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Improvement of the crack resistance of reinforced concrete sleepers using modified concretes

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Abstract. This paper presents research on the potential use of modified fiber-reinforced concrete for reinforced concrete sleepers, intending to increase their strength characteristics, crack resistance, and service life. To investigate the influence of reinforcing elements on the crack resistance of heavy concrete, chopped basalt fiber and, for comparison, polypropylene fiber were added to the concrete mix, both of which have shown promising performance. The results of the study showed that the modified heavy concrete exhibited improved crack resistance due to the formation of additional low-basic calcium hydrosilicates, compaction, and strengthening of the cement matrix, as well as the contribution of fibers to the formation of a spatially reinforced cement stone structure. The nature of the fracture of prism samples made from modified concrete and their crack resistance characteristics were evaluated. The results showed that samples with basalt fiber had a 40.59% increase in maximum load, a 40.5% increase in the conditional stress intensity factor, and a 40.49% increase in bending stress compared to the reference samples without fiber. In addition, the samples with basalt fiber demonstrated increases of 7.1%, 6.93%, and 6.9% in maximum load, bending stress, and stress intensity factor, respectively, compared to samples containing polypropylene fiber.
Keywords: modified fiber-reinforced concrete, reinforced concrete, crack resistance, concrete sleepers, fiber.

1. Introduction

It is known that railway sleepers, foundations of machines with dynamic loads, aerodrome and road slabs, and bridge structures are subjected to dynamic effects. Moreover, the sources of dynamic effects can be both external to the structures and internal, located inside the structure [1]. In turn, these loads can have different directions and the nature of application of loads to the structure – distributed load, moments, concentrated forces. As a result of the impact of these loads, there is an accumulation of damage at the micro-level, further development of which leads to the formation and opening of cracks, which significantly reduces the service life, load-bearing capacity, and the degree of resistance in aggressive environments. Reinforced concrete sleepers for railway lines are subject to a set of requirements for strength and crack resistance [2]. To improve the performance characteristics of concrete, fly ash, metakaolin, blast furnace slag, rice husk ash, amorphous microsilica, and other types of pozzolanic additives are introduced into the concrete mixture.

The solution to the problem of obtaining effective concrete for reinforced concrete railway sleepers with improved performance indicators in terms of strength and crack resistance can be achieved by densification and strengthening of the cement matrix structure through the joint application of condensed microsilica suspension with plasticizer and basalt fiber [3].

During the study of loads acting on heavy concrete products, in particular, reinforced concrete sleepers working in special operating conditions, resistance to dynamic effects is a special criterion. The presence of macro- to micro-sized cracks in the material and the step structure of the cracking process create prerequisites for effective dispersed fiber reinforcement of the material [4]. Under the influence of external load in the composite material, the destruction of the process structure is initiated, which is expressed in the development of the first microcracks in the branching region. At the mouths of cracks, at the same time, a critical energy reserve is released, which entails further development of the microcrack network and leads to deterioration of the mechanical properties of the composite material [5].

In total, the given local fracture processes at the microscale level lead to the failure of the investigated sample, which provides a task for studying dispersed reinforcement of the material to improve crack resistance. Based on the hypothesis that dispersed-reinforcing fibers correspond in structure to cracks occurring at the meso-, macro-, and micro-levels of structural systems, it is recommended to develop a concrete mix composition taking into account multilevel reinforcement. Such an approach allows for providing increased resistance of the material to crack formation and propagation [6]. Despite significant progress, many studies focus on either the mechanical properties, chemical durability, or isolated effects of specific fibers without offering a systematic approach to combining multiple modifying agents. Some researchers explored microsilica and polymer fibers, yet did not fully assess their synergistic effects with basalt fibers.

It is worth noting that dispersed fillers should act as reinforcing elements at the microscale level, and elementary fibers at the macroscale level [7]. To investigate the influence of reinforcing elements on the crack resistance characteristic of heavy concrete, chopped basalt fiber and, for comparative analysis, polypropylene fiber were introduced into the concrete mix, which have proved themselves well [8].

The problem, therefore, lies in the lack of comprehensive research that integrates condensed microsilica suspension, modern plasticizers, and both micro- and macro-scale fibers to form a multiscale reinforcement system. There is a need to evaluate the combined effect of these modifiers under dynamic load conditions relevant to railway sleepers, where both fatigue resistance and crack control are critical. The goal of this research is to develop and investigate a modified heavy concrete mixture incorporating condensed microsilica suspension, a polycarboxylate-based plasticizer, and basalt fiber to improve crack resistance and mechanical properties under dynamic loading conditions, thus ensuring the structural durability of reinforced concrete sleepers.

2. Methods

In this research, Portland cement of the CEM I 42.5N grade, meeting the requirements of [9], was used as a binder. The cement was produced by ALACEM, LLP (Saryozek, Almaty region, Kazakhstan). The characteristics of the cement, provided by the factory testing laboratory, are presented in Tables 1 and 2.

Table 1 – Characteristics of Portland cement

Brand	Manufacturer	Chemical composition, % by weight						
		Na_2O	SO_3	MgO	Fe_2O_3	CaO	AL_2O_3	SiO_2
CEM I 42.5N	ALACEM, LLP	0.6	0.62	0.96	4.01	64.88	5.01	23.97

Table 2 – Mineral composition of Portland cement clinker

Brand	Mineral content in clinker, %			
	C_4AF	C_3A	C_2S	C_3S
CEM I 42.5N	10.24	6.87	12.77	60.94

An analysis of the presented data showed that the cement meets the required standards [9].

Natural sand from the Arna quarry (Arna village, Almaty region, Kazakhstan) was used as a fine aggregate. The properties of the sand were determined by [10] and are shown in Table 3.

Table 3 – Characteristics of sand

Manufacturer	True density, kg/m^3	Coarseness module	Bulk density, kg/m^3	Specific effective activity of natural radionuclides, Bq/kg	The content of clay and pulverized particles, %
LLP «Arna»	2595	2.46	1585	71.7	1.4

Based on the content of clay, fine impurities, and its granulometric composition, this sand meets the requirements of [11].

Granite crushed stone with a particle size ranging between 5 and 20 mm, produced by Kentas, LLP (Bayterek village, Almaty region, Kazakhstan) was used as the coarse aggregate. Its characteristics are presented in Table 4.

Table 4 – Test results of coarse aggregate

Manufacturer	Lamellar and needle-shaped grains, %	Pulverized, silty, and clay particles, %	Grade of crushed stone by crushing capacity	Frost resistance	Bulk density, kg/m^3	Specific effective activity of radionuclides, Bq/kg	The brand of rubble by abrasion
Kentas, LLP	12	0.89	1300	350	1380	85	I-1

The data in Table 4 confirm that the coarse aggregate meets the requirements of [12].

The superplasticizer "AR Premium" from ARGP, LLP (Astana, Kazakhstan) was used. According to its consumer properties, the "AR Premium" additive complies with the requirements of [13]. It is a superplasticizer based on polyoxyethylene derivatives of polycarboxylic acids. It is used in the production of concrete and reinforced concrete structures made from heavy and fine-grained concrete, either under normal curing conditions or using electric heating. It is also used in the manufacture of building mortars. The recommended dosage of "AR Premium" is 0.6–1.0% by weight of cement. Dosage must be carried out with an accuracy of ±1% of the calculated amount. The normalized physico-chemical properties of the additive are presented in Table 5.

Table 5 – Physico-chemical parameters of the superplasticizer

Appearance	Density at 20 °C, g/cm^3, not less than	Hydrogen ion activity index (pH), not less than	Mass fraction of chlorine ions, %, not more than
Light brown aqueous solution	1.03	4.2	0.01

Condensed microsilica (MC-95), a pulverized industrial by-product produced by Tau Ken Temir, LLP (Karaganda, Kazakhstan), was used as a micro-filler. This microsilica obtained from ferrosilicon production via electrostatic precipitators has particle sizes ranging from 5 to 50 microns. Its qualitative characteristics are presented in Table 6.

Table 6 – Characteristics of MC-95 grade silica

Indicators	Qualitative characteristics
Mass fraction of silicon dioxide, %, not less (SiO_2)	95.91
Mass fraction of phosphorus oxide (P_2O_5), %, max	0.1
Mass fraction of magnesium oxide (MgO), %, max	0.6
Mass fraction of aluminum oxide (Al_2O_3), %, max	0.16
Mass fraction of iron oxide (Fe_2O_3), %, max	0.22
Mass fraction of sulfuric anhydride (SO_3), %, max	0.41
Mass fraction of calcium oxide (CaO), %, max	0.37
Mass fraction of free alkalis (Na_2O,K_2O),%, max	1.55
Mass fraction of water, %, max	0.29

Analysis of data in Table 6 above confirms that the coarse aggregate meets the requirements of [14].

To improve crack resistance, micro-reinforcing components were introduced during the dry mixing stage of the binder (Portland cement) with the fine and coarse aggregates. These included chopped basalt fiber, produced according to [15], and polypropylene fiber, manufactured by “Damu-Khimiya” (Karaganda, Kazakhstan). The general appearance and physical-mechanical properties of the fibers are shown in Figure 1 and Table 7.

a) Basalt fiber

b) Polypropylene fiber

Figure 1 – Micro-reinforcing component

Table 7 – Physical and mechanical characteristics of basalt fiber and polypropylene fiber

Indicator	Characteristics	
	Basalt fiber	Polypropylene fiber
Melting point, °C	1350	170
Length of the segment, mm	10.77	11
Alkali and corrosion resistance	High	Medium
Diameter of the elementary fiber, microns	18,24	50
Elongation at break, %	1.5-3.8	25-36
Tensile strength, R, MPa·10^3	2.7-3.6	0.78
Density, g/cm^3	2.51	0.97
Modulus of elasticity F_f, MPa·10^3	90-95	4.8

The goal of improving both the strength and economic characteristics of the heavy concrete mix was achieved by optimizing its structural density through the introduction of active silica and by reducing bending moments via dispersed fiber reinforcement. This approach increases the stability of the composite.

Concrete compositions containing silica, micro-reinforcing fibers, and chemical admixtures, calculated using the absolute volume method [16], are listed in Table 8.

Table 8 – Studied compositions of modified heavy concrete

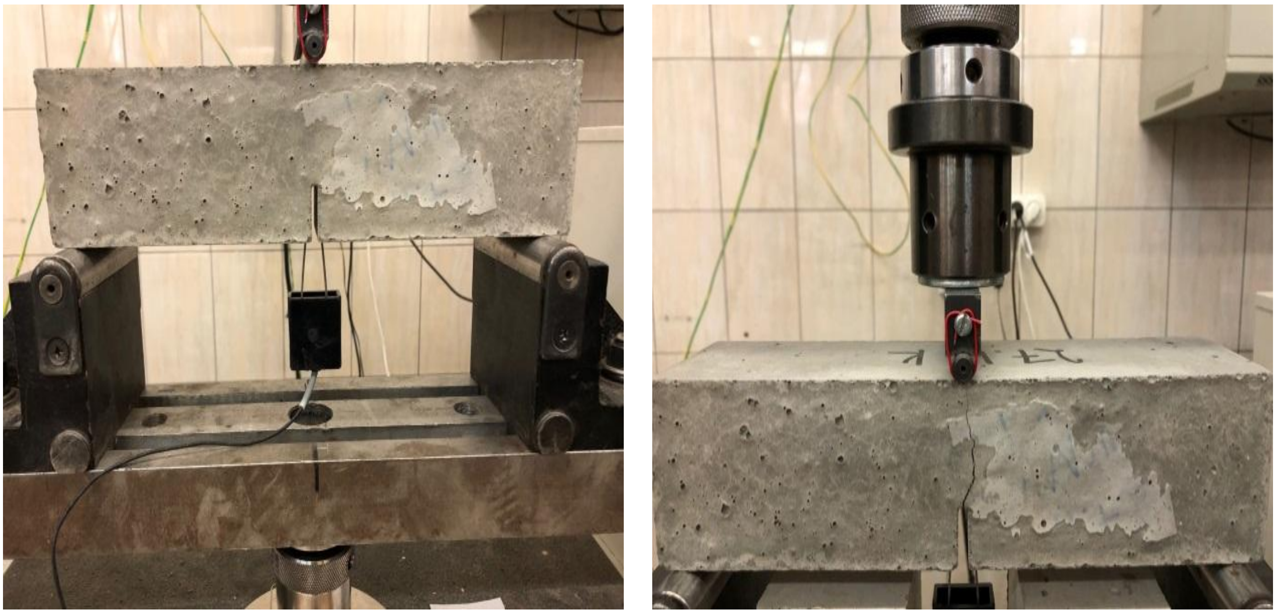
Materials	Composition and consumption per 1 m^3 of concrete mix, kg/m^3				
	No. 1 – Reference	No. 2 – 15% MG	No. 3 – 20% MG	No. 4 – 20% MG +0.75% BV	No. 5 – 20% MG +0.75% PF
CEM I 42.5N	420	357	336	336	336
Water	150	150	150	150	150
Granite rubble	1000	1000	1000	1000	1000
Sand	810	810	810	810	810
“AR premium” superplasticizer	4.2	4.2	4.2	4.2	4.2
Microsilica MCU-95	-	63	84	84	84
Basalt fiber (BF)	-	-	-	2.68	-
Polypropylene fiber (PPF)	-	-	-	-	2.68
In/C (C+MC)	0.36	0.36	0.36	0.36	0.36

According to the studies of Kaprielov S.S. and Sheinfeld A.V. [17], [18], the recommended silica content is 15–20% of the binder weight per 1 m^3 of concrete. This range was adopted in the mix design. To determine the appropriate amount of MC-95 microsilica required for high-performance concrete, the additive was used in the same 15–20% range by binder weight.

The dosage and type of micro-reinforcing fiber were determined based on the works of Bazhenov Yu.M. and Mailyan L.R. [19], [20], where fiber lengths up to 12 mm and fiber content in the range of 0.5–1% by binder weight were recommended. The introduction of microsilica allowed for a reduction in cement consumption. This is due to its high reactivity, which leads to local clustering of cement particles during hydration. If not controlled, this can negatively affect the matrix structure. Economically, reducing cement content is also beneficial. According to [21], maintaining a distance between cement particles equal to the diameter of silica particles ensures uniformity and stability of the modified cement matrix.

The optimal composition of the combined admixture—including the high-range water-reducing "AR Premium" additive and MC-95 microsilica—was determined experimentally. For this, 100 × 100 × 100 mm cube samples were cast, cured under standard conditions for 28 days, and tested for strength characteristics.

To evaluate crack resistance under non-equilibrium loading, prism samples of size 70 × 70 × 280 mm were prepared, with four samples per mix, each featuring a 25 mm deep and 2 mm wide notch. Prior to testing, two loading/unloading cycles up to 10% of the expected load were performed. The samples were then continuously loaded (Figure 2a) until fracture (Figure 2b), at which point the load value F_c^* was recorded.



a) Sample before loading before testing b) After loading

Figure 2 – Loading of a prism sample made of heavy modified concrete during the crack resistance test

The crack resistance characteristics of the prism samples are summarized in Table 9.

After testing, the crack resistance coefficient K_c^* was calculated using the following equation as proposed in [22]:

$$K_c^* = \frac{3F_c^* L_0}{2b^{1/2}\, t}\sqrt{a_0/b}\,(1.93 - 3.07\lambda + 14.53\lambda^2 - 25.11\lambda^3 + 25.8\lambda^4), \quad (1)$$

where: K_c^* – conditional stress intensity coefficient, [MPa·$m^{0.5}$]; F_c^* – load corresponding to the onset of crack propagation under dynamic testing, [MN]; b, t, L_0, L, D – sample dimensions, [m]; a_0 – initial notch length, [m]; $\lambda = a_0/b$ – relative notch length; K_c^* – is the conditional stress intensity coefficient.

Table 9 – Characteristics of concrete samples for crack resistance testing

Marking of the sample	Sample number	Weight, g	Density, kg/m^3 ρ	Density, kg/m^3 ρ_{med}	Thickness at the incision site, mm
Composition 1 – Reference	1	3314.7	2416	2405.7	45.0
	2	3303.8	2408		45.0
	3	3294.2	2401		45.0
	4	3290.0	2398		45.0
Composition 2 – 15% MG	5	3298.3	2404	2403.2	45.0
	6	3302.4	2407		45.0
	7	3295.5	2402		45.0
	8	3292.8	2400		45.0
Composition 3 – 20% MG	9	3291.4	2399	2395.7	45.0
	10	3287.3	2396		45.0
	11	3283.2	2393		45.0
	12	3285.9	2395		45.0
Composition 4 – 20% MG +0.75% BV	13	3281.8	2392	2391.2	45.0
	14	3279.1	2390		45.0
	15	3276.3	2388		45.0
	16	3285.9	2395		45.0
Composition 5 – 20% MG +0.75% PF	17	3269.5	2383	2382.5	45.0
	18	3265.4	2380		45.0
	19	3266.7	2381		45.0
	20	3273.6	2386		45.0

3. Results and Discussion

For the reference sample (Composition 1), the values were: $F_c^* = 0.002086$ MN, $L_0 = 0.266$m, b=0.07m, t=0.07m, a_0=0.025m, $\lambda = 0.357143$, hence: $K_c^* = \frac{3*0.002327*0.266}{2*0.07^{\frac{1}{2}}*0.07} * \sqrt{\frac{0.025}{0.07}} * (1.93 - 3.07 * 0.357143 + 14.53 * 0.357143^2 - 25.11 * 0.357143^3 + 25.8 * 0.357143^4) = 0.052709$ MPa×m$^{0.5}$.

Similarly, the conditional stress intensity factor K_c^* calculated for the remaining compositions:

- Composition 2 (15% MG): $F_c^* = 0.002201$ MN, $L_0 = 0.266$m, b=0.07m, t=0.07m, a_0=0.025m, $\lambda = 0.357143$, hence: $K_c^* = 0.055619$ MPa×m$^{0.5}$.
- Composition 3 (20% MG): $F_c^* = 0.002328$ MN, $L_0 = 0.266$m, b=0.07m, t=0.07m, a_0=0.025m, $\lambda = 0.357143$, hence: $K_c^* = 0.058829$ MPa×m$^{0.5}$.
- Composition 4 (20% MG+0.75% BV): $F_c^* = 0.002933$ MN, $L_0 = 0.266$m, b=0.07m, t=0.07m, a_0=0.025m, $\lambda = 0.357143$, hence: $K_c^* = 0.074122$ MPa×m$^{0.5}$.
- Composition 5 (20% MG+0.75% PF): $F_c^* = 0.002741$ MN, $L_0 = 0.266$m, b=0.07m, t=0.07m, a_0=0.025m, $\lambda = 0.357143$, hence: $K_c^* = 0.069270$ MPa×m$^{0.5}$.

Table 10 presents the maximum bending stress values, load, conditional stress intensity factor, and sample loading graphs, as shown in Figure 3.

Table 10 – Characteristics of crack resistance of samples during nonequilibrium tests

Marking of the sample	Indicator: Load F_c^*, kN	Indicator: Voltage, MPa	Indicator: Conditional stress intensity coefficient K_c^*, MPa×m$^{0.5}$
Composition 1 – Reference	2.086	5.974	0.052709
Composition 2 – 15% MG	2.201	6.304	0.055619
Composition 3 – 20% MG	2.328	6.405	0.058829
Composition 4 – 20% MG +0.75% BV	2.933	8.064	0.074122
Composition 5 – 20% MG +0.75% PF	2.741	7.542	0.069270

An analysis of the results in Table 10 and the graphs in Figure 3 indicates that concrete samples modified with basalt fiber (composition 4) demonstrate improved performance. Specifically, the maximum load increased by 40.59%, the conditional stress intensity factor by 40.5%, and the bending stress by 40.49% compared to the reference composition without fiber reinforcement (composition 1).

Composition 4 also shows increases in maximum load, bending stress, and the conditional stress intensity factor by 7.1%, 6.93%, and 6.9%, respectively, compared to composition 5, which contains polypropylene fiber. Thus, the dispersed reinforcement of heavy concrete with basalt fiber enhances its physical and mechanical properties due to its positive effect on the concrete structure. An additional factor contributing to the structural strength of the concrete is microsilica, which promotes the binding of portlandite to form poorly soluble hydrosilicates. During crack resistance testing, stress redistribution occurs within the concrete and between the components of the cement matrix. This results in a reduction of stress concentration in areas of macrodefects, which limits the propagation and growth of major cracks. These findings are consistent with those of the study [23], which examined shrinkage in fiber-reinforced concrete with elementary fibers ranging from 6 to 18 mm in length. The data confirm increased adhesion between the cement-sand matrix and the basalt fibers added to the concrete mix, providing enhanced micro-reinforcement and enabling stress relaxation at the matrix–filler interface, outperforming polypropylene fiber in this regard. This conclusion aligns with the results of previous studies [24], [25].

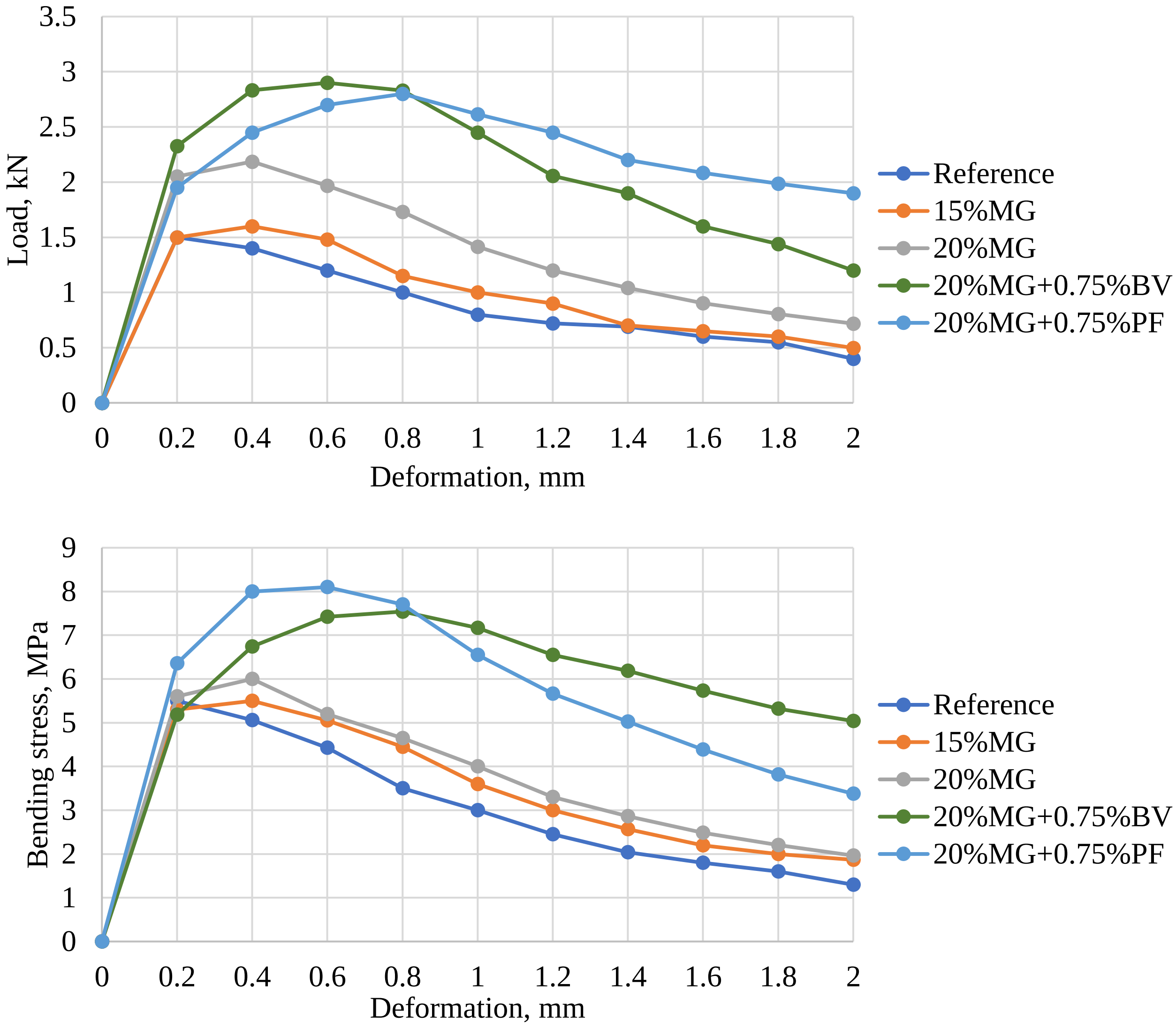


Figure 3 – Loading graphs of samples from modified heavy concrete

Analysis of Figure 3 shows that the prolonged crack opening behavior observed in samples of compositions 4 and 5 (reinforced with fibers) compared to the reference composition 1 (without fibers) indicates a high degree of fiber engagement during failure. The increased fracture toughness of the fiber-reinforced samples is characterized by relatively gradual descending branches in the load-deflection graphs for compositions 4 and 5.

Additionally, increased stress concentration along the micro-reinforcing fibers led to a marked difference in performance between compositions 1, 2, and 3 (without fibers) and compositions 4 and 5 (with micro-reinforcement), corroborating the findings reported in [19], [26].

4. Conclusions

The failure mechanisms and key crack resistance characteristics of the modified concrete samples were identified. Concrete samples containing basalt fiber (composition 4) exhibited increases in maximum load by 40.59%, the conditional stress intensity factor by 40.5%, and bending stress by 40.49% compared to the reference sample without fiber (composition 1). Furthermore, composition 4 demonstrated improvements of 7.1%, 6.93%, and 6.9% in maximum load, bending stress, and the conditional stress intensity factor, respectively, compared to composition 5 with polypropylene fiber. Therefore, dispersed reinforcement of heavy concrete with basalt fiber improves crack resistance due to its favorable impact on the concrete's internal structure. When evaluating crack resistance under prism loading, stress within the concrete is equalized and redistributed among the components of the cement matrix. This leads to a reduction in stress concentration near macrodefects, thereby limiting the development and propagation of primary cracks.

It has been established that the improved strength characteristics of modified heavy concrete compared to ordinary concrete are achieved through the introduction of high-performance fibers with a significantly higher modulus of elasticity than the concrete matrix and strong chemical resistance. The most effective approach is multiscale reinforcement, where microscale reinforcement is provided by highly dispersed fillers (e.g., silica) introduced along with cement, and macroscale reinforcement is achieved through fiber incorporation.

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Vladislav Pak – data collection.
Yerkyn Turarov – data collection.

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