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НАУЧНАЯ СТАТЬЯ/RESEARCH ARTICLE

Comparative Study of High-Performance Concrete Beams Reinforced with St 37 Rebar and Damascus Steel Rebar

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Abstract. This study investigated the differences between reinforcement with St 37 steel bars and Damascus steel bars. The studied beams were made of high-performance concrete (HPC) reinforced with St 37 steel rebars (SSR) of ∅10, ∅12 and ∅14, as well as 150-, 250- and 350-layers of Damascus steel rebars (DSR). The flexural strength tests results showed that HPC beams with 250-layers of DSR (with an average tensile strength of 857.27 MPa) can withstand an average flexural load of 52.19 kN, while HPC beams with SSR of ∅10 (with an average tensile strength of 485.34 MPa) can withstand an average of 69.52 kN. HPC beams with SSR, due to the ribbed structure of the steel rebars, are capable to withstand high flexural loads, whereas due to the absence of ribs on the surface of the DSR, HPC beams with it are capable to withstand low flexural loads, although the tensile strength of DSR is higher than that of SSR. The ribbed structure of the steel rebars is of fundamental importance for increasing the flexural strength, as it ensures the bond strength between the steel rebar and the concrete.

Несущая способность железобетонных балок из высокопрочного бетона с продольной арматурой из стали St 37 и дамасской стали

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Ключевые слова: высокопрочный бетон, арматура из стали St 37, арматура из дамасской стали, предел прочности на разрыв, предел прочности на изгиб

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Аннотация. В данном исследовании были рассмотрено влияние на несущую способность железобетонных балок из высокопрочного бетона продольного армирования, выполненного стержнями из стали St 37 и из дамасской стали. Исследуемые балки были изготовлены из высокопрочного бетона (HPC) и армировались стальными стержнями St 37 (SSR) диаметром ∅10, ∅12 и ∅14, а также 150-, 250- и 350-слойными стальными стержнями из дамасской стали (DSR). Результаты испытаний несущей способности при изгибе показали, что балки из высокопрочного бетона и арматурой из дамасской стали (DSR) с 250 слоями со средней прочностью на разрыв 857,27 МПа могут выдерживать нагрузку 52,19 кН, в то время как балки из высокопрочного бетона, армированные стержнями SSR ∅10 со средней прочностью на разрыв 485,34 МПа, могут выдерживать в среднем 69,52 кН. Балки из высокопрочного бетона с арматурой из стали SSR благодаря периодическому профилю способны выдерживать более высокую нагрузку при изгибе, в то время как балки с арматурой из дамасской стали DSR с гладкой поверхностью воспринимали более низкие нагрузки, хотя прочность на разрыв DSR выше, чем у SSR. Периодический профиль арматурных стержней имеет основополагающее значение для увеличения несущей способности при изгибе, поскольку обеспечивает прочность сцепления между стальной арматурой и бетоном.

INTRODUCTION

High-performance concrete (HPC) has excellent performance and is widely used in construction due to its high compressive strength, high toughness, high durability, high compact and density [1–4]. Many experiments have been conducted to study HPC and HPC structural elements using different types of reinforcement such as different types of fibers, 3D-printed reinforcement, steel rebars, etc. Hasanzadeh et al. [5] and Kharun et al. [6] carried out experimental studies on the effect of chopped basalt fiber on the mechanical properties of HPC. Their experimental result showed that chopped basalt fiber improved the mechanical properties of HPC. Alaraza et al. [7] investigated the effect of MiniBars basalt fiber fraction on the mechanical properties of HPC. The results of their experiment showed that a small amounts of MiniBars basalt fiber does not affect the compressive strength and elastic modulus of HPC, and when the dosage of MiniBars basalt fiber increases by more than 1.2 %, it even has a negative effect. However, MiniBars basalt fiber significantly increased the flexural strength even at low percentages, reaching the optimum effect at 0.9 %. Hematibahar, et al. [8] studied the compressive strength and compressive stress-strain of basalt fiber reinforced HPC. Their study results show that the inclusion of basalt fiber in HPC resulted in a decrease in the compressive strength. Vatin, et al. [9] conducted a series of laboratory experiments on the chopped basalt fiber and MiniBars basalt fiber reinforced high-performance concrete. They found that both chopped basalt fiber and MiniBars basalt fiber improved the flexural properties of HPC. Moein, et al. [10] investigated the impact resistance of HPC containing different types of steel fibers. They found that steel fibers improved the mechanical properties of HPC, and hooked steel fibers were more effective in increasing impact strength than crimped steel fibers.

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Afroughsabet et al. [11] conducted experiments to study the effect of steel and polypropylene fibers on chloride diffusivity and drying shrinkage of HPC. They observed that the inclusion of steel fibers improved the mechanical properties and chloride diffusivity of HPC, whereas the inclusion of polypropylene fibers resulted in a decrease in the chloride diffusivity. Farias et al. [12] studied the flexural behavior of concrete beams reinforced with glass fiber reinforced polymer and steel bars. They found that adding steel rebars into the concrete beam as load-bearing reinforcement successfully withstand the flexural load. Chiadighikaobi et al. [13] evaluated the mechanical behavior of HPC beams reinforced with different types of 3D-printed trusses. They noted that the use of the 3D-printed Warren truss showed the best performance among other types of trusses in terms of flexural strength, which means that the geometry of the reinforcement is the most important factor in improving mechanical properties. Hematibahar et al. [14] studied HPC beams reinforced with 3D-printed trusses and 3D-printed hyperboloid shells on the mechanical properties and load-bearing capacity. They found that 3D-printed trusses performed better than 3D-printed hyperboloid shells. Hematibahar et al. [15] investigated the mechanical properties of HPC beams reinforced with four types of 3D-printed patterns. They found that 3D-printed honeycomb structure performed better than other 3D-printed structures. Chen Z. et al. [16] investigated the pull-out performance of steel rebar in HPC with hybrid steel fibers and synthetic fibers. Mohinderu et al. [17] conducted an experimental study of hybrid fiber reinforced HPC on beam-column joints fabricated using high-yield strength deformed steel bars to improve seismic performance. Their study demonstrated a significant increase in the strength of the experimental samples compared to control samples.

St 37 steel are made from a low-carbon steel and are widely used in construction. They are characterized by good weldability and ductility [18–22], which makes them more suitable for use in reinforcing concrete structures that require flexibility. In the USA it is usually designated as A36, in Europe as S235JR, in India as IS226, in China Q235B and in Japan as SS400.

The term “Damascus steel” originates in the medieval city of Damascus, Syria, possibly as an early example of branding, however, it is now generally accepted that the steel ingots were imported either from South India (where it was known as Wootz steel), where steel production techniques were first developed [23], or from Khorasan, Iran [24]. Damascus steel is a high-carbon steel known for its strength and hardness, characterized by a distinctive layered pattern produced by pattern welding [25–30], however, the lack of research on the application of this type of steel rebars in concrete structures hinders decision making in construction.

Analysis of scientific and technical information shows that many studies have been devoted to HPC with various types of reinforcement, but the use of St 37 steel rebars (SSR) and Damascus steel rebars (DSR) as reinforcement has not yet been studied.

The objective of this study is to investigate the physical and mechanical characteristics of SSR and DSR, and the use of SSR and DSR as reinforcement in HPC beams and compare their flexural performance.

MATERIALS AND METHODS

The present experimental study focuses on HPC reinforced with SSR and DSR. The materials used in this study and their characteristics are described below.

The following composition was used to produce the HPC mixture (Table 1):

- Binder — Portland cement CEM I 42.5 N;
- Fine aggregate — sand with a fineness modulus of 2.7;
- Coarse aggregate — granite crushed stone of fraction 7–14 mm;
- Filler — glass powder;
- Organo-mineral additive — microsilica;
- Plasticizer — SikaPlast®Concrete in liquid form;
- Tap water for mixing.

Table 1

Composition of HPC mixture

Cement, kg/m^3	Fine aggregate, kg/m^3	Coarse aggregate, kg/m^3	Glass powder, kg/m^3	Microsilica, kg/m^3	Plasticizer, l/m^3	Water, l/m^3
500	1,100	350	200	100	10	190

In this experiment, SSR with diameters of 10, 12 and 14 mm, and DSR of 150-, 250- and 350-layers were used.

For the compressive strength testing of HPC, control samples of 100 × 100 × 100 mm^3 were produced.

To visualize the external morphology and crystalline structure of the rebars, as well as to determine their elemental composition, scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) analysis were performed, respectively.

Tensile strength tests on rebars were conducted in accordance with ASTM A370-24.

For flexural strength testing, HPC beams of 35 × 10 × 10 cm^3 size reinforced with SSR and DSR were produced. Control beams of size 35 × 10 × 10 cm^3 were produced without SSR and DSR.

All HPC samples were kept in wet sawdust in an air-humid environment for 28 days at room temperature of 19–23 °C.

Compressive strength tests were performed in accordance with ASTM C109/C109M-20 and flexural strength tests were performed in accordance with ASTM C78/C78M-18. Strength tests were carried out on a hydraulic press with a force of up to 1,500 kN in compression and 150 kN in bending. The schematic diagram of the flexural strength test of HPC beams is shown in Fig. 1.

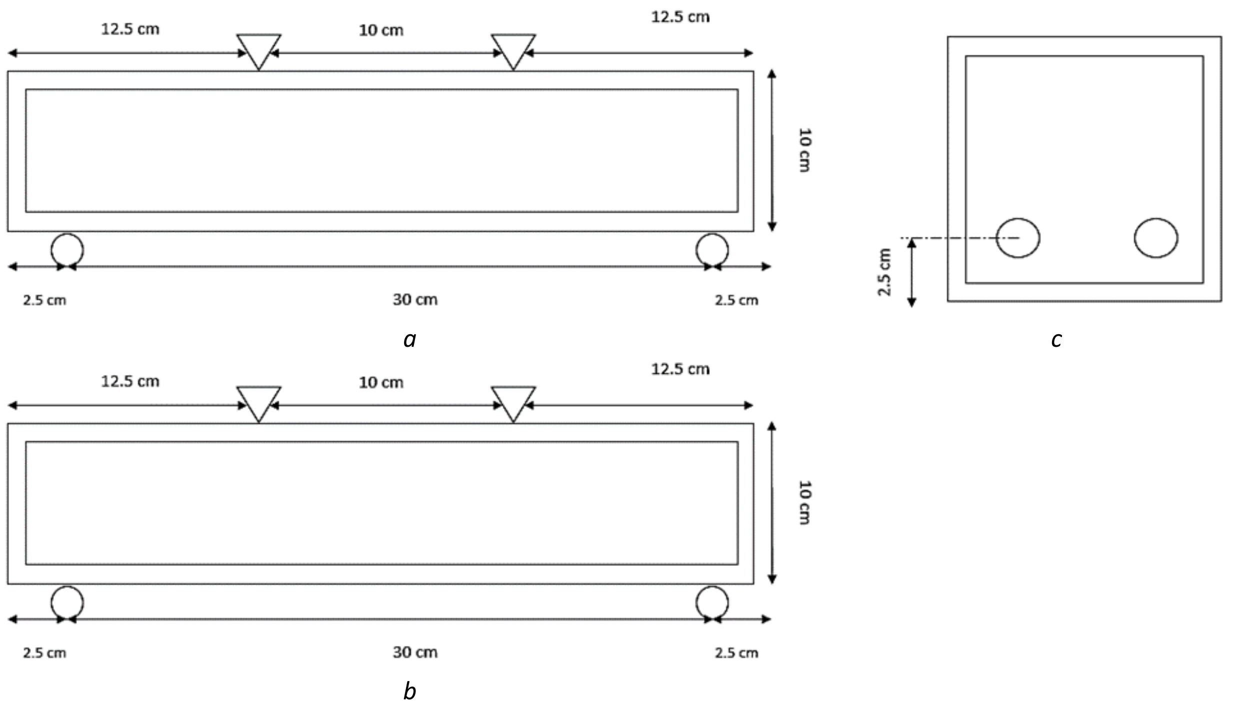


Fig. 1. Schematic diagram of the flexural strength test of beams:
a — four-point flexural strength test scheme of beams; *b* — placement of steel rebars in beams; *c* — side section of beams with steel rebars

RESULTS AND DISCUSSION

The results of the compressive strength tests of HPC control samples are shown in Fig. 2. According to our tests, the average compressive strength of HPC control samples was 43.64 MPa.

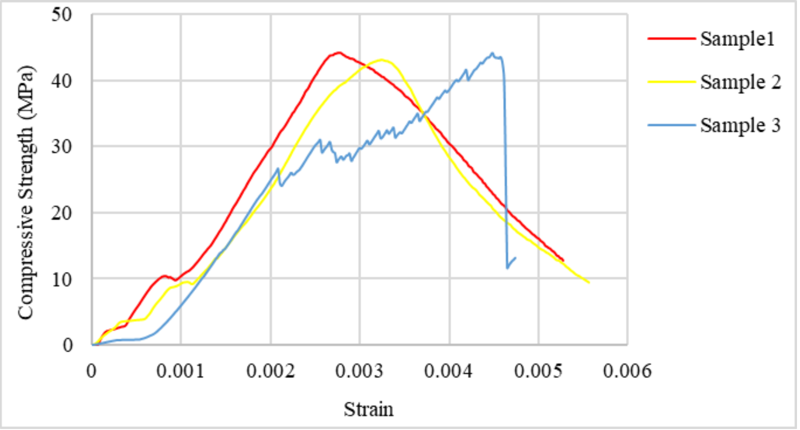


Fig. 2. Dependence of compressive strength on deformation of high-performance concrete control samples

The nature of the destruction of SSR during tensile testing is shown in Fig. 3. The results of the tensile strength tests of SSR are presented in Table 2 and Fig. 4.

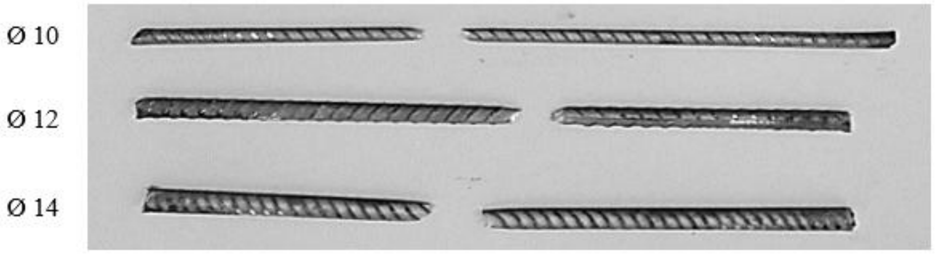
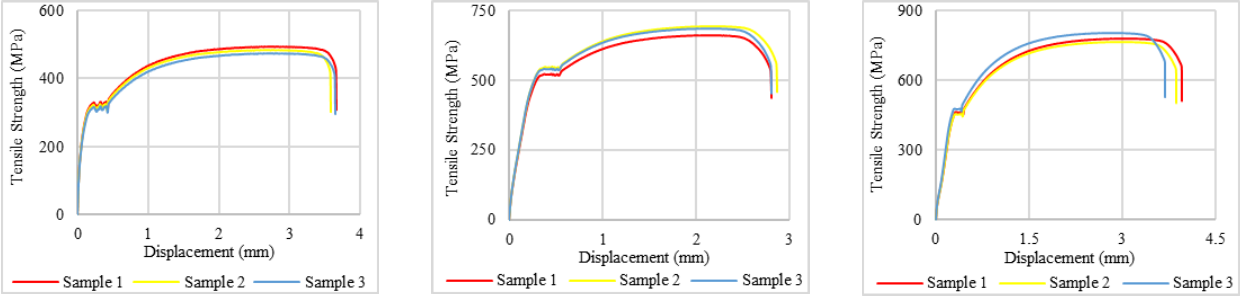


Fig. 3. Nature of the destruction of steel rebars of grade St 37 during tensile testing



a *b* *c*

Fig. 4. Tensile strengths of steel rebars of grade St 37: *a* — ∅10; *b* — ∅12; *c* — ∅14

Table 2

Tensile strengths of steel rebars of grade St 37

St 37 steel rebars	Maximum tensile strengths, MPa	Average tensile strengths, MPa	Maximum displacements, MPa	Elongations, %
∅ 10	495.18	485.34	3.65	21.87
∅ 12	692.53	679.23	2.86	13.91
∅ 14	802.61	782.33	3.95	23.76

Fig. 5 shows the nature of the destruction of DSR during tensile testing.

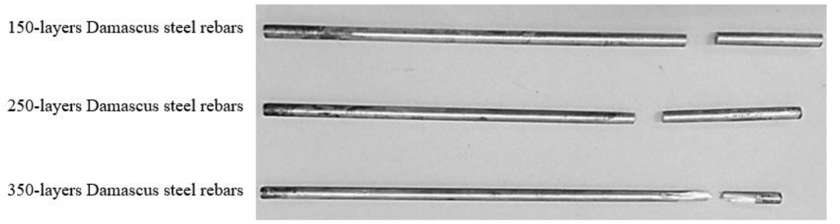


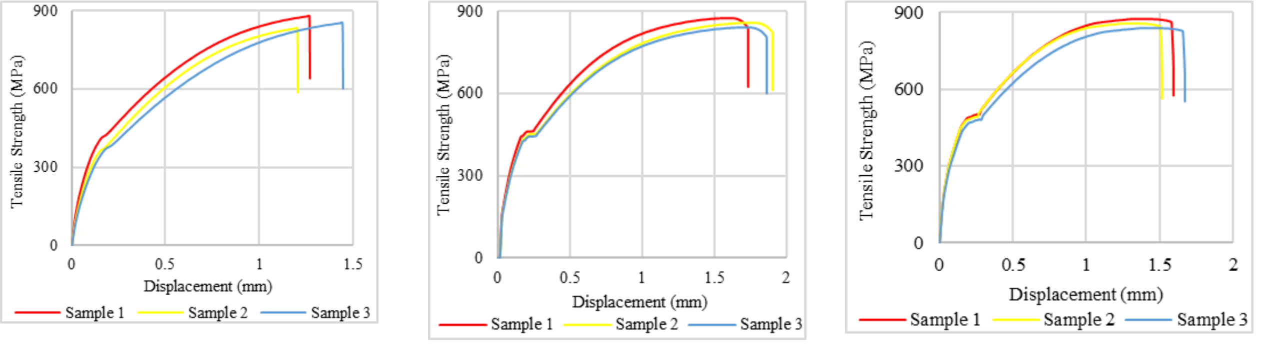
Fig. 5. Nature of the destruction of Damascus steel rebars during tensile testing

The results of the tensile strength tests of DSR are presented in Table 3 and Fig. 6.

Table 3

Tensile strengths of Damascus steel rebars

Samples	Maximum tensile strengths, MPa	Average tensile strengths, MPa	Maximum displacements, MPa	Elongations, %
150-layers	881.38	855.52	1.44	7.16
250-layers	874.65	857.27	1.91	6.8
350-layers	869.41	852.13	1.66	6.74



a *b* *c*

Fig. 6. Tensile strengths of Damascus steel rebars: *a* — 150-layers; *b* — 250-layers; *c* — 350-layers

To understand the differences between the different types of HPC beams, control beams were first tested. Table 4 and Fig. 7 provide data on flexural load and displacement of the control beams.

Table 4

Flexural strength test data for control beams

Samples	Maximum flexural load, kN	Average flexural load, kN	Maximum displacement, mm
Control beam 1	11.15	10.83	2.21
Control beam 2	10.32		2.22
Control beam 3	11.02		2.26

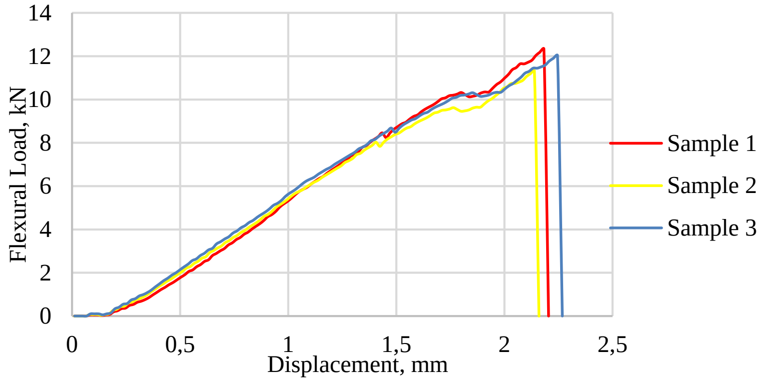


Fig. 7. Dependance of flexural load and displacement of control beams

Table 4 shows that the control beams failed at an average flexural load of 10.83 kN, and the maximum displacement was 2.26 mm. The control beams (beams without any reinforcement) broke suddenly, without any cracks before failure (Fig. 7).

Table 5 and Fig. 8 present the flexural load and displacement data for HPC beams reinforced with 10-, 12- and 14-mm diameter SSR.

Table 5

Flexural strength test data for beams with 10-, 12- and 14-mm diameter St 37 steel rebars

Samples	Maximum flexural load, kN	Average flexural load, kN	Maximum displacement, mm
SSR-10 (1)	70.02		5.45
SSR-10 (2)	71.66	69.52	5.67
SSR-10 (3)	66.89		5.56
SSR-12 (1)	66.87		14.39
SSR-12 (2)	64.56	65.26	13.67
SSR-12 (3)	64.36		16.40
SSR-14 (1)	70.43		9.27
SSR-14 (2)	66.59	69.76	9.02
SSR-14 (3)	72.27		9.74

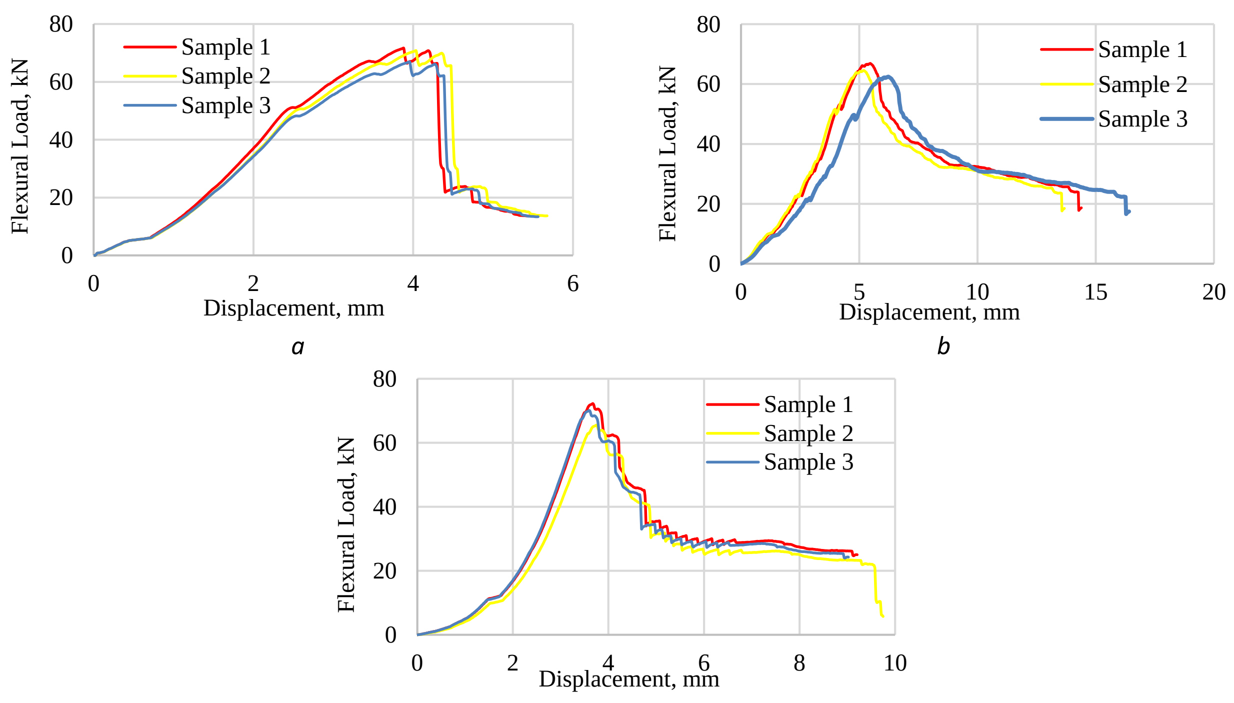


Fig. 8. Dependance of flexural load and displacement of beams with St 37 steel rebars: *a* — ∅10; *b* — ∅12; *c* — ∅14

Compared to the control beams, the beams with SSR failed slowly, with cracks appearing that gradually widened before failure (Fig. 8). The flexural strength of the HPC beam reinforced with ∅10 SSR increased by more than 640 % compared to the control beams, while the average flexural load before failure of the HPC beams reinforced with ∅12 and ∅14 SSR increased to 65.26 kN and 69.76 kN, respectively (Table 4, 5).

Table 6 and Fig. 9 show the flexural load and displacement data for HPC beams reinforced with 150-, 250- and 350-layers DSR.

Table 6

Flexural strength test data for beams with 150-, 250- and 350-layers Damascus steel rebars

Samples	Maximum flexural load, kN	Average flexural load, kN	Maximum displacement, mm
DSR-150 (1)	47.18		7.53
DSR-150 (2)	45.84	46.42	7.76
DSR-150 (3)	46.23		7.99
DSR-250 (1)	55.23		9.15
DSR-250 (2)	51.43	52.19	9.31
DSR-250 (3)	49.88		9.78
DSR-350 (1)	36.98		13.23
DSR-350 (2)	36.12	36.98	14.55
DSR-350 (3)	37.85		11.64

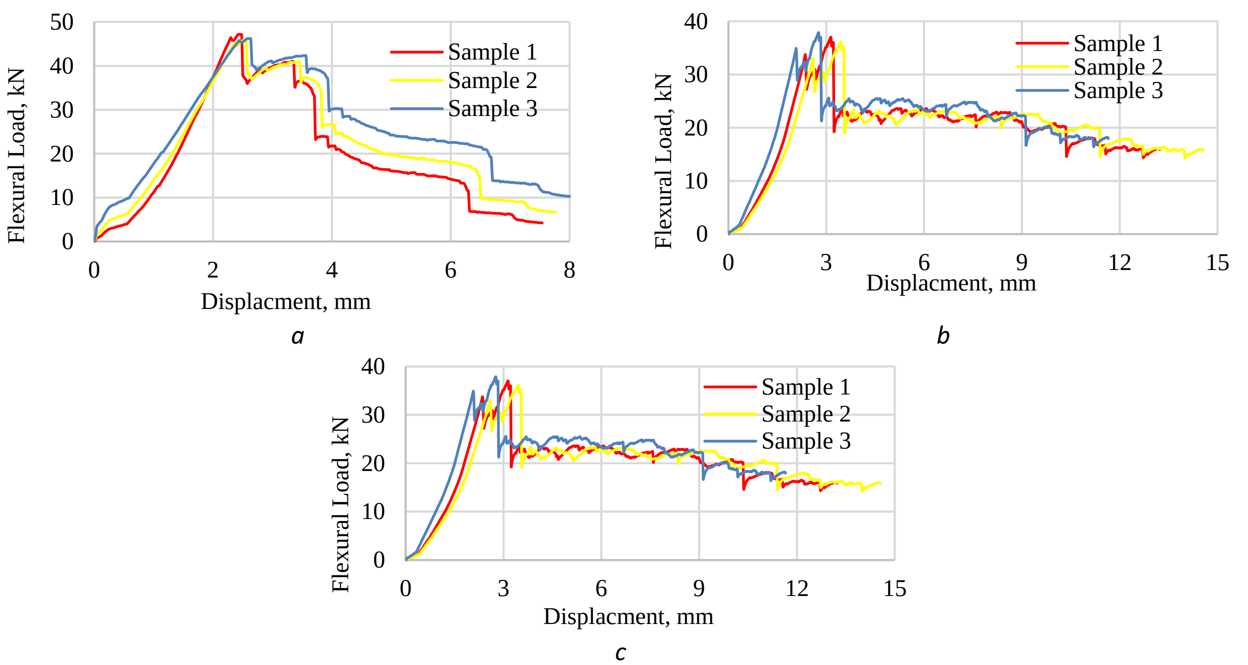
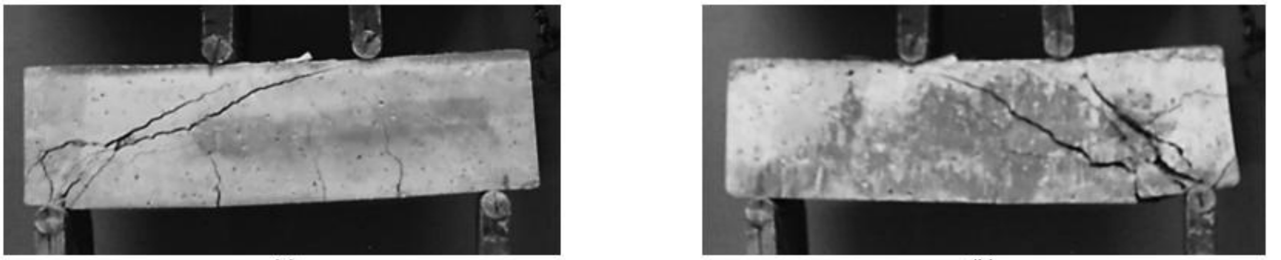


Fig. 9. Dependance of flexural load and displacement of beams with Damascus steel rebars:
a — 150-layers; *b* — 250-layers; *c* — 350-layers

HPC beams reinforced with DSR also failed slowly, as in the case of SSR, with cracks appearing that gradually widened before failure (Fig. 9). The best performance was demonstrated by HPC beams reinforced with 250-layers DSR, the average flexural load before failure was 52.19 kN with a maximum displacement of 9.78 mm (Table 6). The maximum displacement of the HPC beam reinforced with 350-layers DSR increased by more than 640 % compared to the control beams (Table 4, 6).

The photographs in Fig. 10 show the crack formation behavior and failure mechanism in HPC samples reinforced with SSR and DSR.

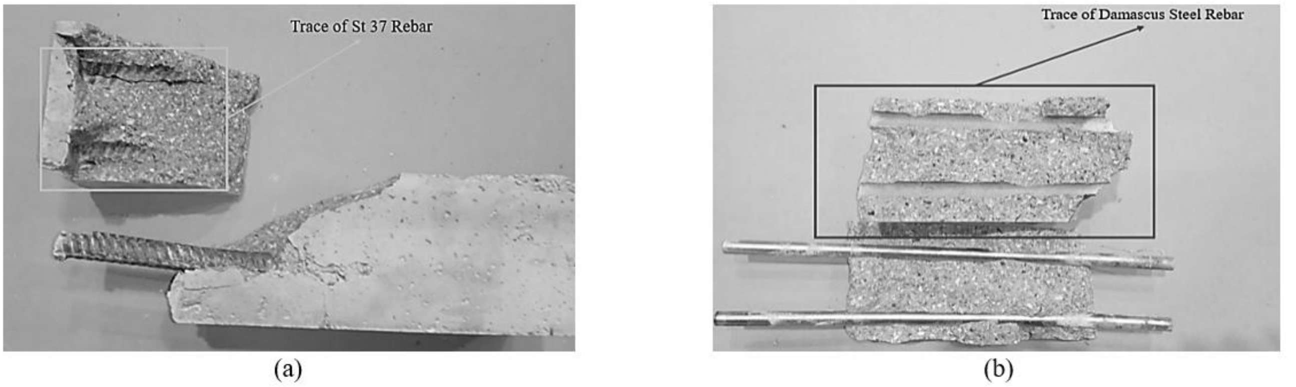


(a) (b)

Fig. 10. Crack formation behavior and failure mechanism of beams reinforced with steel rebars: *a* — St 37 steel rebars; *b* Damascus steel rebars

Beams reinforced with SSR exhibited vertical cracks at midspan at the onset of loading followed by shear cracks near the supports, while beams reinforced with DSR exhibited share cracks from the onset until failure. Flexural strength tests show that although DSR has better mechanical properties such as tensile strength than SSR, the flexural strength of HPC reinforced with SSR exceeds the flexural strength of HPC reinforced with DSR.

The photographs in Fig. 11 illustrate the bonding of HPC to the steel rebars. As can be seen from the photos, the bond between HPC and DSR was poor, so the flexural strength was less than HPC with SSR. The bond behavior between concrete and steel rebars has been studied and well recognized by many researchers. Abed et al. [31] and Alharbi et al. [32] found that good bonding between concrete and steel rebar increased the flexural strength by 40–64 %. The ribbed structure of the steel rebars such as SSR is fundamental to improving flexural strength as it provides the bond strength of steel rebars to concrete. Damascus steel can be very strong. However, its layered structure may not provide the same level of uniform strength as modern high-strength steel alloys used in rebars, especially under the stresses of concrete reinforcement, and is not a practical choice for structural reinforcement in construction.



(a) (b)

Fig. 11. Trace of rebars inside concrete: *a* — St 37 steel rebar; *b* Damascus steel rebar

CONCLUSIONS

This study investigated the differences between reinforcing high-performance concrete beams with St 37 steel rebars and Damascus steel rebars. The results of the research indicate the following:

1. Damascus steel rebars demonstrate significant tensile strength compared to St 37 steel rebars.

2. High-performance concrete beams reinforced with St 37 steel rebars are capable to withstand high flexural loads compared to beams reinforced with Damascus steel rebars, although the tensile strength of Damascus steel rebar is higher than that of St 37 steel rebars.

3. The ribbed structure of St 37 steel rebars, compared to Damascus steel rebars, is of fundamental importance for increasing the flexural strength, since it ensures the bond strength of steel rebars to concrete.

4. High-performance concrete beams reinforced with St 37 steel rebars exhibit vertical cracks at midspan at the onset of loading followed by shear cracks near the supports, indicating a controlled failure mechanism, while beams reinforced with Damascus steel rebars exhibit share cracks from the onset until failure, indicating a non-ductile behavior.

5. The layered structure of Damascus steel rebars does not provide the same level of uniform strength as St 37 steel rebars and is not a practical choice for reinforcing load-bearing structures.

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