CORROSION PROTECTION IN PREFABRICATED ELEMENTS OF LIGHTWEIGHT AGGREGATE CONCRETE WITH OPEN STRUCTURE

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ABSTRACT

The current Danish Code-of-Practice for lightweight structures of lightweight concrete elements DS 420 [1] and the future European product standard for precast reinforced components of lightweight aggregate concrete with open structure prEN 1520 [2] allow both verification by testing of the corrosion protection of the structural reinforcement, but differ in their test methods, corrosion classifications and acceptance criteria.

The paper describes the results of an investigation and a test program to verify the current corrosion protection systems (cover, density, coating) and to verify the new test methods.

The conclusions are that a short-term test method is suitable and corresponds well to experience in practice and that the requirements in prEN 1520 lead to realistic assessments of the corrosion protection.

Keywords: Corrosion, testing, lightweight aggregate concrete, open structure.

1. INTRODUCTION

The use of pre-cast concrete elements of lightweight aggregate concrete with open structure (LAC) dominates the construction of offices and houses in Denmark. The LAC-elements are produced by roller-compaction of no-slump concrete [3, 4, 5, 6] and this process results in a concrete with more or less open structure and a more or less efficient corrosion protection. The LAC ranges in strength from 3 to 30 MPa and in dry density (ρ) from 500 to 2000 kg/m^3 as illustrated in Figure 1.

The Danish Code-of-Practice for lightweight structures of lightweight concrete elements DS 420 [1] prescribes an initial type-testing [4], which also includes a testing of the corrosion protection of the reinforcement. The future European product standard prEN 1520 [2] requires an initial type testing, including the corrosion protection.

The required test methods, classification of corrosion degrees in the tested samples and the acceptance criteria do, however, differ between the code and the product standard. This lead the Danish Association of Full-wall Element Producers (BIH) to finance an investigation and a testing of the corrosion protection (densities, covers and coating) in order to gain experience with the new European standards and establish an overview of the current corrosion protection.

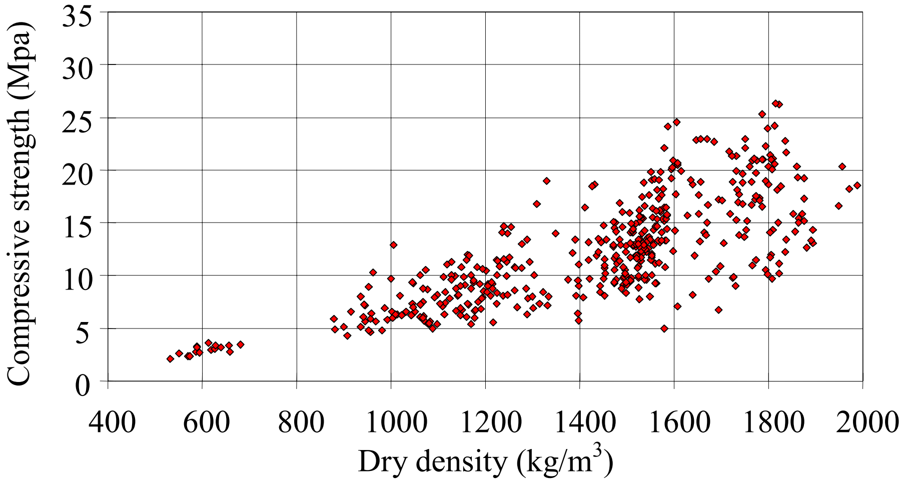

Figure 1. Dry density and compressive strength in current Danish LAC-production [3,4,5].

2. CURRENT PRACTICE

The current practice for the corrosion protection of structural reinforcement in precast lightweight aggregate concrete elements is that the reinforcement is either embedded in a fairly dense concrete with a high density (above 1200 kg/m^3 is usually found to be a realistic limit in the current Danish productions), or that the reinforcement is coated with a cement-latex coating and embedded in the LAC.

The elements are used for building structures and protected against rain and excessive amounts of water, which means that the elements are used either in passive environments or in moderate environments, where the relative humidity rarely exceeds 75 %. The elements are not subjected to salt and the risk of corrosion is therefore limited. The DS 420 [1] does, however require that one of the following procedures are followed:

- The corrosion protection of the reinforcement is tested annually,
- the reinforcement is embedded in dense concrete with a cover of 10 or 20 mm,
- the reinforcement is only used for transport purposes either in passive environments with no risk of corrosion or where any corrosion or corrosive products will not harm the elements performance.

This system seems so far to have worked well, as no observations of corrosion have been made in the moderate environment where the elements are intended to be used.

A large Norwegian investigation [9] and some Danish investigations [7,8] have looked into this by sampling reinforcement bars from roof or floor elements in slightly more aggressive environments, leading to the observations in Table 1.

The main conclusion from the Norwegian investigation was that the cement-latex coating gave a sufficient corrosion protection in the normal environments, where the relative humidity only occasionally exceeded 75 %.

Table 1. Observations in Norwegian and Danish structures. C-L denotes cement-latex coating and G galvanized surface. (Normal cover is 10 to 15 mm in this type of elements).

Id	Storage	Exposure time	ρ kg/m^3	Coating	Carbo-nated	Corrosion	Ref
	Outdoors	7 years	1400	C-L	Yes	Almost none	[7]
	Outdoors	7-10 years	1400	C-L	Yes	No	[8]
Type A	15-20^{o}C, 50%RF	24 years	1000	C-L	No	Rust on 2/3 of surface	[9]
Type C	25^{o}C, 60-90%RF	24 years	1000	G		No	[9]
Tovik 1	20-50^{o}C, 75-100%RF	15 years	1000	C-L	Yes	Surface rust	[9]
Tovik 2	20-50^{o}C, 75-100%RF	15 years	1000	C-L	Yes	Surface rust	[9]
Stjørdal 1	20-30^{o}C, 75-95%RF	15 years	1000	C-L	Yes	Surface rust	[9]
Vestnes 1	20-50^{o}C, 75-100%RF	12 years	1600	C-L	No	Rusty layer	[9]
Vestnes 2	20-50^{o}C, 75-100%RF	12 years	1600	C-L	Yes	Rusty layer	[9]
Vestnes 3	20-50^{o}C, 75-100%RF	12 years	1600	C-L	No	No	[9]

This conclusion is consistent with observations in normal concrete, where the concrete is able to protect the reinforcement in environments without chlorides, as long as the concrete is not carbonated. Reinforcement embedded in a carbonated concrete will corrode, but only slowly unless the relative humidity is above app. 80 % [10].

3. TEST PROGRAMME

3.1 Test methods

The testing of the corrosion protection can be carried out according to one of the four methods in EN 990 [11], which has been implemented in all CEN-countries since the mid-nineties. The four methods differ roughly in the following way:

- Method 1: The test specimens are exposed to 10 cycles of drying and soaking in salt water.
- Method 2: The test specimens are exposed to 30 cycles with drying in ventilated air for 21 hours at 40^{o}C, followed by wetting in tap water (2 hours at 20^{o}C), corresponding to the short-term method in DIN 4232 [12].
- Method 3: The test specimens are exposed to 4 daily temperature cycles between 25^{o}C and 55^{o}C in air with a RH > 95 % for a total of 28 days (corresponding to DS434.8 [13]).
- Method 4. The test specimens are stored for one year in humid air (RH > 95 %), corresponding to the long-term method in DIN 4232 [12].

It was decided to use methods 2 and 4 in the testing, as the method 4 was intended as the reference method in prEN 1520, while method 2 seemed to correspond best to the moderate environment, where the elements are used.

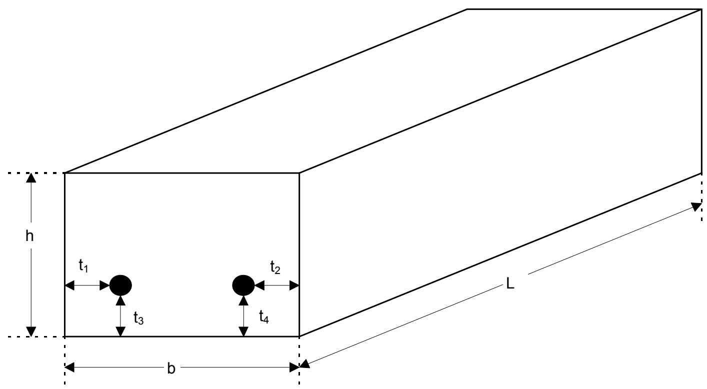

Figure 2. Geometry of the test specimens . (L = 400 mm, b = h = 100 mm, $t_1,\dots,t_4$ = 10 or 20 mm).

3.2 Testing plan

It was decided to test the corrosion protection of the reinforcement in four representative concrete types, which are produced today in order to cover the most relevant density range (above 1000 kg/m^3). It was also decided to test the corrosion protection with and without a cement-latex coating and with two different cover depths, as shown in Table 2.

Table 2. Testing plan (the strength class denotes a lower characteristic value and the Danish producers associations density class denotes a lower density, including a certain water content).

Series	Strength class (MPa)	Density class (kg/m^3)	Intended cover (mm)	Coating
1	13	1800	10	No
2	13	1800	20	No
3	13	1800	20	C-L
4	9	1500	10	No
5	9	1500	20	No
6	9	1500	20	C-L
7	5	1200	10	No
8	5	1200	20	C-L
9	5	1200	20	No
10	5	1000	10	No
11	5	1000	20	C-L
12	5	1000	20	No

The test specimens were manufactured by three factories in the autumn 1997, by producing a number of precast elements with some of the concrete types and cement-latex coatings currently used in their productions.

All the 12 test specimens in each series were cut from the same element and each specimen contains two Ø 10 mm reinforcement bars. The 144 specimens were coated on the ends as prescribed in EN 990, using Isopunkt [14] and transported to RAMBOLL's laboratory for the testing, which was carried out in 1997 and 1998 [15,16].

4. TEST RESULTS

The moisture contents were determined by weighing at the delivery (D) to RAMBOLL's laboratory and later at the end of the short-term testing, when the 36 specimens (S) and the corresponding 36 reference samples (SR) were opened and the reinforcement bar extracted. The same procedure was used for the 36 long-term tested specimens (L) and their 36 reference samples (LR).

Table 3. Results of the short-term testing (D denotes at delivery, S and SR denotes the value at the end of the short-term test for respectively the test samples and for the reference samples).

Series	Coating	ρ	Moisture content (% by mass)			Cover (mm)	Corroded area (%)	
		(kg/m³)	D	S	SR	Mean	S	SR 2)
1	No	1911	3.9	3.6	2.2	12.3	8.3	2.9
2	No	1949	3.9	3.7	2.4	21.5	2.6	6.8 1)
3	C-L	1938	3.7	3.9	2.4	18.1	0.0	0.2
4	No	1577	4.2	4.8	2.4	13.6	1.7	1.1
5	No	1563	4.4	4.8	2.7	18.2	2.2	1.3
6	C-L	1586	4.3	4.4	2.9	22.4	0.0	0.0
7	No	1134	16.2	10.7	6.4	12.2	21.7	6.9
8	C-L	1166	13.8	9.8	6.0	20.4	0.6	0.7
9	No	1133	14.7	9.9	6.0	19.0	7.5	6.0
10	No	1048	15.2	7.5	3.4	7.9	12.2	0.9
11	C-L	1074	9.8	8.2	3.2	17.6	0.1	0.0
12	No	1065	10.9	7.9	3.8	18.2	5.3	0.1

Note 1): The measurement of the corroded area along one of the lines of one of the bars did show an extreme degree of corrosion. Ignoring this extreme observation will lead to a decrease of the corroded area from 6.9 % to 3.9 %.

Note 2): The reinforcement bars were selected from the bars used in the normal production in the factories and had in some cases a minor amount of corrosion before the castings.

Table 4. Results of the long-term testing (D denotes at delivery, L and LR denotes the value at the end of the long-term test for respectively the test samples and for the reference samples).

Series	Coating	ρ	Moisture content (% by mass)			Cover (mm)	Corroded area (%)	
		(kg/m³)	D	L	LR	Mean	L	LR 2)
1	No	1918	3.7	8.4	1.7	12.2	0.8	1.8
2	No	1941	3.7	8.2	1.6	21.6	1.9	1.7
3	C-L	1933	3.6	8.9	1.7	18.9	0.5	0.4
4	No	1576	4.4	5.5	2.0	11.9	1.3	1.3
5	No	1568	4.4	5.6	2.0	18.0	2.1	1.0
6	C-L	1588	4.5	5.5	2.1	23.7	0.0	0.0
7	No	1129	15.5	16.2	3.5	12.1	5.9	6.3
8	C-L	1162	14.4	15.2	3.7	20.8	1.1	1.1
9	No	1130	14.3	16.8	3.1	18.4	6.9	4.5
10	No	1063	13.5	13.5	2.0	10.3	1.4	1.7
11	C-L	1077	8.9	13.8	2.2	21.0	0.0	0.0
12	No	1069	11.2	12.3	2.1	20.8	1.1	0.1

Note 2): See note 2 to Table 3.

The weight of the remains of each specimen were then determined before and after the oven drying in order to determine the moisture contents, listed in Tables 3 and 4.

The corroded area was measured along four lines on each reinforcement bar, ignoring the 50 mm near the specimens ends and the average values from the 2*3=6 bars are listed in the Tables 3 and 4. The average of the four cover depths from Figure 2 measured on each specimen are also listed in Tables 3 and 4.

A sample was taken from one of the specimens of the four concrete types used in the long-term testing and plane-sections and thin-sections were produced in order to determine the structure of the LAC as shown in Figure 3.

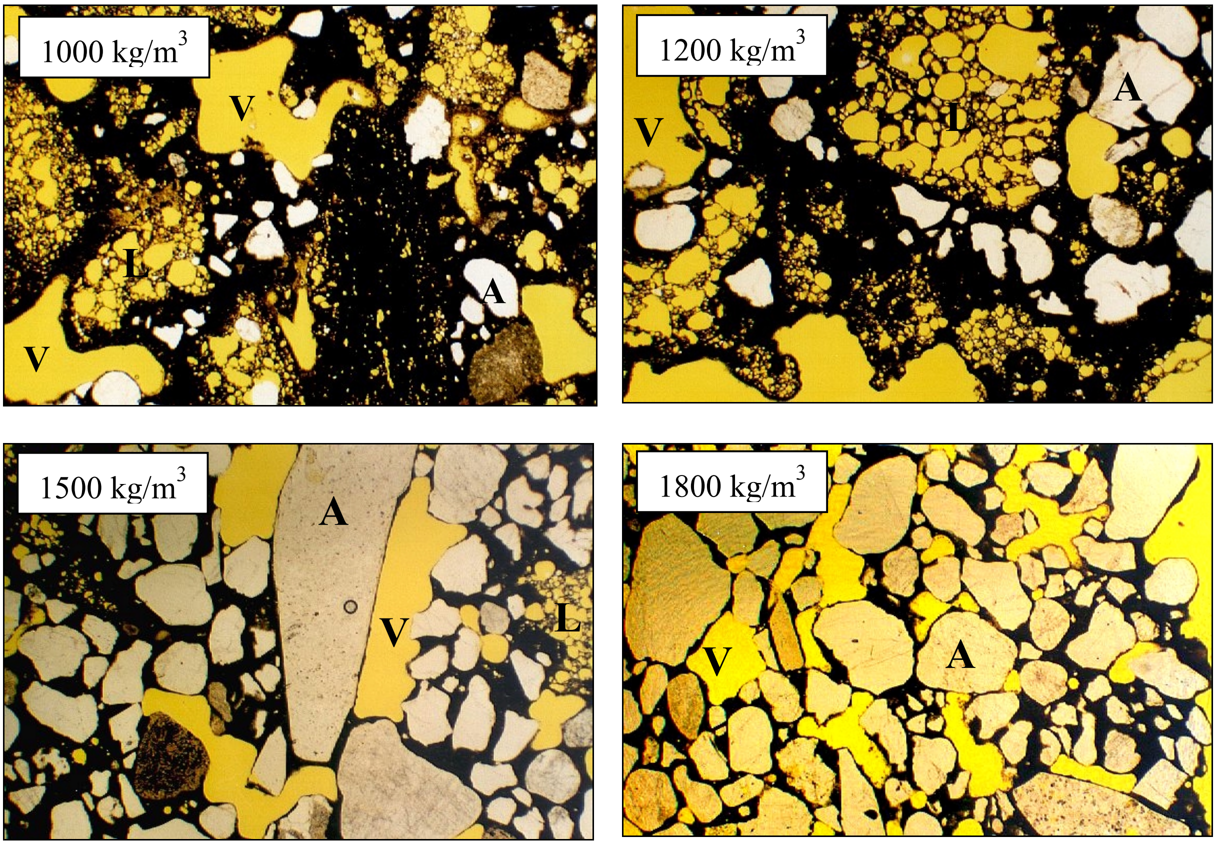

Figure 3. Thin-sections images (4 x 3 mm) of different typical types of lightweight aggregate concrete. A denotes aggregate, L lightweight aggregate and V voids.

The density classes of 1000, 1200, 1500 and 1800 kg/m^3 shown in the Figures 3 and 4 correspond to average dry densities in the series of 1066, 1142, 1576 and 1932 kg/m^3.

Figure 4 illustrates the fact that the carbonation has progressed fairly deep into the concretes, but it also shows that the carbonation depth is not a function of the density. This is probably due to the fact that a low density can be obtained by a number of different combinations of air in fairly large voids in the concrete and of lightweight aggregates, so that a decrease of the amount of lightweight aggregate and an increase of large air voids may not change the density, but may make the concrete more porous and thus increase the carbonation depth.

Figure 4 also illustrates that the carbonation front is less clear than in ordinary concrete with dense structure, where the zone between the fully carbonated concrete and the non-carbonated concrete usually has an extension of app. 1 mm. Use of thin-section showed that the concrete in the long-term reference samples after 1 year in the laboratory had carbonated areas all through the samples, but that isolated pockets of non-carbonated concrete were found, even near the surface.

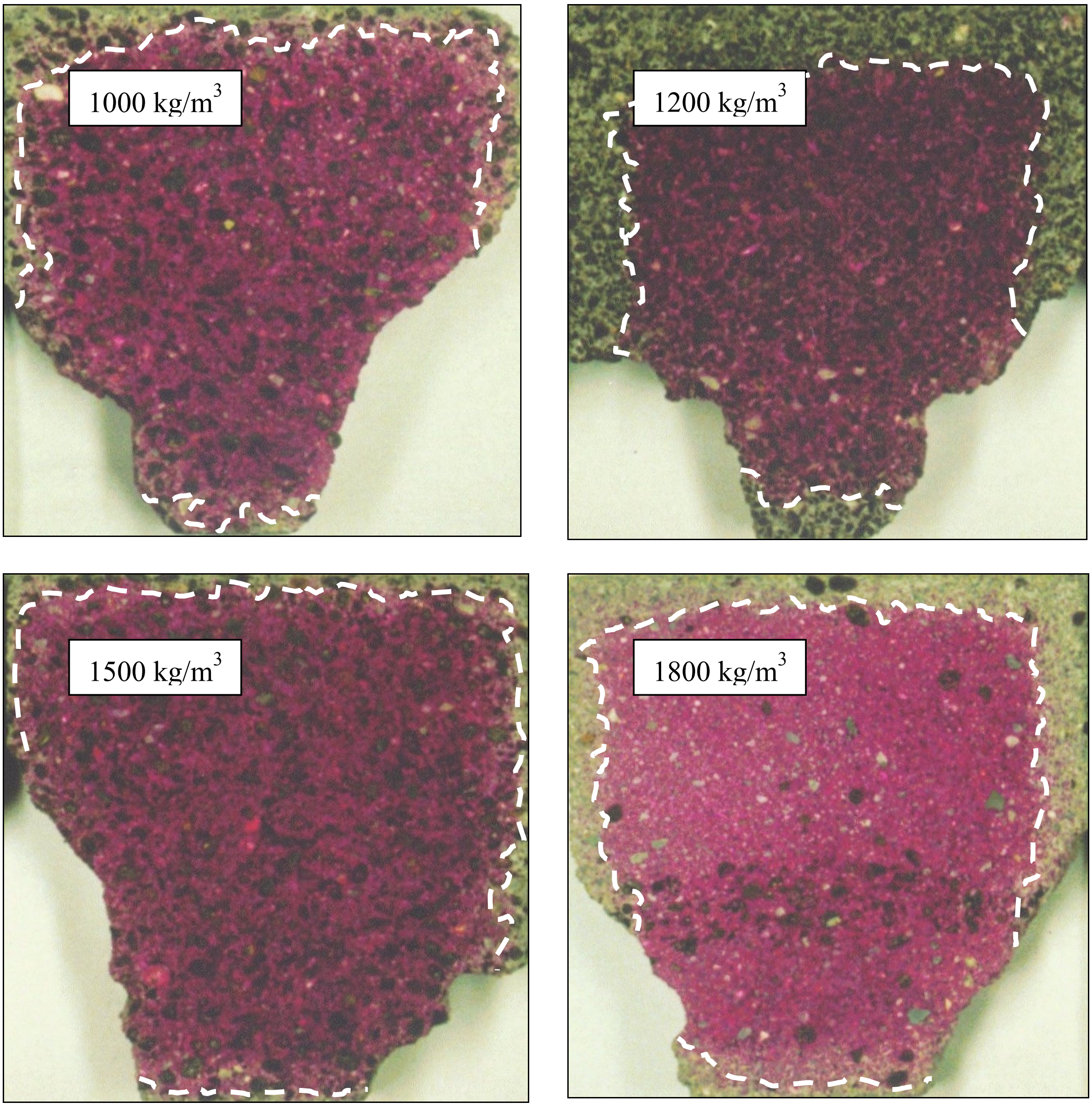

Figure 4. *Cross-sections (10 x 10 cm) from long-term testing. Dark (violet) colour marks the non-carbonated parts of the reference samples. The frames indicate the original cross-section before the extraction of the bars and the dashed curves the approximate carbonation front.*

4.1 Other results

A few other results of corrosion testing with the same or similar test methods have been obtained from different sources as shown in Table 5. The corrosion protection was approved in all cases.

Table 5. Other test results.

Id	Test method	ρ kg/m^3	Cover mm	Coating	Corrosion	Ref
	84 cycles of 4 hours at 55°C and 4 hours 20°C at 100 % RF	1470	15	No	None	[17]
LBH 8/1.6	DIN 4232, Short-term	1614	18/20	No	Negligible	[18]
LBH 8/1.6	DIN 4232, Long-term	1614	18/20	No	Negligible	[18]
LBH 8/1.8	DIN 4232, Short-term	1848	18/20	No	Negligible	[18]
LBH 8/1.8	DIN 4232, Long-term	1848	18/20	No	Negligible	[18]
LB 5/1.2	DIN 4232, Short-term	1248	20	No	None	[19]
LB 8/1.6	DIN 4232, Short-term	1647	20	No	None	[19]
LB 8/1.8	DIN 4232, Short-term	1818	20	No	None	[19]

5. EVALUATION OF RESULTS

5.1 Rules for classification of degrees of corrosion.

The Danish Code-of-Practice DS 420 prescribes that testing of the corrosion protection should be carried out according to DS 434.8 [13], and that the corrosion degree must be classified according to the Swedish standard SIS 18 51 11 [20] "Europeisk rostgradsskala för rostskyddsfärger (European corrosion scale for protective paints)".

SIS 18 51 11 was published in 1964, but has been withdrawn in 1985 and is not easily obtained. It was, however, replaced by SS 18 42 03 [21], which is identical to ISO 4628-3 "Paint and varnisches - Evaluation of degradation of paint coatings - Designation of intensity, quantity and size of common types of defects - Part 3: Designation of degree of rusting" [22].

ISO 4628-3 uses a scale for the degree of corrosion (from 0 to 5), which does not correspond to the scale in SS 18 51 11 (from 0 to 9). The ISO 4628-3 presents, however, both a typical picture and a percentage of corroded surface for each step in the scale, whereas the SS 18 51 11 only defines the scale by a typical picture for each level.

Table 6. Corrosion degree classification in ISO 4628-3 and the correlation to the scale in SIS 18 51 11 as prescribed in ISO 4628-3 (Corroded area 40/50 indicates 40 to 50 %).

ISO 4628-3	European classification SIS 18 51 11	Corroded area %
Ri 0	Re 0	0
Ri 1	Re 1	0.05
Ri 2	Re 2	0.5
Ri 3	Re 3	1
	Re 4	5 (interpolated)
Ri 4	Re 5	8
	Re 6	10/20 (interpolated)
Ri 5	Re 7	40/50

5.2 Acceptance criteria in DS 420 and prEN 1520

The Danish code DS 420 specifies the following criteria for the reinforcement to be regarded as adequately protected:

- if the degree of corrosion for one or more of the non-corrosion tested reference steels is 0-2, the degree of corrosion for the steel in the corresponding corrosion tested prim(s) should not exceed 3, or
- if the degree of corrosion for one or more of the non-corrosion tested reference steels is 3-6, the degree of corrosion for the steel in the corresponding corrosion tested prism(s) should not exceed this value by more than 1.

The test standard DS 434.8 specifies that the degree of corrosion is determined by comparison to the pictures in the European corrosion degree scale for corrosion protection measures SIS 18 51 11 [20].

The European standard prEN 1520 requires testing according to at least one of the three short-term test methods in EN 990 and approves the corrosion protection in the following situations:

- if the steel surface is free from corrosion or if only first signs of corrosion (no flaky rust or pitting) are visible in separate places which are approximately uniformly distributed over the bars and cover not more than 5 % of the steel surface, or
- if the area of corrosion does not exceed by more than 5 % that observed on bars of the corresponding reference specimens stored in a non-corrosive atmosphere at a relative humidity $\leq$ 70 %, or
- if the reduction of the rust grade number is not greater than 1.

It is clearly specified in EN 990 that the corrosion is primarily described by the percentage of the surface, which shows sign of corrosion, whereas the use of the European scale is only mentioned in a footnote: ”In some countries the effect of the corrosion test is judged by the reduction of the rust grade according to the European Scale for degree of rusting. The rust grade of the reference bars and that of the exposed bars are determined. The reduction in rust grade number is calculated by subtracting the rust grade of the exposed bars from that of the reference bars. The effect of the protective system is assumed to be satisfactory if the reduction of the rust grade number is not greater than 1”.

5.3 Evaluation of test results

The evaluation of the test results has been carried out on the basis of the measured percentage of corroded area, as required in EN 990. The Table 6 has been used for the classification according to SIS 18 51 11 and ISO 4628-3.

The evaluations of the results of the short-tem testing is presented in Table 7 and the similar evaluation of the results of the long-term testing is presented in Table 8.

Table 7. Evaluation of the short-term testing.

Series	ρ (kg/m^3)	Cover (mm)	Coa-ting	Classification by ISO 4628-3		Classification by SIS 18 51 11		DS420	PrEN1520
				S	SR	S	SR		
1	1911	12.3	No	Ri 4	Ri 4	Re 5	Re 4	Passed	Passed
2	1949	21.5	No	Ri 3/4	Ri 3/4	Re 4	Re 5	Passed	Passed
3	1938	18.1	C-L	Ri 2	Ri 2	Re 2	Re 2	Passed	Passed
4	1577	13.6	No	Ri 3	Ri 3	Re 3	Re 3	Passed	Passed
5	1563	18.2	No	Ri 3	Ri 3	Re 3	Re 3	Passed	Passed
6	1586	22.4	C-L	Ri 0	Ri 0	Re 0	Re 0	Passed	Passed
7	1134	12.2	No	Ri 4/5	Ri 3/4	Re 6	Re 4/5	Rejected	Rejected
8	1166	20.4	C-L	Ri 2/3	Ri 2/3	Re 2/3	Re 2/3	Passed	Passed
9	1133	19.0	No	Ri 4	Ri 4	Re 4/5	Re 4/5	Passed	Passed
10	1048	7.9	No	Ri 4/5	Ri 3	Re 5	Re 3	Rejected	Rejected
11	1074	17.6	C-L	Ri 1	Ri 1	Re 1	Re 1	Passed	Passed
12	1065	18.2	No	Ri 3/4	Ri 1	Re 4	Re 1	Rejected	Rejected

Table 8. Evaluation of the long-term testing.

Series	ρ (kg/m^3)	Cover (mm)	Coa-ting	Classification by ISO 4628-3		Classification by SIS 18 51 11		DS420	PrEN1520
				L	LR	L	LR		
1	1918	12.2	No	Ri 3	Ri 3	Re 3	Re 3/4	Passed	Passed
2	1941	21.6	No	Ri 3/4	Ri 3	Re 3/4	Re 3/4	Passed	Passed
3	1933	18.9	C-L	Ri 2	Ri 2	Re 2	Re 2	Passed	Passed
4	1576	11.9	No	Ri 3/4	Ri 3	Re 3/4	Re 3	Passed	Passed
5	1568	18.0	No	Ri 3/4	Ri 3	Re 3/4	Re 3	Passed	Passed
6	1588	23.7	C-L	Ri 0	Ri 0	Re 0	Re 0	Passed	Passed
7	1129	12.1	No	Ri 3/4	Ri 3/4	Re 4	Re 4	Passed	Passed
8	1162	20.8	C-L	Ri 3	Ri 3	Re 3	Re 3	Passed	Passed
9	1130	18.4	No	Ri 4	Ri 3/4	Re 5	Re 4	Passed	Passed
10	1063	10.3	No	Ri 3	Ri 3	Re 3	Re 3	Passed	Passed
11	1077	21.0	C-L	Ri 0	Ri 0	Re 0	Re 0	Passed	Passed
12	1069	20.8	No	Ri 1	Ri 1	Re 3	Re 1	Passed	Passed

The evaluation according to DS 420 in Tables 7 and 8 is independent of which of the corrosion classification systems, that has been used. The evaluations after prEN 1520 are all based on corrosion percentage and the ISO-classification.

The results of the short-term testing as a function of the cover and the density are shown in Figure 5. The results of the long-term testing are not illustrated, as all types passed the long-term testing.

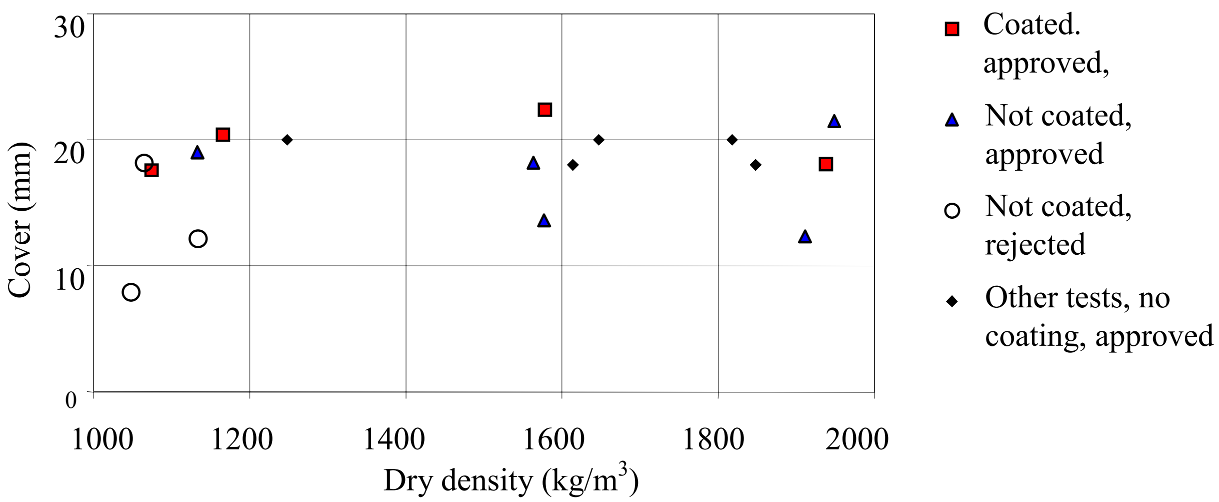

Figure 5. Result of short-term testing and evaluation of the corrosion protection.

6. CONCLUSIONS

The rules for classification of corrosion degrees and the acceptance criterias in DS 420 and in prEn 1520 are quite different, but lead to the same assessments in each of the tests and show that the corrosion protection is sufficient when the reinforcement is protected by a LAC-cover of at least 10-15 mm and a density of more than 1200-1500 kg/m^3 or when the reinforcement is coated with a cement-latex coating. The DS 420 and the prEN 1520 do, however, still prescribe a mandatory initial testing and an annual testing of the corrosion protection, in order to prevent corrosion problems due to changes in the production, mix design or coating.

The corrosion classification rules and the acceptance criterias in DS 420 can therefore be replaced by the use of the percentage of corroded surface areas, when the acceptance criterias in prEN 1520 are used.

The results of the short-term testing (EN 990, method 2) corresponds well with the current practice and the few observations from practice.

The long-term testing (EN 990, method 4) have so far approved the corrosion protection in all the tests, independent of coating, cover or density of the concrete. This indicates that the long-term testing may be un-conservative and should not be used.

The test method EN 990 is currently under revision and the enquiry version prEN 990 [23] has actually removed the long-term testing. The revision has also removed the corrosion classification by a certain corrosion degree class and uses solely the corroded surface area to describe the test results with.

7. ACKNOWLEDGEMENT

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