Stainless Reinforcing Steels

1.0 Introduction

In normal atmospheric exposure conditions, with adequate concrete cover and appropriate detailing, corrosion of reinforcing steel in concrete is not a problem; the concrete provides a protective environment for the reinforcing steel. In certain aggressive environments, or where inadequate cover is provided, corrosion of reinforcing steels can occur, with effects that have been well documented. The problems of maintenance and replacement of corrosion-affected structures are thought to account for a multi-billion dollar problem world-wide.

One solution is to use stainless reinforcing steels, which are inherently resistant to corrosion. Stainless reinforcing steels have the potential to:

- Allow relaxation in design for durability criteria normally used for carbon steel reinforced structures.
- Significantly decrease the inspection and maintenance cost of structures at risk of reinforcement corrosion.
- Extend the design life of structures at risk of reinforcement corrosion.

All of this can lead to cost saving when the whole-life cost of a structure is considered, despite the cost of stainless compared to carbon steel reinforcement.

The use of stainless steel reinforcement is growing significantly in certain parts of the world, notably the Middle East, the Far East, and North America. Although the use of stainless reinforcing steel is at relatively modest levels within the UK, recent reports have demonstrated the potential economic benefits of stainless reinforcing steels when whole life costs are considered. This is leading to growing acceptance. Recent examples of the use of stainless reinforcing steels, both in the UK and worldwide, have been reported, and the use of stainless reinforcement is expected to increase (**Figure 1 and 2**).

Gateway Bridge

Figure 1 Selective use of stainless reinforcement on the pile cap of the 300 year life Gateway Bridge, Australia, specified by Aecom using predictive modelling. Courtesy of Outokumpu

From 2001, as a response to the market requirement for stainless reinforcing steels, UK CARES has extended its product certification scheme for reinforcing steels, to cover the particular requirements of this product. The aim is to provide purchasers of CARES approved stainless reinforcing steels with the same level of confidence in specification and purchasing, as has become the established norm in the UK for carbon steel reinforcement.

In the UK, stainless reinforcing steels are specified to BS 6744:2001. The 2001 revision introduced new steel types and grades, and Grade 500 is similar to the Grade B500B in the carbon steel standard BS 4449:2005. BS 6744:2001 is the basis of the CARES scheme for stainless reinforcing steels.

2.0 Corrosion of reinforcing steel in concrete

Carbon reinforcing steel is generally passive in terms of corrosion behaviour at the pH levels normally found within concrete (pH = 13). However, corrosion can be accelerated by a number of different chemical processes in certain environmental conditions. The most commonly cited causes of corrosion of reinforcing steel in concrete are:

a) Carbonation of the concrete due to atmospheric attack. The absorption of water and carbon dioxide from the atmosphere into concrete, can cause a lowering of the pH, due to the formation of carbonic acid. Once the pH is sufficiently reduced, corrosion of the reinforcement can occur.

b) Ingress of chloride ions into the concrete. When chloride ions reach a certain threshold level at the steel surface, passivity is broken down, and corrosion of the reinforcing steel proceeds.

Carbonation is normally controlled by the correct provision of concrete cover.

Structures most at risk of chloride attack are those exposed to marine environments or de-icing salts, particularly those parts of the structure experiencing wetting and drying cycles. These may be marine structures exposed to wetting and drying (for example in the inter-tidal or splash zones), or in highway structures or car parks exposed to road de-icing salts.

Stainless steels are generally defined as those having a minimum of 12% chromium present as an alloying constituent. The presence of chromium results in a thin layer of stable chromium oxide forming on the surface of the steel. The oxide layer is passive, and highly resistant to atmospheric corrosion. Moreover, the oxide layer is instantaneously self-healing in oxidising conditions, so that cracks, defects or surface damage do not affect corrosion resistance. Stainless steels retain passivity in concrete at low pH levels, and high chloride concentrations, hence their use in structures at risk of chloride induced corrosion.

The Highways Agency's Design Manual For Roads and Bridges document, BA 84/02, provides guidance on the use of stainless reinforcement. This states:

"Correctly specified stainless steel reinforcement should prevent chloride attack for the full design life of any structure."

3.0 Stainless reinforcing steels

Within the broad definition of stainless steels, there are many different types available. BS EN 10088-3 lists more than 60 different available alloy compositions. The different steels are grouped by type, according to their metallurgical structure; austenitic, ferritic, martensitic or duplex.

Stainless Reinforcing Steel in a Nuclear Waste Tank in France

Figure 2 Courtesy of Valbruna UK Ltd

Most stainless reinforcing steels are austenitic, with some duplex steels also being used; ferritic and martensitic steels are not normally used for reinforcing applications.

BS 6744:2001 includes eight stainless steel designations from BS EN 10088-3 and 5, of varying chemical analysis, and corrosion resistance characteristics (see **Table 1**).

These steels are austenitic, except for 1.4462 and 1.4501, which are both duplex steels.

Table 1

Stainless steel bar chemical composition (cast analysis) % by mass (from BS 6744:2001)

BS EN 10088-1 Steel Designation	C (max)	Si (max)	Mn (max)	S (max)	Cr (min/max)	Ni (min/max)	Mo (min/max)	P (max)	N (max)
1.4301[a]	0.07	1.0	2.0	0.03	17.0/19.5	8.0/10.5	-	0.045	≤0.11
1.4436[a]	0.05	1.0	2.0	0.015	16.5/18.5	10.5/13.0	2.5/3.0	0.045	≤ 0.11
1.4429	0.03	1.0	2.0	0.015	16.5/18.5	11.0/14.0	2.5/3.0	0.045	0.12/0.22
1.4162	0.04	1.0	4.0/6.0	0.015	21.0/22.0	1.35/1.70	0.10/0.80	0.040	0.20/0.25
1.4362	0.03	1.0	2.0	0.015	22.0/24.0	3.5/5.5	0.10/0.60	0.035	0.05/0.20
1.4462	0.03	1.0	2.0	0.015	21.0/23.0	4.5/6.5	2.5/3.5	0.035	0.10/0.22
1.4501[b]	0.03	1.0	1.0	0.015	24.0/26.0	6.0/8.0	3.0/4.0	0.035	0.20/0.30
1.4529[b]	0.02	0.50	1.0	0.010	19.0/21.0	24.0/26.0	6.0/7.0	0.03	0.15/0.25

[a] Nitrogen content of these steels may be increased to 0.22% max.
[b] These designations are available on request but are only required for special applications.

Tensile properties of BS 6744:2001 grades

Grade	0.2% Proof Stress, $R_{p0.2}$ MP_a	Stress ratio, $R_m/R_{p0.2}$ (min) (%)	Elongation at fracture, A_5 (min)	Total elongation at maximum force, A_{gt} (min) (%)
200	200	1.10	22	5
500	500	1.10	14	5
650	650	1.10	14	5

Table 2

The most widely used stainless reinforcing steels are 1.4301, 1.4436 and increasingly 1.4462. Steel 1.4301 is a basic austenitic steel, whilst 1.4436 is also austenitic, but with a minimum 2.5% molybdenum addition, for enhanced resistance to pitting corrosion. Steel 1.4462 is a duplex type. Steel 1.4429 is commonly used in North America, but less frequently in Europe. It has high corrosion resistance, and provides superior mechanical properties in large bar sizes. The other two steels in BS 6744 are used for special, highly corrosive applications.

4.0 Manufacturing process routes for stainless reinforcing steels

Most stainless steels are made by the electric arc process. This is followed by a secondary refining process, either AOD (Argon Oxygen Decarburising) or VOD (Vacuum Oxygen Decarburising). Steels are continuously cast into blooms or billets, prior to hot rolling.

Stainless reinforcing steels may be hot rolled to achieve their final mechanical properties. This normally requires close control of rolling temperatures. Alternatively they may be hot rolled into coil, followed by a cold rolling operation to achieve the final profile and properties. Stainless steels are supplied in the surface cleaned condition, with rolling scale removed.

Stainless reinforcing steels can be cut, bent and processed in the same way as carbon steel, according to BS 8666 (**Figure 3**).

Bending of Stainless Reinforcing Bar

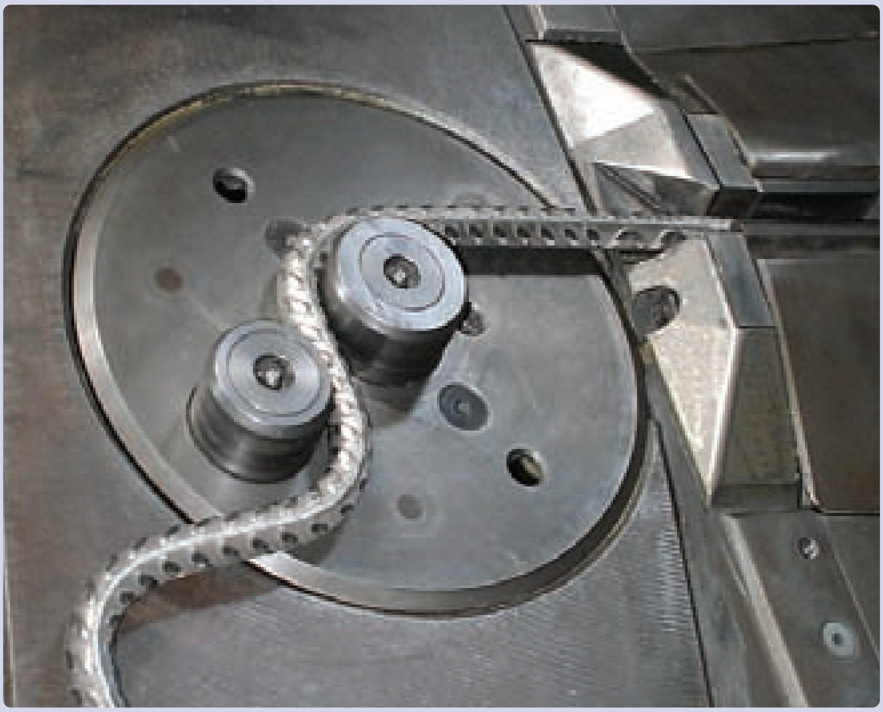

Figure 3 Courtesy of Arminox

5.0 Mechanical properties of stainless reinforcing steels

BS 6744:2001 specifies three grades with different mechanical properties. The term "grade" is often confused with alloy type. In BS 6744, "grade" refers only to the mechanical properties, and not to the chemical composition, which is determined by the steel type (designation). The three mechanical grades may be supplied in any of the steel designations. The three grades specified are given in **Table 2**.

Grade 200 is only available in the plain round section. This is used for dowel bar applications. All grades are potentially available in a ribbed profile, with bond characteristics equivalent to those for type 2 bond in carbon steel reinforcement. The range of grades and designations available in different sizes varies between manufacturers, as does the manufacturing process routes used.

It should be noted that the mechanical properties for Grade 500 would meet all of the mechanical requirements of BS 4449:2005 Grade B500B. These grades may therefore be substituted for normal carbon steel, without significant design modification.

"Relaxed" specification concrete chloride at depth profile shown in the Simple Representative Model using the chloride diffusion coefficients from AGEDDCA and ceasing aging at 25 years

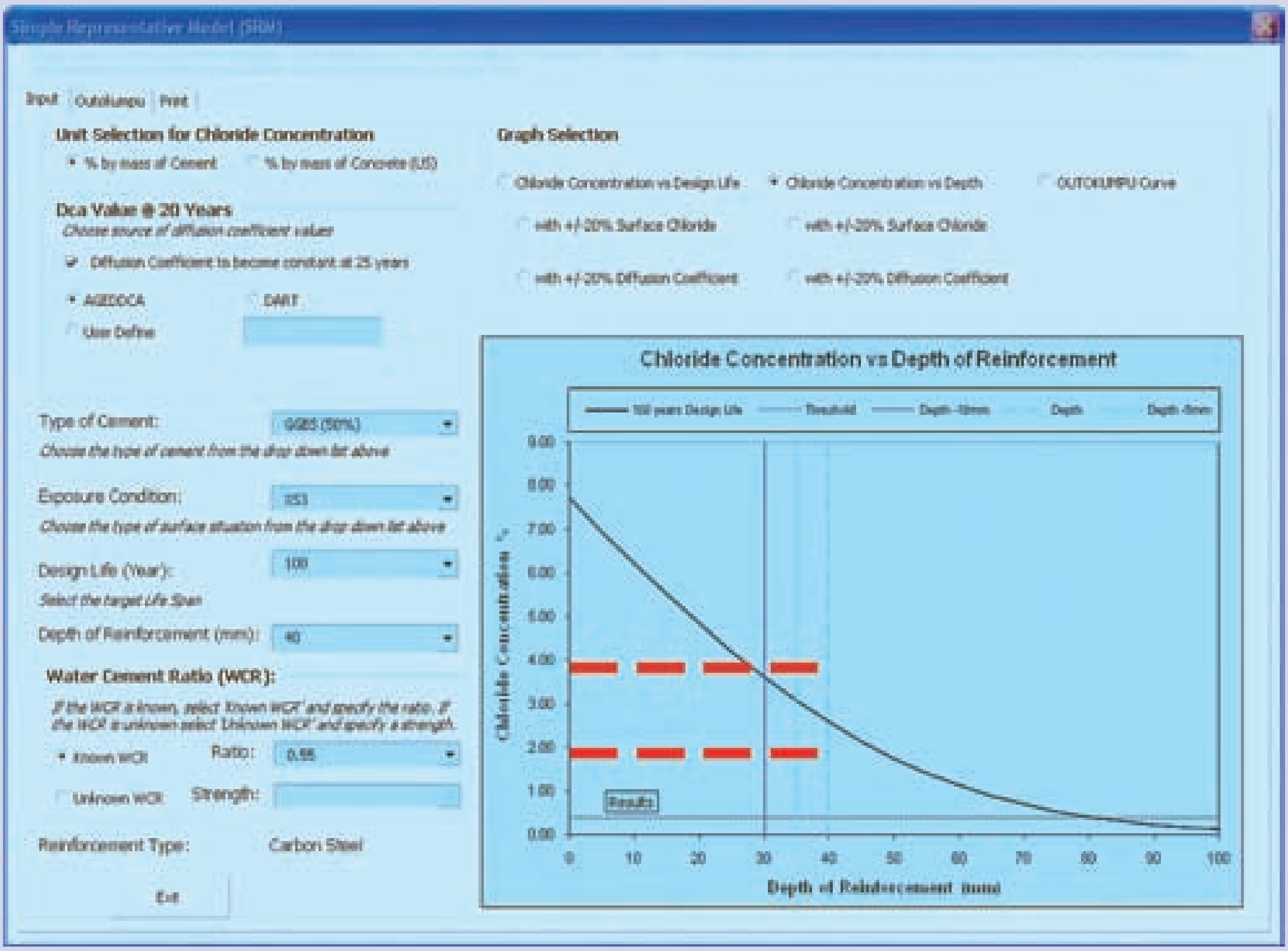

Figure 4 Courtesy of Outokumpu

Stainless reinforcing steels are "non-ageing", because of their austenitic structure, and hence there is no requirement to perform a re-bend test. A bend test is included in BS 6744:2001.

The fatigue performance specified for the stainless steels in BS 6744:2001 is similar to that for carbon steels in BS 4449:2005. Again this means that stainless steels may therefore be substituted into fatigue designs based on carbon steel, without significant design modification.

Apart from its corrosion resistant applications, austenitic stainless reinforcing steel can also be used in cryogenic applications, where its toughness at low temperatures is required. In certain special applications, the non-magnetic nature of austenitic stainless can also be advantageous, such as for the reinforcement of structures housing magnetic resonance equipment.

6.0 Guidance on the use of stainless reinforcing steels

Guidance on the use of stainless steel reinforcement has been available for some time in the form of the Concrete Society Technical Report 51 "Guidance on the use of stainless steel reinforcement 1998," BS 6744:2001 Annex B and the Nordic Innovation Centre report "Guide for the use of stainless steel reinforcement in concrete". The UK Highways Agency advice note "BA84/02" specifically covers where to use stainless steel in the concrete design and is explained in a report "The use of stainless steel reinforcement in bridges" which is available from the BSSA. The design guidance in BA 84 / 02 is prescriptive in where to use the stainless reinforcement and is still quoted in many specifications.

More recently the trend in durability design for reinforced concrete is moving towards performance methods where the designer predicts the concentration of chlorides which have penetrated the concrete structure at design life. The designer then turns to the supplier and/or manufacturer for the most economic stainless reinforcement alloy that will be corrosion resistant at that concentration. This performance method of design guidance is the approach taken in the Fib model Code for service design life Bulletin 34 and is explained in Concrete Society Technical Report 61 "Enhancing reinforced concrete durability 2004" which contains a spreadsheet tool for calculating the chloride diffusion curve. Corrosion resistance of the stainless reinforcement can be measured by an adaptation of EN 480 when 90% of the samples pass the test with predetermined chloride contents. The figure overleaf (**Figure 4**) shows a typical chloride diffusion curve and how the designer could specify either a 2% chloride resistance alloy or a 4% chloride resistant alloy.

7.0 The CARES Scheme for manufacturers of stainless reinforcing steel

Based on its extensive experience of assessing manufacturing and fabricating operations for carbon steel reinforcement, the CARES scheme for the stainless reinforcing steel sector has been effective since 2001. Two Quality and Operations Schedules are available, one for manufacturers of stainless reinforcement, and one for processing and supply.

The schemes provide for:

- Independently verified compliance with the specified standards (BS 6744:2001 and BS 8666).
- Quality management system approval to ISO 9001:2008.
- Approval for the whole process route, from steelmaking, rolling, processing, fabricating to delivery to site.
- Full traceability throughout the supply chain.
- Removing the need for purchasers to have their own testing and inspection regime on site, saving time and cost.

Approval is gained by a manufacturer only after demonstrating that their quality systems meet the requirements of ISO 9001:2008, and the additional product-specific CARES requirements. An extensive programme of witness and independent testing also has to be passed, with independent testing being conducted by UKAS accredited laboratories to ensure integrity and competence.

Once approval has been granted, it is maintained by regular surveillance audits conducted by CARES specialist assessors. At these inspections, the system is audited, and random checks are made on product quality, by both witness and independent testing.

Approval is gained by a processor after demonstrating that their quality management system meets the requirements of ISO 9001:2008 and the product-specific CARES requirements. Regular surveillance visits include both quality system audits and verification of cutting and bending capability to the requirements of BS 8666.

7.1 The CARES Scheme- verified compliance

The CARES scheme for stainless reinforcing steel, through its combination of auditing and independent testing throughout the supply chain, ensures consistent compliance of stainless reinforcing steels with the specified requirements.

When using CARES approved fabricators, specifiers can be confident that all steel supplied will be from CARES approved manufacturers. The product can be used without the need for further product testing. Where CARES approved fabricators are not specified, the onus is on the purchaser to verify compliance, which may require inspection and testing involving both significant cost and potential site delays.

8.0 Specification of CARES approved stainless reinforcing steel

The May 2006 amendment of the Highways Agency specification for highway works states the following:

"All stainless steel reinforcement shall conform to BS 6744 and shall be cut and bent in accordance with BS 8666 and shall be obtained from companies holding valid CARES (or fully equivalent scheme) certificates of approval for the production and supply of stainless steel reinforcement.

Stainless steel reinforcement shall be ribbed Grade 500 conforming to BS 6744."

Stainless reinforcing steel offers designers the possibility of producing durable structures with inherent resistance to reinforcement corrosion. The CARES scheme for stainless reinforcing steels offers purchasers the confidence that the product has been produced and tested in accordance with the specification.

9.0 References

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