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Effect of Amount of Fibre and Damage Level on Service Life of SFR Recycled Concrete in Aggressive Environment

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Abstract: The paper presents a numerical calculation of the service life of concrete structures considering the effect of chlorides in the case of the material properties of structural lightweight waste aggregate concrete. Different amounts of fibres (0.0%, 1.0%, and 1.5%) and different values of compressive preloading (0%, 50%, and 100% of the ultimate strength capacity-USC) were considered. The subject of the research was the comparison of the influence of the constant diffusion coefficient and the time-dependent diffusion coefficient regarding the service life of the selected structure. Nine groups of material characteristics in combination with two numerical models are compared. A time-dependent diffusion coefficient and maturation coefficient, which were determined based on long-term monitoring (up to 461 days), were accepted for the numerical modelling. Thanks to time-dependent parameters, it is possible to observe the results of the theoretical service life of the structure and the influence of the mentioned factors. The analysed structure can be considered as the upper layer of an industrial floor in a chemical plant. It is important to determine the theoretical service life at which the structure shall be inspected or replaced. The results, in general, show that a higher amount of fibres reduces the service life as well as the preloading of the structure. An exception was a mixture with 1% of fibre loaded to 50% USC, which shows a lower diffusion coefficient than the specimens without preloading.

Keywords: waste aggregate; service life; chloride; modelling; steel fibres; lightweight concrete

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1. Introduction

Currently, for predicting or designing the service life of reinforced concrete structures, one dominant deteriorating mechanism (carbonation, chloride penetration, etc.) is used, while the structures are always exposed to a complex simultaneous action of mechanical and environmental loads [1–3]. Therefore, if the combination of two or more loads occurs simultaneously or consecutively, the service life prediction determined for only one load is not realistic, and it is overestimated. It is of high interest to design a proper testing procedure and an adequate model for successful use in practice. It has been observed that in the compressed zone of bended beams the chloride ion penetration slowed down [4–6]. To provide more realistic tests of the simultaneous action of both phenomena, RILEM TC 246-TDC [7] has developed a method to determine the service life of concrete exposed to the combined action of chloride penetration and mechanical load (compression or tension). However, the method is based on constant penetration of the surface for several days and after the tests, the powders of the specific layers of concrete specimens are drilled and the chloride concentration is measured by a chemical method based on potentiometric titration. Therefore, the tests take a lot of time and are very labour demanding, moreover, they are also destructive. On the other hand, as the alternative to these tests, the damage in concrete can be monitored and measured also by electrical resistivity techniques [8–10], which is non-destructive and can capture the time-dependent variables.

Structural lightweight waste aggregate concrete (SLWAC), which is the subject of testing in this project, was designed in the laboratory of Koszalin University of Technology to examine the possibility of using the waste red ceramic fine aggregate as a replacement for conventional aggregate [11]. The final mixture consists of the mentioned red ceramic fine aggregate, expanded clay coarse aggregate, cement, water and is reinforced by copper coated crimped fibre in various amounts. It should be noted that the aggregates were pre-soaked. The mechanical characteristics were tested and discussed in the contribution [12]. The research about the service life of this type of concrete in an aggressive environment followed and is described in [13]. In the paper [14], the relationship of surface and bulk electrical resistivity was determined for SLWAC, also in the case of mechanically damaged and reinforced specimens. The measured bulk resistivity is used in this project to calculate the concrete's diffusion coefficient.

Due to the very high porosity of the concrete, it is not surprising that the concrete does not stand out in terms of service life and cannot be used as the main structural member of the typical construction that appears in the aggressive environment (bridges, sea pier, floor, etc.). However, less quality light material made of waste could be used as a temporary part of a construction. A numerical calculation of the service life of concrete structures with respect to the action of chlorides [15] combinate with the material properties of SLWAC with different amounts of fibres and different values of preloading is presented. The time-varying diffusion coefficient and maturation coefficient were determined based on long-term monitoring (up to 461 days). Therefore, it is possible to observe the results of the theoretical service life of the structure and the influence of the above-mentioned factors. A typical numerical example was prepared for comparing individual groups of input values. The analysed structure can be considered as a covering layer of a bridge structure exposed to chlorides from de-icing salts, or it is possible to consider the structure as the upper layer of an industrial floor in a chemical plant. For both cases, it is important to determine the theoretical service life at which the structure shall be inspected or replaced. The subject of the research is the comparison of the constant diffusion coefficient and the time-dependent regarding the service life of the selected structure. Nine groups of material characteristics, which differ in the amount of fibre and preloading, in combination with two numerical models are compared.

2. Experimental Approach

Of the many factors that affect the service life of concrete and reinforced concrete structures, chloride can be considered as one of the most harmful. Chlorides enter the structure because of protection against freezing of roads in traffic, but they can also occur in industrial plants [16,17]. Chloride diffusion has a significant effect on the degradation of concrete, the initiation of corrosion of steel reinforcement, and other undesirable processes. Chloride penetration can be accelerated by cracks, but if cracks are missing, chloride diffusion is mainly dependent on the nature of the porosity [18,19]. However, the concrete in the structure is usually in a stress state, and therefore, it is necessary, to consider the effect of stress, loading, or damage simultaneously with environmental loading for the proper determination of the service life of the structure. Concrete is not an inert material and some of the ions react with the concrete matrix and become physically or chemically bound, which reduces the rate of diffusion. It should be noted that for this reason, only free chlorides are discussed here.

2.1. Samples and Mechanical Properties

As has been mentioned above, the studied mixture contains waste red ceramic fine aggregate (WRCFA) and expanded clay coarse aggregate (ECCA). Some of the tested specimens were also reinforced by copper coated crimped steel fibre (CCCSF) in various percentages. CCCSF cross-section is circular. Diameter is 0.73 mm, length is 30.8 mm, fibre intrinsic efficiency ratio is 169.4, density is 7800 kg/m^3 and ultimate tensile strength is determined as 1.7 $\pm$ 0.3 GPa [12]. Concreting of all the samples analysed in this article was performed on 30 April 2019.

There are three types of mixtures that differ in the amount of fibre (V_f)—0.0%, 1.0%, and 1.5%. The volumes of added fibre represent the most common additions of steel fibre to concrete. Adding less than 0.5% of fibre does not influence concrete in a noticeable way. On the other hand, using more than 1.5% of fibre would require the utilization of an admixture or special mixing and compaction techniques. The mixture proportions are given in Table 1.

Table 1. Mixture proportions of a cubic meter of mixture [12].

Composition	Quantity (kg·m^{-3})	Absorbed Water (kg·m^{-3})
WRCFA-dry	378.38	322.33
ECCA-dry	247.07	138.98
Cement	320.49	-
CCCSF, V_f = 0.0%	0.0	-
CCCSF, V_f = 1.0%	78.0	-
CCCSF, V_f = 1.5%	117.0	-

The specimens for testing of the mechanical characteristics were prepared and tested in the laboratories of Koszalin University of Technology and some other testing data have been presented in earlier publications [12–14]. The resulting information from basic mechanical tests is summarized in Table 2.

Table 2. Mechanical characteristics.

V_f	0.0%	1.0%	1.5%
Compressive strength (MPa)	15.4	14.7	17.1
Splitting Tensile Strength (MPa)	1.7	1.9	2.2
Static Modulus of Elasticity (GPa)	8.2	8.9	9.6
Dynamic Modulus of Elasticity (GPa)	12.9	13.2	13.5
Flexural tensile strength (MPa)	1.4	1.7	1.6
Shear Strength (MPa)	2.2	2.3	2.6

The specimens for the durability tests were cast in the form of three cylinders of every type of mixture for standardized resistivity measurements and three plates of every type of mixture, which were loaded by compression to 0%, 50%, and 100% of ultimate strength capacity (USC) 120 days after casting (28th August 2019). These plates were then cut into three pieces horizontally with the applied load for the purposes of bulk resistivity testing, which has been carried out 461 days after casting (3rd August 2020) in the laboratory of Technical University in Ostrava.

The dimensions of the specimens are described in detail in [14] together with the description of the process of resistivity measurements, which is also the content of the following chapter. The aim is to evaluate the amount of fibres and the effect of mechanical load on the results of electrical measurements and subsequently on the service life calculations on the selected example. Thus, three groups of different amounts of fibres (0.0%, 1.0%, and 1.5%) were combined with three values of different preloading (0%, 50%, and 100%), resulting in nine groups of samples (see Table 3).

Table 3. Marking of nine groups of examined samples.

Amount of Fibers	USC 0%	USC 50%	USC 100%
F 0.0%	USC 0% F 0.0%	USC 50% F 0.0%	USC 100% F 0.0%
F 1.0%	USC 0% F 1.0%	USC 50% F 1.0%	USC 100% F 1.0%
F 1.5%	USC 0% F 1.5%	USC 50% F 1.5%	USC 100% F 1.5%

2.2. Electrochemical Test Method

In addition to the basic material properties previously published for these concretes, the electrical resistance in time was analysed for the purposes of the introduction of the diffusion coefficient as an input value into the solved numerical example. Therefore, it was necessary to determine the diffusion coefficient for each of the nine groups separately at the same time (using volume resistivity for higher accuracy) and perform the measurements of concrete resistivity over the time for the calculation of time-dependent diffusion coefficient and the aging factor (using surface resistivity) for the three categories of samples according to the amount of fibres.

2.2.1. Surface Electrical Resistivity and Diffusion Coefficients

One of the first steps was to determine the properties related to the curing and improvement of concrete, as it has been shown that the diffusion of chlorides in concrete slows down over the time [20–22]. The surface electrical resistivity analysis of SLWAC is briefly presented in [14,23], where only measurements up to 91 days are included. Complete conductivity results for all groups include measurements at 8 time points (7, 14, 28, 51, 91, 161, and 461 days). A Wenner Probe [24] was used to measure the electrical resistance according to the procedure of AASHTO T358 [25].

The method is often used by our scientific team to analyse a wide range of types of concrete mixtures (see, for example, [26,27]) for obtaining the parameter describing the change of the diffusion coefficient in time-the aging factor (*m*-factor). This parameter is important in the calculation of the service life related to the effect of chlorides, as it describes the improvement in resistance of concrete in time.

As this method is non-destructive, it was possible to measure the electrical resistance in specific time points on the same samples with different amounts of fibre. Figure 1 shows the conductivity (opposite value to resistance) of the individual mixtures over time. It should be noted that the test results from this method are subject to some error rate, but it is very quickly feasible and is sufficient to describe the curing of concrete.

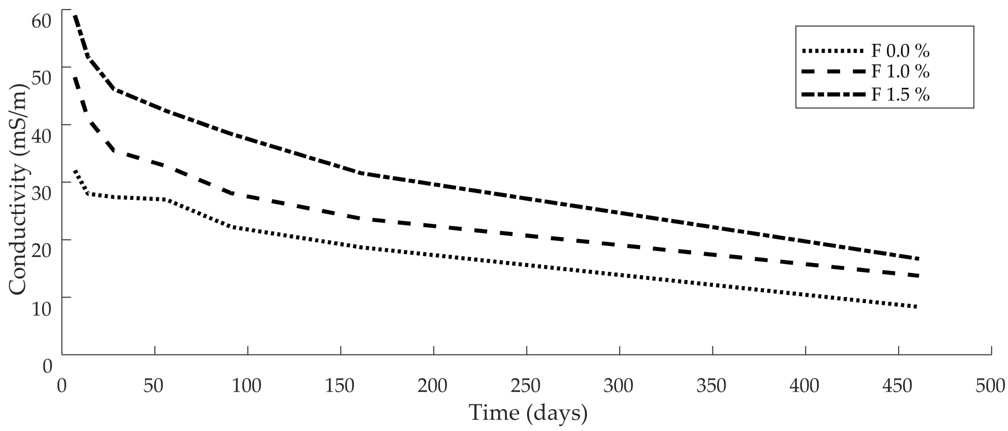

Figure 1. Conductivity of the SLWAC in time with different amounts of fibres.

For the three groups of concrete samples, which differ in the amount of fibre (F 0.0%, F 1.0%, and F 1.5%), three samples were always measured and analysed at the above-mentioned times. Therefore, it was possible to obtain a diffusion coefficient related to the specific time (see Table 4) by the Nernst–Einstein Equation (1), which expresses the relationship between the electrical resistivity and chloride diffusivity [27,28]:

$$D = \frac{RT}{Z^2F^2} \cdot \frac{t_i}{\gamma_i C_i \rho_{BR}} \quad (1)$$

where D is the diffusivity of the chloride ion ($m^2 \cdot s^{-1}$); R is the universal gas constant (J/K·mol); T is the absolute temperature (K); Z is the ionic valence (-); F is the Faraday constant (C/mol); t_i is the transfer number of chloride ion (-); γ_i is the activity coefficient for chloride ion (-); C_i (C/mol) is the concentration of ions i in the pore water, and ρ_{BR} is the bulk electrical resistivity (Ω·m).

Table 4. Diffusion coefficient [m^2s^{-1}] in time calculated based on surface resistivity measurements.

Time (Days)	7	14	28	56	91	161	461	*m* (-)
F0.0%	2.37	2.07	2.03	2.00	1.65	1.39	0.62	0.20
F1.0%	3.57	3.05	2.64	2.44	2.09	1.75	1.02	0.24
F1.5%	4.37	3.84	3.43	3.15	2.85	2.35	1.24	0.22

The *m*-factor shown in Table 4 was obtained by approximating Equation (2) [29,30] by the least-squares method [31,32].

$$D_{c,t} = D_{c,ref}\left(\frac{t_{ref}}{t}\right)^{m} \tag{2}$$

where $D_{c,t}$ is the apparent diffusion coefficient for a selected age (m^2/s), m is the aging factor (-) describing the reduction of diffusion coefficient over the time of measurement for concrete samples since casting t (years), while t_{ref} (years) is the age related to the diffusion coefficient $D_{c,ref}$ at the reference period.

2.2.2. Bulk Resistivity and Diffusion Coefficients

As a second step, it was necessary to measure and calculate the reference diffusion coefficient for all nine examined groups. Original research [14] has shown that there is a correlation between surface and bulk resistivity depending on the amount of fibre and the value of preloading. Furthermore, in the article was shown that the correlation factor is different for each group and therefore the volume resistivity of all groups was used separately. An RCON instrument [33] was used to determine the bulk according to ASTM C1760-12 [34] Figure 2 shows one of the samples tested by the instrument.

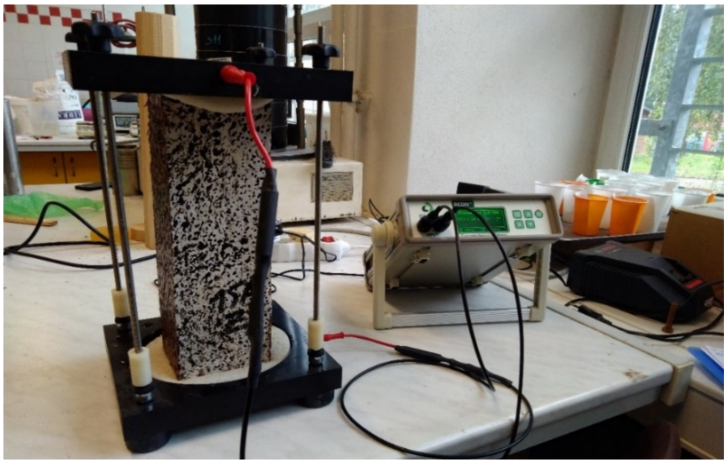

Figure 2. Testing of the bulk resistivity with RCON [14].

From the measured values of bulk resistance, the diffusion coefficients were obtained based on Equation (1). The results of diffusion coefficients at 461 days after concreting (3 August 2020) for all studied groups are shown in Figure 3. The standard deviation of the measurement is also displayed, it shows the degree of measurement inaccuracy from the average. The standard deviation for concretes with fibre is higher than for concretes without fibre, but it is not a significant phenomenon affecting the results of numerical models. It should be noted that within the diffusion coefficients, the difference is significant only when considering different decimal orders. However, it is not possible to directly deduce from the measured and calculated values which concretes will be more advantageous in terms of service life because it is necessary to combine the results with the aging factor on a numerical example.

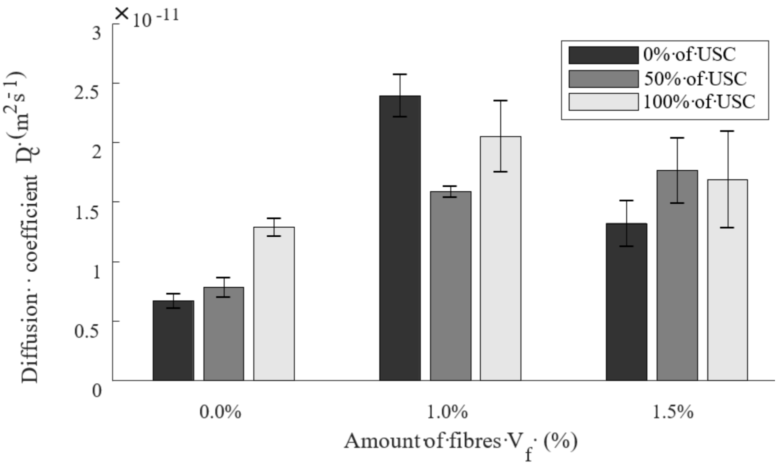

Figure 3. Results of diffusion coefficients at 461 days after concreting for all studied groups.

3. Numerical Analysis of Service Life Related to Chloride Increase

The numerical analysis scenario is set up to evaluate the possibilities of the application of the above-mentioned combination of material parameters and the Finite Element Analysis model presented in the contribution [15].

The penetration rate of chloride into concrete is generally modeled as a function of depth and time based on the second Fick's Law of Diffusion [15]:

$$\frac{\partial C(x,t)}{\partial t} = D_c \frac{\partial^2 C(x,t)}{\partial x^2} \tag{3}$$

where $C(x,t)$ is the chloride ion concentration (%) at a distance x from the surface of concrete in time t; D_c is effective diffusion coefficient (m^2/s), which characterizes the concrete ability to withstand the penetration of chlorides.

The chloride concentration is then compared to the chloride threshold C_{th} to obtain the year when corrosion can be theoretically initiated.

The difference is observed in the case of a model with a constant diffusion coefficient (obtained at 461 days-see Figure 3) and a model considering the maturation of concrete using Equation (2) and the *m*-factor (see Table 4). The calculation of the diffusion parameters given above is the same for every group.

The object examined in this example is a covering concrete slab exposed to the ingress of chloride, the cross-sectional dimensions of which are 1.0 m wide and 0.1 m high. The service life of the specified concrete layer related to the time of exceeding the threshold concentration throughout the whole depth of the layer was analysed. The numerical example was performed by a deterministic approach and the input parameters for the analysis are summarized in Table 5.

Table 5. Input parameters of numerical model.

Parameter Name	Value
Width (m)	1.0
Depth (m)	0.1
Chloride threshold for corrosion initiation C_{th} (%)	0.4 [35]
Concentration of chlorides at the surface C_0 (%)	0.6 [36]
Initial concentration of chloride in concrete C_b (%)	0
Monitored life span t (years)	100
Reference time (day)	461

The chloride threshold for corrosion initiation was adopted as a typical value of approximately 0.4%, based on long-term experience [35,37]. The diffusion coefficient and the aging factor depending on the amount of fibre also enter into the calculation for each group. Information about these input values is shown in Table 6. As has been mentioned above, for the first model only the constant diffusion coefficient was used as a reference, but for the second model, both the diffusion coefficient and the maturation factor were used.

Table 6. Constant diffusion parameters measured at 461 days and the aging factor determined in time.

MIX NAME	Diffusion Coefficient D_{cnom} ($m^2 \cdot s^{-1}$) × 10^{-11} (461 Days)	Aging Factor *m* (-) (461 Days)
USC 0% F 0.0%	0.67	0.20
USC 0% F 1.0%	2.39	0.24
USC 0% F 1.5%	1.32	0.22
USC 50% F 0.0%	0.78	0.20
USC 50% F 1.0%	1.59	0.24
USC 50% F 1.5%	1.76	0.22
USC 100% F 0.0%	1.29	0.20
USC 100% F 1.0%	2.05	0.24
USC 100% F 1.5%	1.69	0.22

4. Results of Service Life and Discussion

Based on the two numerical models it was possible to obtain the course of the value of chloride concentration over time. In Figures 4 and 5 it is possible to compare the courses of all analysed mixtures.

Considering the constant diffusion coefficient, the increase in chloride is faster and therefore, the chloride threshold value is exceeded faster. Different mixtures show different curve shapes and thus different service life in the analysed case. The fastest increase is shown by the USC 0% F 1.0% curve and the best curve shape, in terms of service life, is the USC 0% F 0.0%. It is also interesting to compare the percentage differences of both models for each mixture, which is shown in Table 7 together with the hypothetical service life. The best mixture USC 0% F 0.0% also has the biggest difference between the constant model and the time-dependent model.

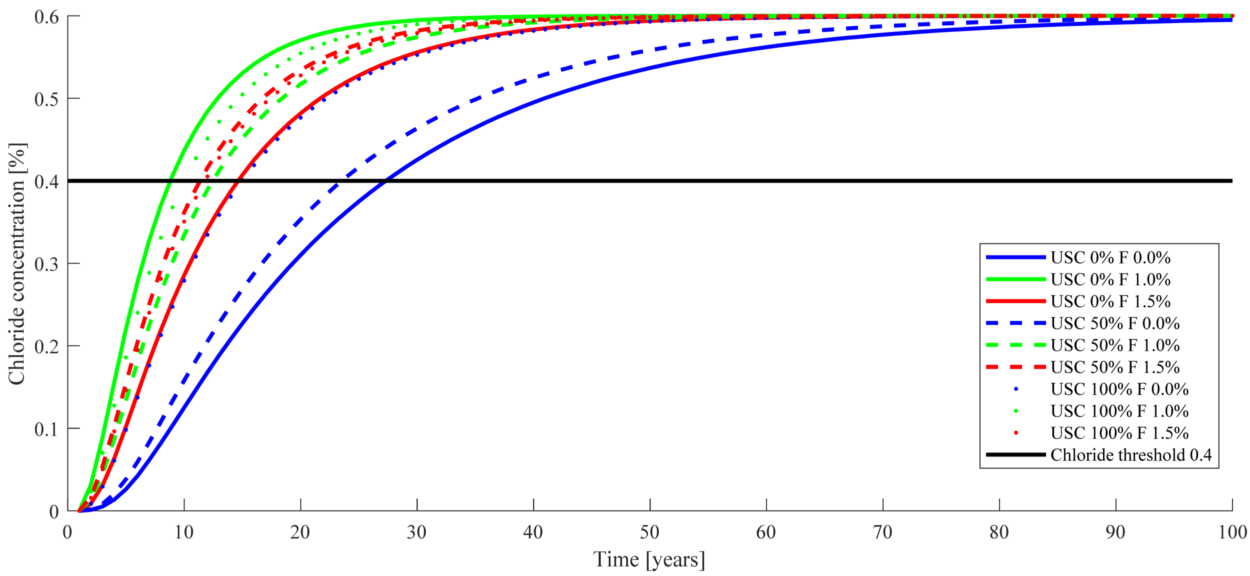

Figure 4. Chloride concentration over time regarding the constant diffusion coefficient.

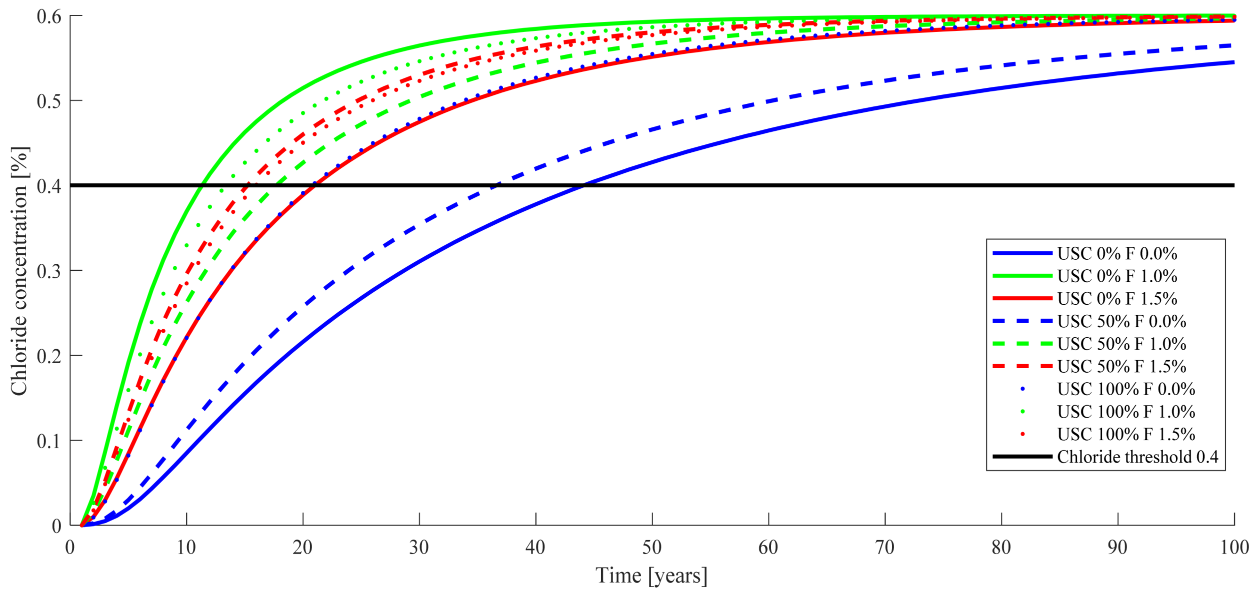

Figure 5. Chloride concentration over time regarding the time-dependent diffusion parameters.

Table 7. Results of service life-time exceeded the threshold concentration.

Mix Name	SL for Constant Coefficient t_i (Year)	SL for Time-Dependent Coefficient t_i (Year)	Difference
USC 0% F 0.0%	27.6753	44.89	62%
USC 0% F 1.0%	23.4536	36.39	43%
USC 0% F 1.5%	14.0349	20.21	53%
USC 50% F 0.0%	8.1752	11.66	55%
USC 50% F 1.0%	12.5336	17.27	38%
USC 50% F 1.5%	10.9916	13.64	36%
USC 100% F 0.0%	14.3582	21.99	44%
USC 100% F 1.0%	11.6244	15.76	24%
USC 100% F 1.5%	11.2032	15.04	34%

The results of the expected service life according to individual groups are displayed in the graph (see Figure 6), therefore, we can analyse the effect of the number of fibre and preloading. The USC 0% F 0.0% mixture shows the best values in terms of service life associated with chloride penetration (44.89 years). Based on the results from both models, a higher number of fibres shortens the service life, but for the model without preloading, the value is higher for USC0% F 1.5% than USC0% F 1.0%. This correlates with the fact that F 1.0% has a lower compressive strength than F 1.5%. However, a better result is observed for the USC 50% F 1.0% sample than for the USC 50% F 1.5% sample.

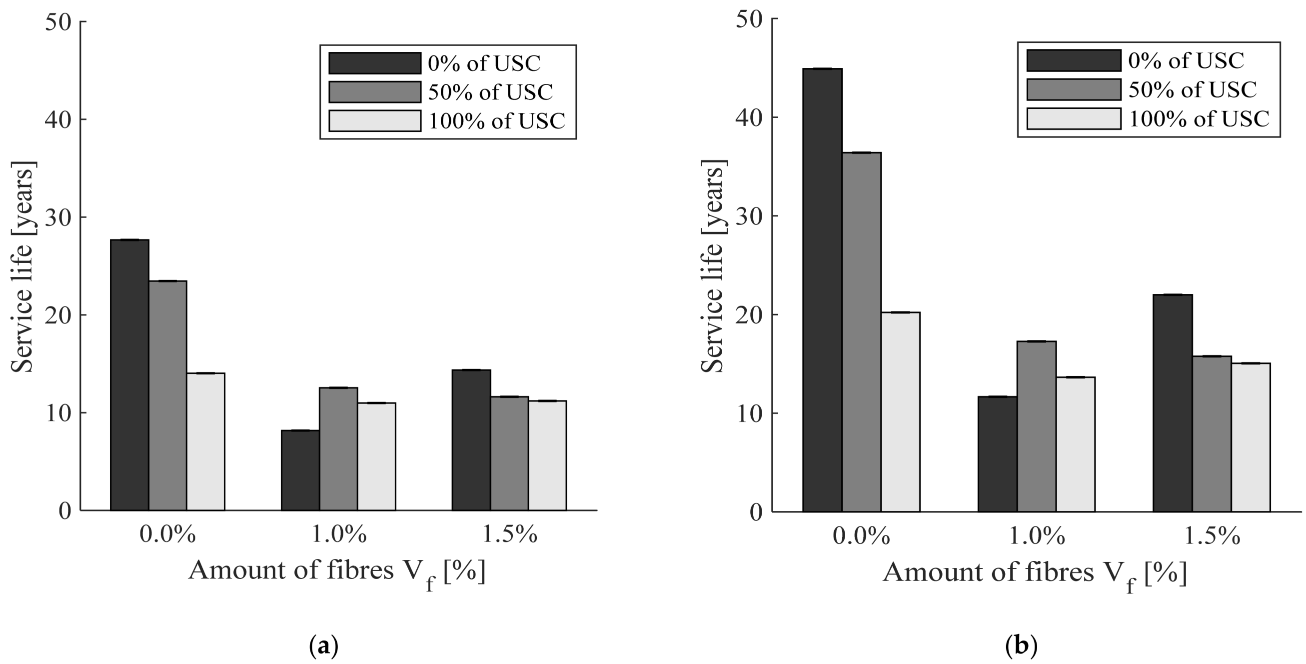

Figure 6. The service life regarding (**a**) the constant diffusion coefficient and (**b**) the time-dependent diffusion coefficient.

5. Conclusions

Two numerical models for the computation of service life of concrete structure related to the effect of chlorides in a combination with a laboratory obtained material properties of structural lightweight waste aggregate concrete with different amounts of fibres (0.0%, 1.0%, and 1.5%) and after different values of preloading (0%, 50% and 100% of USC) were presented.

The first model considers the constant diffusion coefficient, and the second model uses the time-dependent diffusion coefficient calculated with the determined aging factor. The article shows a possible procedure for the analysis of various mixtures. The following conclusions were drawn from the results:

- the USC 0% F 0.0% mixture, which is concrete without fibre and without preloading, shows the best results in terms of service life associated with chloride penetration,
- the USC 0% F 1.0% mixture, which is concrete with 1% of fibre and without preloading, shows the worst results,
- the preloading negatively affects the service life, except for the group with 1% of fibre, where the service life is slightly higher when the preloading is considered,
- differences in variability are significant despite the small differences in basic material properties, for example, compressive strength,
- mixtures reinforced by fibre show lower service life than the mixture without fibre,
- the hypothetical service life is approximately 40% longer if the time-dependent diffusion parameters are considered,
- the value of the diffusion coefficient does not correspond to all results of service life if a time-dependent model with a maturation factor is considered.

It is possible to present and also verify other models for the determination of the service life and service life of reinforced concrete structures. It is also possible and highly encouraged to perform the probabilistic analysis for the verification of the results by including the standard deviations.

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