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Research paper

COMPARATIVE ANALYSIS OF ASTM C1202 AND SRPS EN 12390-18 TESTING METHODS FOR ASSESSING CHLORIDE ION PENETRATION IN CONCRETE SUPPLEMENTED WITH RECYCLED CRT GLASS AS CEMENTITIOUS MATERIAL

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Abstract

Durability is crucial for reinforced concrete, directly influencing the service life of structures. The presence of aggressive agents, especially chloride ions, significantly impacts durability. This study investigates the differences between ASTM C1202 and SRPS EN 12390-18 standards in concrete supplemented with recycled CRT glass as cementitious material. The percentage of replacement of cement with glass is: 10% and 20%, by mass. In addition to fresh state testing, the following mechanical tests were also performed: compressive strength and splitting tensile strength. The aim of this research was to determine how the addition of finely ground cathode glass affects the resistance of concrete to chloride penetration, as well as to compare the results of chloride penetration after conducting two standardized but completely different test procedures. A review of the literature revealed very few comparative tests of chloride penetration according to the mentioned standards.

Key words: *CRT glass, comparative analysis, chloride ion penetration, mechanical characteristics*

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1. INTRODUCTION

Cathode ray tube (CRT) glass contains significant amounts of heavy metals, such as lead, making it hazardous if not disposed of properly. Consequently, advancements in safe processing and decontamination technologies enable recycling facilities to handle CRT glass with minimal environmental impact. Increasing environmental awareness also influences public behavior, further encouraging collection efforts—meaning that even if the total amount of waste declines, the systematically collected material can grow as a larger portion of available older electronic waste is properly recovered.

The use of supplementary cementitious materials (SCMs) in concrete brings environmental and practical benefits, such as reducing industrial waste and promoting sustainable production. However, their effectiveness must be proven through key performance factors, like pozzolanic reactivity, strength improvement, and long-term durability. One crucial test in this process is assessing chloride ion penetration, which helps determine how well concrete can withstand corrosion—particularly in harsh conditions like marine environments or areas exposed to de-icing salts, where embedded steel reinforcement faces significant risks.

The most widely used methods for testing chloride penetration include the standardized approach established by the American Society for Testing and Materials (ASTM) C1202 [1] and the method developed in Finland - NT Build 492 [2]. When it comes to domestic regulations in this area, the first standard SRPS EN 12390-18 [3] was published in 2021. The latest standard currently in force in our country carries the designation SRPS EN 12390-18:2024 [4].

Roz-Ud-Din Nassar and colleagues [5] from the University of Michigan researched the strength and durability of concrete made with recycled concrete aggregate and cement partially replaced with milled waste glass. The waste glass used in the experiment came from collected glass packaging of various colors and was ground to an average fineness of 19 µm. Five concrete mixtures were prepared with a water-to-binder ratio of 0.38. The authors found that the inclusion of milled waste glass resulted in a 54% reduction in the number of coulombs passed through concrete specimens containing 100% recycled aggregate compared to corresponding specimens without milled waste glass. Concrete containing milled waste glass as a partial cement replacement demonstrated improved resistance to chloride ion penetration, with slightly over 2000 coulombs passed in testing. This enhanced durability is attributed to the pozzolanic reactions of milled waste glass, which refine pores, block pathways, and fill voids, thereby reducing the conductivity of pore fluid and limiting ion movement. Due to this increased resistance, such concrete is well-suited for infrastructure like bridge decks, pavements, and parking lots that regularly face chloride-induced damage from deicing salts [5].

Ahmed Omran and colleagues [6] investigated the long-term effects of incorporating recycled glass as a partial cement replacement on the properties of concrete used in various structural elements in Canada. The replacement percentage ranged from 10% to 30% by mass. During in-situ construction, one element was made with concrete containing glass, while another was made with conventional concrete. Additionally, two concrete mixtures were prepared in a laboratory to examine properties at 28 and 91 days, comparing modified concrete with a reference mix without glass. Between 2013 and 2016—2.1 to 6.7 years after concrete placement—core samples were extracted for various tests, including chloride penetration resistance assessments. The results from real-world conditions were then compared with laboratory findings. The study found that concrete mixes containing glass powder (GP) exhibited better resistance to chloride ion penetration compared to conventional concrete mixes. Reference mixtures without GP had higher permeability, with values of 4815 C and 3815 C, indicating susceptibility to chloride attack. In contrast, GP-modified mixes demonstrated significantly lower permeability, with values of 360 C, 660 C, and 280 C, falling below 1000 C according to ASTM C1202. This improvement is attributed to the pozzolanic reactions of GP, which generate additional hydration products and densify the concrete's microstructure over time, enhancing its durability against chloride-induced deterioration [6].

Ablam Zidol and colleagues [7] also examined the resistance of concrete to chloride exposure when part of the cement was replaced with different supplementary cementitious materials (SCMs), including finely ground glass packaging (GP), fly ash (FFA), and ground granulated blast furnace slag (GGBS). Multiple series of mixes were prepared with varying water-to-binder ratios ranging from 0.35 to 0.65. The average particle size of cement was 14.9 µm, while the glass, fly ash, and slag had average particle sizes of 10.9 µm, 9.2 µm, and 8.4 µm, respectively. The study found that concrete with 30% supplementary cementitious materials (SCMs) has significantly lower permeability—ranging from 2 to 6 times less than conventional concrete—depending on the water-to-binder ratio following ASTM 1202 standards. This reduction is attributed to various reaction mechanisms, including the filler effect, pozzolanic reactions, and the ability of mineral additives to bind chloride ions. While different SCMs led to similar permeability improvements, the concrete incorporating 30% glass powder exhibited the lowest permeability values, highlighting its superior performance in reducing chloride ion penetration.

A review of the literature revealed that there was lack of the studies in which the testing of chloride penetration on concretes with the addition of waste glass was conducted according to the provisions of the EN standard. A notable gap in research is the lack of comparative studies examining chloride penetration resistance according to both EN and ASTM standards. This study investigates the differences between ASTM C1202 and SRPS EN 12390-18 standards in concrete supplemented with recycled CRT glass as cementitious material. The percentage of replacement of cement with glass is: 10% and 20%, by mass.

2. PROCEDURE OF CHLORIDE ION PENETRATION TESTING ACCORDING TO EN 12390-18 AND ASTM C1202

According to the EN 12390-18, migration cells are positioned relative to the sample as shown in Figure 1. The reservoir of the migration cell is filled with a 5% NaCl solution and connected to the anode (negative charge), while the other cell is filled with either NaOH or KOH solution and connected to the cathode (positive charge). The duration of the test depends on the electrical resistance of the sample. Since the chloride migration coefficient (Mnss) is unknown at the start, the initial voltage should be 30 ± 0.2 V. Depending on the measured current strength at 30 V, this voltage can be maintained throughout the test. After the electric current has been applied for the specified duration, the samples are split in half parallel to the chloride penetration direction. Both halves are sprayed with a silver nitrate ($AgNO_3$) aqueous solution, causing the portion of the concrete affected by chloride penetration to change color. The chloride penetration depth is measured at nine points, with an accuracy of 1 mm (xd1, xd2, ... hd9) using a caliper gauge. When measuring, the edges of the sample within 10 mm from its sides should not be considered.

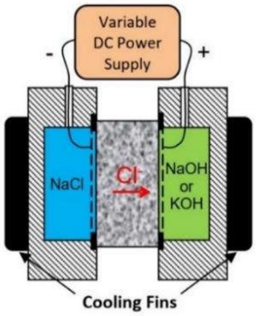

Figure 1. Schematic appearance of the chloride penetration test through a concrete sample

The chloride migration coefficient is calculated according to the equation from standard EN 12390-18. According to the SRPS U.M1.206 standard, section 5.3.2, concrete can be classified into one of three resistance classes, provided that the calculated individual values and the average migration coefficient meet the criteria specified in Table 1.

Table 1. Criteria for assessing the resistance of concrete to chloride penetration are defined based on the chloride migration coefficient [8]

Exposure class	Resistance class	Criterion	
		Value	Chloride migration coefficient
XD1	CL-1	Average	$\leq 15.0 \cdot 10^{-12}$ m^2/s
		Single	$\leq 18.0 \cdot 10^{-12}$ m^2/s
XD2	CL-2	Average	$\leq 10.0 \cdot 10^{-12}$ m^2/s
		Single	$\leq 12.0 \cdot 10^{-12}$ m^2/s
XD3	CL-3	Average	$\leq 7.0 \cdot 10^{-12}$ m^2/s
		Single	$\leq 9.0 \cdot 10^{-12}$ m^2/s

The ASTM C1202 test method covers the determination of the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions. This test method is applicable to types of concrete where correlations have been established between this test procedure and longterm chloride ponding procedures such as those described in AASHTO T 259. The concrete sample is cut into cylindrical discs with a diameter of 100 mm and a thickness of 50 mm. The sides of the sample are coated with an epoxy layer to prevent lateral ion penetration and ensure controlled migration through the specimen. The sample is placed in a vacuum chamber for 3 hours to remove air from the concrete pores. Afterward, it is submerged in deionized water for 18 hours to achieve full pore saturation. This sample conditioning process is almost identical to the conditioning specified by the European standard SRPS U.M1.206. This method consists of monitoring the amount of electrical current passed through 50-mm thick slices of 100-mm nominal diameter cores or cylinders during a 6 hours period. A potential difference of 60 V direct current is maintained across the ends of the specimen, one of which is immersed in a 3% NaCl solution (30 g NaCl in 970 g of water), the other in a 0.3 N NaOH solution (12 g NaOH in 1 liter of distilled or deionized water). The total charge passed, in coulombs, has been found to be related to the resistance of the specimen to chloride ion penetration. According to appendix of the standard C1202 qualitative indications of the chloride ion penetrability based on the measured values from this test method are provided in Table 2. These values were developed from data on slices of cores taken from laboratory slabs prepared from various types of concretes.

Table 2. Chloride ion penetrability based on charge passed [1]

Charge Passed (coulombs)	Chloride Ion Penetration
> 4000	High
2000 – 4000	Moderate
1000 - 2000	Low
100 – 1000	Very Low
<100	Negligible

From the previously described chloride penetration testing procedures according to European and American standards, it can be observed that the preparation and conditioning of test specimens itself are practically identical. The key difference lies in the applied voltage and the duration of the test. Additionally, in the European standard, calculating the migration coefficient requires measuring both the average and maximum chloride ion penetration. In contrast, the American standard does not involve splitting the specimen; instead, the assessment of concrete resistance to chloride ingress is based on the charge passed (in coulombs) during a six-hour examination.

3. MATERIALS AND METHODS

3.1. USED MATERIALS

For the production of the experimental concrete series, pure Portland cement CEM I 52.5R from Moravacem Novi Popovac was used, meeting all quality requirements outlined in EN 196-1, EN 196-3, EN 196-6, and EN 197-1 standards. The first fraction of river aggregate (0/4 mm) was sourced from the Trans DN Kop separation in Čapljinac, while two fractions of crushed aggregate (4/8 mm and 8/16 mm) were obtained from Bisina, Raška. The granulometric composition of the aggregate mixture is presented in Figure 2.

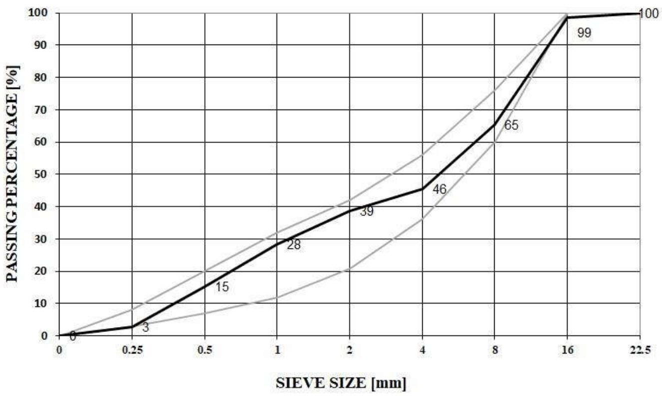

Figure 2. Granulometric composition of aggregate mixture

The CRT glass used in the concrete mixture was supplied by the recycling center Jugo - Impex E.E.R. d.o.o. from Niš. The cathode glass was finely ground using a laboratory ball mill to ensure complete passage through a 0.063 mm sieve. The chemical composition of finely ground CRT glass and cement is presented in Table 3. To enhance the workability of the concrete, a superplasticizer commercially known as MC-PowerFlow Evo 580 was incorporated into the mixture. This latest-generation MC superplasticizer is designed for high rheological demands in transport concrete and has a specific mass of 1.05 g/cm³. Finally, water from the municipal supply was used in the preparation process.

Table 3. Chemical composition of cathode ray tube glass and cement CEM I 52.5R

Binder	Chemical Compound							
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3
CRT glass	60.61	2.88	0.58	1.31	0.53	6.45	7.61	0.09
Cement	19.30	4.28	2.87	62.8	2.22	0.91	0.21	3.05

3.2. Plan and program of testing

The following tests were conducted on fresh concrete:

- Slump test (EN 12350-2 [9])
- Density (EN 12350-6 [10])
- Air content - Pressure methods (EN 12350-7 [11]).

The following tests were conducted on hardened concrete:

- Compressive strength (EN 12390 – 3 [12])
- Chloride ion penetration (EN 12390-18 [4] and ASTM 1202 [1]).

Special attention was given to the blending of cement and the appropriate amount of finely ground cathode glass before preparing each concrete batch. For this purpose, a container of suitable volume with a lid, a mixer, and a specialized attachment (Figure 3) were used. The mixing process lasted for 5 minutes, with the specialized attachment operating at 850 revolutions per minute.

Figure 3. The container and special attachment for mixing cement and glass

3.3. Concrete mixture composition

Three experimental concrete mixtures were prepared (Table 4). In addition to the reference mixture, which was made using only PC 52.5 R, two additional mixtures were produced where a partial replacement of cement with finely ground glass was implemented.

The percentage of cement replacement with CRT crushed glass was 10% and 20%, based on the mass of the cement. The series labels with the glass addition were formed by combining the abbreviation for cathode ray tube glass (CRT) and the percentage of cement replacement with the glass. The target slump class for all concrete mixtures was S4 (minimum slump 160 mm), achieved by applying a chemical additive from the superplasticizer group.

Table 4. Composition of experimental concrete mixtures

Concrete	Aggregate			Cement	CRT	Water	w/b	Additive
	0/4 mm	4/8 mm	8/16 mm	CEM I 52.5 R	<0.063 mm	City Wat. Supply	-	Super-plasticizer
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	-	kg/m^3
Reference (R)	840	375	655	360	-	175.0	0.486	2.52
CRT10	840	375	655	324	36	175.0	0.486	2.52
CRT20	840	375	655	288	72	175.0	0.486	2.52

4. EXPERIMENTAL RESULTS AND DISCUSSION

The slump test results are in the range from 160 mm to 170 mm, class S4, which was the goal when designing concrete mixtures. The results of fresh concrete density and air content testing are shown in Figure 4. The density of fresh reference concrete was 2386 kg/m³, while the concrete with 10% cement replacement by glass exhibited a slight increase of approximately 1%, reaching 2408 kg/m³. The air content in both the reference mix and CRT10 was 3.5%, exceeding the typical value of 2%. Given that no air-entraining additives were used, it can be inferred that the superplasticizer itself contributes to increased air entrainment in the mix.

More pronounced changes in these properties were observed when 20% of the cement was replaced with glass. Specifically, the CRT20 series exhibited a significantly lower density of 2321 kg/m³, directly linked to increased air content in the concrete mixture. The average air content in CRT20 reached 6.5%, which is considerably higher than the expected range.

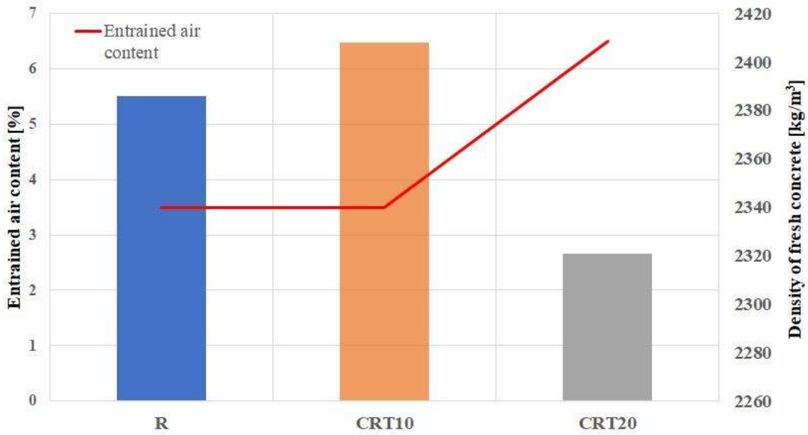

Figure 4. Density and air content of fresh concrete

These notable variations in fresh concrete properties due to CRT powder addition do not align with previous findings from the authors' earlier research [13]. In study [13], where cement replacement by glass reached 35%, only a slight decrease in bulk density (-1%) was observed compared to the reference mix, while changes in air content remained within the resolution limit of the porosimeter device. Further testing is necessary to provide a clearer explanation for the significant air entrainment observed in the CRT20 concrete mix.

For the compressive strength tests, digital, hydraulic press "UTEST UTC - 5740" measuring range 0 - 3000 kN and accuracy class 0.5% is used. Test are conducted at the concrete age of 7 and 28 days. Figure 5 provides the graphic presentation of achieved compressive strengths of concrete mixtures in time.

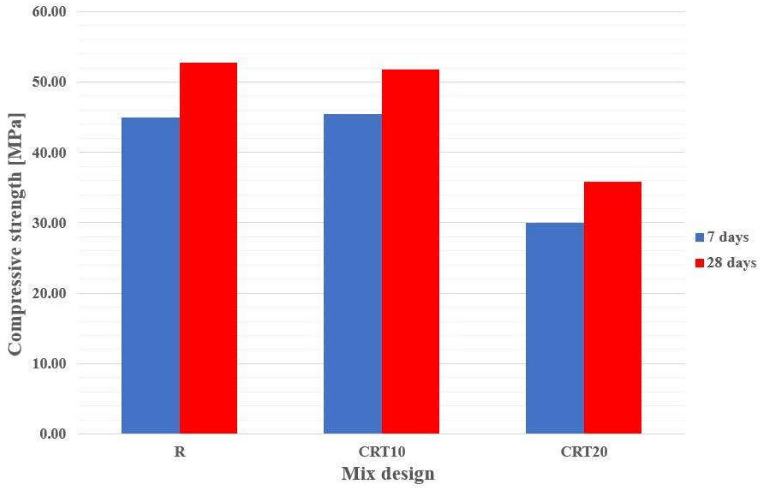

Figure 5. Graphic presentation of achieved compressive strengths of concrete series in time

Replacing 10% of cement with recycled glass did not significantly reduce the compressive strength of concrete during testing at 7 and 28 days compared to the reference mix. However, the CRT20 series exhibited a notable decrease in compressive strength, with reductions of 33% and 38%, respectively, at these ages. This drastic strength loss is primarily attributed to the high amount of entrained air in the concrete mixture. Based on the authors' previous research, it is anticipated that the difference in compressive strength between CRT20 and the reference mix will be somewhat less pronounced at 90 days. This is due to the pozzolanic reaction, which occurs later than the cement hydration process and becomes most intense after 28 days. The obtained results align with the findings of Aliabdo et al. [14], who concluded that replacing up to 10% of cement with glass does not negatively impact compressive strength at later concrete ages.

The results of the chloride migration coefficient M and charge quantity Q at a concrete age of 28 days are presented in Table 5. Based on the test results, it can be concluded that with the increase in the level of cement replacement with CRT glass, there is an increase in the depth of chloride ion penetration, which is directly related to the increase in the migration coefficient value. Based on the individual and average values of the migration coefficient and criteria from Table 1, referent concrete series and CRT10 can be classified to resistance class CL-2. Furthermore, CRT20 belongs to lowest resistance class CL-1. Unfortunately, the obtained results are not consistent with the research results [15-17].

Table 5. Results of chloride penetration testing according to EN 12390-18 and ASTM C1202

Mix design	Sample Designation	Chloride migration coefficient M_{nss} [m^2/s]	Average chloride migration coefficient $M_{nss,\ average}$ [m^2/s]	Charge passed Q [C]	Average charge passed $Q_{,average}$ [C]
R	R1	$9.2\cdot10^{-12}$	$8.9\cdot10^{-12}$	2149	2131
	R2	$8.3\cdot10^{-12}$		2298	
	R3	$9.1\cdot10^{-12}$		1945	
CRT10	CRT10/1	$9.0\cdot10^{-12}$	$9.7\cdot10^{-12}$	2245	2258
	CRT10/2	$9.6\cdot10^{-12}$		2362	
	CRT10/3	$10.5\cdot10^{-12}$		2168	
CRT20	CRT20/1	$11.4\cdot10^{-12}$	$11.4\cdot10^{-12}$	2265	2205
	CRT20/2	$10.0\cdot10^{-12}$		2181	
	CRT20/3	$12.9\cdot10^{-12}$		2170	

When it comes to the charge passed results, we can see that the results for all three concrete mixtures are fairly uniform. According to the criteria in Table 2, the chloride penetration can be descriptively classified as 'moderate' for all mixtures. There is no direct correlation that connects the chloride ion migration coefficient with the charge quantity. Both parameters are influenced by numerous factors, the most significant of which are: water-cementitious materials ratio, type and quantity of supplementary cementitious materials in the concrete mixture, the presence of polymeric admixtures, ionic solutions of admixtures like calcium nitrite, specimen age, air-void system, aggregate type, degree of consolidation, and type of curing. For the specific composition of the concrete mixture and the levels of cement replacement with cathode glass of 63 μm fineness (Table 4), as well as for the obtained chloride penetration results according to EN and ASTM standards (Table 5), a dedicated curve was established to represent the dependency between the migration coefficient and total charge quantity, as shown in Figure 6. This is a logarithmic function with a correlation coefficient of $R^2 = 0.82$. To determine a more precise dependency, a comparative study on a larger number of samples needs to be conducted. A sufficient number of concrete samples were set aside for chloride penetration testing at 90 days, aiming to assess whether the pozzolanic reaction of the glass by that stage enhances the concrete's resistance to chloride ingress.

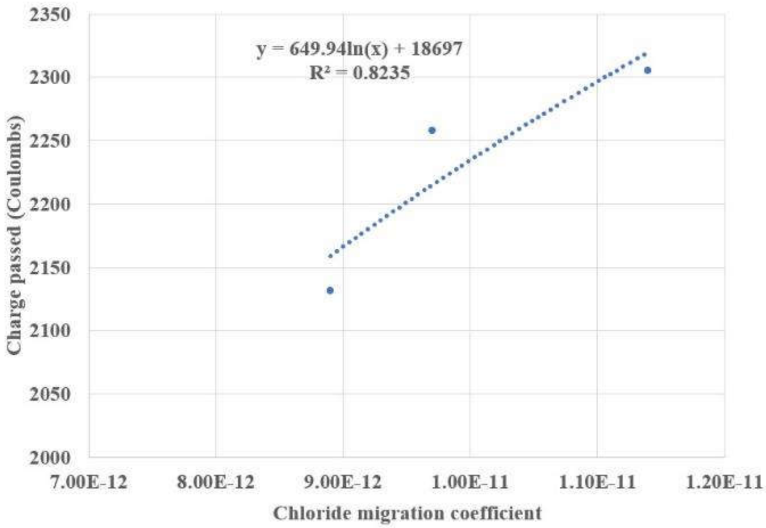

Figure 6. Logaritham function between chloride migration coefficient and charge passed

5. CONCLUSIONS

Based on the obtained experimental results, a number of conclusions can be drawn:

- The replacement of cement with ground CRT glass up to a level of 10% insignificantly affects the fresh concrete's volume density, as well as the percentage of entrained air. The CRT20 concrete mixture had a low volume density value of only 2321 kg/m³ and an entrained air content of as much as 6.5%.
- Replacing 10% of the cement with recycled glass slightly reduced the compressive strength of the concrete when tested at 7 and 28 days compared to the reference concrete. The CRT20 series, at the aforementioned ages, had 33% and 38% lower strength compared to the reference series.
- Based on the determined resistance classes of the experimental concrete series, it can be concluded that the reference concrete and the CRT10 mixture satisfy the XD2 exposure class, while the CRT20 series satisfies the XD1 exposure class.
- The charge passed value is uniform for all three concrete mixtures according to ASTM C 1202, while the level of chloride penetration can be characterized as "moderate" according to the annex of the mentioned standard.
- The logarithmic relationship has been established between the migration coefficient and charge passed, with a correlation coefficient of 0.82.
- A sufficient number of concrete samples were set aside for chloride penetration testing at 90 days, aiming to assess whether the pozzolanic reaction of the glass by that stage enhances the concrete's resistance to chloride ingress.

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