, no. 3, pp. 203–207, 1983.

[14] M. Weck and R. Hartel, "Design, manufacture and testing of precision machines with essential polymer concrete components," *Precision Engineering*, vol. 7, no. 3, pp. 165–170, 1985.

[15] M. C. Bignozzi, A. Saccani, and F. Sandrolini, "New polymer mortars containing polymeric wastes—part 2: dynamic mechanical and dielectric behaviour," *Composites A*, vol. 33, no. 2, pp. 205–211, 2002.

[16] C. Bruni, A. Forcellese, F. Gabrielli, and M. Simoncini, "Hard turning of an alloy steel on a machine tool with a polymer concrete bed," *Journal of Materials Processing Technology*, vol. 202, no. 1–3, pp. 493–499, 2008.

[17] C. Bruni, A. Forcellese, F. Gabrielli, and M. Simoncini, "Effect of the lubrication-cooling technique, insert technology and machine bed material on the workpart surface finish and tool wear in finish turning of AISI 420B," *International Journal of Machine Tools and Manufacture*, vol. 46, no. 12-13, pp. 1547–1554, 2006.

[18] F. Cortés and G. Castillo, "Comparison between the dynamical properties of polymer concrete and grey cast iron for machine tool applications," *Materials & Design*, vol. 28, no. 5, pp. 1461–1466, 2007.

[19] S. Orak, "Investigation of vibration damping on polymer concrete with polyester resin," *Cement and Concrete Research*, vol. 30, no. 2, pp. 171–174, 2000.

[20] I. Tanabe and K. Takada, "Thermal deformation of machine tool structures using resin concrete," *JSME International Journal C*, vol. 37, no. 2, pp. 384–389, 1994.

[21] I. Tanabe, "Development of ceramic resin concrete for precision machine tool structure," *JSME International Journal C*, vol. 36, no. 4, pp. 494–498, 1993.

[22] G. Vrtanoski and V. Dukovski, "Design of polymer concrete main spindle housing for cnc lathe," in *Proceedings of 13th International Scientific Conference on Achievements of Mechanical and Materials Engineering*, pp. 696–698, Gliwice, Poland, 2005.

[23] J. P. Gorninski, D. C. Dal Molin, and C. S. Kazmierczak, "Strength degradation of polymer concrete in acidic environments," *Cement and Concrete Composites*, vol. 29, no. 8, pp. 637–645, 2007.

[24] P. Mani, A. K. Gupta, and S. Krishnamoorthy, "Comparative study of epoxy and polyester resin-based polymer concretes," *International Journal of Adhesion and Adhesives*, vol. 7, no. 3, pp. 157–163, 1987.

[25] C. Vipulanandan and N. Dharmarajan, "Flexural behavior of polyester polymer concrete," *Cement and Concrete Research*, vol. 17, no. 2, pp. 219–230, 1987.

[26] H. Abdel-Fattah and M. M. El-Hawary, "Flexural behavior of polymer concrete," *Construction and Building Materials*, vol. 13, no. 5, pp. 253–262, 1999.

[27] A. J. M. Ferreira, "Flexural properties of polyester resin concretes," *Journal of Polymer Engineering*, vol. 20, no. 6, pp. 459–468, 2000.

[28] M. Ribeiro, C. M. L. Tavares, M. Figueiredo, A. J. M. Ferreira, and A. A. Fernandes, "Bending characteristics of resin concretes," *Materials Research*, vol. 6, no. 2, pp. 247–254, 2003.

[29] M. C. S. Ribeiro, P. R. Nóvoa, A. J. M. Ferreira, and A. T. Marques, "Flexural performance of polyester and epoxy polymer mortars under severe thermal conditions," *Cement and Concrete Composites*, vol. 26, no. 7, pp. 803–809, 2004.

[30] Y. Ohama, "Mix proportions and properties of Polyester Resin Concretes," *American Concrete Institute*, pp. 283–294, 1973.

[31] K. S. Rebeiz, "Precast use of polymer concrete using unsaturated polyester resin based on recycled PET waste," *Construction and Building Materials*, vol. 10, no. 3, pp. 215–220, 1996.

[32] J. M. Laredo Dos Reis, "Mechanical characterization of fiber reinforced Polymer Concrete," *Materials Research*, vol. 8, no. 3, pp. 357–360, 2005.

[33] J. M. L. Reis, "Fracture and flexural characterization of natural fiber-reinforced polymer concrete," *Construction and Building Materials*, vol. 20, no. 9, pp. 673–678, 2006.

[34] K. Kobayashi and T. Ito, "Several physical properties of resin concrete," in *Proceedings of the 1st International Congress on Polymer Concretes—Polymers in Concrete*, pp. 236–240, London, UK, 1975.

[35] K. Okada, W. Koyanagi, and T. Yonezawa, "Thermo dependent properties of polyester resin concrete," in *Proceedings of 1st International Congress on Polymer Concretes—Polymers in Concrete*, pp. 210–215, London, UK, 1975.

[36] R. D. Maksimov, L. Jirgens, J. Jansons, and E. Plume, "Mechanical properties of polyester polymer-concrete," *Mechanics of Composite Materials*, vol. 35, no. 2, pp. 99–110, 1999.

[37] K. T. Varughese and B. K. Chaturvedi, "Fly ash as fine aggregate in polyester based polymer concrete," *Cement and Concrete Composites*, vol. 18, no. 2, pp. 105–108, 1996.

[38] W. Bai, J. Zhang, P. Yan, and X. Wang, "Study on vibration alleviating properties of glass fiber reinforced polymer concrete through orthogonal tests," *Materials & Design*, vol. 30, no. 4, pp. 1417–1421, 2009.

[39] C. Vipulanandan, N. Dharmarajan, and E. Ching, "Mechanical behaviour of polymer concrete systems," *Materials and Structures*, vol. 21, no. 4, pp. 268–277, 1988.

[40] J. P. Gorninski, D. C. Dal Molin, and C. S. Kazmierczak, "Study of the modulus of elasticity of polymer concrete compounds and comparative assessment of polymer concrete and portland cement concrete," *Cement and Concrete Research*, vol. 34, no. 11, pp. 2091–2095, 2004.

[41] K. S. Rebeiz, S. P. Serhal, and A. P. Craft, "Properties of polymer concrete using fly ash," *Journal of Materials in Civil Engineering*, vol. 16, no. 1, pp. 15–19, 2004.

[42] M. Bărbuţă, M. Harja, and I. Baran, "Comparison of mechanical properties for polymer concrete with different types of filler," *Journal of Materials in Civil Engineering*, vol. 22, no. 7, pp. 696–701, 2010.

[43] B.-W. Jo, S.-K. Park, and D.-K. Kim, "Mechanical properties of nano-MMT reinforced polymer composite and polymer concrete," *Construction and Building Materials*, vol. 22, no. 1, pp. 14–20, 2008.

[44] K. S. Rebeiz and A. P. Craft, "Polymer concrete using coal fly ash," *Journal of Energy Engineering*, vol. 128, no. 3, pp. 62–73, 2002.

[45] K. S. Rebeiz, "Time-temperature properties of polymer concrete using recycled PET," *Cement and Concrete Composites*, vol. 17, no. 2, pp. 119–124, 1995.

[46] M. E. Tawfik and S. B. Eskander, "Polymer concrete from marble wastes and recycled poly(ethylene terephthalate)," *Journal of Elastomers and Plastics*, vol. 38, no. 1, pp. 65–79, 2006.

[47] Y. Ohama and K. Demura, "Relation between curing conditions and compressive strength of polyester resin concrete," *International Journal of Cement Composites and Lightweight Concrete*, vol. 4, no. 4, pp. 241–244, 1982.

[48] L. Kapasny, "Design of the optimum grading of aggregates for resin mortars," in *Proceedings of the International Symposium on Plastics in Material and Structural Engineering*, pp. 306–310, 1982.

[49] V. V. L. K. Rao and S. Krishnamoothy, "Aggregate mixtures for least-void content for use in polymer concrete," *Cement, Concrete and Aggregates*, vol. 15, no. 2, pp. 97–107, 1993.

[50] M. Muthukumar, D. Mohan, and M. Rajendran, "Optimization of mix proportions of mineral aggregates using Box Behnken design of experiments," *Cement and Concrete Composites*, vol. 25, no. 7, pp. 751–758, 2003.

[51] P. Mani, A. K. Gupta, and S. Krishnamoorthy, "Some structural studies on polyester resin-concrete containing silane coupling agents," *Journal of Materials Science Letters*, vol. 1, no. 11, pp. 467–470, 1982.

[52] P. Mani, A. K. Gupta, and S. Krishnamoorthy, "Efficiency of some silane coupling agents and of the method of their application in polyester resin concrete," *Journal of Materials Science*, vol. 18, no. 12, pp. 3599–3605, 1983.

[53] B. Chmielewska, L. Czarnecki, J. Sustersic, and A. Zajc, "The influence of silane coupling agents on the polymer mortar," *Cement and Concrete Composites*, vol. 28, no. 9, pp. 803–810, 2006.

[54] A. K. Gupta, P. Mani, and S. Krishnamoorthy, "Interfacial adhesion in polyester resin concrete," *International Journal of Adhesion and Adhesives*, vol. 3, no. 3, pp. 149–154, 1983.

[55] T. Broniewski, Z. Jamrozy, and J. Kapko, "Long life strength polymer concrete," in *Proceedings of the 1st International Congress on Polymer Concretes—Polymers in Concrete*, pp. 179–184, London, UK, 1975.

[56] R. Valore and D. J. Naus, "Resin bound aggregate material systems," in *Proceedings of the 1st International Congress on*

Polymer Concretes—Polymers in Concrete, pp. 216–222, London, UK, 1975.

[57] T. W. Brockenbrough, "Fiber reinforced methacrylate polymer concrete," *ACI Journal*, pp. 322–325, 1982.

[58] C. Vipulanandan and S. Mebarkia, "Aggregates, fibers and coupling agents in polymer concrete," in *Proceedings of the 1st Materials Engineering Conference*, pp. 785–794, Denver, Colorado, August 1990.

[59] S. Mebarkia and C. Vipulanandan, "Compressive behavior of glass-fiber-reinforced polymer concrete," *Journal of Materials in Civil Engineering*, vol. 4, no. 1, pp. 91–105, 1992.

[60] K. Sett and C. Vipulanandan, "Properties of polyester polymer concrete with glass and carbon fibers," *ACI Materials Journal*, vol. 101, no. 1, pp. 30–41, 2004.

[61] P. Xu and Y.-H. Yu, "Research on steel-fibber polymer concrete machine tool structure," *Journal of Coal Science and Engineering*, vol. 14, no. 4, pp. 689–692, 2008.

[62] C. Vipulanandan and E. Paul, "Performance of epoxy and polyester polymer concrete," *ACI Materials Journal*, vol. 87, no. 3, pp. 241–251, 1990.

[63] C. Vipulanandan and E. Paul, "Characterization of polyester polymer and polymer concrete," *Journal of Materials in Civil Engineering*, vol. 5, no. 1, pp. 62–82, 1993.

[64] M. Bărbuţă and D. Lepădatu, "Mechanical characteristics investigation of polymer concrete using mixture design of experiments and response surface method," *Journal of Applied Sciences*, vol. 8, no. 12, pp. 2242–2249, 2008.

[65] M. Haidar, E. Ghorbel, and H. Toutanji, "Optimization of the formulation of micro-polymer concretes," *Construction and Building Materials*, vol. 25, no. 4, pp. 1632–1644, 2011.

[66] H. S. Kim, K. Y. Park, and D. G. Lee, "A study on the epoxy resin concrete for the ultra-precision machine tool bed," *Journal of Materials Processing Tech*, vol. 48, no. 1-4, pp. 649–655, 1995.

[67] J. D. Suh and D. G. Lee, "Design and manufacture of hybrid polymer concrete bed for high-speed CNC milling machine," *International Journal of Mechanics and Materials in Design*, vol. 4, no. 2, pp. 113–121, 2008.

[68] K. Kobayashi, Y. Ohama, and T. Ito, "Fatigue Properties of Resin concrete under repeated compression loads," *Seisan Kenkyu*, vol. 26, no. 3, pp. 116–118, 1974.

[69] G. Woelfl, M. McNerney, and C. Chang, "Flexural fatigue of polymer concrete," *Cement, Concrete and Aggregates*, vol. 3, no. 2, pp. 84–88, 1981.

[70] J. T. McCall, "Probability of fatigue failure of plain concrete," *Journal of the American Concrete Institute*, pp. 233–244, 1995.

[71] C. Vipulanandan and S. Mebarkia, "Fatigue crack growth in polyester polymer concrete," *American Concrete Institute*, pp. 153–168, 2001.