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Effects of resins on mechanical performance of polymer concrete

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Research Paper

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Effects of resins on mechanical performance of polymer concrete

Cement manufacturing is currently responsible for one of the highest levels of carbon dioxide (CO_2) emissions and energy consumption in construction industry. Thus, the use of sustainable binder materials instead of cement has become a worldwide issue. Previous studies have shown that polymers are a reliable and sustainable alternative to cement in construction, while polymer concretes (PCs) are seen as the biggest alternative to conventional cement concretes in the long term. In this study, the main objective is to investigate the effects of resins, which are used as binder components in polymer concrete, on the mechanical properties of the PCs. To achieve this, ten different orthophthalic unsaturated polyester resins (OUPR) that are commonly used in construction industry are considered, and fresh concrete tests and hardened concrete tests are performed on deck plates prepared with these resins. Based on the analysis results, each resin is given a performance index. The experimental results indicate that the type of resin has a significant impact on mechanical properties of polymer concrete.

Key words:

polymer materials, polymer concrete, resin, orthophthalic unsaturated polyester resin, physical properties, mechanical properties

Prethodno priopćenje

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Utjecaj smola na mehanička svojstva polimernog betona

Industrija cementa je danas odgovorna za najveće razine emisije ugljičnog dioksida (CO_2) i potrošnje energije u građevinskoj industriji. Stoga je u današnje vrijeme primjena održivih vezivnih materijala kao zamjene za cement postalo pitanje od globalnog značenja. Iz prethodnih se radova vidi da su polimeri pouzdana i održiva alternativa cementu u graditeljstvu, a dugoročno gledano, polimerni betoni (PC) smatraju se najprikladnijom zamjenom tradicionalnih betona s cementom. U ovom se radu kao glavni cilj postavlja istraživanje utjecaja smola, koje se koriste kao vezivne komponente u polimernom betonu, na mehanička svojstva polimernih betona. U tom se smislu u radu analizira deset ortoftalnih nezasićenih poliesterskih smola (OUPR) koje se često koriste u građevinarstvu, te se provode ispitivanja svježeg i očvrsnulog betona u obliku ploča koje sadrže navedene smole. Nakon analize, svakom se tipu smole dodjeljuje indeks učinkovitosti. Eksperimentalni rezultati pokazuju da vrsta smole bitno utječe na mehanička svojstva polimernog betona.

Ključne riječi:

polimerni materijali, polimerni beton, smola, ortoftalna nezasićena poliesterska smola, fizikalna svojstva, mehanička svojstva

1. Introduction

Currently, construction industry is one of the leading sources of energy use and greenhouse gas emissions. A statement by the Global Status Report on Buildings and Construction indicates that 38 % of global energy-based carbon dioxide (CO_2) emissions are produced in construction industry [1]. Significant portions of emissions stemming from construction industry are associated with cement and steel manufacturing [2]. Around 8 % of the total CO_2 emissions worldwide are caused by cement manufacturing [3]. In recent years, in order to reduce carbon dioxide (CO_2) emissions caused by cement production, various binding materials have started to be used in concrete production as an alternative to cement. As an alternative, polymers have been used in concrete production as a binder instead of cement for the last fifty years. The American Concrete Institute (ACI) has focused on polymer use in concrete since 1971 through ACI Committee 548 [4]. According to ACI, there are three distinct polymer-based concretes: Polymer Portland Cement Concrete (PPCC) (also known as Polymer Modified Concrete (PMC)), Polymer Impregnated Concrete (PIC), and Polymer Concrete (PC) [4]. Since PC is completely cement-free, it is the most interesting polymer-based concrete available for construction applications. As constituents of sustainable concrete, these materials have become essential products of the modern age and are used extensively in construction industry [5, 6].

Prema podacima iz literature, istraživači najveće zanimanje According on literature review, researchers are mostly interested in the PCs and how to use them in construction. For example, Gagandeep [7] focused on the strength characteristics of the PC with epoxy resin. In the study, polymer resin concrete containing 3 % and 5 % of resin was mechanically tested and compared with polymer fibre concrete with glass fibre percentages of 0.5 % and 1 %. The results indicated that an increase in resin content from 3 % to 5 % improved workability and also compressive strength and flexural strength. In addition, adding glass fibre to polymer concrete increased its compressive strength. Kiruthika et al. [5] investigated polyester PC andS various aspects of this material for sustainable construction. The authors presented a method for making polymer concrete that uses isophthalic resin, and reported that the PC has a service life exceeding 20 years due to its durability properties, thereby reducing maintenance costs compared to cement-based concrete. Another study conducted by Seco et al. [8] focused on the durability of the PC based on metallurgical wastes, and on its potential to manufacture and build products. The study demonstrates the potential of this recycled target material in the manufacture of durable and more sustainable PC products. The study has shown that the use of 1 to 2 % of polymer to modify concrete can still decrease the passing electric charge and increase the resistance of concrete to chloride ion penetration. An experimental study by Shen et al. [9] was conducted to analyse shrinkage of lightweight polymer concrete containing waste rubber powder and ceramsite. It was found that the PC composites with ceramsite used as aggregate show significantly less free shrinkage than crushed stone composites. Jafari et al. [10] found that even though the strength of PCs can be reduced by an increase in temperature, it can be increased by increasing the epoxy resin ratio and the coarse aggregate size. Mohamed et al. [11] conducted a study on the compressive and flexural strength of PC. Within the scope of the study, the compressive and flexural strength of PCs were investigated by using four different quantities of resin. The results showed that the epoxy resin content of 20 % and 25 % by weight exhibited the best mechanical properties in all grain sizes, and that PCs containing 20 % resin had a higher strength than those constructed using 25 % of resin. Lokuge and Aravinthan [12] investigated the effect of fly ash on mechanical properties of PC. The study concluded that the amount of resin reduced when fly ash was added to the mixture as filler material. Besides, the study emphasized that while the compressive strength and modulus of elasticity increased, the strength of split tensile and flexural fractures decreased with an increase in fly ash content. Kumar et al. [13] examined mechanical properties of PCs containing varying amounts of fly ash (8, 12 %), red mud (12, 25 %) and resin (30, 35 %). According to the study, the PCs specimen with 35 % of resin, 25 % of fly ash, and 15 % of silica fume exhibited the highest flexural strength. It was also reported in this study that PCs containing fine fillers may be characterized by extremely strong mechanical properties due to high molecular compaction.

According to previous studies, polymer-based concretes have proven to be quite important in construction industry. While the literature currently assesses different types of polymer-based concretes and their applications, and supports the view that polymer-based concretes could be among the most important construction materials, the impact of the components on mechanical and physical performances of the PCs have not been thoroughly investigated. Thus, the emphasis of this study was on the resins, which constitute the major component of polymer-based concretes. Based on experimental results for fresh and hardened PCs, the study examines the effects of resins on the mechanical performance of PC. A total of ten commercial resins were selected, and the gel time, peak temperature, peak time, flow tests (fresh concrete tests), density, compressive strength, and flexural strength tests (hardened concrete tests) were performed using concrete samples prepared with each resin. For each PC, a performance score was generated, and the results of the analyses were evaluated based on the performance scores. The present study is unique in that fresh concrete and hardened concrete tests were performed in this study. It also took into consideration the most popular resins on the market. Furthermore, with the performance index used in this study, it was ensured that many different experimental data points were used properly, and that the most appropriate resin was determined.

2. Materials and methods

This study was conducted at Gebze Technical University (GTU), in collaboration with Istanbul Aydin University (IAU), and Mert Casting Inc. The samples used in the experiment were supplied by Mert Casting Inc. and the experimental tests were performed in the Mechanical Lab of Mert Casting Inc. PCs were prepared using the concrete mixture recipe obtained from Mert Casting Inc. in the scope of the study. The recipes have already been used for constructing polymer drainage channels in Mert Casting Inc. In the scope of the study, no concrete mixture recipe was given for this mixture since these are trade secrets. Material from the same package was used throughout the study so as to ensure compatibility of samples and to avoid experimental errors. In this part of the study, the information about materials used in PCs is given and the concrete mixing process is summarized.

2.1. Materials

2.1.1. Natural Aggregates

A variety of silica sand sizes, i.e. 0.3–1 mm, 1–2 mm, 2–3 mm and 3–5 mm, were used as aggregates in this study. The aggregates obtained from riverbeds were provided by Yelten Mining and Kumsan Döküm from Kirklareli, Turkey, and Istanbul, Turkey, and specific gravity of the aggregates was around 2.65 g/cc. To remove contamination, all aggregates were washed in clear water and dried before use. Chemical compositions of the aggregates are given in Table 1.

Table 1. Chemical composition of aggregates

Chemicals	Aggregates		
	0.3-1 mm	**1-3 mm**	**3-5 mm**
MgO	0.10	0.06	0.06
Al_2O_3	0.245	1.80	1.86
SiO_2	98.86	94.20	94.15
CaO	0.01	0.45	0.39
Fe_2O_3	0.148	0.46	0.46
SO_3	-	0.10	0.10
K_2O	0.03	1.52	1.56
Na_2O	0.02	1.16	1.12
Ignition loss	0.24	0.25	0.30

2.1.2. Resins

Polyester resins can be categorized into four main types. In order to distinguish them, these four types of resin are classified as vinyl ester, aloud, saturated polyester, and unsaturated polyester. Basic characteristics of unsaturated polyester resin (UPR) are its heat resistance, low shrinkage, good mechanical strength, and cold cross-linking. In the manufacture of unsaturated polyesters, styrene is the most common monomer used. "Isophthalic" and "orthophthalic" resins are two types of unsaturated polyester resin. The majority of UPRs on the market today are orthophthalic due to the average specifications, prices, and performance-based value of orthophthalic UPRs (OUPRs). In general, they can be applied for a variety of uses.

Table 2. Technical properties of resins

Resins	Acid value [mg KOH/g]	Solid content [%]	Viscosity [cps]	Specific gravity [g/cm³]	Gel time [min]	Time to peak [min]	Peak exoterm [°C]
Resin-1	10-25	65-70	500-700	1.10-1.20	10-20	15-30	130-180
Resin-2	30-35	40-45	450-550	1.11-1.23	7-9	14-20	145-165
Resin-3	25-35	60-62	300-400	1.12-1.20	5-7	10-12	175-195
Resin-4	20-30	65-67	400-800	1.13-1.15	7-10	15-25	145-160
Resin-5	15-35	59-62	300-400	1.10-1.20	5-7	12-14	175-195
Resin-6	25-30	34-36	250-450	1.10-1.12	10-15	20-24	150-180
Resin-7	25-27	65-67	70-90	1.20-1.25	14-16	26-30	150-165
Resin-8	25-30	65-70	500-600	1.10-1.12	10-12	20-25	155-185
Resin-9	20-24	62-66	280-320	1.10-1.12	5-6	12-15	150-170
Resin-10	14-20	41-43	250-300	1.12-1.15	5-7	14-18	155-170

Table 3. Technical properties of the accelerator

Properties	Values
Density	0.92 g/cm^3 (20 °C)
Viscosity	300 mPa.s (20 °C)
Self-Accelerating decomposition temperature (SADT)	≥ 150 °C
Flash point	62 °C
Cobalt content	1.5 %

Table 4. Technical properties of hardener

Properties	Values
Flash point	> 60 °C
Density, 20°C	1055 kg/m^3
Viscosity, 20°C	21 mPa.s
Self-Accelerating decomposition temperature (SADT)	60 °C
Total active oxygen	4.0 - 4.2 %
Peroxide content	33 %
Diethylene glycol + water + diacetone alcohol	67 %

Therefore, it is of interest in this study to determine which Orthophthalic Unsaturated Polyester Resins (OUPRs) have the best mechanical properties. For this study, the use is made of ten distinct OUPR resins that are widely used commercially. Since the resins are commercial products, their names are not given in this study, i.e. the resins were identified by numbers. Technical properties of resins used in this study are given in Table 2.

2.1.3. Accelerator

The main purpose of accelerator is to speed up the curing reaction between the resin and hardener. Accelerators usually speed up epoxy reactions by raising temperature in the system. Cobalt naphthenate (0.3 % resin) was selected in this study as an accelerator for activating the curing agent. In cobalt naphthenate, which is widely used for OUPRs, aphthenic acids (NAs) are converted to cobalt. Technical properties of the accelerator are given in Table 3.

2.1.4. Hardener

For the cure of epoxy resins, Acetylacetone Peroxide (AAP) was selected in this study, among the most common hardening materials for PCs, as a hardener component. With cobalt accelerator, AAP can cure OUPR at room temperatures and, when used together, AAP and cobalt provide the fastest curing and peak temperatures. Technical details about the hardener are presented in Table 4.

2.2. Preparation of PCs

When preparing polymer concrete, aggregates of different diameters were first mixed in specific percentages according to appropriate grading. To avoid damage to the aggregates and to mix them well enough, at this mixing stage the mixing process was conducted very slowly and regularly. After an aggregate mixture of good grading was obtained, the resin and accelerator were added to the mixture and the mix is then thoroughly mixed by a mechanical stirrer. At this stage, it was ensured by effective mixing that the resin and accelerator cover all aggregate surfaces evenly, without damage to the aggregates. A hardener was added to the mixture at the last stage, and a suitable mixing procedure was used so as to ensure proper mixing of all components. Since PCs harden very quickly, fresh concrete tests must be carried out before the concrete hardens, and samples must be placed in moulds for hardened concrete tests. Two distinct working groups were formed to avoid problems at these stages and to ensure efficient operations. In the first group, fresh concrete tests were carried out on the prepared concrete mix, while in the second group hardened concrete experiments were carried out through

Figure 1. Preparation of PCs and test equipment

moulding studies. For hardened tests, fresh PC mixtures were placed into the prism and cube moulds for flexural and compression tests, respectively. Each mould was then vibrated on a concrete vibrating table to obtain compacted samples. The dimensions of the samples used in flexural tests were 40 mm×40 mm×200 mm, while the dimensions of the samples used for compression tests were 50 mm×50 mm×50 mm (Figure 1). For the tests, five samples were prepared for each PC group. After ten minutes of curing, the samples were moulded. Following the demoulding of the test samples, all test samples were kept in a curing room to obtain the same conditions. A total of 50 cube specimens and 50 prism specimens were produced in the study.

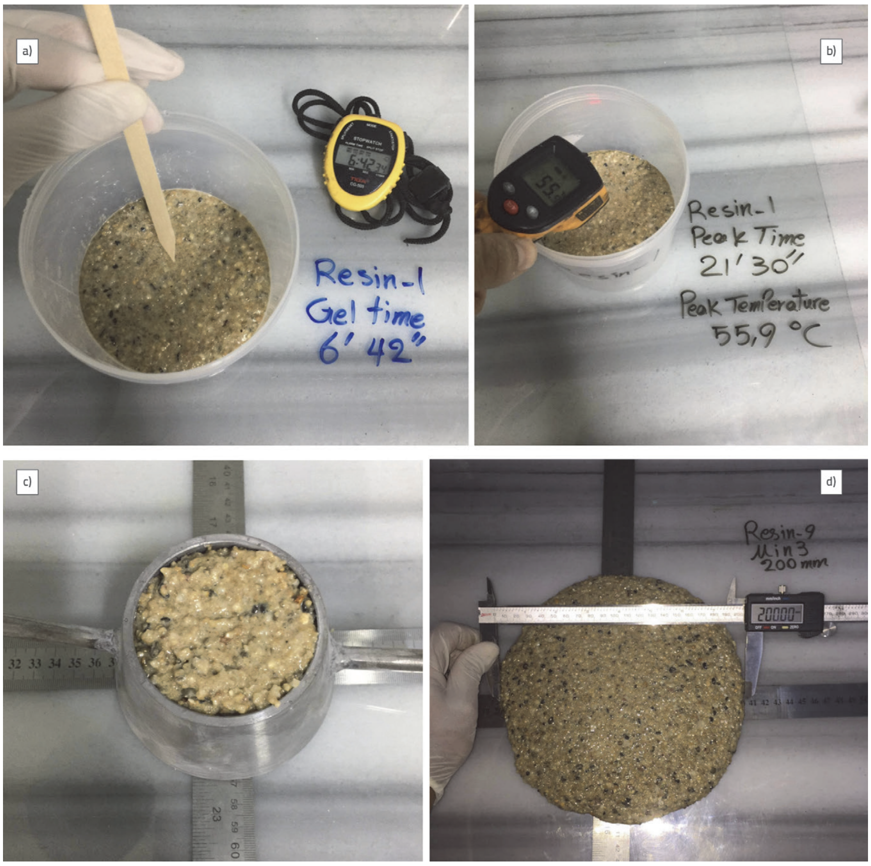

Figure 2. Fresh concrete tests: a) gel time, b) peak temperature, c) and d) flow test

3. Experimental studies

The information about experimental studies is given in this part of the study. Experimental studies carried out within the scope of the study were divided into two categories: fresh concrete properties and hardened concrete properties. Since there are no international standards for testing strength of polymer concretes, the experimental studies were conducted in accordance with international regulations on cement-based concretes and mortars.

3.1. Properties of fresh polymer concrete

A PC should be homogeneous, not segregated, easily mixed, transmitted, compressed, and its surfaces should be able to be fine-tuned. Moreover, they should fill their moulds without leaving any gaps and losing their homogeneity. Therefore, the fact that fresh concrete has good properties is an important indicator of concrete quality. Fresh PC properties are thus analysed in the first part of the study. Four key properties of fresh concrete that significantly influence its workability and hardness are discussed in the paper: gel time, peak time, peak temperature, and flow (Figure 2). In the fresh concrete experiments, ASTM D 2471–99 [14] was used to determine gel time, peak time, and peak temperature. It can be used to determine exactly how long it takes from the time when reactants are mixed to the time when solidification begins, under conditions approximating actual usage. Additionally, the method allows for the measurement of peak exothermic temperatures, as well as the interval between mixing and reaching this temperature.

The ASTM C143/C143M-20 [15] was utilized to determine workability of concrete. Currently, there are no regulations on how polymer concretes should be tested for workability, and so tests relating to cement-based concretes were used. The test method has been originally developed to provide a procedure for determining consistency of unhardened concrete, and it can be applied to plastic concrete having aggregate particles smaller than 37.5 mm. This standard was applied since the maximum aggregate size in this study is less than 37.5 mm. The data obtained in fresh concrete testing are summarized in Table 5.

3.2. Properties of hardened polymer concrete

Compression, flexural, and density tests were conducted in the second part of the study to assess properties of hardened concrete. Hardened concretes were tested according to ASTM C109/C109M [16] for compressive strength, ASTM C78/C78M [17] for flexural strength, and ASTM C642 [18] for density. According to Sokoowska [19], PCs regain more than 80 % of their mechanical strength within three days, and there are no major changes in their long-term strength within seven days. Thus, seven-day samples were used for testing hardened concrete samples relating to the study [19]. To determine the compressive and flexural strengths of hardened samples, these

Table 5. Results obtained by fresh concrete testing

Polymer concrete	**Gel time** [s]	**Peak temperature** [°C] (room temperature: 25 °C)	**Peak time** [s]	**Flow test** [mm] (X / Y direction)
PC-1	380	53.9	1290	S1: 152/160 S2: 165/175 S3: 180/190 S4: 187/197 S5: 177/180
PC-2	560	53.3	1500	S1: 160/160 S2: 175/170 S3: 185/185 S4: 195/190 S5: 178/176
PC-3	180	52.8	690	S1: 140/150 S2: 160/165 S3: 175/180 S4: 185/185 S5: 168/172
PC-4	375	45.4	1110	S1: 140/140 S2: 155/155 S3: 165/165 S4: 170/170 S5: 158/160
PC-5	195	53.3	660	S1: 160/165 S2: 170/175 S3: 180/185 S4: 190/190 S5: 175/178
PC-6	570	48	1500	S1: 145/145 S2: 155/155 S3: 165/170 S4: 170/175 S5: 159/160
PC-7	360	40.1	1650	S1: 155/155 S2: 170/170 S3: 185/185 S4: 195/195 S5: 176/175
PC-8	390	45.8	1290	S1: 160/160 S2: 170/170 S3: 180/180 S4: 190/190 S5: 170/170
PC-9	210	57.5	780	S1: 170/180 S2: 195/200 S3: 200/205 S4: 200/210 S5: 180/178
PC-10	230	58.2	1170	S1: 195/195 S2: 205/205 S3: 214/214 S4: 215/215 S5: 198/201

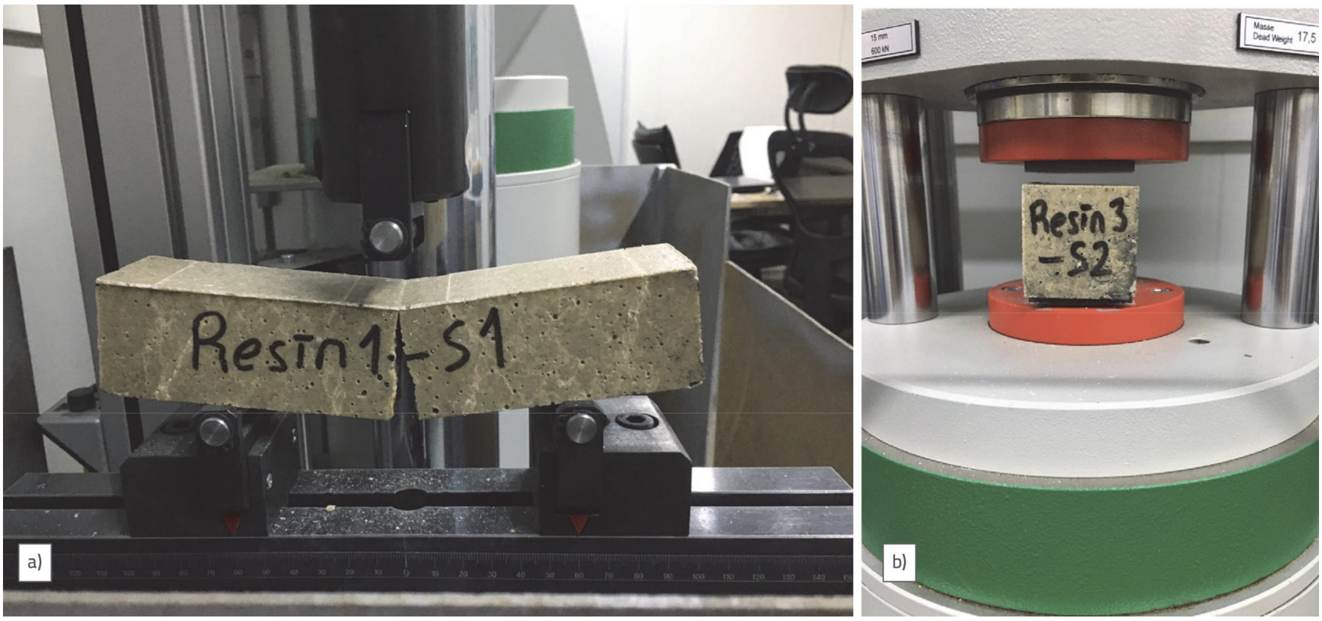

Figure 3. a) Flexural strength test, b) compressive strength test

samples were tested until failure using a 600 kN Form-Test machine (Figure 3). When determining compressive strength of samples, cube samples were preferred to cylindrical ones because the aggregates used in the study had a maximum diameter of 5 mm. A summary of the hardened concrete test results is provided in Table 6.

Table 6. Hardened concrete test results

Polymer concrete	Compression strength [MPa]	Flexural strength [MPa]	Density [kg/m^3]
PC-1	S1: 69.11 S2: 73.85 S3: 68.93 S4: 68.30 S5: 74.31	S1: 19.71 S2: 19.62 S3: 16.48 S4: 18.63 S5: 17.06	S1: 2106.80 S2: 2043.63 S3: 2057.58 S4: 2079.84 S5: 2092.30
	Average: 70.90	**Average: 18.3**	**Average: 2076.03**
PC-2	S1: 90.71 S2: 114.48 S3: 109.93 S4: 103.83 S5: 100.81	S1: 27.92 S2: 27.06 S3: 26.76 S4: 27.89 S5: 27.11	S1: 2242.30 S2: 2232.66 S3: 2234.77 S4: 2236.09 S5: 2246.09
	Average: 103.95	**Average: 27.35**	**Average: 2238.38**
PC-3	S1: 99.73 S2: 101.26 S3: 99.56 S4: 102.81 S5: 99.98	S1: 28.95 S2: 24.02 S3: 26.56 S4: 26.83 S5: 25.34	S1: 2300.51 S2: 2328.01 S3: 2351.41 S4: 2332.37 S5: 2323.97
	Average: 100.67	**Average: 26.34**	**Average: 2327.25**
PC-4	S1: 91.48 S2: 88.34 S3: 89.87 S4: 90.87 S5: 88.22	S1: 24.21 S2: 23.23 S3: 25.79 S4: 24.39 S5: 25.02	S1: 2227.34 S2: 2205.94 S3: 2190.86 S4: 2190.31 S5: 2205.45
	Average: 89.76	**Average: 24.53**	**Average: 2203.98**

Table 6. Hardened concrete test results - nastavak

Polymer concrete	Compression strength [MPa]	Flexural strength [MPa]	Density [kg/m³]
PC-5	S1: 82.93 S2: 85.07 S3: 82.96 S4: 83.32 S5: 84.43	S1: 21.52 S2: 20.65 S3: 19.83 S4: 19.98 S5: 20.02	S1: 2252.93 S2: 2302.46 S3: 2263.38 S4: 2283.40 S5: 2287.21
	Average: 83.74	**Average: 20.40**	**Average: 2277.88**
PC-6	S1: 77.85 S2: 99.29 S3: 99.42 S4: 97.14 S5: 80.61	S1: 24.73 S2: 31.32 S3: 23.03 S4: 25.91 S5: 28.19	S1: 2270.16 S2: 2247.66 S3: 2256.52 S4: 2220.31 S5: 2183.55
	Average: 90.86	**Average: 26.64**	**Average: 2235.64**
PC-7	S1: 69.62 S2: 67.82 S3: 67.61 S4: 68.78 S5: 69.71	S1: 19.59 S2: 20.13 S3: 19.13 S4: 19.36 S5: 19.26	S1: 2327.66 S2: 2324.14 S3: 2260.82 S4: 2243.59 S5: 2319.36
	Average: 68.71	**Average: 19.49**	**Average: 2295.11**
PC-8	S1: 78.23 S2: 79.91 S3: 79.92 S4: 78.34 S5: 79.14	S1: 17.84 S2: 21.19 S3: 20.67 S4: 20.46 S5: 19.70	S1: 2186.05 S2: 2182.85 S3: 2173.24 S4: 2219.84 S5: 2184.73
	Average: 79.11	**Average: 19.97**	**Average: 2189.34**
PC-9	S1: 98.00 S2: 93.56 S3: 83.11 S4: 94.03 S5: 92.98	S1: 24.14 S2: 26.95 S3: 24.80 S4: 27.35 S5: 23.65	S1: 2263.98 S2: 2199.06 S3: 2221.45 S4: 2195.78 S5: 2273.95
	Average: 92.34	**Average: 25.38**	**Average: 2230.84**
PC-10	S1: 82.34 S2: 82.32 S3:84.18 S4: 83.29 S5: 86.24	S1: 20.88 S2: 21.05 S3: 30.23 S4: 29.53 S5: 23.18	S1: 2129.84 S2: 2171.84 S3: 2172.11 S4: 2140.31 S5: 2134.73
	Average: 83.67	**Average: 24.97**	**Average: 2149.77**

4. Discussion of results

The results obtained during fresh concrete tests and hardened concrete tests are examined and compared in this part of the study. The first section concerns the data obtained during the fresh concrete tests, including the gel time, peak temperature, peak time, and the spreading diameter, and average values of the results are evaluated. In terms of gel times, Resin 3 had the shortest gel time at 180 seconds, while Resin 6 had the longest at 570 seconds (Figure 4). According to Table 2 that contains technical information about the resins, the gel times obtained in polymer concretes are directly related to the gel times of the resins. It appears that in cases where resin gels relatively quickly, polymer concrete also gels relatively quickly. In the same way, if the resin has a long gel time, then the polymer concrete has a long gel time as well. These results obtained from the study are similar to the results obtained in the studies conducted by Haddad and Sbarski in 2017 [20]. Haddad and Sbarski [20] determined low gel time in polymer concretes produced with resins with low gel times, and high gel times in polymer concretes produced with resins with high gel times. Additionally, peak time and peak temperature values follow the same pattern. When investigating the average peak temperature values, it was determined that the lowest peak temperature was 40.1 °C in Resin 7 while the highest peak temperature value was 58.2 °C in Resin 10. It was also observed that peak temperature values generally remain between 55 °C and 60 °C (Figure 4). Results differ greatly when average peak times are compared to each other, i.e. it can be seen that Resin 5 has the shortest average peak time, while Resin 7 exhibits the highest peak time (Figure 5). When peak times of these two resins are compared, it can be seen that Resin 7 has a peak time that is almost two times greater compared to Resin 5. The reason for the high peak time of the Resin 7 can be attributed to its low peak temperature value. Based on these results, it can be concluded that fresh PC properties are directly dependent on resin properties. Flow tests show that Resin 10 has the greatest spreading of approximately 205 mm, while Resin 4 exhibits the smallest spreading of approximately 158 mm (Figure 6). In this case, resin viscosity is directly responsible for the situation. Considering spreading diameters, it was small in PCs produced with high-viscosity resins, but it was large in PCs produced with low-viscosity resins.

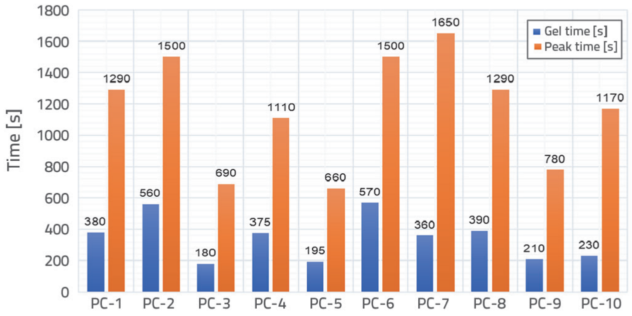

Figure 4. The average gel time and peak time (sec)

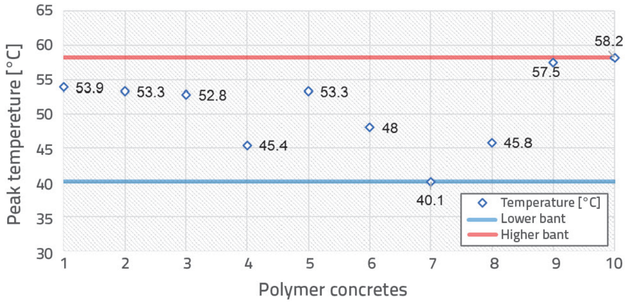

Figure 5. Average peak temperature (°C)

As to mechanical tests performed on the hardened concrete samples, the compressive strength ranges from 68 MPa to 104 MPa (Figure 7). According to the hardened state tests, Resin 7 has the lowest compressive strength while

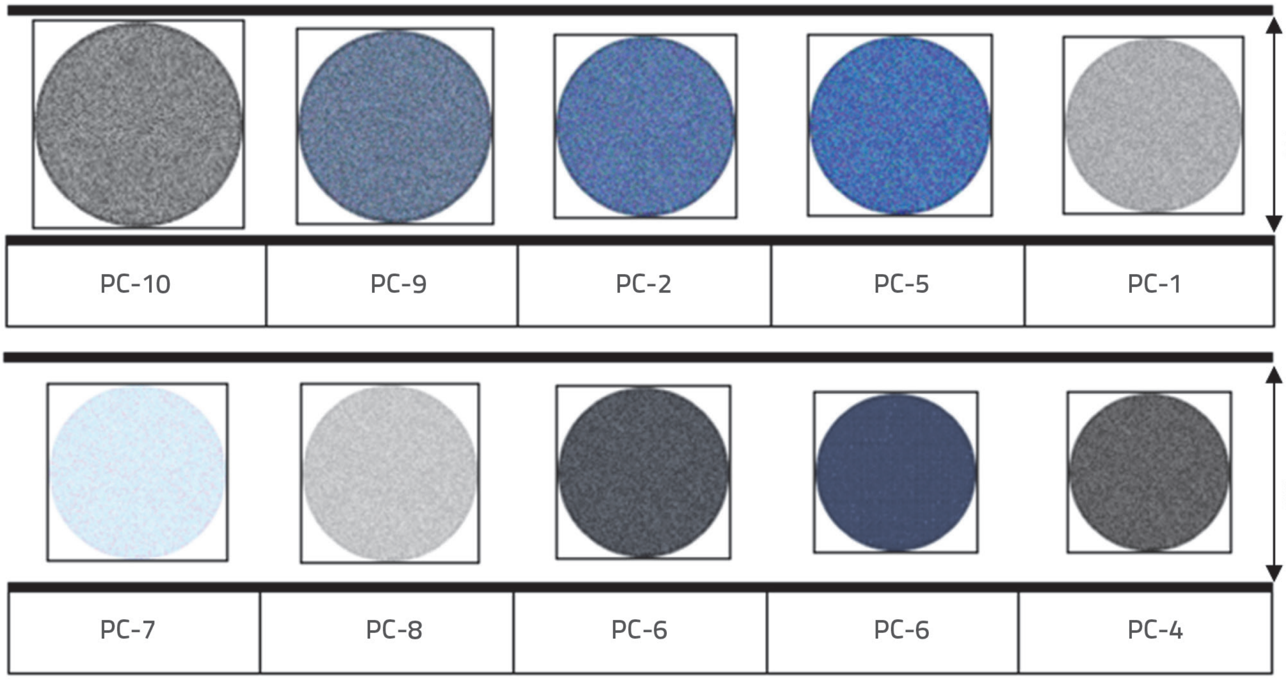

Figure 6. Average spread diameter obtained during flow tests (from the largest to lowest values)

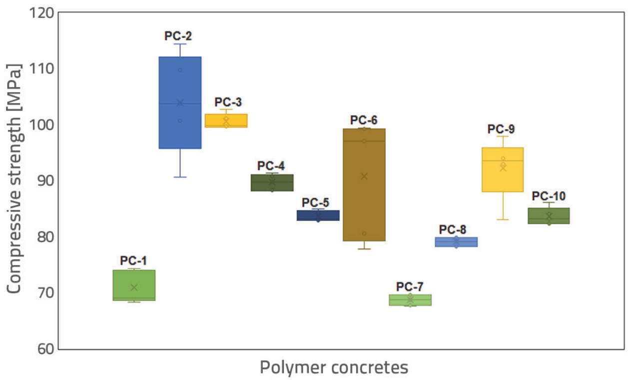

Figure 7. Average compressive strengths [MPa]

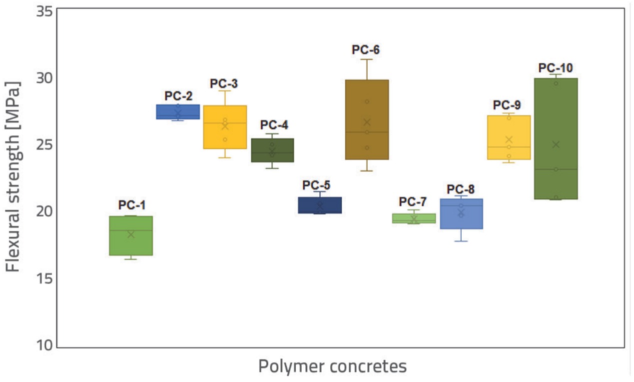

Figure 8. Average flexural strengths [MPa]

Table 7. Worst and best scores of each parameter

Parameters Resultats	**Gel time**	**Peak temperature**	**Peak time**	**Flow test**	**Compression strength**	**Tensile strength**	**Density**
Worst score	MIN	MAX	MIN	MIN	MIN	MIN	MAX
Best score	MAX	MIN	MAX	MAX	MAX	MAX	MIN

Resin 2 exhibits the highest compression strength. As to flexural strength, the lowest value is 18.30 MPa, and the highest one, observed in resin 1, is 27.35 MPa (Figure 8). Based on standard deviations of five samples, the results of the experimental studies were found to be compatible. Compared with cement-based concrete, PCs have higher compressive and flexural strengths. Based on the results, it can be seen that the type of epoxy also impacts mechanical properties of PCs. The results of this study are similar to those obtained in the study conducted by Vipulanandan and Paul[21]. The direct effect of resins on the compression and tensile strengths of PCs was established in this study based on experimental studies and constitutive modelling. Similarly, Muthukumar and Raju [22] reported that mechanical performance of PCs depends on the type of polymer binder, aggregate type and grading. Since the aggregate types and grading were kept constant in this study, it can be concluded that mechanical properties of PCs directly depend on the resin type.

5. Performance Index

In the context of this study, the performance of resins was measured using fresh concrete and hardened concrete test results. When this information is analysed, it is difficult to determine which concrete has the best properties based on experimental data. For this reason, performance indexes were used in samples to interpret all experimental results and compare PCs more effectively. This study considered seven different parameters as fresh concrete properties and hardened concrete properties. Each of these parameters may have a positive or negative effect on polymer concrete performance. Thus, the impact of these seven parameters on polymer concretes was first determined as shown in Table 7. Based on the table, high values could have a very negative effect on polymer concretes, while low values may have a very positive impact on polymer concretes. In order to overcome this problem, the parameters were all graded from 0 to 100, where 0 represents the worst score and 100 represents the best score.

After that, performance indexes were determined using the formula given in Equation (1). Considering the performance indexes, radar charts were prepared depending on the final stage of the evaluation, and each resin performance was evaluated with the help of these charts (Figure 9). Following the preparation of the radar charts, the performance index for each concrete was determined, considering the areas included in the radar chart. Performance indexes are presented, from highest to lowest, in Figure 10. According to the performance indexes, Resin 6 has the best performance index of 92.59 out of 100, while Resin 5 has the worst performance index of 67.71 out of 100.

$$PI_i = \left(\frac{PTime_i}{max(GTime)} + \frac{\min(PTemp)}{PTemp_i} + \frac{PTime_i}{max(PTime)} + \right) \\ + \left(\frac{FTest_i}{max(FTest)} + \frac{CSt_i}{max(CSt)} + \frac{TSt_i}{max(TSt)} + \frac{\min(Density)}{Density_i}\right)\frac{1}{7}\cdot 100 \qquad (1)$$

where, Gtime, PTemp, PTime, FTest, CSt, TSt, Den stand for gel time, peak temperature, peak time, flexural test, compression test and density, respectively.

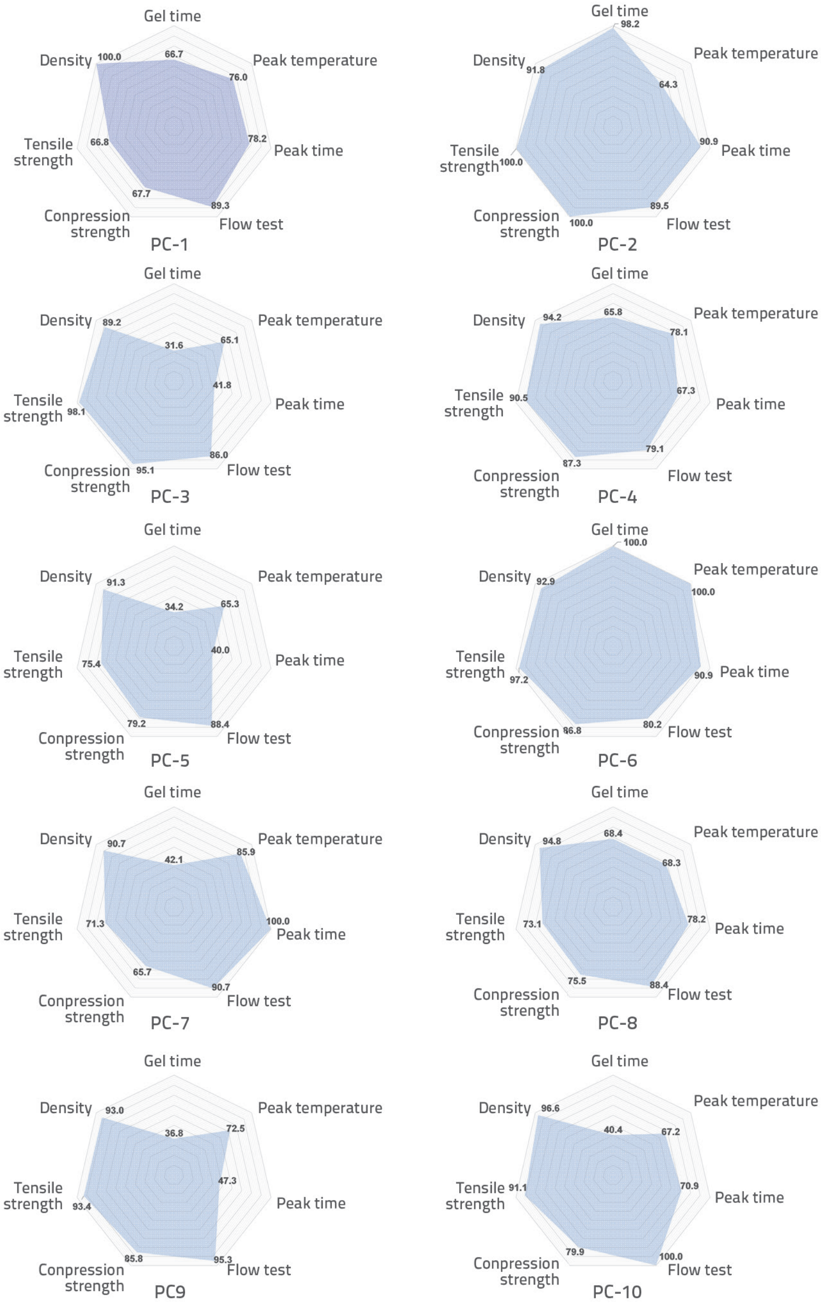

Figure 9. Closeness to performance for each PC sample

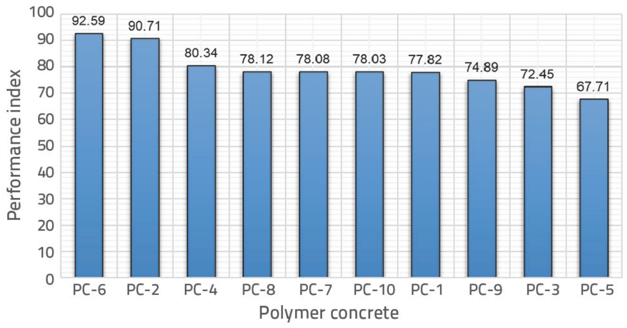

Figure 10. Performance indexes of samples

6. Conclusion

The use of polymer concretes (PC) has increased in many sectors in recent years. In view of high performance of PCs, they are considered to be the most effective alternative to cement-based concretes (CBCs). This study examines how resins affect mechanical performance of PC by examining experimental results of fresh and hardened PCs. Ten commercial resins are selected in this study. Concrete samples prepared using each resin are examined using gel time, peak temperature, peak time, and flow tests (fresh concrete), as well as compressive strength, flexural strength and density tests (hardened concrete). At the last stage, a performance index is generated for each PC, and the results of the analysis are evaluated using performance scores. Test results show that resins play a critical role in the performance of PCs. Based on performance indexes, it has been established that Resin 6 has the best performance index of 92.59, while Resin 5 has the worst performance index of 67.71. Mechanical tests are used to examine brittle fracture in all samples, and it has been established that PC samples have either poor plastic deformation capacity or no plastic deformation capacity. Since all samples have brittle fracture, it can be concluded that the resin type does not affect the failure mechanism of PC.

It is believed that results obtained in this study will be beneficial for many studies. Additionally, the study also guides the researcher to investigate PC components, and to better evaluate these components.

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