CORROSION RESISTANCE

Carbon steel used in rebars is normally protected from corrosion since concrete is an environment subject to high basicity (pH 12-13); Under those conditions iron , a basic element in carbon steels, is under passive conditions.
However, depending on operating conditions, it is not always possible to guarantee the physical and structural integrity of concrete. If a carbonation phenomenon occurs (chemical aggression of carbon dioxide contained in the atmosphere in concrete and in particular in lime mix), a decrease in the pH level can be seen, following the relevant reaction

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

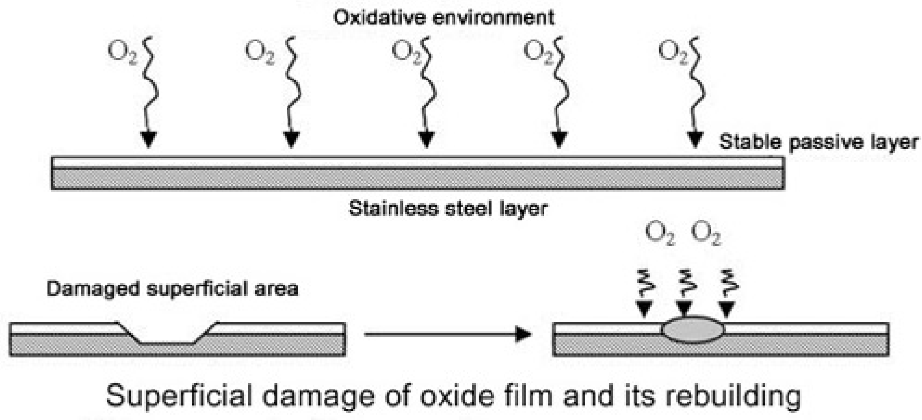
A decrease in concrete alkalinity permits the development of a broad range of corrosive phenomena in carbon steel rebars through the formation of oxides and/or iron hydroxides (typical rust).

Moreover since in some applications concrete is contaminated generally by salt solutions (chlorides penetrate into concrete), the highlighted problem can become very important as regards the structural resistance.

In some examples shown in picture 1, it is obvious how corrosive phenomena are often linked to the formation of rust which having a specific volume up to 6-8 times greater than the iron bars, causes the splitting, the disintegration and in some cases the cracks of the thin concrete coating. (phenomenon called “spalling”).

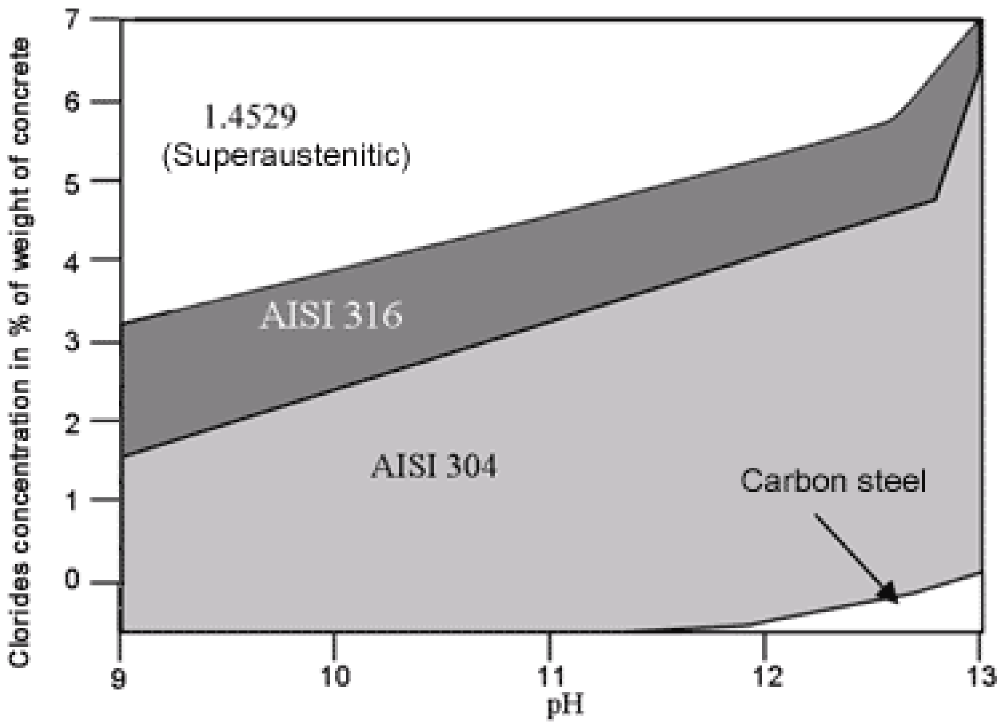
Picture 1

In stainless steels, the presence of chromium in huge quantities gives them the capacity to “self passivate” in a spontaneous way when the clean surface is in contact with an external environment, corrosive or oxidative (picture 2).



Picture 2 - Drawing showing stainless steel passivation mechanism..

In addition to chromium the elements which contribute to increase corrosion resistance are:
Molybdenum
Nickel
Nitrogen
Carbon acts in an inversely proportional way:the lower its content , the greater its resistance to corrosion.
In concretes with alkaline pH or even neutral (after carbonation processing) stainless steels do not undergo corrosion (Picture 3).
Corrosion phenomena in stainless steel rebars can be observed only if there is a relevant concentration of chlorides in concrete made porous from carbonation itself. Once such a contraction overcomes a critical threshold then a localised reduction and elimination of the passive oxide layer can be noticed and corrosion then can start, provided that there is an appropriate quantity of oxygen. The phenomenon is better known as pitting.



Picture 3 - Use conditions in safety of different steels depending on chlorides concentration and pH

A simple way to evaluate corrosion resistance to pitting of stainless steels is the so-called coefficient or PREN index (Pitting Resistance Equivalence Number) calculated as follows:

PREN = %Cr + 3,3%Mo + 16%N (for austenitic steels)
PREN = %Cr + 3 ,3%Mo + 30%N (for duplex steels)

On the basis of the above formula we can set a classification for common stainless steels such as stainless steel rebars:

AISI	EN 10088-1	Cogne Grade	PREN index
304L - austenitic	1.4301	304HT	18
316L - austenitic	1.4436	316HT	25
329 - duplex	1.4462	329HT	35
---- **superaustenitic**	1.4529	354/1	45

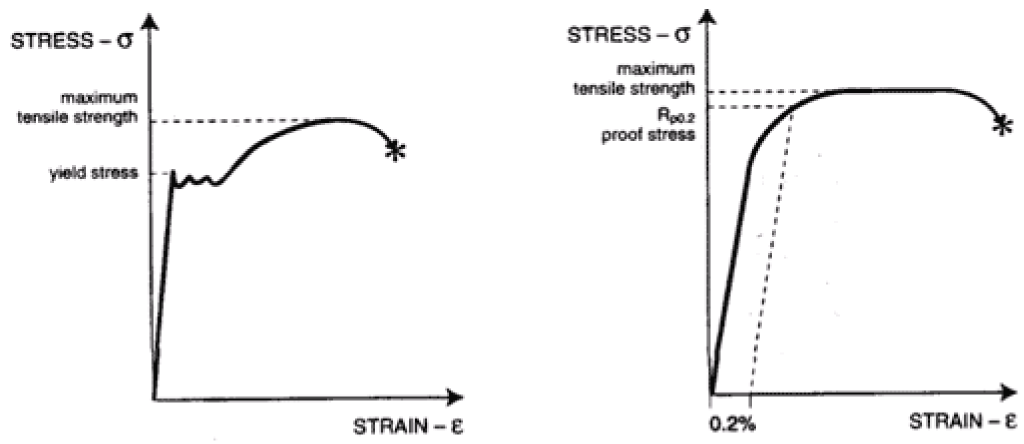
Tab. 2 - Classification of Stainless steels used in concrete according to their resistance to pitting

Class	Concrete type and environmental conditions	Aggression level	Recommended stainless steel grade	
			Common applications	High-level safety structures
1	• Carbon enriched concrete • Environment slightly alkaline • Chlorides free	Modest	1.4301 (AISI 304L)	1.4301 (AISI 304L)
2	• Concrete with a normal level of alkalinity and Cl^- <1% • Slightly Carbon enriched concrete	Rather aggressive	1.4301 (AISI 304L) 1.4436 (AISI 316L)	1.4436 (AISI 316L)
3	• Carbon enriched concrete with Cl^- >1% • Slightly Carbon enriched concrete with chlorides presence	Very aggressive	1.4436 (AISI 316L)	1.4462 (AISI 329)
4	• Carbon enriched concrete in a high chlorides concentration environment • Reinforced concrete Structures without any possibility of entry for controls • Hinges connecting separate blocks in reinforced concrete exposed to high Cl^- or to highly aggressive environments	Extremely aggressive	1.4462 (AISI 329) 1.4529 (354/1)	1.4529 (354/1)

Tab.3 Indications of stainless steels applications according to the different environmental conditions. (Euroinox)

DUCTILITY

Due to their ductile nature, austenitic and austenitic-ferritic stainless steels show not only high percentage elongations to rupture but also ratios ft/fy rather high being either annealed or work-hardened. The strain-stress curve is rather different from that of carbon steel as shown on picture 5.



(a) Carbon steel **(b)** Stainless steel

Picture 5 - Comparison between carbon steel and stainless steel in the strain-stress curve

Bearing in mind that the area subtended by the two curves is proportional to the mechanical energy absorbed in the tensile test, we can easily understand the relevant difference in the capacity of dissipating energy linked to events which are subject to important deformations.
In stainless steel rebars, the relevant difference of both materials in terms of percentage elongation to rupture is to be noticed (almost 12% for carbon steel, almost 20% for stainless steel) as reported in the table.

	Carbon steel	**1.4301**	**1.4436**	**DM. 9.1.96**
Structure		**Austenitic**	**Austenitic**	**FeB44k**
$R_{p0,2}$ [N/mm^2] (yield characteristic strenght **f_{yk}**)	>=430	670 Ø <= 6 ÷12 mm 540 Ø >12 mm		>=430
R_m [N/mm^2] (Rupture strenght **f_{tk}**)	>=540	810 Ø <= 6 ÷12 mm 780 Ø >12 mm		>=540
Elongation A_5%	>=12	20 Ø <= 6 ÷12 mm 35 Ø >12 mm		>=12
Ratio $(f_t/f_y)_k$	>=1.13	1.20 Ø <= 6 ÷12 mm 1.40 Ø >12 mm		V. Tab 5a e 5b
Elastic modulus [kN/mm^2]	190	200		

Tab. 4 - Mechanical characteristics of steels applied for stainless steel rebars.

By ductility, we mean the capacity the material to undergo high deformation with reduced resistance either under monotonic or cyclic loads.Considering stainless steel from a ductilitity point of view the classification relates to final stress (on drawing 5 indicated as “maximum tensile strength”) u and the ratio ft/fy turns out to be interesting. Model Code 90 gives the three categories B, A , S subject to increasing ductility and advises use of Grade S steel in seismic areas provided that ratio between rupture and yield strength shall not overcome 1.3 value (Table 5a.)
Eurocode 2, on the contrary, considers two different stainless steel rebars, called High ductility (HD) and normal ductility (ND) (Table 5 b).
On the other hand greater restrictions are provided in Eurocode 8 for stainless steel rebars in buildings in a seismic area (still in Table 5b).

CEB Model Code 90			
	Category B	Category A	Category S
ε_u	>=2.5%	>=5%	>=6%
f_t/f_y	>=1.05	>=1.08	>=1.15

Tab. 5a - Minimum values of resistance ratios and of final stress according to Model Code 90

	Eurocode 2		Eurocode 8	
	ND	HD	DC-M	DC-H
ε_u	>=2.5%	>=5%	>=6%	>=9%
f_t/f_y	>=1.05	>=1.08	>=1.15	>=1.20

Tab. 5b - Minimum values of final resistance and stress according to EC2 and EC8.

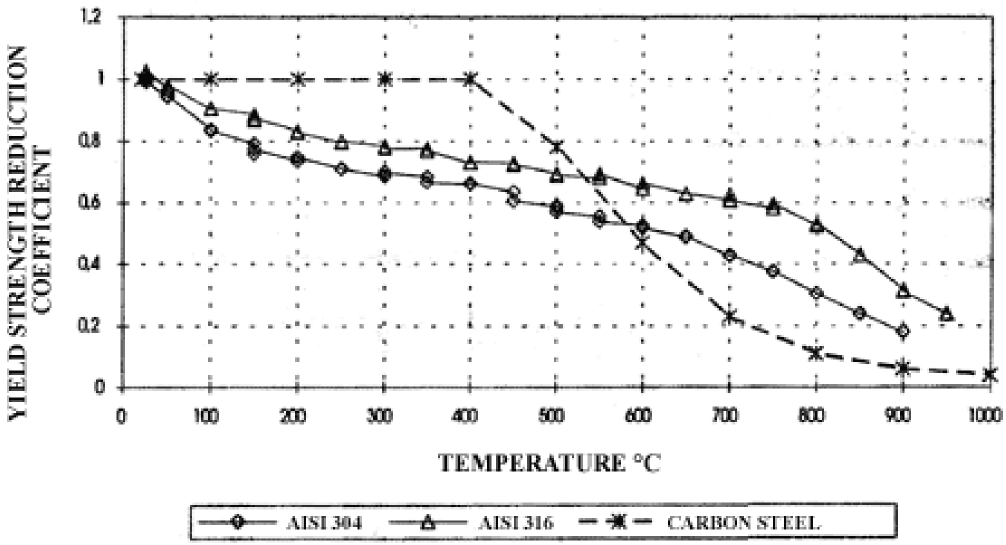
However we should point out that a high material ductility does not correspond, of course, to a high structural ductility since in rebars other phenomena appear, linked to cross section behaviour or to the structural element and to other specific problems capable of affecting the ductility itself. On that point studies are being carried out aimed at improving concrete quality.

TOUGHNESS

This is the resistance of a material to brittle fracture:it is determined by a Charpy test that measures impact properties.
Austenitic stainless steels (with a typical fcc structure, stable at all temperatures.) differ from carbon steels by their high toughness level (In some cases a double level can be achieved); austenitic-ferritic steels with a mixed structure of homogeneous austenite and ferrite grains and with a ratio between the two structures close to 1, present intermediate toughness values ranging between those of full austenitic steels and those of common C steels.
Two interesting factors are to be highlighted:
Stainless steels toughness does not vary much when the work hardening level varies. That is particularly interesting since possible different production techniques (cold drawn or hot rolling) do not create great differences in resistance to fatigue cycles, and are able to generate notche effects at the base of the ribs (if the radius is minimum) (See Fatigue resistance);
Stainless steels toughness is not so much influenced by temperature since it does not present a transient ductile-fragile speed at around 0-20°C as happens in Carbon steels. That means that the mechanical behaviour of a stainless steel (in particular of an austenitic structure) does not change even at low temperatures (generally as low as -196 °C) (See Resistance at high and low temperatures).

Austenitic stainless steel maintains high resistance to high temperatures. Even over 500°C the decrease of yield strength is still negligible. That is not so for austenitic-ferritic where temperatures over 300°C greatly reduce their inner toughness.
Some tests carried out in recent years within the framework of European research produce very interesting outcomes, as reported in picture 6.

When comparing the coefficients of thermic expansion reported in table 6 it transpires that stainless steels hold values slightly superior to carbon steel whereas they show a thermic conductivity of less than half.



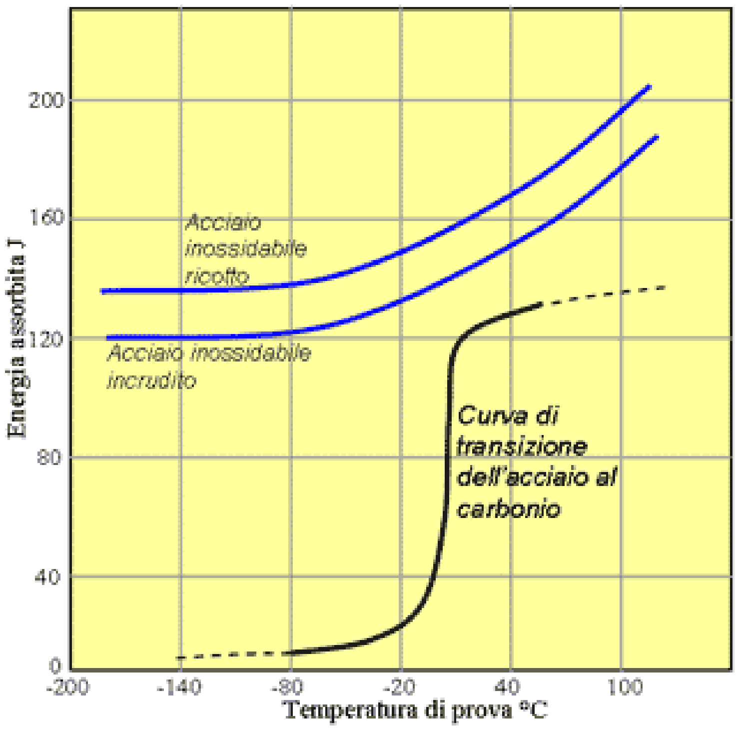
Picture 6 - Reduction of yield strength for austenitic stainless steels (304-316) compared with carbon steel according to eurocode 3 part 1.2 (source:VTT)

		1.4301 1.4401	1.4462
Structure	**Carbon steel**	**Austenitic steels**	**Austenitic-Ferritic**
Thermic linear expansion coefficient between 20 and 100 °C	10-12	16	13
Thermic conductivity at 20°C [W/m x°K]	40-50	15	18

Tab. 6 - Characteristic stainless steel values of conductivity and thermic linear expansion for different steel grades in rebars.

Overall, stainless steels behaviour is improving, compared with carbon steels, which collapse at higher temperatures.
The major thermic expansion coefficient that stainless steels show compared with carbon steels does not cause a negative effect on the reinforcement since such an effect is counterbalanced by the reduced thermic conductivity of stainless steel.
Moreover we should point out that also at high temperatures no oxide appear on steel surface with the consequent crack on the thin concrete coating (spalling), splitting the bar from the concrete.

Equally interesting is stainless steel behaviour at low temperatures, when a better steel toughness is generated without any effect of ductile-fragile transient, as it happens in carbon steels, at nearly 0°C (see picture 7).



Picture 7 - Comparisons on resilience at various temperatures between stainless steels and carbon steels.

Duplex stainless steels (austenitic-ferritic) , due to the presence of ferritic phases show a collapse of properties at around - 50°C.