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New Weldable Steel for Rebars

Abstract: A new steel grade, developed at the Celsa steelworks in Ostrowiec Świętokrzyski and used in the production of rebars, contributes greatly to the development of industrial and civil engineering. Steel B600B is characterised by yield point f_{yk} = 600 MPa and immediate tensile strength f_{tk} = 700 MPa. Tests revealed that the steel satisfies all requirements of related standards, both in terms of strength and processing properties. The mechanical properties of the new steel grade are higher by 20% than those of currently produced steels characterised by the highest mechanical properties (characteristic yield point R_e= 500 MPa). As a result, the application of the new steel provides notable technical and economic advantages. The new steel grade meets requirements concerning technical class C in accordance with PN-EN 1992-1-1, which indicates that the steel has a significant yield point margin (being an important advantage in terms of limit state design). Plastic steels are easier to weld and less susceptible to welding crack formation. Technological (research-related) tests revealed the favourable welding properties of the new steel. Welding tests were performed using the manual metal arc welding method, i.e. the most common welding process used when making structural reinforcements. The welding tests involved the making of butt, overlap and cruciform joints. The strength and technological tests revealed that the steel satisfied the requirements specified in the PN-EN ISO 17660-1 standard.

Keywords: reinforcing steel, welding of rebars, high-rise building

DOI: 10.17729/ebis.2021.3/3

Reinforced concrete, a commonly used building material, is a structural composite, which consists of concrete strengthened with reinforcement or one steel element referred to as a reinforcing rod. Concrete as such is also a composite and consists of cement and filler. Cement is a powdered binding agent (binder) having hydraulic properties. It is a material, which after mixing with water hardens and retains its strength properties both in air and water. A filler (an important element of concrete structure) is an aggregate, which, depending on its type and granularity, affects the strength of concrete. Concrete transfers compressive loads and is characterised by very low tensile strength. The application of steel reinforcement leads to the formation of structures characterised by significantly higher operational properties than those of concrete itself. Reinforced concrete is used in areas of tensile stresses exceeding the strength of concrete alone. Reinforced concrete is formed by pouring concrete mix into a

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reinforcing cage located in planking. After solidification, concrete along with its reinforcement forms a reinforced concrete structure or a structural element. The advantages of reinforced concrete include refractoriness, significant resistance to fixed and changing loads, considerable service life and the possibility of making structures of nearly any shape. The primary disadvantages of reinforced concrete include heavy weight and difficulties changing the shape of solidified structures. Both industrial building and civil engineering are dominated by structures made of reinforced concrete. Structural elements or entire monolithic objects made of reinforced concrete adopt their shape in wooden (boarding), steel or plastic moulds.

Important factors affecting the strength of structures made of reinforced concrete are mechanical properties of steel. Such properties are decisive for the transfer of loads by a given structure and for its weight. The combination of steel and concrete into a reinforced concrete structure enables the erection of structures capable of transferring both compressive and tensile stresses. Reinforcement is made using bars, wire ropes, strings, cables and lattice, connected by means of a binding wire. Because of the necessity of transferring loads already before being poured with concrete and its solidification, some reinforcements must be shaped by means of rigid connections (welded joints).

Presently, the design of reinforced concrete structures is covered by the PN-EN 1992-1-1 standard [1] (Eurocode), replacing PN-B-03264 [2]. Both standards (differently) specify design-related requirements concerning reinforcing bars. Although PN-B-03264 is no longer valid, many of its provisions are still used in design practice and the standard itself is cited in national document [3], which means it can still be applied. However, the PN-EN 1992-1-1 standard is increasingly often used in design and, with time, is likely to entirely replace PN-B-03264. For this reason, it is worth paying attention to the requirements specified in both standards. PN-EN 1992-1-1 specifies requirements in relation to reinforcing steel. These requirements include characteristic yield point f_{yk}, characteristic tensile strength f_{tk}, ductility expressed by elongation at maximum force during tensile tests ε_{uk}, ductility parameter k=(f_{tk}/ f_{yk}) (including three technical classes, i.e. A, B and C), bendability, adhesion expressed by the ribbing index, cross-sectional dimensions, tolerances, fatigue strength and joinability. The PN-B-03264 standard presents the division of steels in accordance with their grades and mechanical properties (A-0, A-I, A-II, A-III and A-III N). Steel grades satisfying the A-III N requirements represent steels characterised by the highest operational and processing properties. The present production of rebars is nearly only concerned with the A-III N group. The comparison of steel grades according to PN-B-03262 with those according to PN-EN 1992-1-1 is no longer of practical nature. All reinforcing steel grades manufactured in the European Union have to satisfy the requirements specified in the PN EN 1992 1-1 standard.

The standard introduces the classification of reinforcing steels, the primary idea of which is the departure from rigidly specified steel grades and their replacement with general requirements concerning mechanical properties and formability. The aforesaid requirements are listed in the PN-EN 10080 standard [4].

Specific standards concerning individual grades of reinforcing steels are presented in the PN-ISO 6935 standard [5]. The weldability-related requirement includes chemical compositions presented in Table 1.

Requirements concerning mechanical properties are presented in Table 2. The standard [1] presents the adopted division of steel grades used in the production of rebars according to the so-called technical classes, i.e. A, B and C. In accordance with [1], only weldable steels should be used in the erection of structures made of reinforced concrete. The steels are categorised

Table 1. Chemical compositions of reinforcing steels

Grade	Chemical composition [%]						
	$C^{1,2)}$	$Si^{2)}$	$Mn^{2)}$	P	S	$N^{3)}$	$C_{eq}^{4)}$
RB 300 RB 400 RB 500	-	-	-	0.060 (0.070)	0.060 (0.070)	-	-
RB 400W RB 500W	0.22 (0.24)	0.60 (0.65)	1.60 (1.70)	0.050 (0.055)	0.050 (0.055)	0.012 (0.013)	0.50 (0.52)

1) – In cases of the RB 400W and RB 500W grades, in relation to rebars, the diameter of which exceeds 32 mm, the maximum carbon content amounts to 0.25% (0.27%) in C_{eq} – 0.55% (0.57%),
C_{eq} =C + Mn/6 +(Cr + Mo + V)/5 + (Ni + Cu)/15
2) – Contents of chemical elements are specified by the manufacturer
3)– Higher nitrogen content is allowed, of the content of nitrogen-bonding elements is sufficient
4) – Values in parentheses concern the check analysis of a given product

according to technical classes related to the margin of plasticity. The latter concern reinforcement operating temperatures restricted within the range of -40°C to 100°C as well as rebars (straight, unwound and used in lattice) having a characteristic actual (f_{yk}) or conventional ($f_{0,2k}$) yield point restricted within the range of 400 MPa to 760 MPa. Table 3 presents properties of steels along with corresponding technical classes.

As can be clearly seen in Table 3, the sequence of A, B and C indicates the level of weldability, resulting from the increasing margin of material plasticity (being an important parameter determining weldability).

The permanent development of building engineering forced by the need for building increasingly high and heavy structures necessitates the use of increasingly modern materials and technologies. One of the elements of the aforesaid development concerns high-strength building materials. It is unthinkable to use low-strength reinforcing steel in today's high-rise buildings and infrastructure. Every increase in reinforcing steel strength of additional 100 MPa [6] translates into measurable advantages. For instance, in terms of comparable high-rise buildings, the use of high-strength reinforcing steel will result in the reduction of steel volume by 20% and that of concrete by 30%. Consequently, also the weight, volume and the laboriousness of timbering (calculated in relation to a specific reinforcement) will be lower. In turn, the reduction of material consumption index will decrease the costs

Table 2. Mechanical properties of steel grades

Steel grade	**Characteristic yield point f_{yk} [MPa]**	**Characteristic tensile strength f_{tk} [MPa]**	**Unit elongation $A_{5.65}$ (A_5) [%]**
RB 300	300	330	16
RB 400, RB 400W	400	440	14
RB 500, RB 500W	500	550	14

Table 3. Criteria of rebar-related technical classes in accordance with [6]

	Straight and unwound from coils			**Lattices**		
	A	**B**	**C**	**A**	**B**	**C**
$k=(f_t/f_y)_k$	≥1.05	≥1.08	≥1.15 <1.35	≥1.05	≥1.08	≥1.15 <1.35
ε_{uk} (A_{gt})[%]	≥2.5	≥5.0	≥7.5	≥2.5	≥5.0	≥7.5
Bendability	Bending and deflecting tests			-		
Shear strength	-			0.3 Afyk		

f_t – characteristic immediate tensile strength
f_y – characteristic yield point
ε_{uk} (A_{gt}) – reinforcement deformation in relation to maximum load
A – wire cross-sectional area
f_{yk} – characteristic margin of material plasticity of rebar lattice

of supply and on-site transport as well as those of logistics (storage and packaging). All of the above-named categories will ultimately result in the reduction of power consumption.

For many years, manufactured reinforcing steel grades have been characterised by properties presented in Tables 1, 2 and 3. In particular, steels having a characteristic yield point f_{yk} of 400 MPa and 500 MPa are produced in complicated processes combining complex metallurgy and plastic working performed within strictly controlled temperature regimes. The necessity of applying such processes results from the need for ensuring appropriate weldability (in terms of both fusion and pressure welding). The improvement of the mechanical properties of steels characterised by the aforementioned properties cannot only result from an increase in the content of carbon as the increased carbon content translates into increased hardness and hardenability/ This, in turn, leads to the reduction of plastic properties, and, consequently, the dramatic worsening of weldability. In the past, high-strength reinforcing steels, e.g. grades 34GS and 35G2Y, reached a yield point of 400 MPa [2]. However, in relation to carbon equivalent CE (which could amount to 0.59), the weldability-related requirements could not be satisfied, not to mention the satisfaction of requirements resulting from an appropriate technical class specified in PN-EN 1992-1-1 [1]. Presently valid standards require that all reinforcing steels should be weldable. As a result, to provide reinforcing steels grades with higher mechanical properties, it is necessary to apply appropriate metallurgical technologies. To address growing needs, the specialists of CELSA – Huta Ostrowiec (steelworks) in Ostrowiec Świętokrzyski developed a new reinforcing steel grade (B600B) intended for the production of

Table 4. Chemical composition of B600B rebars

Content [%]	Analysis results for rebar having a diameter of			According to technical conditions by CELSA (product analysis) [7]	According to the requirements specified in PN-EN 10080 [4]
	Φ32	Φ16	Φ10		
C	0.209	0.205	0.220	0.24	0.24
Si	0.135	0.140	0.130	0.60	NZ
Mn	0.853	0.837	0.877	1.65	NZ
P	0.024	0.009	0.010	0.055	0.055
S	0.041	0.023	0.025	0.055	0.055
Cr	0.187	0.184	0.191	NZ	NZ
Mo	0.034	0.033	0.034	NZ	NZ
Ni	0.103	0.104	0.104	NZ	NZ
Cu	0.278	0.260	0.266	0.85	0.85
Al	0.002	0.001	<0.001	NZ	NZ
Co	0.008	0.008	0.008	NZ	NZ
Nb	0.003	0.002	0.003	NZ	NZ
Sn	0.018	0.016	0.017	NZ	NZ
Ti	<0.001	<0.001	<0.001	NZ	NZ
V	0.002	0.002	0.003	NZ	NZ
W	0.009	0.011	0.016	NZ	NZ
Zr	0.001	<0.001	0.003	NZ	NZ
N	NZ	NZ	NZ	0.013	0.014
CEV	0.42	0.41	0.44	0.52	0.52
NZ – not required					

rebars in all diameters manufactured by the company. The final stage of research involved the performance of joinability tests. To this end, it was necessary to develop the programme of tests including the analysis of the base material as well as tests concerning fusion and pressure welded joints.

The research-related tests involved reinforcing bars having a diameter of 10 mm, 16 mm and 32 mm. The first stage involved the

Table 5. Mechanical properties of the rebars having a diameter of 10 mm

No.	Lot identification	Specimen designation	Mechanical tests						Description
			R_e	R_m	R_m/R_e	A_5	A_{10}	A_{gt}	
			[MPa]	[MPa]	-	[%]	[%]	[%]	
1	Ribbed rebars; Ø10 mm; grade B600B	fi10/R/1	614	695	1.13	20.8	16.2	10.3	plastic fracture
2		fi10/R/2	604	690	1.14	22.2	17.0	9.6	plastic fracture
3		fi10/R/3	619	703	1.14	23.0	15.9	9.7	plastic fracture
4		fi 10/Z/1	Test of bending up to 90° and test of deflection by 20°						without scratches and cracks
5		fi 10/Z/2							without scratches and cracks
6		fi 10/Z/3							without scratches and cracks

Table 6. Mechanical properties of the rebars having a diameter 16 mm

No.	Lot identification	Specimen designation	Mechanical tests						Description
			R_e	R_m	R_m/R_e	A_5	A_{10}	A_{gt}	
			[MPa]	[MPa]	-	[%]	[%]	[%]	
1	Ribbed rebars; Ø16 mm; grade B600B	fi16/R/1	606	699	1.15	22.0	16.4	9.1	plastic fracture
2		fi16/R/2	609	702	1.15	21.1	16.3	9.1	plastic fracture
3		fi16/R/3	608	702	1.15	21.0	16.4	8.6	plastic fracture
4		fi 16/Z/1	Test of bending up to 90° and test of deflection by 20°						without scratches and cracks
5		fi 16/Z/2							without scratches and cracks
6		fi 16/Z/3							without scratches and cracks

Table 7. Mechanical properties of the rebars having a diameter 32 mm

No.	Lot identification	Specimen designation	Mechanical tests						Description
			R_e	R_m	R_m/R_e	A_5	A_{10}	A_{gt}	
			[MPa]	[MPa]	-	[%]	[%]	[%]	
1	Ribbed rebars; Ø32 mm; grade B600B	fi32/R/1	630	722	1.15	19.0	15.1	11.6	plastic fracture
2		fi32/R/2	623	716	1.15	20.1	14.5	11.3	plastic fracture
3		fi32/R/3	627	719	1.15	18.0	13.7	11.4	plastic fracture
4		fi 32/Z/1	Test of bending up to 90° and test of deflection by 20°						without scratches and cracks
5		fi 32/Z/2							without scratches and cracks
6		fi 32/Z/3							without scratches and cracks

performance of tests aimed to verify (confirm) the properties of the base material (rebars) in accordance with the requirements specified in the PN-EN 10080 [4] and PN-EN 1992-1-1 [1]. The chemical composition of the rebars was identified using a Q4 Tasman spark emission spectrometer (BRUKER). Table 4 presents the chemical analysis results. Mechanical tests also involved reinforcing bars having a diameter of 10 mm, 16 mm and 32 mm (as provided in the requirements of related standards) [8, 9]. The test results are presented in Tables 5, 6 and 7.

The chemical composition analysis results concerning the material of all of the tested rebars revealed that the contents of individual chemical elements satisfied the requirements of the PN-EN 10080 standard [4]. The primary parameter determining joinability, i.e. carbon equivalent C_{eq}, was by approximately 17% lower than the maximum value ($C_{eq\ max}$ = 0.52). The above-presented carbon equivalent value indicated favourable welding properties, yet requiring the use of a qualified welding procedure. It should be emphasized that, in accordance with the requirements of the PN-EN ISO 17660-1 standard, [10] (regardless of a steel grade), each rebar joining process must be performed using a qualified welding procedure (in terms of fusion and pressure welding). The tests of mechanical properties revealed that all of the rebars satisfied the requirements resulting from assumed yield point $R_{e\ min}$ = 600 MPa. In terms of design-related requirements, i.e. technical classes specified in PN-EN 1992-1-1 [1] (Table 3), the new steel satisfied the requirements related to technical class C, which indicates the highest usability when making reinforcements in structures made of reinforced concrete. Only as regards the steel of the rebars having a diameter of 10 mm (Table 5), the immediate tensile strength-yield point ratio was slightly lower (by slightly below 1%) than the limit value. It should be noted that the steels subjected to analyses were manufactured for testing purposes and are not produced on a mass scale yet, where statistical principles of quality assessment apply. In all likelihood it can be assumed that after the commencement of the mass production this little imperfection will be removed and the entire range of production will satisfy the requirements of technical class C.

The research work involved the performance of welding tests and the development of standard technologies. The tests involved joints used when connecting rebars and recommended in the PN-EN ISO 17660-1 standard [10], i.e. butt joints with a backing strip and cruciform joints. Because of the fact that reinforcements will be made under construction site conditions, the welding of rebars (to a great extent) will involve the application of method 111 (manual metal arc welding). The joints were designed as V-butt joints with a metal strip. Figure 1 presents the manner of pre-weld joint preparation.

Butt joints with V-welds on a backing strip are used when making welded reinforcements [10]. The joints were made using method 111 (manual metal arc welding). Figure 2 presents an exemplary MMAW butt joint made of rebars having a diameter of 32 mm.

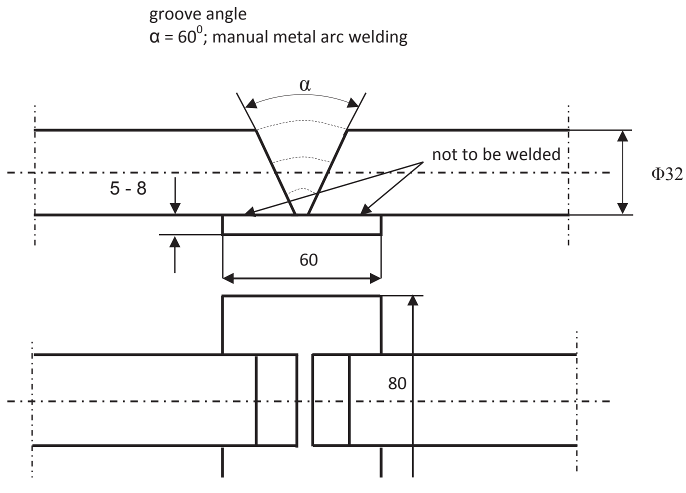

Fig. 1. Pre-weld preparation of butt joints

Fig. 2. Weld made using method 111

Table 8 presents tensile test results concerning test butt joints. The strength parameter was breaking force [10]. Table 8 (for comparative purposes) presents breaking force values.

The bend tests of butt joints involving the use of a mandrel having a required diameter of 210 mm were performed in accordance with standard [10]. During the tests it was possible to obtain a required bend angle exceeding 60° without scratches and cracks.

Table 8. Tensile test results in relation to butt joints and rebars

No.	Breaking force [kN]		Remarks
	Rebar Φ 32	Welded joint	
1	579	575	rupture outside the weld in the HAZ
2	552	576	rupture outside the weld in the HAZ
3	576	561	rupture outside the weld in the HAZ
Av.	569	571	

In practice, the making of reinforcement usually requires lap or overlap joints. This results from the fact that the pre-weld preparation of such joints is easiest under welding conditions in restricted positions (typical of reinforcement preparations). Welding test involved the making of overlap joints using rebars having a diameter of 16 mm and 10 mm. Figure 3 presents an exemplary joint having a diameter of 16 mm.

A parameter qualifying a given overlap joint is bar breaking force. Tensile tests involved three joints representing each diameter. In all of the cases, the rupture took place outside the joint. In relation to the joints made of the rebars having a diameter of 10 mm, immediate tensile strength R_m was restricted within the range of 677 MPa to 681 MPa. In turn, in relation to the joints made of the rebars having a diameter of 16 mm, immediate tensile strength R_m was restricted within the range of 700 MPa to 708 MPa.

Fig. 3. Exemplary overlap joint made of the rebars having a diameter of 16 mm

Cruciform joints should not be designed as joints transferring primary loads. Because of their nature, such joints are able to transfer tensile and shear loads. Figure 4 presents an exemplary cruciform joint.

In accordance with the PN-EN ISO 17660-1 standard [10], one of the criteria indicative of joint quality is breaking force during the tensile test. During the performance of related tensile tests, the immediate tensile strength (R_m) of the cruciform joints made of rebars having a diameter of 10 mm was restricted within the range of 664 MPa to 674 MPa, whereas that of the cruciform joints made of the rebars having a diameter of 16 mm was restricted within the range of 699 MPa to 708 MPa.

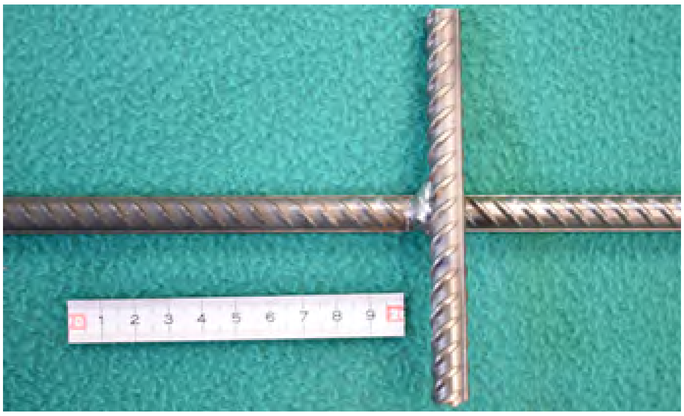

Fig. 4. Exemplary cruciform joint made of the rebars having a diameter of 10 mm

Another criterion indicating the quality of a cruciform joint is the shear test [10]. Figure 5 presents exemplary cruciform joint prepared for the shear test.

The shear tests involved the joints having a diameter of 10 mm and 16 mm. Table 9 presents the test results. The quality parameter of the joint was shear coefficient Sf, expressed by the following formula:

where S_f – shear coefficient,

A_s – nominal cross-sectional area of an anchored

rebar [mm2],
F_s – shear force [N],
$R_{e\ char}$ – characteristic yield point

$$S_f = \frac{F_S}{A_s\ R_{e\ char}}$$

of the rebar material.

In accordance with [10], shear coefficients S_f were categorised in classes from SF30 to SF80 (subsequent designations increasing every 10), where the number in the class symbol designated the percentage value minimum of S_f. Where obtained coefficient S_f exceeded 80%, class SF80 was adopted for design-related purposes. Table 9 reveals that the tested cruciform joints satisfy the requirements of class SF80 and, as a result, can be used when making joints representing the highest strength-related properties.

Fig. 5. Cruciform joints made of the rebars having a diameter of 10 mm – prepared the shear test

Table 9. Shear test results concerning two-sided cruciform joints welded using method 111

No.	Specimens			Mechanical properties		Shear coefficient S_f [%]
	Specimen designation	Specimen dimensions		F_s [kN]	$R_{e\ char}$ [MPa]	
		d_0 [mm]	A_s [mm^2]			
1	EO/10/Ś/1	10	78.5	49 000	600	105
2	EO/10/Ś/2			47 600		101
3	EO/10/Ś/3			48 800		102
4	EO/16/Ś/1	16	201.1	133 000		110
5	EO/16/Ś/2			130 000		108
6	EO/16/Ś/3			119 700		97

In the summary it should be emphasized that the new steel developed at the CELSA steelworks in Ostrowiec Świętokrzyski, intended for the production of rebars, contributes significantly to the development of industrial building and civil engineering. According to assumptions, the new steel grade (designated as B600B) will be characterised by yield point f_{yk} = 600 MPa and immediate tensile strength f_{tk} = 700 MPa. The above-presented tests demonstrated that the steel satisfies all of the requirements specified in the PN-EN 10080 standard [4], both in terms of mechanical and processing properties. In comparison with presently manufactured steels having the highest mechanical properties (including characteristic yield point R_e= 500 MPa as regards steel grade RB 500W in accordance with PN-ISO 6935-2 [5]), the mechanical properties of the new steel are higher by 20%. This fact translates into measureable technical and economic advantages, enumerated at the beginning of the article. Therefore, it is justified to recommend the use of steel B600B, particularly in high-rise building. The fact that the steel satisfies the requirements of technical class C in accordance with PN-EN 1992-1-1 [1] indicates that the steel is characterised by a significant plasticity margin, which is an important advantage as regards the limit state design. The exceeding of the ultimate limit state of load-carrying capacity by the steel (having an appropriate plasticity margin) will not lead to sudden and catastrophic results. The foregoing is also reflected in welding properties. Plastic steels are easier to weld and less susceptible to welding crack formation. The technological welding tests also confirmed the favourable properties of the steel. The welding tests involved the manual metal arc welding method, i.e. the method most commonly used when making reinforcements in construction site conditions. The welding tests included butt, overlap and cruciform joints. The mechanical and technological tests confirmed that the steel satisfies the requirements specified in the PN-EN ISO 17660-1 [10] standard. The tests enabled the development and documentation of welding technologies. Because of the significant number of documents, the Authors decided not to present them in this article; the documents can be the subject of a subsequent publication. The developed technologies include the entire range of diameters obtained in the production of reinforcing bars performed at CELSA steelworks in Ostrowiec Świętokrzyski. Presently, CELSA is the only manufacturer of the technologically advanced steel and reinforcing bars.

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