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Experimental studies on mechanical properties of corroded steel bars after elevated temperature

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Abstract

The mechanical properties of steel bar deteriorates after erosion and elevated temperature. In the study 16 mm diameter bars were corroded by an electrochemical accelerated corrosion technique, and then heated at temperatures 300, 500 and 700℃. The bars were cooled naturally in furnace to ambient temperature and were tested in tension. The nominal yield strength, nominal ultimate strength and elongation were observed. The observations showed that nominal yield strength, nominal ultimate strength and elongation was changed significantly on the coupling effects of corrosion and temperature.

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1. Introduction

Steel corrosion and fire have great damage to construction structure, which causes a large number of casualties and economic losses. Chloride ions in environmental media and the raw materials of concrete penetrate around the steel bar and destroy the Passive Film, which cause corrosion of steel bars and reduce the effective cross section of

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the steel bars. These damages will lead to the change of the Macro performance and Microstructure of the steel. Steel bar strength weakening and expansion cracking after corrosion cause the decrease of bond property between steel bar and concrete, which leads to the decrease in load-carrying capacity of structure. Mechanical properties of corroded steel bars after high temperature will show different attenuation laws with the elevated temperature experienced.

Xu Gang [1] studied the mechanical properties of corroded steel bars in concrete under the environment of chloride salt. The influence of different corrosion degree on the nominal yield strength, nominal ultimate strength, equivalent yield strength, equivalent ultimate strength, elongation and yield step Strength of reinforcement was discussed in the paper. Yu Xiaofen [2] studied the effect of Cl- concentration on the corrosion behavior of HPB300 steel in simulated concrete pore fluid. Shen Dejian [3] carried out experimental research and simulation analysis on the performance of corroded steel bar in concrete with seawater wave splashing, and discussed the relationship between yield strength, ultimate strength, ultimate elongation and failure mode with corrosion rate. Zhang Yan-nian [4] carried out the test on the mechanical properties of the rebar in concrete under immersion corroded by the impressed current, and analyzed the variation law of yield strength, ultimate strength and mass loss rate of steel bars after rusting. Li Fenglan [5] analyzed the variation law of mechanical properties of rebar with different corrosion degree, and established a computational model for the nominal yield strength of corroded rebar. Yuan Yingshu [6] studied the structural degradation model of corroded reinforced concrete beam, established the stress-strain relation of corroded steel bar and the degenerate model of bond stress-slip relationship between corroded steel bar and concrete. Wu Qing [7] carried out experimental research on the deterioration of mechanical properties of corroded steel bars, analyzed and compared the changes of the mechanical properties of rebar under different corrosion degree. Zhang Wei Ping [8]studied the stress-strain relationship of corroded steel bar , and he established the mathematical model of stress - strain relation of corroded steel bars under different environmental conditions .Wu Hongcui [9] tested the mechanical properties of HRB500 high strength steel bars after high temperature, and studied the variation law of stress-strain relation curve, yield strength, ultimate strength, elastic modulus, elongation ratio and section shrinkage of high strength steel HRB500 after high temperature. Yu Zhiwu [10] carried out the experimental study on the mechanical properties of the new Ⅲ grade steel bars after high temperature, and suggested the formula for calculating the yield strength, ultimate strength, elastic modulus, elongation and tensile stress-strain full curve of new Ⅲ-grade steel bars after high temperature. Wang Quanfeng [11] studied the mechanical properties of HRBF500 fine grain steel bars after high temperature, and suggested a formula for calculating the yield strength, tensile strength, elastic modulus and elongation after high temperature after fine grain. Wang Kongfan [12] studied the mechanical properties of steel bars at elevated temperatures and after high temperature cooling and to understand the changes in mechanical properties of steel bars. Wang Yuzhuo [13] studied the mechanical properties of cold-rolled ribbed bars after high temperature, and fitted the regression mathematical model formula with temperature change for the mechanical properties of cold-rolled ribbed bars after high temperature.

In this paper, the accelerated corrosion and high temperature test of 48 HRB335 hot rolled steel bars with 16mm diameter were studied, and the mechanical properties including elongation, nominal yield strength and nominal limit strength of steel bars considering coupling effect of corrosion degree and high temperature were investigated.

2. Test Overview

2.1 Specimen production

To study the mechanical properties regarding corrosion degree and high temperature, ten concrete slabs (dimensions 400mm × 350mm × 100mm) were prepared for the accelerated corrosion test. Six deformed bars were embedded in the middle of each concrete slab as shown in Fig. 1 and 2. The type of bars used are HRB335 hot rolled ribbed bars of diameter 16 mm.

Fig. 1. Geometry of the test specimen (all in mm)

Fig. 2. Production of corroded reinforced concrete slabs

2.2 Reinforcement accelerated corrosion

The specimens prepared were demoulded 24 h later and kept in standard cure conditions with 20 ± 2 ℃ temperatures for 28 days. After the curing, the specimens were corroded using an electrochemical accelerated corrosion technique that involves impressing a direct current through the specimens to accelerate the oxidation process in a 5% NaCl solution. Table 1 lists the tested specimens, the expected corrosion ratio ranged from 3% to 9%. The maximum required artificial corrosion process took approximately 45 days for the specimens of expected corrosion ratio 9%.

2.3 Specimen heating

Not corroded steel bars were exposed to temperatures as high as 20, 300, 500 and 700℃. Corroded steel bars were cleaned using a 12% hydrochloric acid solution to remove scale and rust products and weighed before exposed to temperatures as high as 20, 300, 500 and 700℃. This was followed by a naturally cooling process; furnace was turned off and let it cool until ambient temperature (20℃).

2.4 Tensile test

Before testing, on the bar surface marks with an initial distance of ten times the nominal diameter of bars, i.e., $10d_{nom}$ = 160 mm, were made to determine the original gauge length. The tensile process was controlled by displacement with 2 mm/min. During the tensile test, the applied load were recorded using a computerized data acquisition system, and the deformation values were obtained with a extensometer with a 50 mm base.The data obtained were utilized to plot load-displacement curve, determine the yield load and ultimate load, and calculate the elongation for each tested bar.

3. Results and discussion

3.1 The apparent characteristics of the specimen

The apparent characteristics of steel bars after accelerated corrosion are shown in Fig. 3. It is shown from Fig. 3 (a, b, c) that, there are also differences in the corrosion patterns of corrosion of rebars with the different degree of corrosion. When the corrosion ratio was small, the surface of corroded of rebars had a large number of "rust spots", the depth of rust was very shallow, so it could be regarded as uniform corrosion. When the corrosion ratio was large, it was more serious and the "rust spot" gradually turned into "rusty pit". The lateral corrosion of the steel bar towards the chlorine salt solution was more serious as shown in Fig. 3(d), the area and depth of the "rust pit” of which had significantly different with the former.

After high temperature and cooling, there would be some changes of corroded steel bar apparent. The apparent color of the corroded steel bar was slightly red after 300 ℃ and cooling, the color deepened to rust red after 500 ℃ and cooling, and the color deepened to reddish brown after 700 ℃ and cooling. Surface spalling accured after 700 ℃, the color of which resulting for high temperature was dark black.

（a） Expected corrosion ratio of 3%

（b） Expected corrosion ratio of 6%

（c） Expected corrosion ratio of 9%

（d）Corrosion of the outer side

Fig. 3.Apparent characteristics of steel after corrosion

3.2 Mechanical properties of the specimen

The mechanical properties of corroded steel after high temperature are shown in Table 1. This paper studied the effects of corrosion and high temperature on mechanical properties of the steel bars, including nominal yield strength, nominal ultimate strength and elongation.

Table 1. Mechanical properties of corroded steel after high temperature

Rebar ID	Expected corrosion ratio /%	Actual corrosion ratio /%	Temperature /℃	Elongation /%	Yield load /KN	Nominal yielding strength /MPa	Ultimate load /KN	Nominal ultimate strength /MPa
G20-0	0	0	20	21.97	87.0	432.6	114.0	566.9
G20-3	3	2.76	20	19.33	82.9	412.5	109.5	544.9
G20-6	6	6.66	20	15.56	75.5	375.4	99.9	496.8
G20-9	9	11.20	20	14.85	67.3	334.7	93.3	463.9
G300-0	0	0	300	19.44	84.7	421.2	114.8	570.9
G300-3	3	2.76	300	19.05	83.2	413.7	112.1	557.4
G300-6	6	6.66	300	17.35	77.9	387.4	105.5	524.6
G300-9	9	11.20	300	17.11	70.3	349.6	97.3	483.8
G500-0	0	0	500	20.36	85.5	425.2	113.5	564.4
G500-3	3	2.76	500	18.26	84.4	419.7	112.6	559.9
G500-6	6	6.66	500	17.41	77.1	383.4	100.7	500.7
G500-9	9	11.20	500	15.87	69.9	347.6	95.2	473.4
G700-0	0	0	700	20.99	76.6	380.9	101.0	502.2
G700-3	3	2.76	700	22.52	71.5	355.5	95.6	475.4
G700-6	6	6.66	700	20.87	68.4	340.1	91.1	453.0
G700-9	9	11.20	700	18.24	56.7	281.9	79.6	395.8

3.2.1 Elongation

Fig. 4 shows the elongation variation of steel bar with corrosion ratio. It can be seen from the figure, the elongation of steel bar decreased with the increase of the corrosion ratio at ambient temperature, after 300 and 500 ℃; and the elongation increaseed at first then decreased with the increase of the corrosion after 700 ℃.

Fig. 5 shows the elongation variation of steel bar with temperature. It can be seen from the figure, when corrosion ratio was 0, the elongation of steel bar was lower than that of ambient temperature after high temperature; when corrosion ratio was 2.76%, the elongation of steel bar was lower than that of ambient temperature after 300 and 500 ℃, but higher than that of ambient temperature after 700 ℃; when corrosion ratio was 6.66% and 11.2%, the elongation of steel bar was higher than that of ambient temperature after high temperature.

3.2.2 Nominal Yield strength

Fig.6 shows the nominal yield strength variation of steel bar with corrosion ratio. It can be seen from the figure, the nominal yield strength of steel bar decreased with the increase of the corrosion ratio at ambient temperature and after high temperature.

Fig.7 shows the nominal yield strength variation of steel bar with temperature. It can be seen from the figure, the nominal yield strength variation was not obvious before and after 300 and 500 ℃, but the nominal yield strength was obviously reduced after 700 ℃.

Therefore, the coupling effects of corrosion and high temperature on the nominal yield strength variation of steel bar was more obvious. The higher the temperature and the larger the corrosion ratio, thus the more obvious the nominal yield strength reduction

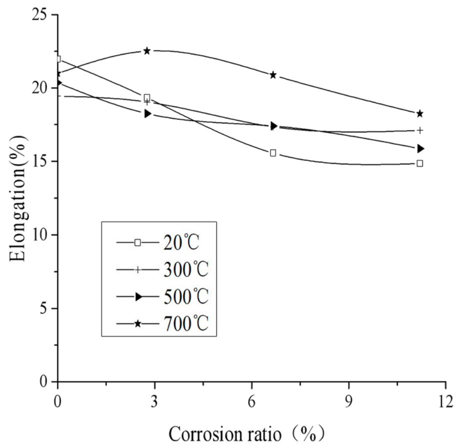

Fig. 4. The elongation variation of steel bar with corrosion ratio

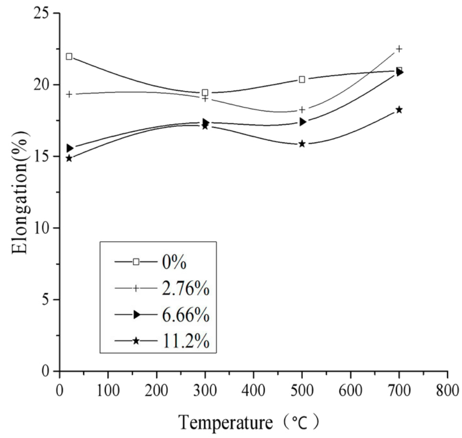

Fig. 5. The elongation variation of steel bar with temperature

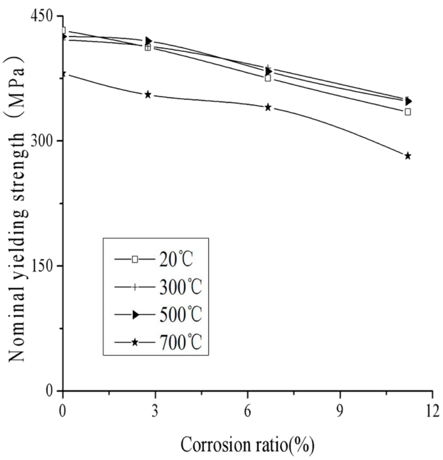

Fig. 6. The nominal yield strength variation of steel bar with corrosion ratio

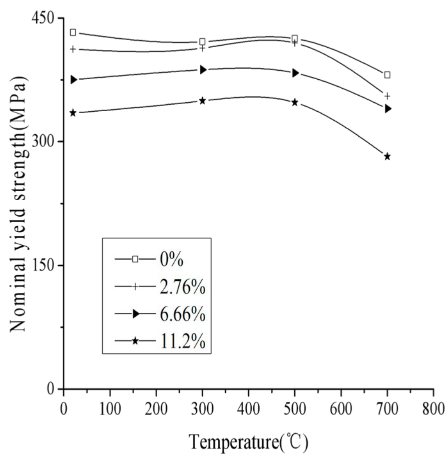

Fig. 7. The nominal yield strength variation of steel bar with temperature

3.2.3 Nominal Ultimate Tensile Strength

Fig.7 shows the nominal ultimate strength variation of steel bar with corrosion ratio. It can be seen from the figure, the nominal ultimate strength of steel bar decreased with the increase of the corrosion ratio at ambient temperature and after high temperature.

Fig.8 shows the nominal ultimate strength variation of steel bar with temperature. It can be seen from the figure, the nominal ultimate strength variation was not obvious before and after 300 and 500 ℃, but the nominal ultimate strength was obviously reduced after 700 ℃.

Therefore, the coupling effects of corrosion and high temperature on the nominal ultimate strength variation of steel bar was more obvious. The higher the temperature and the larger the corrosion ratio, thus the more obvious the nominal ultimate strength reduction.

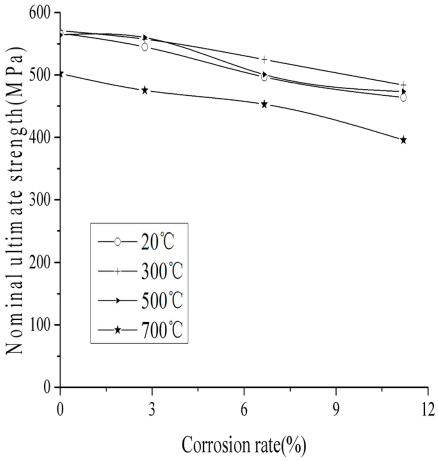

Fig. 8. The nominal ultimate strength variation of steel bar with corrosion ratio

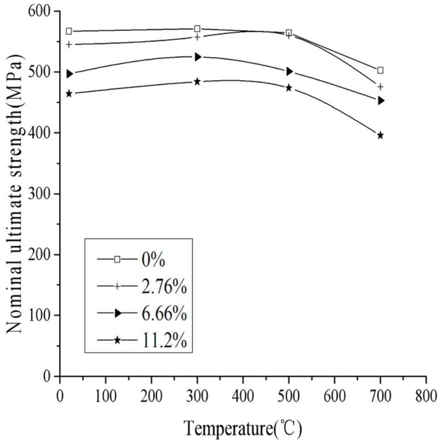

Fig. 9. The nominal ultimate strength variation of steel bar with temperature

4. Conclusions

In this paper, experiment research on the mechanical properties of corroded rebar after elevated temperature were carried out. The variation law of elongation, nominal yield strength and nominal ultimate strength of steel bar with corrosion ratio and temperature were obtained. The main conclusions are as follows:

- After electrochemical accelerated corrosion, when the corrosion ratio was small, the depth of rust was very shallow, so it could be regarded as uniform corrosion. When the corrosion ratio was large, it was more serious and the "rust spot" gradually turned into "rusty pit".
- After high temperature and cooling, surface color of the corroded steel bar varied with the temperature color varies with the temperature. The surface color of the steel bar was slightly red after 300 ℃ and cooling, and the surface color deepened to rust red after 500 ℃ and cooling. The surface color deepened to reddish brown after 700 ℃ and cooling. The color of surface peeling resulting for high temperature was dark black.
- After corrosion and high temperature, nominal yield strength, nominal ultimate strength and elongation of steel bar would change with corrosion ratio and temperature. The coupling effects of corrosion and high temperature on nominal yield strength, nominal ultimate strength and elongation variation of steel bar was more obvious.

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