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The effect of reinforcement corrosion on the adhesion between reinforcement and concrete

Влияние коррозии арматуры на сцепление между арматурой и бетоном

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Ключевые слова: коррозия; потеря массы; прочность сцепления; анкеровка

Abstract. Due to aggressive environmental conditions, the adhesion between reinforcement and concrete deteriorates. This factor has a significant influence on the safety and efficiency of buildings and structures. The strength of adhesion between reinforcement and concrete decreases in the process of corrosion, and therefore requires a longer anchoring length of the reinforcement. The longer the anchoring length, the greater the guarantee that the destruction of the reinforcement in concrete does not occur until the lifetime of the reinforced concrete elements is expired. Various parameters affecting the reinforcement adhesion strength in reinforced concrete elements are considered. The ratio of the thickness of the protective layer and the diameter of the reinforcement (*c/ds*) affects the adhesion strength. With a higher (*c/ds*) ratio the loss of the adhesion strength is less than with a lower (*c/ds*) ratio. The mass loss of the reinforcement is an important parameter, and it can determine the level of corrosion. This value can be used for the development of the correlation between corrosion, cracking, the adhesion and ultimate strength of reinforced concrete elements.

Аннотация. Из-за агрессивных условий окружающей среды происходит ухудшение сцепления между арматурой и бетоном. Это значительно влияет на безопасность и работоспособность зданий и сооружений. Прочность сцепления между арматурой и бетоном уменьшается в процессе коррозии, и поэтому требуется большая длина анкеровки арматуры. Чем больше длина анкеровки, тем больше гарантия, что разрушение арматуры в бетоне не происходит до окончательного срока службы в железобетонных элементах. Рассматриваются различные параметры, влияющие на прочность сцепления арматуры в железобетонных элементах. Соотношение толщины защитного слоя и диаметра арматуры (*c/ds*) влияет на прочность сцепления. С более высоким (*c/ds*) отношением потеря прочности сцепления меньше, чем с более низким (*c/ds*) отношением. Потеря массы арматуры является важным параметром, и она определяет уровень коррозии. Это значение используется для разработки корреляции между коррозией, растрескиванием, прочностью сцепления и предельной прочностью железобетонных элементов.

1. Introduction

The object of the study is the analysis of analytical data of 60x40 cm reinforced concrete beams strengthened with steel bars.

Many scientists were engaged in studying the problems of corrosion of reinforcement in concrete in the field of theoretical and experimental research of reinforced concrete elements. Such names as V.E. Rumyantsev, V.S. Konovalova [1], A.I. Mozhukhina, S.E. Nikin [2, 8], D.S. Popov [3], A.G. Tamrazyan [3–7], L. Amleh [11], W.L. Jin [10, 12], Zhang Ju [15] and many others should be noted.

The relevance of research. Corrosion is a permanent destruction caused by physical and chemical damage of materials under environmental conditions [1]. Metal corrosion is a destructive result of a chemical or electrochemical reaction between a metal and the surrounding environment. It is regulated by energy changes, the release of free energy from the system into the environment. The phenomenon of metal corrosion has attracted much more attention of researchers around the world than any other type of material deterioration. This is because many metals and alloys, including steel, which is an important building material, are corroded and pose a serious challenge for our economy.

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The behavior of the reinforced concrete element to a certain extent depends on the adhesion between the reinforcement and the surrounding concrete [2]. When the tensile force in the reinforcement can not be transferred to the concrete, or when the adhesion breaks, the resistance of the element will be significantly reduced. The problem of adhesion can be more dangerous than reducing the cross-sectional area of the reinforcement [3–7]. When the reinforcement corrodes due to carbonation or chloride absorption, the amount of corrosion products can increase significantly, thereby producing strong radial pressure inside the concrete on the surface of the reinforcement. Longitudinal and transverse cracking can develop when the radial pressure exceeds the ultimate strength of the concrete. This can worsen the adhesion between the reinforcement and concrete and reduce the bearing capacity of the reinforced concrete element.

The adhesion between the reinforcement and the concrete is due to the engagement of protrusions on the reinforcement surface (mechanical blocking), clutching and friction in the concrete [8].

The mechanical blocking between the reinforcement and the concrete depends on the surface profile of the reinforcement. For the deformed reinforcing steel bars, the geometry of the ribs along the bar length increases the mechanical blocking by the bar and the concrete. At higher load levels, the force is mainly transmitted by mechanical blocking between the ribs and concrete protrusions with adhesion and friction between the concrete and the reinforcement. When the ultimate strength of adhesion is reached, the tensile force in the reinforcement generates considerable crushing around the reinforcement ribs, then the shear cracks begin to form in the concrete protrusions. Two mechanical failures can appear on the edges of the deformed reinforcing steel bars. In one case, the concrete presses locally on the supporting surface of the concrete protrusion (Fig. 1b). Another mechanism is the destruction from shear over the concrete protrusion between the ribs (Fig. 1a). Two mechanisms are shown in the Figure 1.

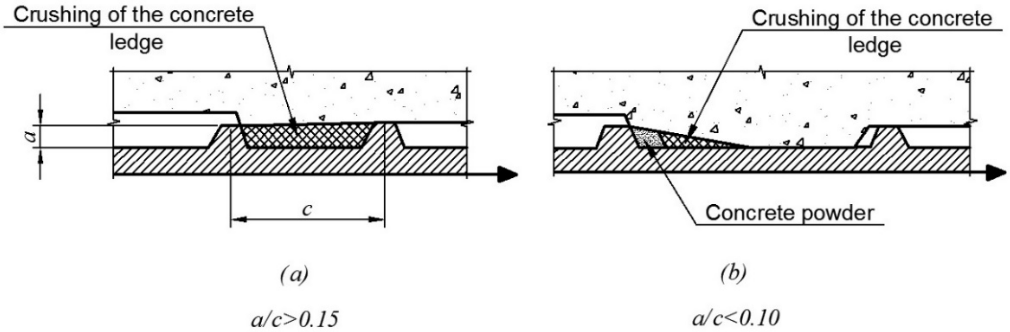

Figure 1. Mechanical failures on the ribs of the deformed reinforcement

Adhesion is a chemical bond on the surface between the reinforcement and the concrete, which plays a significant role in the development of adhesion at relatively low loads. But it is quickly lost as the load increases, so this factor is not reliable. The adhesion strength due to adhesion is generally from 0.48 to 1.03 MPa [9].

Friction: the surface characteristics of the reinforcement influence the frictional adhesion of the reinforcement. Friction engagement serves as a function of adhesion after the loss of chemical adhesion. Friction engagement can provide up to 35 % of the ultimate adhesion strength due to the concrete layer splitting [9].

The aim of the study is to determine the effect of reinforcement corrosion on the adhesion strength between reinforcement and concrete at different levels of corrosion.

Tasks of the study:

- determination of the level of corrosion of the reinforcement from the mass loss of the reinforcement during the process of corrosion;
- influence of various parameters (*W/C*, the ratio of the thickness of the protective layer to the diameter of the reinforcement (c/d_s), the profile of the reinforcement) on the adhesion strength between reinforcement and concrete at different levels of corrosion;
- finding the required length of anchoring in concrete elements.

2. Methods

The adhesion behavior on the reinforcing concrete interface is mainly determined by the surface characteristics of the reinforcing bar, so the transmission of forces at the junction for smooth reinforcing bars and bars of the deformed reinforcement is different [2]. After the reinforcement begins to corrode, corrosion products are formed on its surface, changing the steel bar surface profile. Therefore, the surface characteristics of the reinforcement and the contact conditions between the reinforcement and the concrete vary significantly, which affects the adhesion characteristics between the reinforcement and concrete.

Smooth reinforcing bar: the adhesion strength between the reinforcement and the concrete is mainly determined by chemical adhesion, engagement and friction on the surface of the reinforcement. When the reinforcement begins to corrode, the rust is gradually formed on the surface of the reinforcement, which changes the surface characteristics of the smooth reinforcing bar. Friction between the reinforcement and the concrete is significantly increased, so the adhesion can increase up to 2-3 times after the reinforcement begins to corrode [10]. As the volume of corrosion products increases, the concrete undergoes increased radial pressure, and when the pressure exceeds the adhesion strength cracking occurs. It leads to a rapid reduction of the adhesion strength due to the decrease of concrete protrusions and the peeling layer of corrosion products on the surface of the bar.

Table 1 shows the results of experimental tests of a detailed study of the strength of a smooth reinforcing bar of [10]. The diameter of a smooth reinforcing bar is d_s = 12 mm, the anchoring length l_{an} = 150 mm, the thickness of the concrete protective layer c = 44 mm, w/c = 0.55, R_{sc} = 389 MPa, R_b = 22.1 MPa.

Table 1: Data of the pull-out adhesion strength of a smooth reinforcing bar in concrete samples

Samples	Adhesion strength, (MPa)	Coefficient of adhesion strength (*)	Wight loss Δ_m , (%)	Thickness of corrosion products, (mm)
1	2.65	1.23	0.27	0.0162
2	3.23	1.01	0.29	0.0174
3	5.97	2.27	0.92	0.0549
4	5.84	2.18	1.13	0.0674
5	7.41	2.82	0.78	0.0466
6	8.63	3.28	1.47	0.0876
7	7.3	2.78	1.85	0.1100
8	7.96	3.03	1.50	0.0893
9	9.29	5.53	1.99	0.1182
10	10.26	3.9	1.04	0.1212
11	5.97	2.27	2.75	0.1628
12	4.84	1.84	2.43	0.2024
13	3.75	1.43	4.77	0.2797
14	1.63	0.62	5.01	0.2934

* Coefficient of the adhesion strength is the adhesion strength of a corroded sample / adhesion strength of a non-corroded sample

The results are shown in Figure 2.

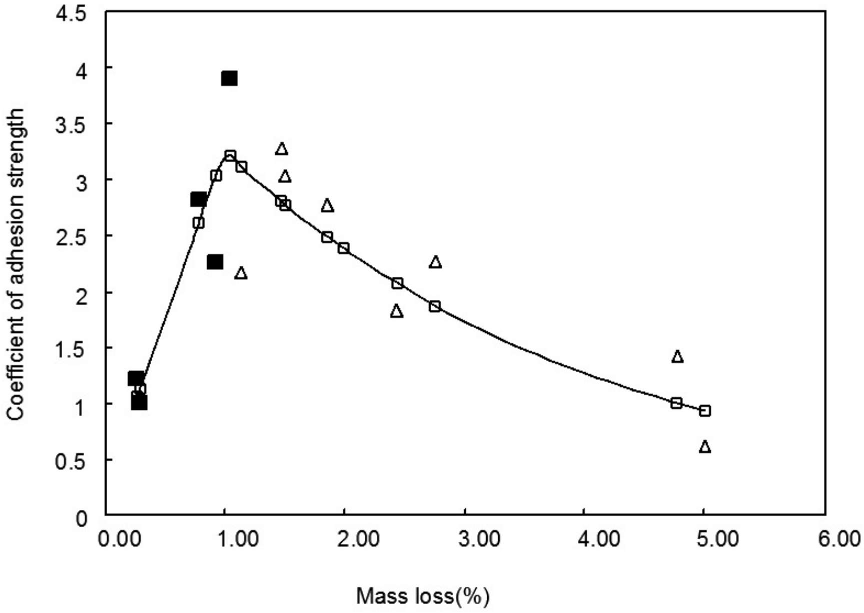

Figure 2. Effect of corrosion on the adhesion of a smooth reinforcement bar in concrete samples [10]

Deformed reinforcement: the adhesion between the deformed reinforcement and the concrete is mainly determined by mechanical blocking between the ribs of the deformed reinforcement and the concrete protrusions and small deposits effected by adhesion and friction [2, 11]. Corrosion affects the connection between the reinforcement and the concrete. Based on the results of pull-out tests (Figure 3 and Table 2) the adhesion strength increases at low corrosion levels (about 1–3 % mass loss) when a thin solid layer of corrosion products forms on the surface of the reinforcement [12]. However, this solid layer of corrosion products is converted into a peeling layer at higher corrosion levels with a corresponding deterioration of both the adhesion strength and sliding characteristics. At higher corrosion levels, the adhesion strength decreases almost linearly with further increase in mass loss. When the mass loss exceeds 20 %, only 15 % of the original adhesion strength remains. A slight improvement in the characteristics of the adhesion strength at low corrosion levels is due to the changes in the characteristics of the deformed reinforcement surface layer. Another crucial factor affecting the change in the adhesion strength between the deformed reinforcement and the concrete at higher corrosion levels is deterioration of the characteristics of the reinforcement protrusions, which significantly reduces the blocking between the reinforcement protrusions and the concrete [13].

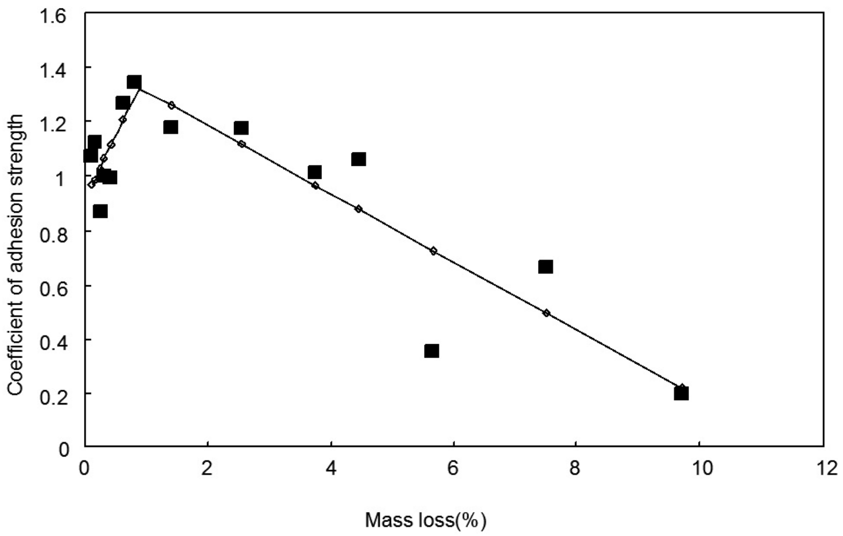

Figure 3. Effect of corrosion on the adhesion for concrete samples with the deformed reinforcement, d_s = 12 mm, the anchoring length is l_{an} = 150 mm, the thickness of the protective layer of concrete *c* = 44 mm, *w/c* = 0.55, R_{sc} = 389 MPa, R_b = 22.13 MPa [10]

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Table 2. Data of the pull-out adhesion strength of the deformed reinforcement in concrete samples [10]

Samples	Adhesion strength, (MPa)	Coefficient of adhesion strength (*)	Mass loss Δ_m, (%)	Thickness of corrosion products, (mm)
1	8.92	1.07	0.12	0.0072
2	9.49	1.12	0.16	0.0092
3	7.36	0.87	0.24	0.0144
4	8.46	1.00	0.32	0.0192
5	8.39	0.99	0.43	0.0257
6	10.62	1.27	0.62	0.0371
7	11.35	1.34	0.81	0.0484
8	9.99	1.18	1.40	0.0834
9	9.95	1.18	2.54	0.1505
10	8.59	1.02	3.75	0.2209
11	8.70	1.06	4.45	0.2603
12	5.97	0.35	5.68	0.3316
13	4.64	0.67	7.50	0.4343
14	1.66	0.20	9.72	0.5177

Figure 4 shows that the tensile samples show a gradual decrease in the relative adhesion strength with increasing corrosion. It can also be seen from Figure 5 that the adhesion strength of concrete samples *w/c* = 0.32 are close to the samples *w/c* = 0.42.

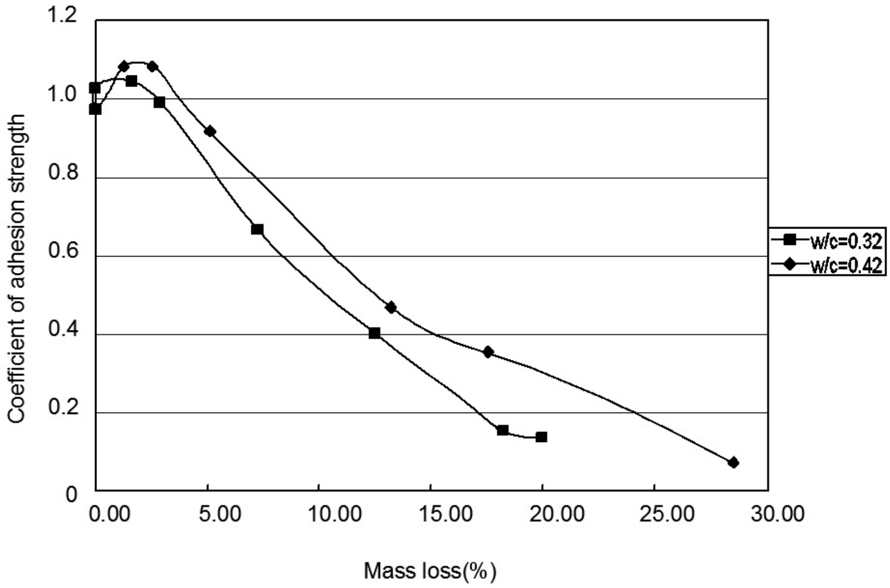

Figure 4. The relationship between the adhesion strength and the reinforcement mass loss [11]

The ratio of the thickness of the protective layer to the reinforcement size (c/d_s) is an equally important variable influencing the concrete resistance to the chloride effect. Figure 5 shows a sharp decrease of the adhesion strength in a sample with a protective layer thickness and bar diameter c/d_s = 1.28, whereas for a sample with a c/d_s ratio of 5.12, a decrease in the adhesion strength is less. It shows that in a sample with a higher (c/d_s) ratio, the loss of bond strength is not as significant as in the case of a lower (c/d_s) ratio. These studies also showed that the ratio of the thickness of the protective layer to the bar diameter is an important indicator of resistance to corrosion of reinforcing bars due to the penetration of chlorides [14–17].

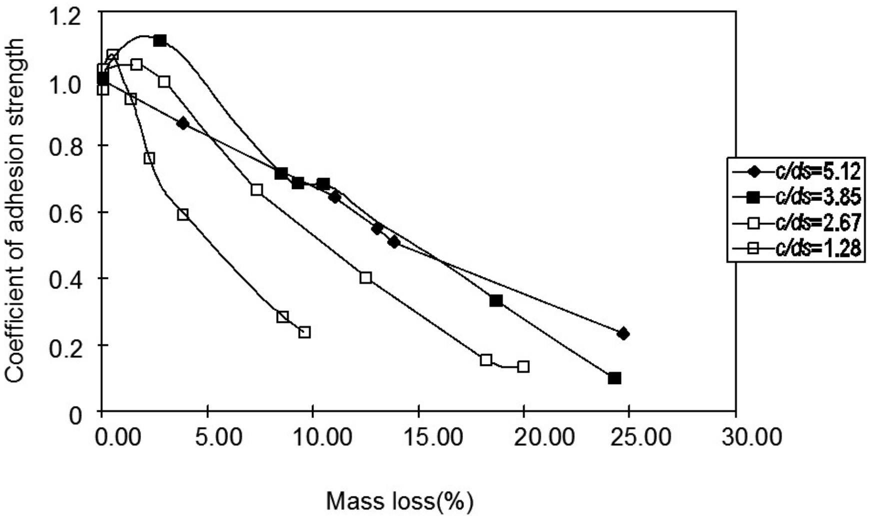

Figure 5. The ratio of the adhesion strength to the corrosion level (ratio of the thickness of the protective layer and the reinforcement diameter (c/d_s)) [11]

Figure 6 shows the mass loss of the reinforcing bar due to chloride corrosion for 70 years for different levels of chloride concentration. This result is applied to a concrete beam in which the reinforcement diameter is d_s = 16 mm, the thickness of the protective layer is c = 40 mm, the compressive strength of concrete, R_b = 30 MPa and the reinforcement strength, R_{sc} = 400 MPa, subjected to different levels of surface chloride varying from 1 to 6 %. In this example, the coefficient of thickness of the protective layer to the reinforcement diameter is c/ds = 2.67. If the structural element is designed for a 70-year lifetime, the mass loss can reach 21% at the end of its lifetime, and loss of the adhesion strength will reach more than 80 % (Figure 5). Therefore, the ratio of the thickness of the concrete protective layer and the size of the reinforcement c/d_s = 2.67 is not sufficient for a lifetime of 70 years. Thus, this design requires a larger ratio of the thickness of the protective layer and the size of the reinforcement (c/d_s).

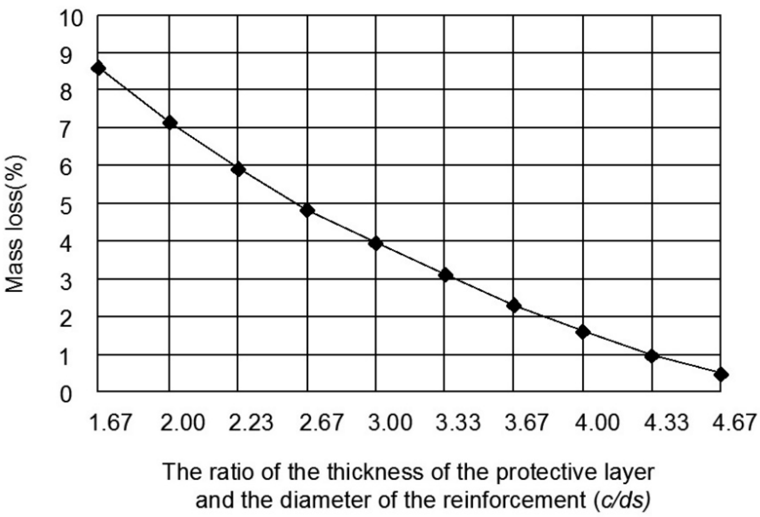

Figure 6. The relationship between the loss of reinforcement mass and the ratio of the thickness of the protective layer and the diameter of the reinforcement (c/d_s) [10]

The examination of the steel bar embedded in the tensile samples showed deep pits on the surface, which showed that the geometric shape and size of the steel bar had a significant effect on the force transfer from steel to concrete due to the mechanical blocking of ribs susceptible to corrosion. Therefore, the adhesion between the deformed reinforcement and the concrete, which mainly depends on the mechanical blocking of the ribs, is weakened by the effect of corrosion.

For durability, you must carefully choose the size and geometry of the reinforcement. Half of the anchoring length remains to ensure safety during the lifetime of the structure in this environment [18–19].

3. Results and Discussion

Based on the pulling-out experimental results [11], formulas for the adhesion strength of the reinforcement depending on the mass loss are presented:

$$\text{at w/c = 0.32, } R_{st} = (0.35 + 0.3\frac{c}{d_s})\sqrt{1.284R_b} - 0.42(\Delta_m \cdot 100\%)$$
$$\text{at w/c = 0.42, } R_{st} = (0.35 + 0.3\frac{c}{d_s})\sqrt{1.425R_b} - 0.34(\Delta_m \cdot 100\%) \quad (1)$$

Let us assume that the reinforcement diameter d_s = 20 mm (the ratio *w/c* = 0.42, R_b = 51 MPa) with a protective layer thick as *c* = 50 mm, has a mass loss Δ_m = 5.1 % for a certain period of the structure. The strength of adhesion between the corroded core and the concrete:

$$R_{st} = \left(0.35 + 0.3\frac{c}{d_s}\right)\sqrt{1.425R_b} - 0.34(\Delta_m * 100\%) = \left(0.35 + 0.3\frac{50}{20}\right)\sqrt{1.425 * 51} - 0.34 * 5.1 = 7.64\ MPa$$

The experimental value of the adhesion strength for the sample (*w/c* = 0.42, Δ_m = 5.1%, thickness of the protective layer *c* = 50 mm, d_s = 20 mm) is R_{st} = 8.14 MPa, which corresponds to the calculated value of R_{st}.

To obtain the estimated strength of adhesion, we take:

$$R_{st.d} = 0.65 \times R_{st} \quad (2)$$

Based on the adhesion strength formulas (1) and (2), the anchoring length l_{an} can be derived. To ensure sufficient adhesion of the reinforcing bar along its length, the anchoring length of the bar l_{an} should be provided. The bar cannot be pulled out if it has sufficient anchoring [20]. When the bar is pulled out, it slides. If at the time of pulling the bar is poorly fixed in the concrete, then it reaches the yield point [21]. The actual adhesion strength will be large near the surface and equal to zero in the anchoring. When the bar slides with a small tensile force, the adhesion strength is higher in the anchoring than in other parts of the bar. With the increase in the applied load, the strength of the adhesion will increase significantly in the anchoring, so the strength of the adhesion along the entire length is not considered. In case of failure, the strength along the bar will be distributed more evenly [22–23]. Therefore, the equilibrium condition between the internal forces of adhesion and the force applied to the anchoring can be:

$$A_s R_{sc} = R_{st} l_{an} \pi d_s \quad (3)$$

where R_{st} – adhesion strength

$A_s = \pi d_s^2 / 4$ – cross-sectional area of the bar

R_{sc} – ultimate tensile strength of reinforcement

l_{an} – length of anchoring of reinforcement in concrete

d_s – bar diameter

Substituting the value of A_s in (3), we obtain:

$$l_{an} = \frac{R_{sc}}{4R_{st}} d_s \quad (4)$$

The structural length of the anchoring of the reinforcement in the concrete can be obtained by increasing the anchoring length l_{an} by 20 % to provide a bearing capacity when the stress in the reinforcement is exceeded, ε_y. Replacing $R_{st,d}$ by R_{st}, to consider the variability of the data:

$$l_{an,d} = 1.2 \times \frac{R_{sc}}{4R_{st.d}} d_s = 1.2 \times \frac{R_{sc}}{4 \times 0.65R_{st}} d_s = 0.462 \frac{R_{sc}}{R_{st}} d_s \quad (5)$$

Therefore, the minimum anchoring length l_{an} under tension at different corrosion levels can be obtained from equation (1):

$$\text{at w/c = 0.32, } l_{an,d} = 0.462 \times R_{sc} \times d_s / \left[(0.35 + 0.3\frac{c}{d_s})\sqrt{1.284R_b} - 0.42(\Delta_m \cdot 100\%)\right]$$
$$\text{at w/c = 0.42, } l_{an,d} = 0.462 \times R_{sc} \times d_s / \left[(0.35 + 0.3\frac{c}{d_s})\sqrt{1.425R_b} - 0.34(\Delta_m \cdot 100\%)\right] \quad (6)$$

where R_{sc} – ultimate tensile strength of reinforcement

c – thickness of concrete protective layer

Let us assume that the reinforced concrete beam (*w/c* = 0.42) has the lifetime of 70 years, the reinforcement diameter d_s = 16 mm; thickness of the protective layer of concrete *c* = 40 mm; strength of concrete for compression, R_b = 30 MPa; yield strength of steel, R_{sc} = 400 MPa; at a surface chloride concentration of 3 %, the threshold level of corrosion is considered equal to 0.4 % (Cl ') by the cement weight.

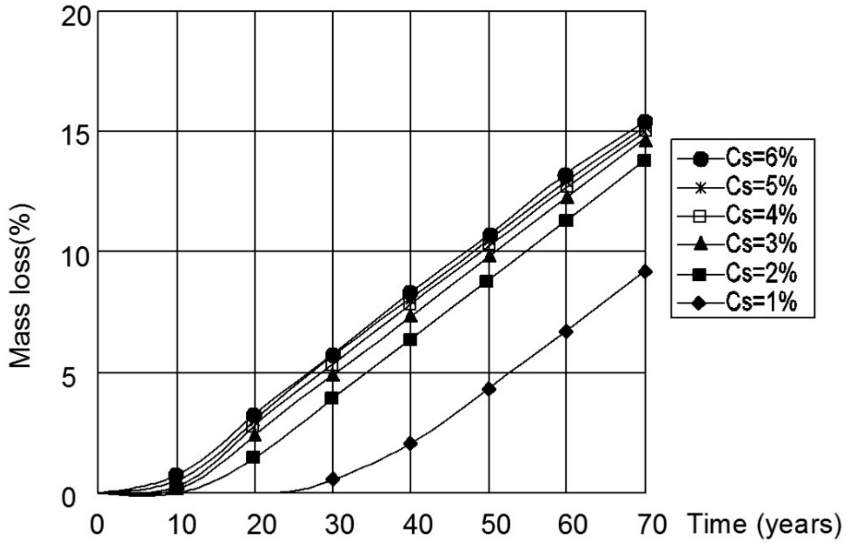

Figure 7. Mass loss of reinforcement due to chloride corrosion over 70 years of lifetime for different concentrations of sodium chloride (Cs))

From Figure 7, the mass loss of the reinforcement in the 70th year is projected at 14.73 %; therefore the estimated length of the anchoring should not be less than:

$$l_{an,d} = 0.462 \times R_{sc} \times d_s / \left[(0.35 + 0.3\frac{c}{d_s})\sqrt{1.425 R_b} - 0.34\left(\Delta_m \cdot 100\%\right) \right] =$$

$$0.462 \times 400 \times 16 / \left[(0.35 + 0.3\frac{40}{16})\sqrt{1.425 \times 30} - 0.34 \times 14.73 \right] = 1350 mm$$

In a corrosion-free environment at Δ_m = 0, the embedment length will be l_{an} = 411 mm.

4. Conclusions

A model for predicting the mass loss of the reinforcement at different levels of corrosion when chloride penetrates concrete is proposed. At the initial stage of reinforcement corrosion due to the peeling layer, the adhesion strength between the reinforcement and concrete is increased to two or three times. The mass loss of the reinforcement is an important parameter; it can determine the level of corrosion and the adhesion strength. The results show that the mass loss of the reinforcing bar in concrete depends on many factors such as chloride concentration on the surface of concrete, the thickness of the protective layer of concrete and permeability of concrete, the size of the reinforcing bar and the ratio of thickness of the protective layer of concrete and the diameter of the steel reinforcement. If the concentration of sodium chloride is more than 2 %, the steel reinforcement in concrete will undergo serious corrosion. An enlarged protective layer of concrete and a lower permeability of concrete can reduce the mass loss of the reinforcement in concrete.

An increase in the ratio (c/d_s) also helps to reduce the mass loss of the reinforcement in concrete, thus prolonging the lifetime of the structural system.

A preliminary design equation for the anchoring length at different corrosion levels is presented. The results show that for an aggressive environment a large anchoring length, approximately 3 times longer than for a non-aggressive environment, for a certain lifetime of the reinforced concrete elements is required. The length of the reinforcement anchoring should not be a "weak link" when chlorides penetrate the concrete.

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