Analysis of the adhesion strength of the A550 reinforcement to concrete B25, B30 and B40

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Abstract. A set of studies has been carried out to determine the controlled parameters of the adhesion strength of class A550 reinforcement to concrete. More than 100 tests have been done on the basis of which an array of empirical data is formed, necessary for comparative analysis and determination of calculated values of bearing capacity and operational suitability of reinforcing bars of class A550. The values of the relative crushing area of the transverse ribs of the reinforcement for Class A 550 meet regulatory requirements is as follows: for rods with a diameter of 8 mm, it is above the strength of the reinforcement; for rods with a diameter of 10 mm, it is close to the strength of the reinforcement; and for rods with a diameter of 12 mm, it is below the strength of the reinforcement, with an anchoring length equal to 6 times the diameter of the reinforcement.

1 Introduction

Reinforced concrete, which is widely used in construction, has both advantages and disadvantages. The main advantages are its strength and durability, as well as its ability to withstand heavy loads. However, there are also some significant disadvantages. For example, the quality of raw materials and manufacturing technology play a crucial role in determining the strength and durability of reinforced concrete. Additionally, the mass of reinforced concrete structures can be a disadvantage, as it can make them difficult to transport and install. Another disadvantage is the presence of internal stresses, which can cause cracks and other defects. Finally, low tensile strength and aging are also concerns for reinforced concrete. Steel reinforcement in concrete is subject to corrosion, which can reduce the performance and reliability of reinforced concrete structures over time. Stress concentration at reinforcement ribs and welded joints can also cause aging of steel, leading to a decrease in strength characteristics. Due to these factors, the parameters of reinforced concrete must be determined using a probabilistic statistical method based on experimental data, rather than relying solely on theoretical calculations.

The problem of developing the theory of reinforcement coupling with concrete was dealt with in Russia by Kholmyansky M.M., Oatul A.A., Karpenko N.I., Tsiskreli G.D., Sudakov G.N., Madatyan S.A. [1], Khotko A.A. [2], Gorshenina E.V. [3], Savrasov I.P. [4], Tsyba O.O. [5], Bedarev V.V., Bedarev N.V., Bedarev A.V. [6], as well as scientists of the St. Petersburg State University of Railway Engineering [7-13],

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Research has been conducted on this issue abroad by U. Mayer [14], M. Y. H. Bangash [15], BriceL.P., Goto, Y. and others.

The class A600 steel reinforcement, commonly used in practice, has better mechanical properties compared to the A550 steel, but there are some significant limitations to its use in concrete. By adding alloying and microalloying elements such as manganese, copper, silicon, vanadium, niobium and titanium, it is possible to ensure the required physical and mechanical properties (yield strength, elongation) and technological properties (weldability and corrosion resistance) in steel.

2 Materials and methods

In accordance with the research conducted at the Research Institute of Bridges, a joint analysis of the results was carried out and experimental test data were processed.

The analysis was performed:

- for control concrete samples;
- for reinforcement samples in determining geometric and physico-mechanical parameters;
- for welded reinforcement products during shear testing;
- for welded reinforcement products during the welding softening test;
- for samples of anchor sections with single reinforcement;
- for samples of anchor sections with welded reinforcement grids.

3 Results

The average compressive strength of the concrete of the control samples corresponded to the concrete class (Table 1).

Table 1. Results of processing concrete strength data

Declared concrete class	The average strength value is 28 days, MPa	Compliance with the concrete class according to GOST	The actual average value of the concrete grade
B25	46.0	B42	B39.5
	40.8	B37	
B30	38.9	B35	B37
	42.7	B39	
B40	50.6	B47	B49
	55.3	B51	

Analysis of the experimental results from the experiment revealed that the actual strength of the concrete in the control cube samples was significantly higher than the value corresponding to the declared concrete class.

Armature studies have shown that the average values of the measurement results for geometric parameters and the determination of the mechanical characteristics of the armature values σtek and σmax for fittings with a diameter of 12 mm are higher for class A500, and for diameters of 8 and 10 mm, on the contrary, for class A550 (Table 2). This can be explained by the fact that reinforcement of class A 550 undergoes surface thermal hardening, which results in a relatively larger cross-sectional area for smaller product diameters.

Table 2. The results of measurements of geometric parameters and determination of mechanical characteristics of fittings

Reinforcement class	Diameter, mm	$P_{тек}$, gf	P_{max}, gf	δ_5, %	$\sigma_{тек}$, MPa	σ_{max}, MPa
A500	12	7.54	8.60	20.62	660	753
	10	4.54	5.54	22.73	578	706
	8	2.74	3.32	26.97	537	650
A550	12	6.61	8.17	18.35	579	715
	10	4.84	5.74	17.19	612	726
	8	2.85	3.50	15.90	566	693

The elongation value δ_5 is lower for valves of class A550, and with a decrease in the diameter of the valve, this difference increases from 11% for valves of 12 mm to 41% for valves of 8 mm, which is also explained by the above-mentioned reasons.

The value of the relative crumpling area of the transverse ribs of the periodic profile (Rohm's criterion f_R) for various diameters and classes of reinforcement showed their regulatory requirements (Table 3).

Table 3. f_R value for different diameters and classes of fittings

Reinforcement class	Nominal diameter of the valve, mm		
	12	10	8
A500	0.067	0.055	0.068
A550	0.069	0.052	0.045

4 Determination of the calculated values of reinforcement adhesion in welded grids with concrete

The basic (basic) anchorage length l_0, necessary to transfer the force in the reinforcement with the full calculated resistance value R_s to concrete, is determined by the formula

$$l_0 = \frac{R_s \cdot A_s}{R_{bond} \cdot u_s} \qquad (1)$$

where A_s and u_s are, respectively, the cross—sectional area of the anchored reinforcement rod and the perimeter of its section, determined by the nominal diameter of the rod, mm; R_{bond} is the calculated adhesion resistance of the reinforcement to concrete MPa, assumed to be evenly distributed along the length of the anchorage and determined by the formula:

$$R_{bond} = \eta_1 \cdot \eta_2 \cdot R_{bt} \qquad (2)$$

where R_{bt} is the calculated resistance of concrete to axial tension MPa; η_1 is a coefficient taking into account the influence of the type of reinforcement surface, for hot—rolled and thermomechanically treated periodic profile fittings, assumed to be 2.5; η_2 is a coefficient taking into account the influence of the size of the diameter of the reinforcement, assumed for non—stressed reinforcement with a diameter of the reinforcement d_s< 32 mm equal to 1.0:

$$R_{bt} = \frac{R_{bt,n}}{\gamma_{bt}} \qquad (3)$$

The values of the tensile strength coefficient of concrete γ_{bt} are taken to calculate the limiting conditions of the first group when assigning a concrete compressive strength class for heavy, fine-grained, straining and light concretes equal to 1.5.

The normative values for the concrete's resistance to axial tension, Rbt,n, are taken into account when assigning a concrete class based on its compressive strength. Therefore, the total designed resistance of the valve can be determined by considering the concrete class and its corresponding Rbt,n value.

$$R_s^1 = R_{bond}\frac{l_0 \cdot u_s}{A_s} \tag{4}$$

With a l_o value equal to $6d_n$ of the longitudinal reinforcement in the test sample, we obtain the value of the total design resistance of the reinforcement $R^1{}_s$ required to transfer force to concrete (Table 4).

Table 4. Values of the total design resistance $R^1{}_s$

Concrete	d, mm	$l_{0,\,an}$ (6d)	A_s, mm^2	u_s, mm	$R_{bt,n}$ MPa	R_{bt} MPa	R_{bond} MPa	$R^1{}_s$, MPa
B25	8.0	48.0	50.3	25.1414	1.55	1.0333	2.5833	62.00
	10.0	60.0	78.5	31.4080	1.55	1.0333	2.5833	62.00
	12.0	72.0	113.1	37.6996	1.55	1.0333	2.5833	62.00
B30	8.0	48.0	50.3	25.1414	1.75	1.1667	2.9167	70.00
	10.0	60.0	78.5	31.4080	1.75	1.1667	2.9167	70.00
	12.0	72.0	113.1	37.6996	1.75	1.1667	2.9167	70.00
B40	8.0	48.0	50.3	25.1414	2.10	1.4000	3.5000	84.00
	10.0	60.0	78.5	31.4080	2.10	1.4000	3.5000	84.00
	12.0	72.0	113.1	37.6996	2.10	1.4000	3.5000	84.00

Comparing the obtained values with the value of the lower limit R_s, established by regulatory documents and the previously obtained actual value $R_{s\phi}$, we determine the values of the calculated and actual reserve coefficients $K^1{}_p$ and $K^1{}_\phi$ of the base anchorage length at l_o equal to $6d_n$ (Table 5).

Table 5. Reserve coefficients of the base anchorage length

Reinforcement class	Concrete class	$R^1{}_s$, MPa	R_s, MPa	$K^1{}_p$	$R_{s\phi}$, MPa	$K^1{}_\phi$	$K^1{}_{0,3}$	$K_н$
A550	B25	62	480	7.74	573.91	9.26	2.322	1.63
	B30	70	480	6.86	502.61	7.18	2.058	1.44
	B40	84	480	5.71	466.96	5.56	1.713	1.20
A500	B25	62	435	7.02	503.48	8.12	2.106	1.47
	B30	70	435	6.21	532.17	7.60	1.863	1.30
	B40	84	435	5.18	492.17	5.86	1.554	1.09

Based on the calculations carried out, we can conclude that formula 1 contains a reserve coefficient for concrete, which is from 5.7 to 7.7 of the calculated value for the considered reinforcement diameters and concrete classes and from 5.5 to 9.2 of the actual value for A550 class reinforcement.

We consider it possible to reduce the size of the reserve by 30%, provided that the reliability coefficient $K_н$ is at least 1.1.

The determination of the anchoring length of reinforcing bars in concrete, taking into account the parameter of the relative area of crushing of the transverse ribs of the reinforcement f_R, is possible provided that the relationship between the values R_{bond} and f_R is established. The R_{bond} value is determined by equation 2. The coefficient η_1 depends on various factors and is equal to

$$\eta_1 = \frac{\sigma_s}{4\lambda R_{bt}} \tag{5}$$

where $\boldsymbol{\lambda} = l/d$ is the relative length of the reinforcement anchorage in concrete; d is the diameter of the reinforcement.

The dependence of η_1 on f_R is well known and is:

$$\eta 1 = 1.5 + 20 fR \text{ for the range } 0.056 \leq fR \leq 0.12 \tag{6}$$

$$\eta 1 = 1.73 + 14 fR \text{ for the range } 0 \leq fR \leq 0.08 \tag{7}$$

As a result of the conducted research, this range amounted to an interval from 0.045 to 0.069, therefore, we take into account formula 7 and substitute it into formula 1.

$$R_{bond} = 1.73 + 14 f_R \cdot R_{bt} \tag{8}$$

Substituting the data, we obtain the values of l_0 depending on the parameter f_R (Table 6).

Table 6. Anchorage length depending on the f_R parameter

Reinforcement class	Concrete class	Diameter of the armature	R_s, MPa	A_s. mm^2	f_R	R_{bt}, MPa	u_s, mm	l_0, mm
A550	B25	8	480	50.3	0.045	1.033	25.1414	393.9195
		10	480	78.5	0.052	1.033	31.408	472.4854
		12	480	113.1	0.069	1.033	37.6996	517.0671
	B30	8	480	50.3	0.045	1.167	25.1414	348.6879
		10	480	78.5	0.052	1.167	31.408	418.2326
		12	480	113.1	0.069	1.167	37.6996	457.6952
	B40	8	480	50.3	0.045	1.4	25.1414	290.6563
		10	480	78.5	0.052	1.4	31.408	348.6267
		12	480	113.1	0.069	1.4	37.6996	381.5216
A500	B25	8	435	50.3	0.068	1.033	25.1414	314.1295
		12	435	113.1	0.067	1.033	37.6996	473.5098
	B40	8	435	50.3	0.068	1.4	25.1414	231.7827
		12	435	113.1	0.067	1.4	37.6996	349.3826

The obtained anchorage length values are close to those calculated, so we can conclude that it is necessary to reduce them.

If transverse reinforcement is present in concrete samples, the calculation for local crumpling is performed

$$N \leq \psi \cdot R_{b.loc} \cdot A_{b.loc} \tag{9}$$

where N is the local compressive force from the external load; ψ is a coefficient equal to 1.0 with a uniform distribution of the local load over the crumpling area; $A_{b.loc}$ is the area of application of the compressive force (crumpling area); $R_{b.loc}$ is the calculated compressive resistance of concrete under the local action of the compressive force.

$$R_{b.loc} = \varphi_b \cdot R_b \tag{10}$$

where φ_b is the coefficient determined by the formula:

$$\varphi_b = 0{,}8 \cdot \sqrt{\frac{A_{b.max}}{A_{b.loc}}} \text{ when } (1 \leq \varphi_b \leq 2{,}5) \tag{11}$$

where $A_{b.max}$ is the maximum calculated area.

The calculations performed showed that the actual load values for all samples were less than the calculated values of the local compressive force, with a difference ranging from 1.29

to 4.55 times. This indicates that condition (9) is met and there is no concrete crumbling under the transverse reinforcement. These results are in agreement with the previously obtained findings. It is suggested to reduce the calculated local compressive force values by no more than 30%, provided that the safety factor is at least 1.1.

5 Analysis of the results

Comparing the obtained values with the normative value of the lower limit of R_s, and the actual value of $R_{sф}$, (Table. 2) it is possible to determine the values of the calculated and actual reserve coefficients $K^1{}_p$ and $K^1{}_ф$ of the base anchor length at l_o equal to $6d_н$ (Table 7).

Table 7. Reserve coefficients of the base anchorage length

Reinforcement class	Concrete class	$R^1{}_s$, MPa	R_s, MPa	$K^1{}_p$	$R_{sф}$, MPa	$K^1{}_ф$	$K^1{}_{0,3}$	$K_н$
A550	B25	62	480	7.74	573.91	9.26	2.322	1.63
	B30	70	480	6.86	502.61	7.18	2.058	1.44
	B40	84	480	5.71	466.96	5.56	1.713	1.20
A500	B25	62	435	7.02	503.48	8.12	2.106	1.47
	B30	70	435	6.21	532.17	7.60	1.863	1.30
	B40	84	435	5.18	492.17	5.86	1.554	1.09

Thus, it can be concluded that the formula (1) contains a reserve coefficient for concrete, which is for the considered diameters of reinforcement and concrete classes with an anchorage length equal to $6d_n$ from 5.1 to 7.0 of the calculated value and from 5.8 to 8.1 of the actual value for A500 class reinforcement and from 5.7 to 7.7 of the calculated value and from 5.5 to 9.2 of the actual value for A550 class fittings. Considering that according to paragraph 10.3.25 [75] for non-tensioned rods, the actual anchorage length is allowed to be at least $0{,}3l_o$. We consider it possible to reduce the margin by 30%, provided that the reliability coefficient $K_н$ is at least 1.1 (Table 4).

6 Conclusion

Fittings of class A550 have a higher values of yield strength and a higher temporary resistance than fittings of class A500, but they also have a lower elongation value.

The values of the relative crumpling area of the transverse ribs of the f_r reinforcement for class A550 comply with regulatory requirements.

For samples of anchor sections with a single straight anchorage, the adhesion strength of the reinforcement to concrete:

- for rods with a diameter of 8 mm is higher than the strength of the reinforcement;
- for rods with a diameter of 10 mm, it is close to the strength of the reinforcement;
- for rods with a diameter of 12 mm and an anchorage length equal to 6 times the diameter of the reinforcement, the strength is lower than that of the reinforcement.

When checking the calculated values of the local compressive force, it was found that the values of the actual load for all samples are less than the calculated values by an amount from 1.29 to 4.55 times, which means that there is no crumpling of concrete under the transverse reinforcement, It is possible to reduce the calculated values of the local compressive force by no more than 30%, provided that the margin coefficient is not less than 1.1.

Based on the results of the calculations performed, it can be recommended to reduce the actual length of the anchoring rods to a value of at least $10d_s$ and 150 mm, and for non-stressed rods also at least $0{,}3l_{0,an}$, provided that the reliability coefficient is at least 1.1.

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