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Polymer concrete production technology with improved characteristics based on furfural for use in hydraulic engineering construction

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ABSTRACT: Introduction. Research of polymer concrete properties show that it differs favorably from conventional concrete by such indicators as mechanical strength, resistance to aggressive impact of various environments, water resistance, abrasion resistance, water-repellency and frost resistance. Currently, it is possible to obtain polymer concrete with characteristic and chemical properties –specified density, strength, deformability, ductility, and corrosion resistance. **Methods and materials.** The research is carried out by comparing laboratory tests of polymer concrete based on furfural binder. Furfural has a high reactivity and can form resin compounds with many chemicals. Diphenylamine was added to furfural in different proportions. Benzenesulfonic acid, sulfuric acid and their mixture at a ratio – 1:1 by weight were used as hardeners. Crushed sand or ground andesite based on nanostructured microfiller served as aggregate for various compositions of polymer solutions. The polymer concrete strength, chemical resistance, lasting properties, water resistance, abrasion resistance, metal adhesion were tested during the research. Structural changes in properties were studied by the electron microscopic analysis method. **Results and discussion.** It is established that the diphenylamine solution in furfural, provided that it is solidified by sulfuric acid, benzolsulfoacid or mixture of these acids, is a polymer binder capable to form a high-strength material under normal hardening conditions by acid-resistant aggregates. It is also determined that to prepare resin, the ratio of furfural and diphenylamine should be within 1:0.5–0.3 by weight. The resin containing 1 weight part (w.p.) of furfural and 0.5 weight part of diphenylamine is conventionally named FD-1; containing 1 weight part of furfural and 0.4 weight part of diphenylamine – FD-2 and resin with 0.3 weight part of diphenylamine – FD-3. **Conclusion.** The introduction of nanostructured microfiller into the polymer concrete composition could save expensive resin. Comparison of the technologies for producing FD resin and polymer concrete, as well as preliminary test data of the studied materials, can determine the possible technical and economic advantages of polymer concrete based on FD resin over the polymer concrete based on FA (furfurolacetone) monomer which is currently used in construction of hydro-engineering structures. Polymer concrete based on FD resin has high strength and exceeds the strength of polymer concrete based on FA monomer by 20–25%.

KEYWORDS: polymer concrete, furfural, diphenylamine, resin, nanostructured microfillers, polymer solution, hydro-engineering structures.

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INTRODUCTION

In hydro-engineering construction, polymer concrete can be used in the building of the individual parts of structures (overflow surface, dampers, etc.) that are subject to intensive destruction. This material is laid on a number of hydraulic structures in Central Asia and Kazakhstan [1].

Fig. 1. **Overflow surface of the Karaspan hydraulic complex**

A survey of the Karaspan hydraulic complex in the Turkestan region of the Republic of Kazakhstan, where the overflow surface is made of polymer concrete by volume 575 m^3 showed that after many years of operation the overflow surface did not collapse (Fig. 1).

The main reason that delays the widespread use of polymer concrete in the hydraulic structures construction is its high cost, the lack of acceptable manufacturing technology, and insufficient knowledge of its properties, which differ significantly from those of conventional concrete [2, 3]. The main rise in price falls on the cost of a synthetic binder, the most common and cheapest of which is resin – furfural acetone FA monomer. The cost of 1 m^3 of polymer concrete made on FA monomer is 2.5–3 times more expensive than reinforced concrete and 4–5 times more expensive than conventional cement concrete. The high cost of the polymer binder is due not only to the high cost of chemical products it is obtained from, but also to the high costs of manufacturing technological operations [4, 5].

Research conducted on furfural resin makes it possible to develop a low-cost technology to obtain binders for polymer concrete. Furfural has a high reactivity and can form resin compounds with many chemicals under fairly simple conditions (normal pressure and low temperatures). An example of this is the production of furfurolaniline resin, as well as the manufacture of other resin products by the interaction of furfurol with aromatic amines and their derivatives. However, the problem of obtaining an economical polymer binder will be solved only if the resin product obtained under simple manufacturing conditions can provide the required qualities of construction products (sufficient strength, durability) [2–5].

In the laboratory of building materials, the authors obtained the polymer binder based on furfural and aromatic amine-diphenylamine. It is established that the diphenylamine solution in furfural, provided that it is solidified by sulfuric acid, benzolsulfoacid or mixture of these acids, is the polymer binder capable to form a high-strength material under normal hardening conditions by acid-resistant aggregates.This polymer binder is called FD resin. In this case, the manufacturing costs will consist of the cost of the initial products [4–6].

METHODS AND MATERIALS

The optimal binder composition was determined as follows. Diphenylamine was added to furfural in different proportions. The mixture was mixed. The product in furfural was dissolved under normal conditions and a resin-like substance was formed. Polymer concrete samples, cubes 3×3×3 cm in size, were made based on the binder, while three types of hardener were used – benzenesulfonic acid, sulfuric acid and a mixture of them at a ratio of 1:1 by weight. The aggregate was ground andesite. After storage for a certain period of time at room temperature or in a drying oven, the hardened samples were tested for strength [7].

Experiments have shown that the ratio of furfural and diphenylamine should be in the range of 1:0.5–0.3 by weight to prepare resin. The resin containing 1 weight part of furfural and 0.5 weight part of diphenylamine is conventionally named FD-1; containing 1 weight part of furfural and 0.4 weight part of diphenylamine – FD-2, and resin with 0.3 weight part of diphenylamine – FD-3. These kinds of resin were used to make polymer-soluble cube-shaped samples of 3×3×3 cm. Each polymer-soluble mixture contained 20% FD resin. These mixtures were solidified by various amounts of sulfuric acid, benzolsulfoacid (BSA) and a combined hardener [7–9].

Solidified samples formed from polymer-soluble mixtures were tested for compression after 28 days storage at room temperature (Fig. 2). The test results allowed us to determine the most optimal compositions of polymer concrete. The test data of the samples are shown in Fig. 3, 4, 5.

The maximum strength of polymer solutions solidified by various hardeners is obtained from the following formulations:

I. Aggregate – ground andesite – 1 w.p.; binder – 0.2 w.p., FD-1 resin; hardener – 0.06 w.p., sulfuric acid; the compression strength is 1270 kg/cm^2 (Fig. 3).

II. Aggregate – ground andesite – 1 w.p.; binder – 0.2 w.p., FD-2 resin; hardener – 0.1 w.p., BSA; the compression strength is 1220 kg/cm^2 (Fig. 4).

Fig. 2. **Compression test of samples**

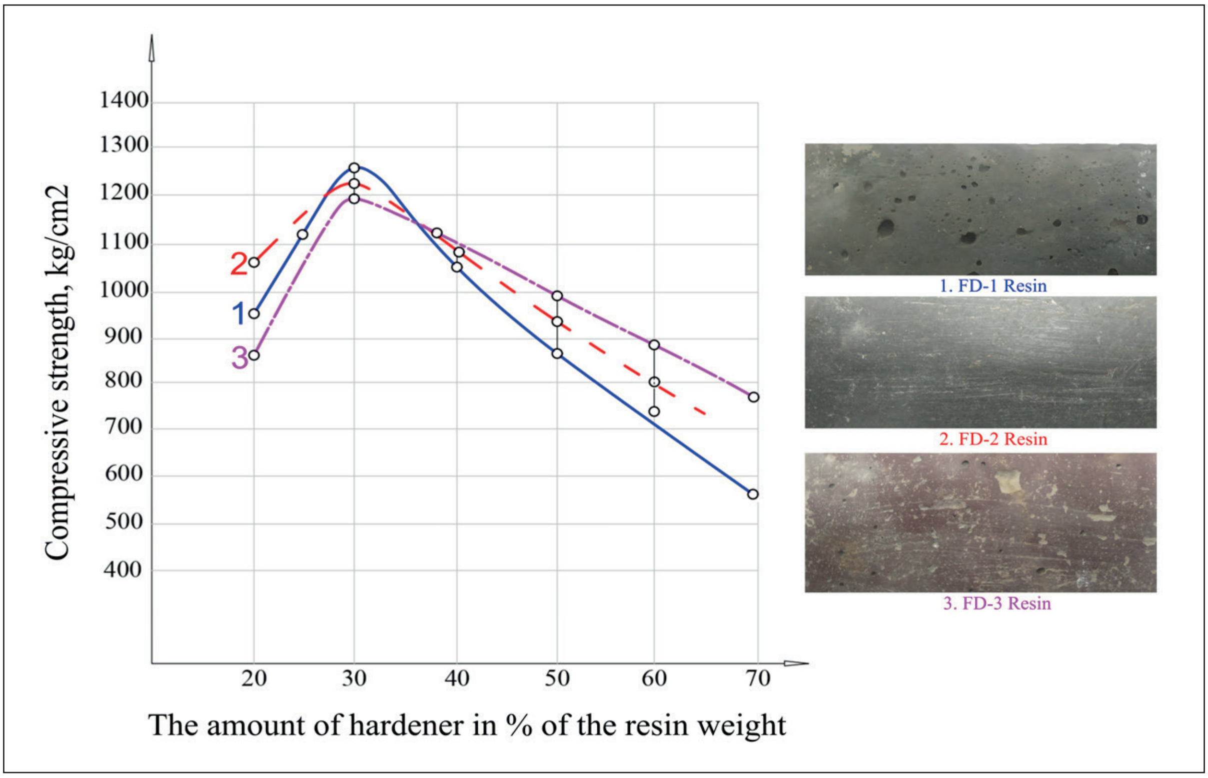

Fig. 3. **Changes in the strength of polymer concrete based on different kinds of resin depending on the amount of hardener-concentrated H_2SO_4:** FD-1 resin; FD-2 resin; FD-3 resin

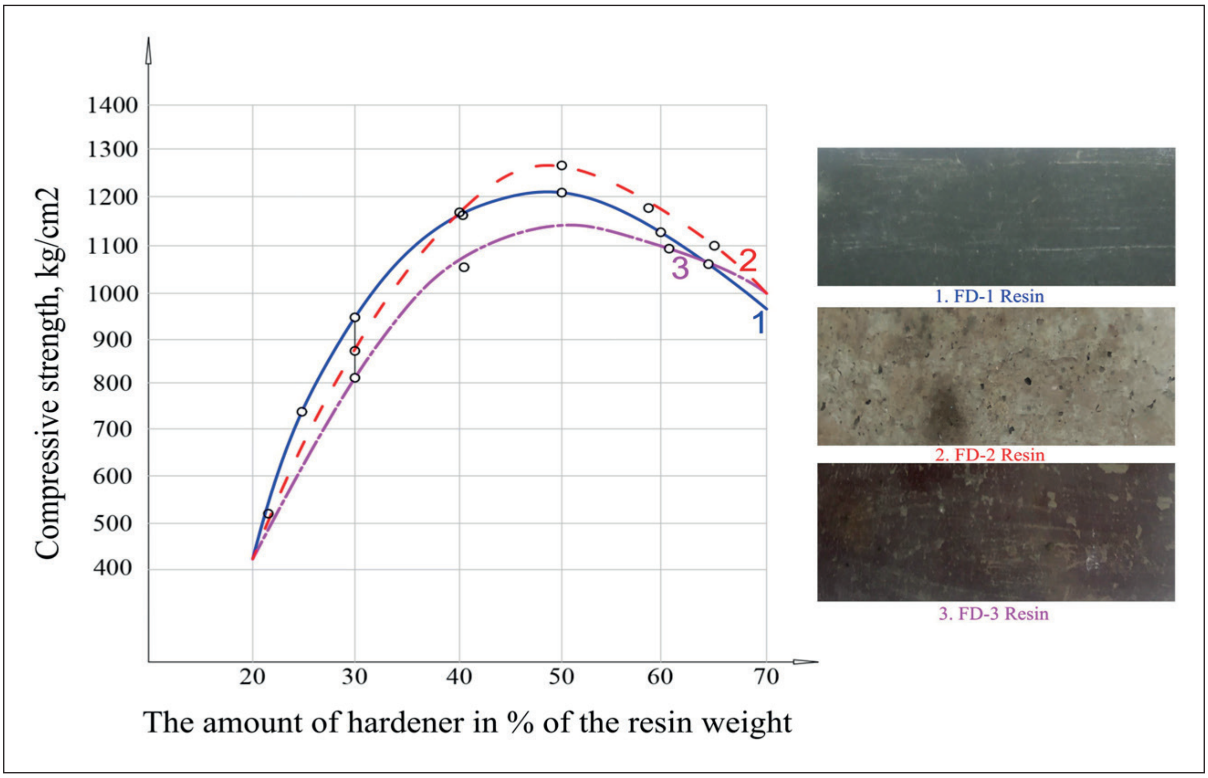

Fig. 4. **Changes in the strength of polymer concrete based on different kinds of resin depending on the amount of hardener-benzolsulfoacid:** FD-1 resin; FD-2 resin; FD-3 resin

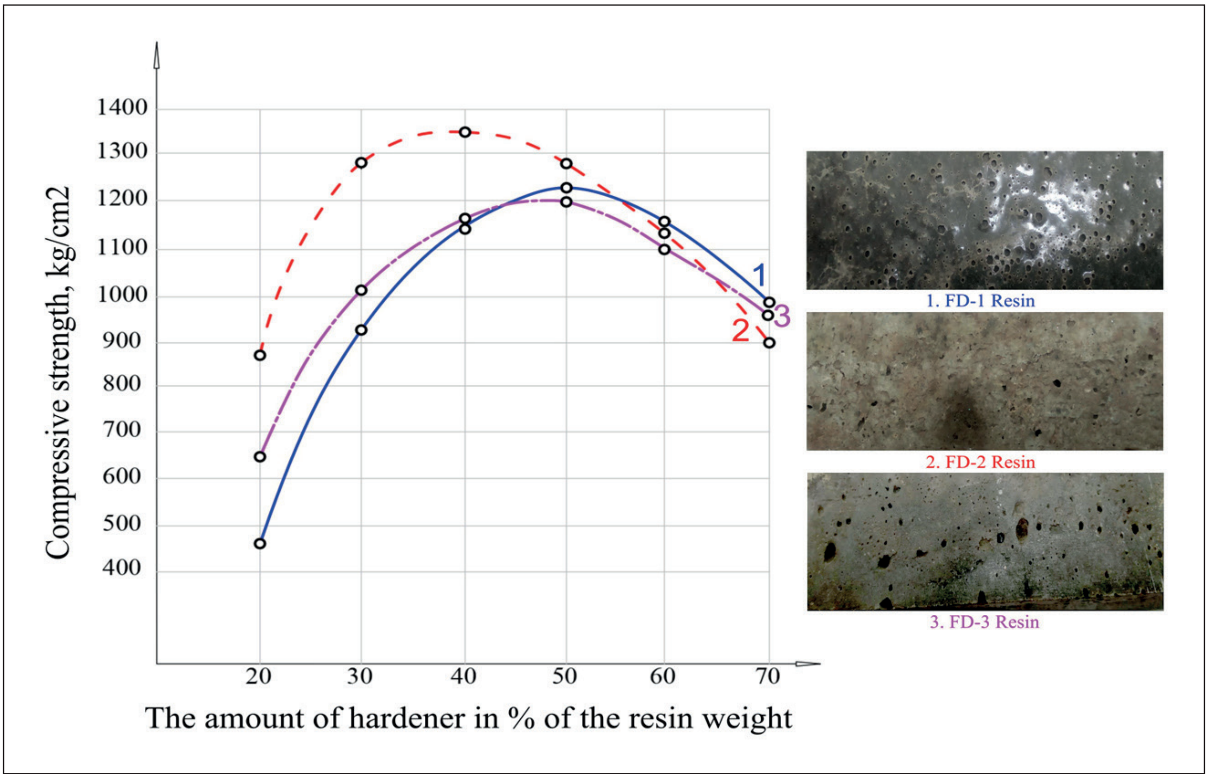

Fig. 5. **Changes in the strength of polymer concrete based on different kinds of resin depending on the amount of hardener-concentrated H_2SO_4 and BSA:** FD-1 resin; FD-2 resin; FD-3 resin

III. Aggregate – ground andesite – 1 w.p.; binder – 0.2 w.p., FD-3 resin; hardener – 0.08 w.p., combined mixture; the compression strength is 1400 kg/cm^2 (Fig. 5).

From the experiments it turned out that the most optimal ratio of furfural and diphenylamine in furfural-diphenylamine resin is 1 weight part of furfural and 0.4 weight part of diphenylamine. According to this formulation, the binder for polymer concrete was obtained. Later studies were carried out on this resin and the hardeners – BSA and combined one. Based on this principle, polymer-solution and polymer-concrete samples of various formulations were prepared, and their optimal composition and properties were determined [10, 11].

To obtain comparative data on the study of the basic properties of polymer concrete of various formulations, it is necessary to prepare and test a large number of samples of different ages [11]. Samples made of polymer concrete for strength testing should be of the following dimensions: cubes – 10×10×10 cm, 15×15×15 cm and 20×20×20 cm, beams – 10×10×40 cm, 15×15×55 cm, etc. (Fig. 6). The production and testing of such samples is labor-intensive and requires a large amount of materials, in addition, conducting appropriate tests to obtain comparative data on the resistance of polymer concrete to the destructive action of water, frost, aggressive environment on large samples will take too long [12]. Therefore, to obtain comparative data on water resistance, corrosion resistance, weather resistance and other properties, we first prepared and tested small polymer-soluble samples (3×3×3 cm cubes, 2×2×10 cm beams). The obtained data on the properties of polymer concrete based on furfural resin with additives was compared with the properties of cement concrete and polymer concrete based on furfural-acetone monomer. The latter is chosen as the most widely studied. The main raw material for obtaining the FA monomer is furfural, which is used for the production of polymer concrete, and which we are studying. The qualities that are supposed to be developed in polymer concrete used in hydraulic engineering and irrigation are strength and water resistance. Therefore, to improve these qualities, some experiments were carried out on polymer concrete produced on a base of various aggregates, kinds of resin and hardeners. Determination of polimer concrete properties on furfural-based binder was carried out according to the appropriate methods of construction material testing [13].

Polymer concrete on furfural-based binder is solidified by acid hardeners-BSA, sulfuric acid and their mixture. This fact makes it necessary to use nanostructured microfillers made of acid-resistant rocks. The ratio of the resin and aggregate amounts to get dense polymer concrete is usually selected in the same way as for cement concrete (the resin should cover the aggregate grains and fill the voids between them). The introduction of nanostructured

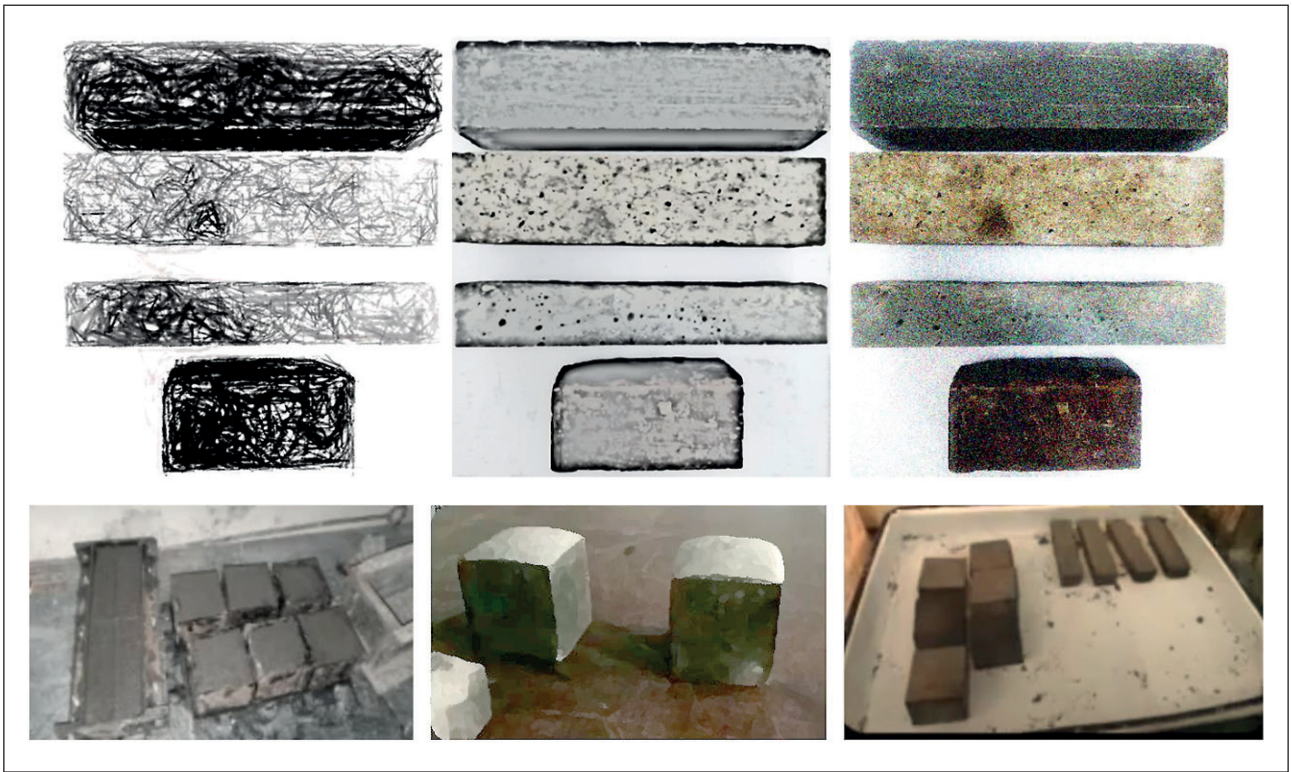

Fig. 6. **Different-sized samples of polymer concrete on furfural-based binder**

microfiller into the polymer concrete composition will save expensive resin [12–14].

Testing of various compositions of polymer solution based on nanostructured microfillers (crushed sand or ground andesite) and furfural-based binder with additives allowed us to establish the following formulations [14, 15].

1. Aggregate – microfiller – 1 w.p.; binder – 0.2 w.p., FD resin; hardener – 0.08 w.p., combined.

With the introduction of fine aggregate – sand Mk = 1.92 into polymer concrete composition, the optimal composition varies within the following limits:

2. Aggregate – fine aggregate and microfiller in the ratio of 1.5:1 by weight – 1 w.p.; binder – 0.12 w.p., FD resin; hardener – 0.05 w.p., combined.

The optimal composition of polymer concrete with coarse aggregate-gravel with a grain size of 5–20 mm can be as follows:

3. Aggregate – coarse aggregate and microfiller in the ratio of 1.5:1 by weight – 1 w.p.; binder – 0.1 w.p., FD resin; hardener – 0.04 w.p., combined.

With the introduction of all three types of aggregates (microfiller, fine aggregate, coarse aggregate) into polymer concrete composition, the optimal composition will be as follows:

4. Aggregate – nanostructured microfiller, fine and coarse aggregates in the ratio of 1:1.6:2,5 by weight – 1 w.p.; binder – 0.15 w.p., FD resin; hardener – 0.06 w.p., combined.

All these compositions will have different strength characteristics (Table 1).

The sample sizes of compositions # 1, 2 are beams – 4×4×4 cm and standard briquettes, compositions # 3, 4 are cubes – 10×10x×10 cm, beams – 10×10×32 cm and beams – 10×10×65 cm with thickened ends.

The strength of polymer concrete is determined by many factors [16–18]. The main ones include: the content of the binder and hardener amounts in polymer concrete, the hardening mode, and the mineral and petrographic characteristics of aggregates. The binder consumption is determined by the voidness of the aggregates and their fineness. The greater the voidness of the aggregate, the more binder and, accordingly, hardener will be required. The amount of hardener has a significant effect on the strength polymer concrete. With its lack, the polymerization of the binder is incomplete, which negatively affects the strength and other qualities of polymer concrete. The excess of hardener leads to rapid mixture setting, a decrease in strength, an increase in brittleness and deterioration of other indicators. The optimal content of binder and hardener should be chosen under the condition of providing such an indicator of the main characteristic of polymer concrete, which will be decisive for its operation [17, 23].

The authors studied the influence of heat treatment modes on the polymer concrete samples strength based on FD resin. We used two methods. The prepared samples

Table 1
Polymer concrete strength of different compositions

Batch composition	Yield strength, kg/cm^2		
	Compressive strength	Flexural strength	Tensile strength
1	1200–1300	270–290	100–120
2	1100–1200	260–270	100–110
3	900–950	235–250	90–100
4	900–950	240–255	75–80

after their daily storage at a temperature of 18–20°C were placed in a thermo cabinet, where they were subjected to dry heating at 60, 80, and 100°C. The time of keeping the samples in the cabinet varied from 2 to 24 hours. Another series of samples was subjected to dry heating under the same conditions immediately after their manufacture. There was no difference in the results obtained by these two heating methods. The best results were shown in the treatment modes at 80°C for 10 hours and at 100°C for 8 hours. It can be concluded that heating of polymer concrete intensifies polymerization of the FD binder [17, 18, 21].

RESULTS

The first condition for high chemical resistance of polymer concretes is to achieve a complete solidification of the resin. Increased chemical resistance is provided to polymer concretes by chemically resistant aggregates, the most common of which include andesite, diabase, quartz, etc. Chemical resistance of polymer concretes is provided by graphite and related materials. To compare the stability of different samples based on FD resin in aggressive enviroment, tests were performed in the same aggressive solutions of polymer concrete samples based on FA monomer [13, 21, 23].

The tests were carried out on a series of 1×1×3 cm samples with the following composition:

a) aggregate – quartz crushed sand – 231w.p.; binder – 100 w.p., FD resin; hardener – 40 w.p., combined;

b) aggregate – graphite – 173 w.p.; binder – 100 w.p., FD resin; hardener – 40 w.p., combined;

c) aggregate – quartz crushed sand – 315 w.p.; binder – 100 w.p., FA monomer; hardener – 20 w.p., BSA; acetone – 1,6 w.p.

The chemical resistance of polymer concrete was determined by changes in the samples bending strength [16, 19, 23]. The samples were preliminarily subjected to heat treatment for 12 hours at a temperature of 80°C 2 days after manufacture. Acid solutions were used as aggressive enviroment: sulfuric acid 1% and 10%, hydrochloric acid 1% and 10%, sodium hydroxide 1% and 10%, as well as various solvents (Tables 2, 3).

Table 2
Chemical resistance of FD-based polymer solution prepared with graphite aggregate when the samples are kept in aggressive environment

Environment	Concentration, %	Variation of flexural strength after 24 hrs., kg/cm^2					
		30	60	90	120	180	360
Air	–	328	334	344	340	334	345
Hydrochloric acid	1	139	167	187	170	162	154
	10	123	221	150	160	165	180
Sulphuric acid	1	130	166	160	177	178	200
	10	156	177	158	–	167	150
Sodium hyrdroxide	1	152	165	141	–	165	172
	10	160	221	193	–	208	210
Toluene	–	439	408	–	374	444	427
Benzene	–	453	411	–	393	315	409
Acetone	–	407	412	–	423	398	430
Benzine	–	419	426	–	405	400	425

Table 3

Chemical resistance of polymer solution prepared on a base of FD, FA monomer and crushed sand when the samples are kept in aggressive environment

Environment	Variation of flexural strength after 24 hrs., kg/cm²					
	Standard, kg/cm²	30	60	120	180	360
On FD resin (furfuraldiphenylamine)						
Air	306	363	410	435	428	410
Toluene	–	352	418	386	403	415
Benzene	–	383	414	439	393	390
Acetone	–	382	315	251	227	213
Benzine	–	390	370	375	320	390
On FA monomer (furfural acetone)						
Air	378	324	344	294	265	290
Toluene	–	392	393	403	385	374
Benzene	–	428	441	378	401	408
Acetone	–	108	81	65	60	54
Benzine	–	433	378	378	384	390

Reference sample strength is 356 kg/cm².

Tables 2 and 3 show that a large decrease in the small samples strength was noted in alkaline and acidic environments during bending tests, and after 30 days after immersion in an aggressive environment, the strength of samples based on ground graphite decreased by 40–50% from the initial one. The strength of the samples based on ground graphite and crushed sand in organic solvents (benzene, toluene, acetone, gasoline) increased by 20–30% from the initial one by 30–60 days of exposure.

Polymer-concrete samples based on FA monomer and crushed sand lost about 75% of their initial strength when kept in acetone, and samples based on ground graphite – about 10–15% (Table 3).

The strength of the same samples in organic solvents (toluene, benzene, gasoline) did not change in comparison with the initial one, and in some cases slightly increased. Solutions of sodium hydroxide and some acids practically do not cause a decrease in strength. It decreases after 30 days – storage in water. Further, the strength is stabilized.

The samples were tested for abrasion according to the standard procedure on the Amsler circle. Cube samples measuring 7×7×7 cm were made from 3 and 7 compositions. Aggregate – 1 w.p.; binder 0.12 w.p. – FA monomer; hardener – 0,4 w.p., BSA.

Gravel with a grain size of 5–20 mm and ground andesite in the ratio of 1.5:1 were used as aggregates (Table 4).

The method of determining the water resistance of polymer concrete is simple. Cube-samples, beams made of polymer concrete of different storage periods were placed in water and tested for compression at different storage periods. Reference samples were stored in dry conditions. The magnitude of the drop in the samples strength stored in water for different periods of time characterizes the water resistance of polymer concrete. To determine the water resistance of polymer concrete based

Table 4

Abrasion resistance of polymer concrete of various compositions at 600 m of the abrasion path (arithmetic mean data for 6 samples of each composition)

Batch composition	Weight of specimens before test, g	Weight of specimens after test, g	Abrasion area, cm²	Abrasion at 600 м/way, g/cm²	Abrasion of cement concrete M-200
7 3	754 742	746 735	49 49	0.16 0.14	0.6–1.2

on FD resin, a series of polymer concrete samples were prepared – cubes and beams based on hardeners of different types and in different quantities [19-22]. The water resistance test results of composition of 28-days age are shown in Table 5; of 60-days age – in the Table 6 and after 10 hours dry heating at a temperature of 80^{o}C – in Table 7.

The softening coefficient K_p and water resistance $K_в$ can be easily calculated from these tables. So, for example, after 60 days period:

$$K_p = 980/1133 = 0.865;\ K_в = 1133/1180 = 0.96.$$

The best water resistance values were obtained by dry heating of the samples for 10 hours at a temperature of 80^{o}C.

To determine the water resistance of polymer concrete with coarse aggregate, samples of composition # 3 were made (Table 8). The compositions were tested for water resistance in mineralized waters. An 8% solution of sodium sulfate was used as mineralized water (Table 9). The decrease in polymer concrete strength occurs more slowly in mineralized water than in pure water [23, 24].

The corrosion effect of polymer concrete on steel reinforcement was studied by the following method [25]. Cube-samples were made from composition # 3 measuring 10×10×10 cm: aggregate – ground andesite and gravel with a grain size of 20–40 mm in a ratio of 1:1.5 by weight – 1w.p.; binder – 0.1 w.p., FD resin; hardener – 0.04 w.p., combined.

Table 5

Change in polymer concrete water resistance at 28 days-age, depending on the time spent in water

Type of hardener, amount out of the binder weight, %	Compressive strength yield of specimens before immersing in water, kg/cm^2	Compressive strength yield of specimens stored in water for 24 hrs., kg/cm^2									
		30	60	90	120	150	180	270	360	540	720
Sulphuric acid, 30	1180	$\frac{1060}{1155}$	$\frac{980}{1133}$	$\frac{910}{1000}$	$\frac{880}{920}$	$\frac{855}{920}$	$\frac{825}{900}$	$\frac{810}{905}$	$\frac{820}{905}$	$\frac{815}{895}$	$\frac{820}{900}$
Benzenesulfonic acid, 50	1120	$\frac{1060}{1155}$	$\frac{965}{1065}$	$\frac{912}{1022}$	$\frac{872}{990}$	$\frac{844}{950}$	$\frac{820}{920}$	$\frac{808}{898}$	$\frac{794}{895}$	$\frac{805}{900}$	$\frac{800}{910}$
Combined, 40	1260	$\frac{1205}{1115}$	$\frac{1155}{1045}$	$\frac{1105}{1000}$	$\frac{1065}{935}$	$\frac{1045}{200}$	$\frac{1025}{872}$	$\frac{1015}{859}$	$\frac{1020}{865}$	$\frac{1010}{854}$	$\frac{1010}{860}$

Table 6

Change in polymer concrete water resistance at 60 days-age, depending on the time spent in water

Type of hardener, amount out of the binder weight, %	Compressive strength yield of specimens before immersing in water, kg/cm^2	Compressive strength yield of specimens stored in water for 24 hrs., kg/cm^2			
		60	120	180	240
Sulphuric acid, 30	1220	1105	930	900	905
Benzenesulfonic acid, 50	1205	1160	1160	1109	1100
Combined, 40	1295	1200	1150	1092	1096

Table 7

Change in polymer concrete water resistance after its dry heating at 80°C for 10 hours, depending on the time spent in water

Type of hardener, amount out of the binder weight, %	Compressive strength yield before immersing in water kg/cm^2	Compressive strength yield of specimens stored in water for 24 hrs., kg/cm^2				
		60	120	150	180	240
Benzenesulfonic acid, 50	1200	1160	1135	1122	1115	1108
Combined, 40	1255	1185	1150	1137	1120	1125

Table 8

Change in the strength of polymer concrete based on FD resin during storage in water

Batch composition	Compressive strength yield of specimens, kg/cm^2						
	before immersing in water	after storing in water for 24 hrs.:					
		30	60	90	120	240	360
3	750	620	650	610	590	550	530

Table 9

Change in the strength of polymer concrete based on FD resin during storage in mineralized water

Batch composition	Compressive strength yield of specimens, kg/cm^2						
	before immersing in mineral water	after storing in water for 24 hrs:					
		30	60	90	120	240	360
3	780	715	680	650	670	640	620

During the manufacturing process, polished steel rods 16 mm in diameter and 80 mm long were embedded in each sample. Before concreting, the rods were cleaned with acetone and weighed. The samples were stored indoors at an air temperature of 18–20^{o}C. After 12 months-storage, some of the samples were crushed, the rods were removed and carefully weighed again. The remaining samples were tested at 18 and 24 months-ages. It was found that the weight of the rods did not change over time. No traces of corrosion were found on the surface of the rods. Consequently, the environment of polymer concrete based on FD resin does not have a corrosive effect on steel reinforcement [25].

The numerator shows the test results of samples in a wet state, and the denominator shows the test results of samples dried to a constant weight.

The metal reinforcement adhesion tests were carried out by extracting steel rods of smooth profile at d = 16 mm of A–1 grade from 10x10x20 cm prisms manufactured from The embedment depth of the rods was 20 cm. The rods were kept 28 and 60 days after the samples manufacture. The test data showed that the adhesion of the reinforcement to polymer concrete is 108 kg/cm^2 [25].

The polymer concrete compressive elastic modulus was defined on prisms measuring 7×7×22 cm by strainmeters reinforced on both sides with a base of 20 mm, with a division value of 1 mm, and dial gauge with a division value of 0.01 mm. The load was carried out in steps equal to prismatic 0.1 R. Each step was followed by a 5-minute exposure time. Due to the elastic aftereffect, the strain readings were made at each step twice: at the time the load was applied to measure elastic deformations and after the exposure to measure plastic, permanent deformation.

During tension tests, the elastic modulus was determined in a similar way on prism samples measuring 10×10×60 cm, with thickened ends. The mean arithmetic test data of 5 samples were as follows: Prismatic strength – 850 kg/cm^2, tensile strength – 90 kg/cm^2; compressive elastic modulus – 298 000 kg/cm^2, and in tension –160 000 kg/cm^2.

DISCUSSION

The test results show that polymer concrete based on FD resin is little different from polymer concrete based on FA monomer. The strength indicators of the first one are 20–25% higher, and other properties don't differ much.

The cost of polymer concrete based on FD resin is 10–15% lower than the cost of polymer concrete based on FA resin. An important advantage of FD resin over FA is that its production does not require technological equipment and labor.

To determine the optimal resin compositions, experiments were conducted similar to those with diphenylamine, and it was determined that the optimal ratio of furfural and diphenylamine production waste is 1:0,75-1, and the amount of hardener (combined) is 40% of the resin weight, which we conventionally call FOD resin (Table 10).

In the study of the properties of polymer concrete based on FOD resin, it was found that it had good water resistance. Samples of the following compositions were made for testing:

8. Aggregate – ground andesite – 1w.p.; binder – 0.25 w.p., FOD resin; hardener – 0.1 w.p., combined.

9. Aggregate – gravel, sand, crushed sand in a weight ratio of 2.5:1.6:1 – 1w.p.,; binder – 0.15 w.p., FOD resin; hardener – 0.06 w.p., combined.

Gravel with a grain size of 5–20 mm and sand Mk = 1.84 were used as aggregates. Composition # 8 was used

Table 10

Basic properties of polymer concrete and polymer solutions

Physical and technical indicators	Unit of measurement	On FA monomer		On FD resin		On FOD resin	
		solvent	concrete	solvent	concrete	solvent	concrete
Volume weight	g/cm^3	2.0–2.1	2.1–2.15	2.0–2.1	2.05–2.2	2.0–2.1	2.1–2.15
Compressive strength yield	kg/cm^2	800–1000	600–700	1100–1300	700–750	900–1000	650–750
Tensile strength yield	kg/cm^2	80–90	60–70	90–100	80–90	85–90	65–75
Flexural strength yield	kg/cm^2	180–200	120–160	200–210	180–190	190–195	150–170
Specific impact strength	kg/cm^2	1.8–2.0	2–3	1.8–2.0	2.5–3	1.8–2.0	2.2–3
Linear shrinkage	mm/linear meter	4.0–4.5	–	3.2–3.6	–	4.0–4.5	–
Volume shrinkage	%	4.5–5	–	3.5–3.8	–	4.2–4.5	–
Elastic modulus	kg/cm^2	–	200000–250000	–	270000–290000	–	210000–240000
Abrasion	g/cm^2	–	0.350	–	0.214	–	0.008
Water absorption in 24 hours	% by weight	–	0.010	–	0.012	–	0.008
Waterproof	atm/day	–	18/90	–	18/90	–	18/90

Table 11

Change in the strength of polymer concrete based on FOD resin during storage in water

Batch composition	Compressive strength yield of specimens, kg/cm^2						
	before immersing in water	after storing in water for 24 hrs.					
		30	60	90	120	180	360
8	930	870	840	810	790	765	750
9	550	510	490	475	470	450	460

to manufacture 3×3×3 cm cubes and composition # 9 for cubes measuring 7×7×7 cm. After storing at room temperature for 60 days, the samples were placed in water. The standards were stored in a dry environment (Table 11).

Microstructure studies of polymer-concrete samples based on FA monomer, FD and FOD resin were performed on a JEOL JSM7500 scanning electron microscope with X-ray spectral analysis attachment (Fig. 7). The results obtained correlate with the above experimental data. A shot study showed that all three samples have a similar structure. There are no significant differences in the structures. The proposed new samples of polymer concretes based on FD and FOD resin have improved characteristics and are equal to polymer concrete based on FA monomer in terms of strength, chemical resistance, lasting properties, water resistance, abrasion resistance and adhesion to metal.

CONCLUSION

Based on the results of the study, the following conclusions can be drawn:

1. In the proposed method to manufacture polymer concrete, it is suggested to use an ordinary solution of one chemical product in another as a binder. In this case, the cost of performing technological operations to obtain a binder is not required, and its cost will be almost the same as the cost of the initial products.

2. From a comparison of technologies for obtaining FD resin and manufacturing polymer concrete, as well as from preliminary test data of the studied materials, it is possible to determine the possible technical and economic advantages of polymer concrete based on FD resin over polymer concrete based on FA monomer which is currently used in construction of hydro-engineering structures.

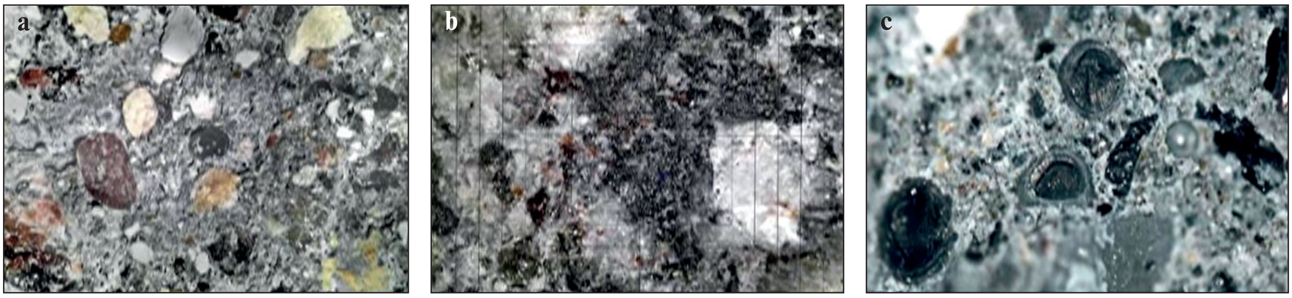

Fig. 7. **Microstructure of polymer concrete samples:** a – based on FA monomer; b – based on FD resin; c – based on FOD resin

3. Polymer concrete based on FD resin has high strength and exceeds the strength of polymer concrete based on FA monomer by 20–25%.

4. A great advantage of polymer concrete based on the binder – mixture of furfural with diphenylamine production waste, in comparison with other types of polymer concrete can be its low cost. The low cost of polymer concrete is due to the low cost of the binder consisting of 1 weight part of furfural and 0.75 weight part of chemical production waste, which is dumped.

5. The technology of manufacturing polymer concrete based on the binder – mixture of furfural and diphenylamine, diphenylamine production waste is similar to the technology of manufacturing polymer concrete based on FA monomer.

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