

The Determination of the Chloride Threshold of Stainless Steel in Concrete – a Review

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ABSTRACT

Reinforced concrete infrastructure frequently requires maintenance and repair before the designed service life is reached despite the fact that the structure complied with the durability design rules at the time of construction. A major reason is the corrosion of the reinforcement due to chloride exposure. One solution to overcome the problem is the use of stainless steel as reinforcement instead of carbon steel. There is a huge variation of stainless steels on the market with different levels of corrosion resistances. To enable the estimation of the structures' service life and for the sake of comparability of steel type during design, it would be beneficial to determine the corrosion resistance of the reinforcing stainless steel. This paper presents a compilation and critical discussion of test methods for corrosion resistance of stainless steel from literature. An agreement of a specific standard test method with a high level of accuracy, repeatability and reproducibility is needed to quantify the advantage of using stainless steel in concrete.

Key words: Stainless steel, corrosion resistance, chloride threshold, reinforced concrete

INTRODUCTION

Corrosion of steel in concrete is a tremendous problem in the case of chloride exposed structures.¹ Chlorides from sources such as marine environment or de-icing salts penetrate through the porous concrete and as soon as the chloride threshold (CTL) reaches the reinforcement, corrosion initiation is the consequence. The so-called initiation phase can take years and depends mainly on (i) the surface chloride concentration in contact with concrete, (ii) the chloride penetration resistance of the concrete, (iii) concrete cover depth and (iv) the chloride threshold value of the reinforcement. The designer or

owner has no influence on the surface chloride concentration of the structure. It's depending on the environmental conditions and e.g. in Germany the surface chloride concentration reaches values up to 6 wt%/b with regard to the binder content in the case of structures with very harsh winter periods. Here, the application of de-icing salts is very high.² In recent years numerous inspection reports in Germany show increasing corrosion damage in relatively young structures due to intensification of chloride exposure. Generally, the surface chloride content in spray zones varies in the range of 0.5 until 2.0 wt%/b and in the splash/ tidal zone values from 2.0 until 4.0 wt%/b can be assumed.³

The prescriptive durability design rules regulate the chloride ingress resistance and the concrete cover depth in dependence of the aggressiveness of the surface chloride concentration.⁴ The common procedure is to use a very dense concrete with low porosity in order to achieve a very high chloride ingress resistance. However, the denser the concrete the more impaired is its workability during concreting. Therefore, this approach has its limitation. Greater concrete cover depths are no solution either, since higher cover depths are more prone to concrete cracking. Furthermore, recent studies show that the current prescriptive durability design cannot ensure a service life of about 50 years in the case of surface chloride concentrations greater than 3.5 wt%/b.⁵ Since the optimization of the concrete composition comes to a limit, the adjustment of the reinforcement material is the only option to achieve acceptable service lives under severe condition.

Normally, the most common reinforcement material is carbon steel. The prescriptive durability design rules consider exclusively the use of carbon steel.⁴ However, higher alloyed steels - stainless steels – are also an option. Stainless steel has at least a chromium content of 10.5 %, which leads to the formation of an inert oxide layer on the metal surface. Consequently, this oxide layer strengthens the passivation and their corrosion resistance is much higher than the corrosion resistance of carbon steels. The addition of elements such as nickel and molybdenum improves the corrosion resistance even further. Other elements such as nitrogen, copper, manganese and so on are also possible as alloying elements. Thus, the variation of stainless steel compositions is huge and all of them show different corrosion resistance.

There is only a very crude method to classify the corrosion resistance of stainless steel: the pitting resistance equivalent number (PREN).⁶ The PREN factorizes the amount of alloying elements linearly based on the experience of stainless steel resisting pitting corrosion in neutral environments. However, its validity is not proven for stainless steels in alkaline environments such as concrete pore solution. Besides the composition of the alloying elements, the microstructure (martensitic, ferritic, austenitic and duplex (austenitic-ferritic)) of stainless steels varies due to different thermo-mechanical treatments. The microstructures affect the corrosion behaviour as well which is not reflected in the PREN approach. Basically, rebar with all types of microstructure are on the market. The PREN enables only the ranking of corrosion resistances of different stainless steels. A quantification of corrosion resistances is not possible. Thus, there is a need for a test method to judge corrosion resistance of stainless steel. Several test procedures have been proposed in the past and are discussed in the following.

BASIC REQUIREMENTS ON CORROSION TESTS

Long-term exposure test provides the most reliable test results for corrosion resistance of metals. The exposure condition should comply with the later condition of the steel during its service live. However, in case of corrosion of steel in concrete this approach is not a feasible option since corrosion initiation under natural condition takes years. Therefore, corrosion tests face two opposite objectives: they should represent the natural condition as close as possible and they should be as fast as possible.

Several possibilities exist to accelerate corrosion tests. One option is the increase of the concentration of the corrosive medium, normally the increase of the chloride concentration with respect to the pH value. Also, the type of corrosive medium has an effect such as water, pore solution, cement paste, mortar, concrete, carbonated concrete, etc.. If concrete or mortar is the medium, the steel-concrete

interface can vary depending on the concrete porosity, casting direction of the steel or the compaction during concreting. The corrosion risk is also enhanced if cracked concrete is used instead of sound concrete since the corrosive medium has an easy access to the rebar. The supply of the corrosive medium in concrete could take place through mixed-in chlorides or by ponding using capillary suction and diffusion as transport processes. The chloride ingress by ponding is dependent on the pre-conditioning / moisture condition of the samples and the duration and the frequency of the wet-dry cycles. In both cases – mixed-in and ponding – the chloride concentration and grading is of importance. As every chemical reaction, corrosion process are accelerated by increasing temperature. In addition, since corrosion is an electrochemical process, the corrosion process can be enhanced through polarization.

Generally, the faster the test, the more its results differ from those obtained under natural conditions. Therefore, it is recommended to include reference material whose corrosion behavior under natural conditions is known.

However, it is of vital importance that corrosion resistance tests shall lead to comparable results. This can only be achieved if they are carried out according to established conditions and procedures. The first step to ensure comparability is the precise description of the samples, including dimension, shape (ribbed, plain), exposed area, mass, composition, formation process (hot-rolled, cold-rolled, forged) and surface condition. The steel surface changes through chemical treatment (pickle), mechanical treatment (sand-blasting), welding or heat-treatment.

Corrosion test results express often the degree of aggressiveness as a function of time. The rating of the aggressiveness can be based on visual examination, mass loss (excluding the corrosion products), loss of cross section, open circuit potential, polarization resistance (LPR, EIS), corrosion rates, chloride threshold value or any other electrochemical parameter, e.g. pitting potential, etc.. Also the time to concrete cracking or spalling is used as corrosion behavior criterion.

Corrosion test results often show certain scatter. Therefore, multiple parallel tests are required.

Taken into account all the variations mentioned above, corrosion test of stainless steel can vary with regard to sample, exposure, test procedure and evaluation. Nevertheless, for the sake of comparability standardized tests are necessary.

CORROSION RESISTANCE TESTS

A review of corrosion resistance tests in literature

The literature provides multiple different research results on corrosion resistance of stainless steel. But not all of them had included all the needed information which are listed in the previous section. The missing information impede to compare the literature data among each other.

Table 1 shows the nomenclature of the selected stainless steel to provide an overview on the used steels in the literature review.