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Investigating fracture mechanics and flexural properties of unsaturated polyester polymer concrete (UP-PC)

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HIGHLIGHTS

- Flexural properties and fracture mechanics of polyester polymer concrete was studied.
- The properties were determined after long term exposure to acid and alkali solutions.
- The morphology of the samples were studied after and before exposure to chemicals.
- The fracture mechanics was studied using LEFM method.

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ABSTRACT

Polymer concretes are particle composites of polymers which are filled by aggregates. Polyesters, epoxies and acrylics have been used as binders in these materials which polyesters due to their suitable properties and acceptable cost are considered by the most of industries. One of the most considered issues about polyester polymer concretes is their weak performance and the low durability against acids and alkaline solutions. In this research, fracture mechanics (CMOD and K_{1c}) and flexural strength (σ) of a polyester polymer concrete after 1, 3, 6 and 12 months of exposure to sulfuric acid (0.5 and $1\,\frac{mol}{lit}$) and carbonate/bicarbonate alkaline solution (0.0622 and $0.1245\,\frac{mol}{lit}$) were investigated. Results showed that both of aggressive solutions degraded polymer concrete samples. However acids caused more decrement in flexural strength and alkaline had more destructive effect on fracture mechanics. Furthermore, the concentration was more important in destructive effects especially for alkaline solution. The highest decrease in flexural strength, fracture toughness and CMOD were 37%, 36.1% and 59% respectively. SEM analysis was used to assess morphological changes accrued at fractured surfaces of the samples.

1. Introduction

Polymer concretes (PCs) are composite materials formed by incorporating aggregates into polymers. PCs were first used as building and construction materials [1]. Today they are used in a range of civil and structural applications such as bridge decking, concrete crack repair materials, pavement overlays, hazardous waste containers, sewer pipes and decorative constructional panels [2]. Due to their specific properties including; higher mechanical strengths [3], and lower weights [4,5], excellent bonding to different substrates [6], higher resistance to corrosive environments and chemical attacks [7], faster curing and lower permeabilities [8] in comparison to portland cement concrete, they become attractive materials in many applications.

Ordinary Portland cements (OPCs) have inherently voids and cracks which formed through hydration of the alkaline binder [9]. These make them susceptible to acid attack and chemical degradation [10].

Continuous maintenance and repair which are needed for conventional concretes, are not required in case of using polymer concretes (PCs). Another strong point of PCs is their fast curing which leads to using them in the production of precast parts which can be demolded a few hours after casting [11].

Various polymers and aggregates have been used in fabrication of PCs such as unsaturated polyesters, epoxies, acrylics [1]. Unsaturated polyester resin (UP) is a category of thermosetting polymers which is widely used in various industrial applications such as composites, automotive paints, protective coatings, storage tanks, piping and construction [12]. Such widespread applications of UP resins are due to their suitable processing characteristics, thermal stabilities, chemical resistance and comparatively low prices.

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These characteristics has made UPs the most popular resins for PCs among other thermosetting resins [13–15].

Despite many desirable characteristics of UP resins, their limited stiffness and strength compared to other thermosetting resins (e.g. epoxies [16]) have restricted their usage in high performance applications. To overcome such deficiencies, many researches have been performed on reinforcing UPs with fibers [17,18] and fillers [19–21]. The other weakness of UPs is their low durability (i.e. retaining mechanical properties after long term exposure to chemicals), especially in alkaline and strong acid conditions [22]. Unfortunately UP resin enters this weakness to polymer concrete parts, too. Several researches have been performed on the physical, mechanical and chemical properties of polyester based mortars and concretes (UP-PCs) [22–24]. However, a few researches have focused on durability and retaining the mechanical properties after long term exposure to chemicals.

In previous studies, different degradation methods were performed. Reis [25] used seven solutions with various pH from 1.2 to 12.8. Pavlik et al. [26] hanged the specimens with exposed surface facing downwards in chemical solutions to evaluate the corrosion depth. Mehta [27] selected different acid solutions to perform the degradation tests. Hashemi et al. [28] and Jamshidi et al. [28–30] immersed UP-PC specimens in different chemicals (i.e. sulfuric acidic, sodium hydroxide, Gas oil, demi realized water, water etc.). They evaluated compressive strength and flexural strength of the samples after a long term (i.e. continuous [28] and cyclic [29]) exposure to the chemicals. The decrease in mechanical properties of PC after exposing to chemical solution is related to many parameters such as resin content, pores in the structure, pH of the solution. The alkaline solution had severe effect on the mechanical properties than the acidic solution did. Also distilled water reported as an aggressive solution which had severe effect on the mechanical properties of PCs.

Some of researchers also studied the performance of the polymer concretes by the fracture mechanics [31,32]. It is investigated by evaluating the toughness, the fracture energy and the modulus of elasticity. The stress intensity factor (K_1) was first developed by Irwin [33]. The stress intensity factor is important because it is used to determine when fracture will take place. In fact, fracture occurs when the stress intensity factor equals the material's fracture toughness [34]. Various test specimens and several experimental methods have been used in the past to evaluate the fracture toughness (K_{Ic}) [31,32,35] and flexure strength (δ) [36–38]. Effects of chemical solutions [22,23,28], rate of loading [39], aging [40–42] and mix design [43–45] have been investigated on fracture mechanics and flexural strength of polymer concretes. In cases that polymer concrete exposed to different chemicals, noticeable decline in fracture mechanics was reported [25]. However, effects of long term exposure to chemicals on fracture mechanics of the UP-PCs has not been assessed, yet.

In the present work, the long-term effect of exposing polyester polymer concrete (UP-PC) to different chemicals on the fracture mechanics and the flexural properties has been investigated. The correlation between results of both tests was investigated. For this purpose two different aggressive, namely, sulfuric acid and Calcium bicarbonate/carbonate alkaline solution at two different concentrations, were used. The specimens were evaluated after 1, 3, 6 and 12 months of exposure to the solutions. The polymer concrete beams were tested by a three point bending apparatus up to failure and a four point bending device for investigating fracture mechanics and flexural behavior, respectively.

2. Experimental

2.1. Materials

Orthophthalic polyester (UP) resin containing 33 wt% styrene was obtained from Iran, Yashm Co. to be used as a binder in this research. The physical and mechanical properties of the resin are listed in Tables 1 and 2. Methyl ethyl ketone peroxide (MEKP) as an initiator and cobalt naphthenate (Co-naphthenate) containing 6 wt% cobalt as a promoter were purchased from Aldrich (Steinheim, Germany) and used as-received. Local crushed gravel and sand were used as coarse and fine aggregates, respectively. The properties of the aggregates are shown in Table 3. The maximum particle size of the aggregates was 10 mm.

2.2. Methods

2.2.1. Mix design

Polymer concrete fresh mixture was prepared by extruder mixing machine. Crushed gravel, sand, calcium carbonate and UP resin were used at concentrations of 60, 14, 14 and 12 wt%, respectively. At the end of mixing process MEKP initiator (1.5 wt% of resin) and cobalt naphthanate accelerator (0.4 wt%) were automatically added to the mixture to activate the curing process. Afterward, the fresh mixtures were poured into metal molds. The specimens removed from molds after 1 h and cured at the room temperature for 24 h.

2.2.2. Fracture mechanics and flexural strength tests

The flexural strength, i.e., strength under normal stress, was calculated by the following equation:

$$\sigma = \frac{PL}{bd^2} \tag{1}$$

Table 1
Physical properties of the used polyester resin.

Properties	Viscosity (mPa.s)	Acid value (mgKOH/g)	Appearance	Colour (Gardner)	Solid content (%)	Gel time (min)	Cure time (min)	Peak temperature (°c)	Density (g/cm3)	Water content (%)	Flash point (°C)
Value	450–550	20–25	Clear	Max 2	65–67	15–20	19–25	150–190	1.1–1.2	0.05–0.10	35

Table 2
Thermal and mechanical properties of the used resin.

Properties	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Flexural strength (MPa)	Flexural modulus (GPa)	Moulding shrinkage (%)	Hardness Barcol	HDT (°c)	Water abs. (%)
Value	70–75	3	2.5	110	3.5	8	45–50	82	0.19

Table 3
Physical properties of the aggregates.

Type of aggregate	Specific gravity (g/cm3)	Absorption (%)	Fineness modulus (GPa)	Particle Size (mm)
Sand	2.53	2.6	2.7	0–2
Coarse	2.56	2.46	6.5	2–10