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The stainless steel appeal as alternative material for reinforcing bars to be applied in long lasting construction

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1. INTRODUCTION

The present product technology of stainless steel rebar is mainly constituted by a first hot rolling of wire followed by cold working; this allows to obtain bars up to 16 mm dia. Larger diameters are obtained directly by hot rolling wire into bars. So far, few official construction standards, developed in USA and in Europe, namely in UK, enclose guidelines for the use of stainless steel. The diffused use of stainless steel derives from the fact that in hostile environments it has an elevated ability to resist corrosion; this allows to substantially reduce the mortar covering required to transfer the steel stresses to the mortar and elements [1]. Moreover, experimental tests had demonstrated clearly that stainless steel structures can be expected to maintain their integrity even after prolonged exposure to the highest temperature reached in hydrocarbon fires, whereas galvanised carbon steels, however can withstand fire for a useful period, suffer some loss of rigidity and may drip molten zinc, constituting a possible additional hazard to personnel [2, 3]. In the case of earthquake event, the high toughness (which is maintained high despite the cold working eventually imparted) of stainless steel is a key property for an antiseismic material; in fact a good material should be able to dissipate the energy induced by seismic waves by conversion into thermal energy. Experimental works present in the open litterature had shown that 304 and 316 austenitic stainless steels exhibit better performance in terms of yield strength, tensile strength, deformation energy absorption, uniform elongation if compared with carbon reinforcing steel [3]. Furthermore, the intrinsic durability and corrosion resistance guarantee that the outstanding seismic and fire resistance properties are kept unaltered during the entire life cycle of components and structure, avoiding the need for maintenance. Therefore, if the whole life cycle of stainless steel, that has a superior corrosion resistance and it is safer in case of seismic accident or fire event and it does not suffer ageing, is considered then actual advantages can be achieved on maintenance and repair costs.

This paper reports a part of a larger mechanical, corrosion and stress-corrosion characterisation performed in the framework of a European Project entitled “Increased Infrastructure reliability by developing a low cost and high performance stainless steel rebars” with HIPER acronym.

2. EXPERIMENTAL PART

Three materials were used for the research work: FeB44K (the typical reinforcing steel), AISI 304 and 316 (the mostly common stainless steels). The chemical composition was determined and the results are reported in the following tables, 1 to 3.

The stainless steels rebars were obtained first as hot rolled and annealed smooth bars step. Such semi-product was then cold rolled to enhance through strain hardening the mechanical properties and to provide the required rib pattern. The nominal diameter was 12 mm.

Table 1: Chemical Composition wt% of specimen FeB 44K, commercially available.

C	Si	Mn	P	S	Cr	Mo	Ni	Co	Cu	Nb	V	W	Sn	As	Fe
0.216	0.188	0.684	0.009	0.035	0.16	0.041	0.20	0.020	0.457	0.003	0.003	0.018	0.024	0.010	Bal.

Table 2: Chemical Composition wt% of specimen AISI 304, COGNE production.

C	Si	Mn	P	S	Cr	Mo	Ni	Co	Cu	Nb	Ti	V	W	Sn	Fe
0.059	0.351	1.137	0.020	0.000	17.440	0.496	8.33	0.119	0.405	0.012	0.003	0.065	0.037	0.008	Bal.

Table 3: Chemical Composition wt% of specimen AISI 316, COGNE production.

C	Si	Mn	P	S	Cr	Mo	Ni	Co	Cu	Nb	Ti	V	W	Sn	Fe
0.032	0.359	1.641	0.017	0.000	16.770	1.948	10.45	0.133	0.579	0.016	0.003	0.064	0.038	0.008	Bal.

500 mm long test pieces were cut from the original coil and straightened for the tensile test. Ten specimen for each type of material. The speed of testing used in determining Rp02 and Rm was 0.2 mm/s (in accordance with EN 10002-1 standard). For the calculation of tensile properties the nominal cross-sectional area was used. 0.2% proof strength was evaluated by the offset method, after the determination of the elastic modulus (E). Elastic properties and Rp02 were measured through an extensometer. Percentage total elongation at rupture was determined by the manual method on a gage length of 60 mm, equal to 5 times the nominal diameter (A5).

100 mm long test pieces were cut from the original coil for corrosion characterization. The first corrosion characterisation has been carried out in saturated calcium hydroxide solution, which simulates the pH value of the aqueous phase of the cement in the pores of the concrete (12.6). The solution was contaminated with sodium chloride, 0.1% and 3.5 % NaCl. This addition of chloride ions due to this salt is found in marine environments, and in roads, bridges and tunnels in countries where de-icing salts are used. The corrosion tests were performed using the following electrochemical techniques:

- Polarisation Resistance, R_p, from which the corrosion current density I_{corr} was estimated through the equation $Icorr=B/R_p$, where B is a constant and R_p the polarization resistance.
- Anodic Polarisation tests (ASTM G61-86) were performed applying anodic potential at a scanning rate of 10 mV/min from corrosion potential to achieving the breakdown potential, E_b, where the reverse sense was imposed until reaching again the new corrosion potential or repassivation potential, E_p. With this technique it is possible to evaluate the susceptibility to pitting corrosion of the materials.

The resistance to stress corrosion cracking (SCC) of AISI 304 and 316 stainless steels was evaluated by performing comparative slow strain rate tests (SSRT) with carbon steel, in air and in calcium hydroxide saturated solution with 3% of chlorides at room temperature, following the international standard ISO 7539-7. Two strain rates were used in the SSRT: i) 8.2E-5 mm/s; ii) 2.2E-5 mm/s. The test specimens were prepared according to the international standard ISO 7539-4. For the preparation of stainless steels test pieces the hot rolled and annealed bars were used instead of the cold rolled rebars.

3. RESULTS AND DISCUSSION

The recorded tensile data are reported in table 4. The yield and tensile strength of AISI 304 are quite higher than the ones of carbon steel. On the contrary, the elongation to rupture of such material is poor, therefore limiting the capability of absorb deformation energy. On the contrary, AISI 316 exhibits a high yield and tensile levels, if compared with carbon steel with the same elongation to rupture.

Figure 1 shows a summary of the corrosion density values obtained for all tested materials in the $Ca(OH)_2$ solution without NaCl and with 3.5 % NaCl. Corrosion density values have the same order of magnitude, for all materials (stainless steels and carbon steel) in saturated calcium hydroxide solution without chloride. Only the carbon steel in saturated calcium hydroxide solution with 3.5% sodium chloride shows an active state with high value of the corrosion density. On the contrary, the stainless steels are in a passive state. A thin, adherent and compact layer is on the surface of the materials. This layer protects the materials from the corrosive medium.

Since all stainless steels are in passive state it was necessary to evaluate the probability of the breakdown of the passive layer. This evaluation was done by drawing the Anodic Polarization Curves.

Table 4. Tensile test according to EN 10002. Average values are calculated on a set of 10 specimens

Material		***ϕ nom [mm]***	***$R_{p0.2}$ [N/mm^2]***	***R_m [N/mm^2]***	***E [Gpa]***	***A5 [%]***	***Z[%]***
FeB44K	*Average*	12	541	658	203	23.00	39.18
	Stdev	-	3.81	4.92	9.33	1.87	4.24
AISI 304	*Average*	12	832	931	158	19.40	54.13
	Stdev	-	12.80	8.70	9.40	2.20	2.51
AISI 316	*Average*	12	755	866	171	23.00	58.27
	Stdev	-	6.75	9.04	9.40	1.05	4.85

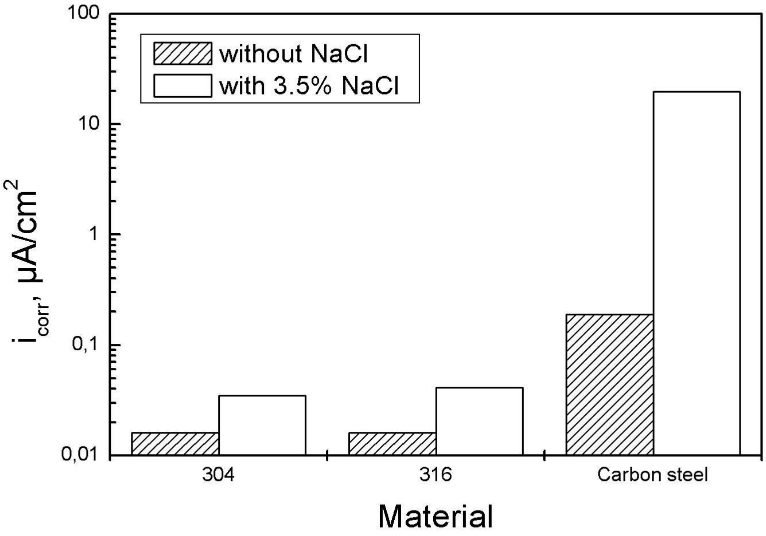

Figure 1. Corrosion current density for all materials tested after 24 h of immersion in saturated $Ca(OH)_2$ solution with different NaCl contents.

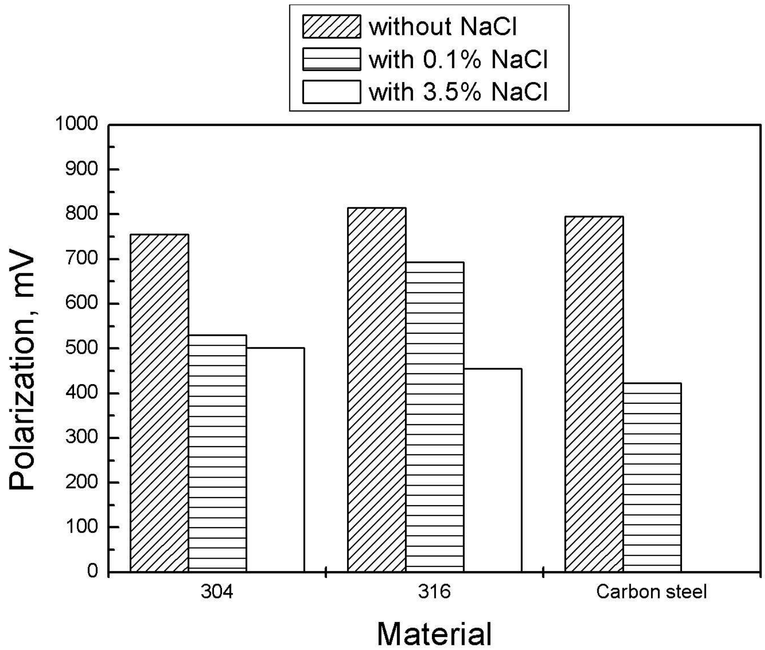

Figure 2. Polarization for the 304 and 316 stainless steels and carbon steel, in saturated $Ca(OH)_2$ solution with different NaCl contents.

The severity of SCC, as a comparative index, is expressed by some of the following parameters: tensile strength, percentage of reduction of area and percentage of elongation at rupture. These results obtained for all the materials studied are summarised in tables 5 and 6. Results from the comparative tests performed in air and in solution show similar behaviour in the two environments. Differences between the values measured in the two environments might be due to the experimental scatters.

Table 5. Results from slow strain rate test for all the materials, tested in air and in saturated $Ca(OH)_2$ solution with 3%Cl^- at 8.2E-5 mm/s.

Material	**Tensile strength [N/mm^2]**		**Elongation [%]**		**Reduction of area [%]**	
	air	**3%Cl^-**	**air**	**3%Cl^-**	**air**	**3%Cl^-**
FeB44K	*598*	*570*	*3*	*3*	*60*	*64*
AISI 304	*761*	*737*	*14*	*12*	*75*	*79*
AISI 316	*558*	*572*	*8*	*10*	*79*	*88*

Table 6. Results from slow strain rate test for all the materials, tested in air and in saturated $Ca(OH)_2$ solution with 3%Cl^- at 2.2E-5 mm/s.

Material	**Tensile strength [N/mm^2]**		**Elongation [%]**		**Reduction of area [%]**	
	air	**3%Cl^-**	**air**	**3%Cl^-**	**air**	**3%Cl^-**
FeB44K	*580*	*580*	*3*	*3*	*63*	*60*
AISI 304	*735*	*702*	*13*	*12*	*81*	*75*
AISI 316	*559*	*559*	*9*	*10*	*85*	*85*

4. CONCLUSIONS

This paper reports a part of the results achieved in the European funded project "Increased Infrastructure reliability by developing a low cost and high performance stainless steel rebars"; HIPER acronym; project number GDR1-2000-25601; contract number G1RD-CT 2000-00339.

The mechanical levels of AISI 304 and 316 recorded in tensile tests at room temperature were quite higher if compared with carbon steel reinforcing bars. However, this enhancement in mechanical levels (yield and tensile strengths) does not deeply affect elongation to fracture and ductility (comparable to those of carbon steel reinforcing bars for AISI 316 and only slightly lower for AISI 304). The corrosion resistance recorded for stainless steels was indeed very high if compared with traditional reinforcing steel, especially in terms of resistance to pitting corrosion. Finally, the tensile properties were observed to be slightly affected by aggressive environments influence; in fact, the tensile tests assisted by corrosion recorded very few modifications of the tensile behaviour in all the materials tested.

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