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The Effect of Uncertainties on Calculation of Initiation of Corrosion of Reinforcement for Assessment of Reliability of Concrete Structures

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ABSTRACT: An important problem with the analysis of corrosion of reinforcements used in concrete structures is the calculation of corrosion initiation time. The type of concrete, water to cement ratio, curing time, surface chlorides concentration, temperature and thickness of concrete cover over reinforcements are among the most important factors influencing the time required for initiation of corrosion of reinforcement. The multiplicity of parameters and errors in measuring these parameters leads to uncertainties in estimation of corrosion initiation time. Qualitative calculation of the effect of uncertainties associated with the aforementioned parameters is very important to the assessment of the precision of the calculated corrosion initiation time. Knowing the corrosion initiation time and uncertainties in the calculated time helps take preventive measures before the initiation of the corrosion of reinforcement in order to protect structural performance. In this paper, uncertainties were introduced into the model through statistical parameters. Moreover, dispersion and precision of the predicted corrosion initiation time are calculated considering that random factors contributing to initiation of corrosion of reinforcement. In this study, the random properties of factors contributing to the prediction of corrosion initiation were considered. Next, the Monte Carlo random sampling method was used to assess the effect of statistical properties of each parameter on corrosion initiation time. According to the results, even with an increase in the estimation of input parameters used to precisely calculate the corrosion initiation time, the resulting time will be associated with at least 40% of uncertainty.

Keywords: Reinforcement Corrosion, Corrosion Initiation Time, Probabilistic Model, Random Sampling

INTRODUCTION

When a concrete structure is exposed to chloride ions, the ions gradually penetrated into the concrete components. Penetration of chloride ions over time leads to destruction of alkaline protection of reinforcements and initiation of corrosion. Ions generally penetrate concrete through diffusion. In addition, the initiation period is the period starting from the construction phase and end when concentration of chloride ions around reinforcements reach a threshold value. Corrosion of reinforcement is initiated following this stage. The type of concrete, the water to cement ratio, curing time, surface chlorides concentration, temperature and thickness of concrete cover over reinforcements are among the most important factors influencing the time required for initiation of reinforcement corrosion (Duffo et al., 2004). Previous studies on prediction of corrosion initiation time were carried out using analytical and experimental methods. In the analytical method, penetration of chlorides is defined in terms of physicochemical processes. Application of numerical models has also led to expression of penetration of chloride ions using the Fick's second law (Chatterji, 1995; Shafei et al., 2012).

Simplifications of the diffusion model and human errors associated with measuring the values of factors influencing the model have led to uncertainties in the predicted corrosion initiation time. In order to calculate the effect of uncertainties, it is necessary to calculate the effect of dispersion of these variables on the value and dispersion of the corrosion initiation time. In this paper, factors influencing the model were considered to be random variables in order to study the effect of uncertainties in parameters. To this end, the statistical studies previously conducted on the basis of field and experimental records were used. The Monte Carlo random sampling method was also used to calculate the results. The necessity of counting the predicted corrosion initiation time and model parameters into the probabilistic models of failure estimation is an important issue that has not been addressed yet.

Corrosion Initiation Time

The penetration of chloride ions into surfaces is expressed as following using the Fick's second law (Crank, 1997; Collepardi et al., 1972):

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2} \qquad (1)$$

Where, **C(x, t)** denotes concentration of chlorides at a depth of **x** and time of **t**. **D** is also the diffusion coefficient. Assuming that D is invariant, the following equation is obtained using boundary conditions:

$$C(x,t) = C_0 + (C_s - C_0)\left[1 - erf\left(\frac{x}{\sqrt{4Dt}}\right)\right] \qquad (2)$$

Where, $\mathbf{C_0}$ is the initial concentration of chlorides in the concrete mortar and $\mathbf{C_s}$ is the concentration of

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chlorides on the concrete surface. In addition, in this relation the diffusion coefficient and other parameters are assumed to be invariant over time. The above relation suggests that concentration of chloride ions at any part of the concrete component increases over time. Relation (2) is a simplified model of diffusion of chlorides over a concrete component. The most important hypothesis underlying this relation is that the concrete is homogenous and saturated. However, this hypothesis is rejected especially in the vicinity of the concrete surface to which this relation applies. Hence, this model is enhanced in order to comply with the experimental results obtained from measuring chloride ions at different times and environmental conditions. As a measure of initiation of corrosion of reinforcement as a result of penetration of chlorides, the increase in the gradual chloride ions on reinforcements is calculated. Corrosion of reinforcement starts when the concentration of ions reaches the critical concentration (C_{cr}) level. The time of reinforcement corrosion initiation (T_i) is obtained as follows by setting the value of Relation (2) to C_{cr} for the reinforcement surface (x=c):

$$T_i = \frac{C^2}{4D}\left(erf\left(\frac{C_s - C_{cr}}{C_s - C_0}\right)\right)^{-2} \qquad (3)$$

The critical concentration for initiation of reinforcement corrosion is influenced by many factors including concrete type, water to cement ratio, temperature and oxygen (Bhargavaa and Mori, 2012). As a result of these factors, values of chloride critical concentration vary drastically. That is to say, the values vary between 0.2% and 2% of cement content (Yu et al., 2012). The values even grow up to 3% of the reported cement content (Alonso et al., 2000). Since concrete is non-homogenous, the critical concentration of chloride ions for initiation of corrosion in different areas of the structure is variant as the results of some studies report the 0.2-0.8% range for cement weight ratio as the critical range (Amey et al., 1998). According to the American Concrete Regulations, introduces the conservative value of 0.15% for the cement content of concrete components exposed to moisture and chlorides at time of operation (ACI, 2011). In the Iranian model "Estimation of Lifetime of Concrete Structures", which is a non-probabilistic model, this limit is also applied (Alizadeh et al., 2006). In regions where conditions for reinforcement corrosion are met, the average value of 0.5 is obtained as the critical value (Gaal, 2001; Polder and Rooij, 2002). In these regions, a smaller critical value is obtained for structures made of low-quality concrete or high water to cement ratio.

Diffusion coefficient indicates the degree of permeability of concrete. Numerous factors influence the value of this coefficient, the most important one of which is the water to cement ratio. Most models give the coefficient value based on the water to cement ratio (Lin, 1990). In these models, an increase in the water to cement ratio leads to an increase in the diffusion coefficient. In obtaining the diffusion model (Relation 2), the diffusion coefficient was assumed to be invariant over time while experimental results showed an increase in the resistance of concrete to chloride ions and a decrease in diffusion coefficient over time (Gaal, 2001; Bamforth, 1999). The rate of increase was high in the early years and was lower in the coming years. The following relation is aimed for considering the effect of variations of diffusion coefficient (Bamforth and Price, 1997).

$$D(t) = D_0\left(\frac{t_0}{t}\right)^n \qquad (4)$$

Where, D_0 is the diffusion coefficient for the initial time, t_0, and n is the lifetime coefficient (0<n<1). The lifetime coefficient varies often. This coefficient falls in the 0.2-0.3 range for concretes with typical Portland cement and falls in the 0.5-0.7 range for cements containing fly-ash or slag (Bamforth, 2004). The time by which concentration of chlorides on reinforcement surface reaches the critical level (C_{cr}) is calculated by considering variations of diffusion coefficient to be a time history and integrating Relation (4) to the desired time limit and putting the result into the diffusion equation.

$$T_i = \left[\frac{(1-n)C^2}{4D_0 {t_0}^n}\left(erf\left(\frac{C_s - C_{cr}}{C_s - C_0}\right)\right)^{-2}\right]^{\frac{1}{1-n}} \qquad (5)$$

Using the above relation, corrosion initiation time is calculated for different environmental conditions and different concrete samples. Numerous attempts have been made to obtain the values of parameters influencing Relation (5) for different concretes and environmental conditions so as to standardize the calculation of corrosion initiation time. Due to the influence of various factors on the corrosion initiation time and due to the uncertainties in calculation of these parameters, it is not possible to predict corrosion initiation time without performing some specific tests on each area. Some of the values obtained for parameters influencing the corrosion initiation model were described in the previous section. In the following, the statistical properties of critical chloride concentration (C_{cr}) and diffusion coefficient (D_0) are presented in Tables 1 and 2.

Table 1. Statistical properties of critical chloride (C_{cr})

Average (kg/m^3)	**Coefficient of variation**	**Distribution**	**Reference**
0.9	0.19	Uniform	(Stewart et al., 1998)
1.4	-	-	(Bamforth, 1997)
3.4	0.6	Lognormal	(Leira et al., 2000)
1.0	0.1	Lognormal	(Enright et al., 1998)
0.6-0.9	-	-	(Lounis et al., 2008)
1.38	0.2	Normal	(Engelund et al., 1995)
2.23	0.1	-	(Nilsson et al., 1997)

Table 2. Statistical properties of diffusion coefficient (D_0)

Average (10^{-12} m^2/s)	**Coefficient of variation**	**Distribution**	**Reference**
0.16-1.64	0.51	Gamma	(Kirkpatrick et al., 2002)
0.6-7.5	0.75	Lognormal	(Hoffman et al., 1994)
1.1-6.81	0.38	-	(Wood et al., 1997)
0.41-1.71	0.57	-	(Cramer et al., 2002)

In order to count the concentration of surface chloride it is necessary to consider operation conditions and the construction environment.

MATERIAL AND METHODS

The values presented in Tables 1 to 2 properly indicate the dispersion of parameters influencing the corrosion initiation model. In order to study the effect of these dispersions on the corrosion initiation time, mean values of each parameter along with the range of their variations is used and then using the Monte Carlo random sampling method the corrosion initiation time is calculated. Values used in the analyses are shown in Table 3. The thickness of concrete cover over reinforcements are 4, 5 and 7.5cm. These values are the minimum values required for concrete cover exposed to the atmosphere (ACI, 2011).

Table 3. Properties of parameters influencing the model

Variable	Unit	Average	C.O.V	Distribution
C_{cr}	Kg/m^3	0.4, 0.8, 1.1	0.05, 0.1, 0.15	Lognormal
D_0	10^{-12} m^2/s	1.0, 3.0, 5.0	0.2, 0.35, 0.5	Lognormal
C_s	Kg/m^3	2.5,5.0,8.0	0.05, 0.10, 0.15	Lognormal
C	cm	4.0, 5.0, 7.5	0.10, 0.15, 0.20	Normal

A total of 200000 samples were taken randomly by applying the Monte Carlo method to each parameter and by using the mean values and pre-defined coefficient of variation. Next, the corrosion initiation time for each sample was calculated using Relation (5). Figure 1 and figure 2 show samples prepared for the upper and lower limits of the coefficient of variation of parameters. According to this figures, with an increase in the coefficient of variation of parameters the space of samples escalates.

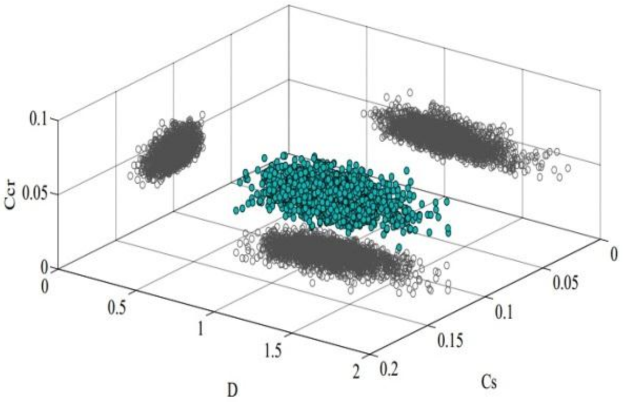

Figure 1. Distribution of random samples prepared using the Monte Carlo method for lower coefficient of variations (Vc=0.1, VCs=0.05,VCcr=0.05, VD=0.2).

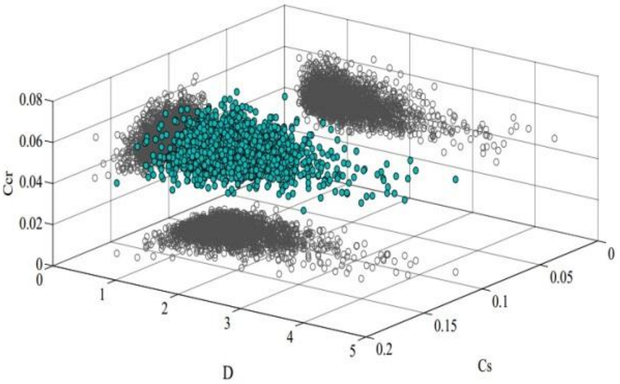

Figure 2. Distribution of random samples prepared using the Monte Carlo method for upper coefficient of variations (Vc=0.2, VCs=0.15, VCcr=0.15, VD=0.5).

Since variables were considered to be stochastic, the corrosion initiation time for samples produced using the Monte Carlo method varies. Hence, for the statistical analysis of these results, the best statistical distribution that matches the results the most is selected. In addition, using the Chi-square test the precision of the statistical distribution fitted to the corrosion initiation time is calculated. According to the results, the log-normal distribution is the best indicator of the statistical properties of corrosion initiation time. In the following, the effect of mean variations and dispersion of input parameters on the corrosion initiation model is studied.

Results of the analyses for concrete cover thicknesses of 4,5 and 7.5 cm are shown in Figure 3. As seen in this figure, an increase in the thickness of reinforcement concrete cover leads to an increase in the corrosion initiation time. Moreover, this figure also depicts the log-normal distribution fitted to the corrosion initiation time. The standard deviation of this distribution increases as **c** grows. The growth shows dispersion of results due to the increase in the mean value of **c** while the concrete cover coefficient of variation (Vc) remains invariant. An increase in the concrete cover coefficient of variation (Vc) also leads to a slight decrease in the mean calculated corrosion initiation time. In order to study the effects of variations of the concrete cover coefficient of variation, see Figure 4, which shows the influence of increased concrete cover coefficient of variation on the coefficient of variation of corrosion initiation time (VT). As seen in this figure, an increase in Vc leads to an increase in the dispersion of results. However, in spite of the growth of standard deviation with the growth of the coefficient of variation of concrete cover, no considerable change is made to the variation coefficient of results. The numerical value of the coefficient of variation of corrosion initiation time (VT) varies between 0.4 and 0.55. The variation shows high uncertainties in the predicted corrosion initiation time. As shown in the following, this value (VT) reaches 0.7 for some cases. This increase reflects 70% standard deviation in the results.

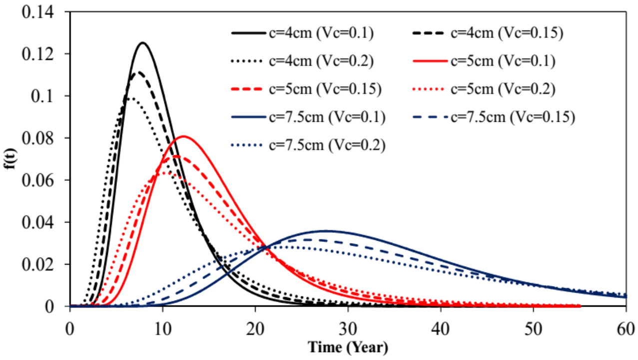

Figure 3. Influence of reinforcement cover properties in statistical distribution of corrosion initiation time.

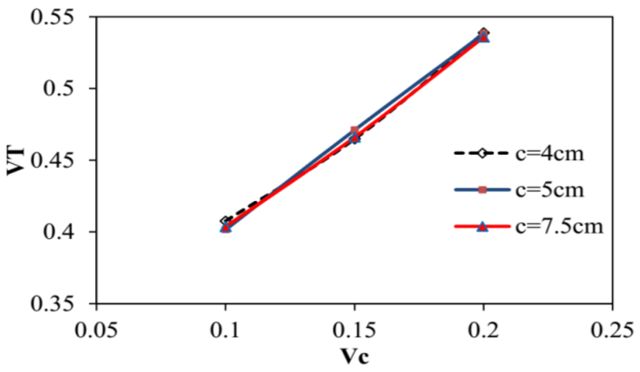

Figure 4. Influence of reinforcement cover properties in coefficient of variation of corrosion initiation time.

The effect of the diffusion coefficient, which is a measure of permeability of concrete, is shown in Figures 5 and 6. An increase in the diffusion coefficient (D) caused by increased concrete permeability is shown in Figure 5. According to this figure, the mean corrosion initiation time decreases. However, according to Figure 6 the decrease does not influence the coefficient of variation of corrosion initiation time. The growth of uncertainties in the estimation of diffusion coefficient applied through increased variation coefficient (VT) adds to the dispersion of results. As seen in Figure 6, the coefficient of variation of each of the diffusion coefficients starts from VT=0.4 for VD=0.2 and grows by VT=0.63 for VD=0.5.

In the analytical model of prediction of corrosion initiation time, the surface chlorides concentration is used as a boundary condition in solving the differential equation of the Fick's second law. Figures 7 and 8 show the effect of mean value and coefficient of variation of surface chloride concentration. An increase in the concrete component's surface chlorides concentration accelerates corrosion. As see in Figure 8, an increase in the uncertainty of surface chlorides concentration (which is increased from VCs=0.05 to VCs=0.15 due to the growth of its coefficient of variation) did not influence dispersion of results for surface chlorides concentration of Cs=5 and Cs=8 kg/m^3. The latter values indicate moderate and severe environmental conditions in this research. The figure also implies that as the mean surface chlorides concentration declines from Cs=5 to Cs=2.5 kg/m^3, dispersion of results increases as a result of an increase in the coefficient of variation of corrosion initiation time (VT).

With an increase in the critical chloride concentration (C_{cr}), which reflects the conditions in the threshold of corrosion of reinforcement, the predicted corrosion initiation time escalates. Figure 9 shows the effect of an increase in the critical chloride concentration on the corrosion initiation time. Unlike the surface chlorides concentration, in the case of critical chlorides concentration a decrease in the mean critical chloride concentration leads to a reduction in the coefficient of variation of corrosion initiation time. According to Figure 10, an increase in VC_{cr} leads to the growth of the variation coefficient of corrosion initiation time. The increase is higher for larger values of mean critical chloride concentration.

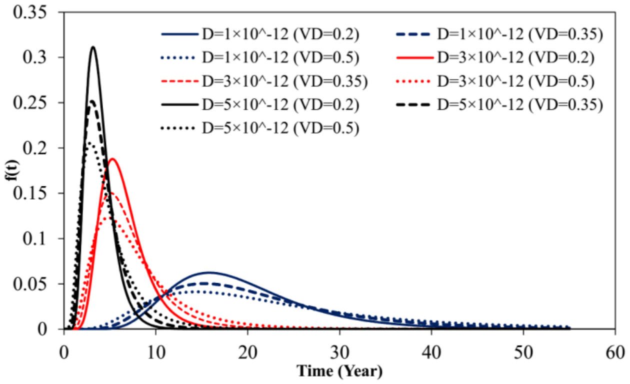

Figure 5. The effect of mean value and coefficient of variation of diffusion coefficient in statistical distribution of corrosion initiation time.

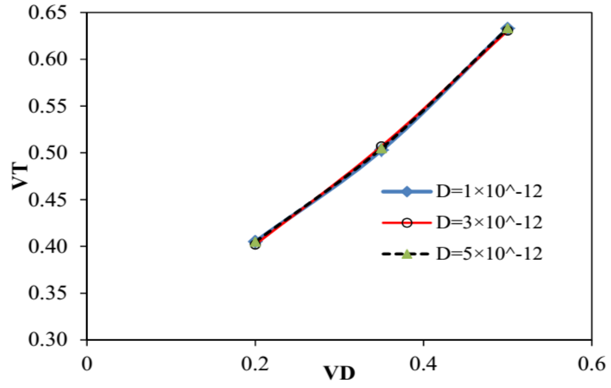

Figure 6. The effect of diffusion coefficient properties in coefficient of variation of corrosion initiation time.

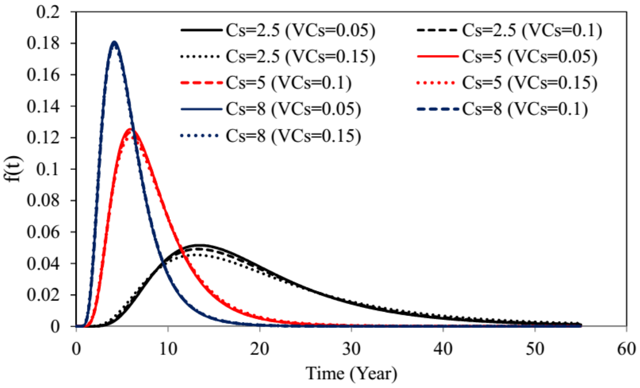

Figure 7. The effect of surface chlorides properties in statistical distribution of corrosion initiation time.

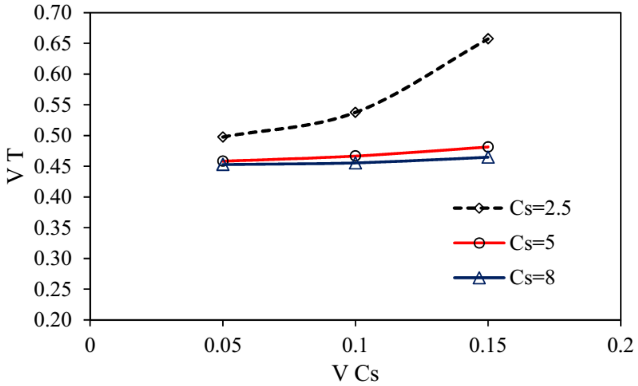

Figure 8. The effect of surface chlorides properties in coefficient of variation of corrosion initiation time.

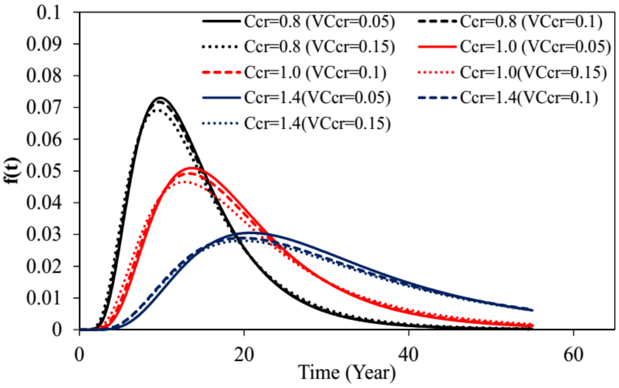

Figure 9. The effect of critical chloride concentration properties in statistical distribution of corrosion initiation time.

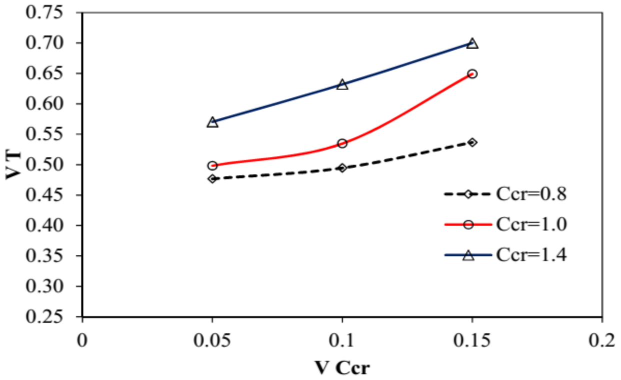

Figure 10. The effect of mean value and coefficient of variation of critical chloride concentration in coefficient of variation of corrosion initiation time.

DISCUSSION AND CONCLUSION

In this research, the effect of random properties of reinforcement concrete cover, diffusion coefficient, surface chlorides concentration, and critical chlorides concentration were taken into account for calculating the corrosion initiation time. Using the statistical properties of these values, the mean value and coefficient of variation of corrosion initiation time as well as dependence coefficient of the model output on input parameters were calculated using the Monte Carlo random sampling model. According to the results, the coefficient of variation of corrosion initiation time is between 0.40 and 0.70, which reflects high uncertainty in the estimation of the required time. Hence, the estimate time shall be used with a large factor of safety. Results also indicated that an increase in the coefficient of variation of reinforcement concrete cover (Vc), critical chloride concentration (VCcr) and diffusion coefficient (VD) leads to an increase in the coefficient of variation of corrosion initiation time (VT). However, an increase in the coefficient of variation of surface chloride concentration (VCs) does not considerably influence the coefficient of variation of corrosion initiation time. Results also reflect that the mean values of concrete cover and diffusion coefficient do not influence the dispersion of the calculated corrosion initiation time. However, an increase in the mean critical chloride concentration leads to an increase in the coefficient of variation of corrosion initiation time.

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