Trabajo de Investigación

3

Mechanical Performance And Durability Of LC3 Cement In Social Housing Using Non-Standardized Aggregates In Mexico.

Rendimiento Mecánico Y Durabilidad Del Cemento LC3 Con Agregados No Estandarizados Usado En Viviendas Sociales En México.

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Mechanical Performance And Durability Of LC3 Cement In Social Housing Using Non-Standardized Aggregates In Mexico.

Abstract

The study evaluates LC3 cement (calcined clay, limestone, and clinker) in social housing in Mexico, empha-sizing its sustainability and technical performance. Conducted in La Perla, Veracruz, in collaboration with Holcim and HPH Mexico, LC3 was compared with conventional Portland cements. Results showed that LC3 achieved mechanical strengths comparable to Portland at 28 days, with 40% lower CO_2 emissions. It also exhibited superior durability in ag-gressive environments (low chloride permeability: 100–2000 Coulombs; electrical resistivity: 10–50 kΩ·cm). Howev-er, non-standardized local aggregates (irregular gradation and high fines content) increased water demand (w/c ratio up to 0.63) and limited final strength. The study concludes that LC3 is a viable alternative for sustainable projects, pro-vided local aggregate quality and construction practices are optimized.

Keywords: LC3 cement, Social housing, Sustainability, Durability.

Resumen

El estudio evalúa el cemento LC3 (arcilla calcinada, piedra caliza y clínker) en vivienda social en México, haciendo hincapié en su sostenibilidad y desempeño técnico. Realizado en La Perla, Veracruz, en colaboración con Holcim y HPH México, se comparó el LC3 con cementos Portland convencionales. Los resultados mostraron que el LC3 alcanzó resistencias mecánicas comparables a las del Portland a los 28 días, con un 40% menos de emisiones de CO_2. También exhibió una durabilidad superior en ambientes agresivos (baja permeabilidad a cloruros: 100–2000 Culombios; resistividad eléctrica: 10–50 kΩ·cm). Sin embargo, los áridos locales no normalizados (gradación irregular y alto contenido de finos) aumentaron la demanda de agua (relación a/c hasta 0,63) y limitaron la resistencia final. El estudio concluye que el LC3 es una alternativa viable para proyectos sostenibles, siempre que se optimice la calidad de los áridos locales y las prácticas constructivas.

Palabras Clave: Cemento LC3, Vivienda social, Sostenibilidad, Durabilidad.

Nota Editorial: Recibido: 29 de enero 2026 Aceptado: 23 de marzo 2026

1. INTRODUCCIÓN

The construction industry faces an unprecedented environmental crisis, derived mainly from the production of Portland cement, responsible for 8% of global CO_2 emissions[1]. This material, a pillar of modern infrastructure, generates approximately 900 kg of CO_2 per ton manufactured, due to the decarbonation of limestone and intensive consumption of fossil fuels [2], [3]. In developing countries, such as Mexico, where the demand for social housing exceeds 500,000 units annually [4], reliance on traditional cement aggravates the sector's carbon footprint, urgently requiring sustainable alternatives.

In this context, low-carbon cements, such as LC3 (Limestone Calcined Clay Cement), emerge as promising solutions. LC3, composed of calcined clays (30%), limestone (15%) and reduced clinker (50%), decreases CO_2 emissions by up to 40% compared to Portland, while maintaining comparable mechanical properties [5], [6]. Its effectiveness has been validated in Cuba, where pilot projects demonstrated 28-day strengths between 25-35 MPa and increased durability in humid environments [7], [8].

However, its implementation on a mass scale faces technical and logistical challenges. Studies such as those by [9] highlight that variability in the quality of local aggregates-common in regions with limited access to standardized materials-can compromise the workability and strength of LC3 concrete. In Mexico, for example, 60% of social housing projects use aggregates extracted from unregulated quarries, with irregular granulometries and high fines content [10], which requires adaptations in dosage and quality control. Added to this is the lack of training in specific construction techniques for alternative cements, identified as a key barrier in middle-income countries [11].

This study addresses these gaps by evaluating LC3 under real-world conditions in La Perla, Veracruz, an environment representative of Mexico's technical and socioeconomic constraints. Unlike previous laboratory-focused research [12], [13], here we analyze the performance of LC3 combined with non-standard aggregates, quantify its impact on durability (chloride permeability and electrical resistivity), and propose training protocols to optimize its use on site. The findings not only expand the technical knowledge on LC3 in resource-limited contexts, but also provide inputs for public policies aligned with Sustainable Development Goals (SDGs) 9 and 11, prioritizing accessible innovation and reduction of urban inequalities.

2. MATERIALS AND METHODS

The tests were carried out in the community of Chilapilla, La Perla, Veracruz, Mexico at 2245 meters above sea level. The weather during the work was occasionally cloudy, with a relative humidity of 86% and temperatures ranging from 15 to 23ºC.

Fig. 1- Location of experimental work

2.1. MATERIALS

Cements used: four cements produced in Mexico, representative of conventional and alternative technologies, were evaluated:

1. CPC 30 Fuerte Más (LC3): cement with calcined clay (Holcim).
2. CPC 30 ECOPlanet: Portland cement (Holcim).
3. Cement HPH 1 and Cement HPH 2: Generic CPC 30 type cements supplied by third parties collaborating with Habitat for Humanity Mexico, with no commercial brand identification.

Table 1 presents the physical properties of the cements used. The evaluated cements show variations in their physical and mechanical properties, but in general they comply with the specifications established by the standard [14].

Table 1-Physical properties of the cements used [14].

Parameter		**Unit**	**Results**				**Especification NMX-C- 414-ONNCCE2017**
			CPC 30 ECOPlanet (Holcim)	CPC 30 Fuerte Mas (Holcim LC3)	Cement HPH 1	Cement HPH 2	
Fluidity		%	110	111	111	109	----
Ratio w/c		%	0,484	0,510	0,510	0,500	----
Consistency Normal		%	26,0	29,7	26,6	25,6	----
Setting time	Initial	min	201	95	165	128	45 min Minimum
	Final		355	280	385	320	600 min Maximum
Density		g/cm^3	2,82	2,84	2,84	2,88	----
False Setting		%	72	94	80	84	----
Fineness Mesh 0,045 (No. 325)		%	3,5	7,8	14,8	3,9	----
Method of air permeability Blaine		cm^2/g	4 340	5 810	4 060	6 250	---
Sanitation		%	-0,05	-0,03	-0,04	-0,03	Expansion Maximum 0.80 % Shrinkage maximum 0.20%.
Bars immersed in water		%	0,001	0,002	0,001	0,001	----
Compressive strength	1 d	N/mm^2	8,1	10,4	6,5	13,9	----
	3 d		20,0	19,2	18,7	24,4	30 R (20 Minimum) 40 R (30 Minimum)
	7 d		24,0	27,7	22,8	29,7	----
	14 d		27,7	30,0	26,9	33,2	----
	28 d		32,2	34,7	30,0	37,7	30 - 30 R (30 Minimum)

Aggregates: The aggregates used in the study (both fine and coarse) are obtained in the town of Chilapilla (Veracruz) belonging to the municipality of La Perla and are the product of rock crushing. Table 2 presents the physical properties of the aggregates used for the production of the concrete, which presented the following particularities:

- Out-of-norm particle size distribution: The granulometric curve (Figure 2) showed significant deviations in particle sizes, especially in the intermediate and fine sieves. For example, the percentage of material retained in key sieves (e.g., No. 4, 8 and 16) did not conform to the ranges established by the regulations.
- Presence of uncontrolled fines: An excess of particles smaller than 75 µm (No. 200 sieve) was observed, which affected the workability and increased the porosity of the concrete.
- Angular shape and rough texture: The coarse aggregate particles showed low sphericity, making compaction difficult and favoring segregation.

Table 2- Aggregate characteristics [15]

Test	**Unit**	**Gravel HPH project**	**Sand HPH project**	**Specification NMX-C-111-ONNCCE-2018**
		05 a 20 mm	00-05 mm	
Determination of clay lumps and crumbly particles	%	0,0	0,2	10.0 max. gravel, 3.0 max. sand
Aggregate sanitation by means of sodium sulfate	%	0,2	2,9	12 max. gravel 10 max. sand
Loose dry volumetric mass	kg/m^3	1 434	1 413	-----
Compacted dry volumetric mass		1 569	1 527	
Water content by drying	%	0,2	1,5	-----
Volumetric coefficient (of shape)	-----	0,16	-----	0,20 mínimo
Abrasion and impact degradation resistance of coarse aggregate using the Angel Machine	%	31	-----	50 max
Flat and elongated pieces	%	29,4	-----	-----
Sand equivalent	%	----	68	-----
Absorption	%	0,3	5,0	-----
Organic impurities	Color	----	3	3 max
Particles finer than 0.075 mm (No 200) sieve by washing	%	1,2	12	1,0 max. gravel 5,0 max. sand
Relative density when saturated and surface dry	Adimensional	2,70	2,38	-----
Potential reactivity of aggregates with cement alkalis by chemical method	----	Innocuo	Innocuo	-----

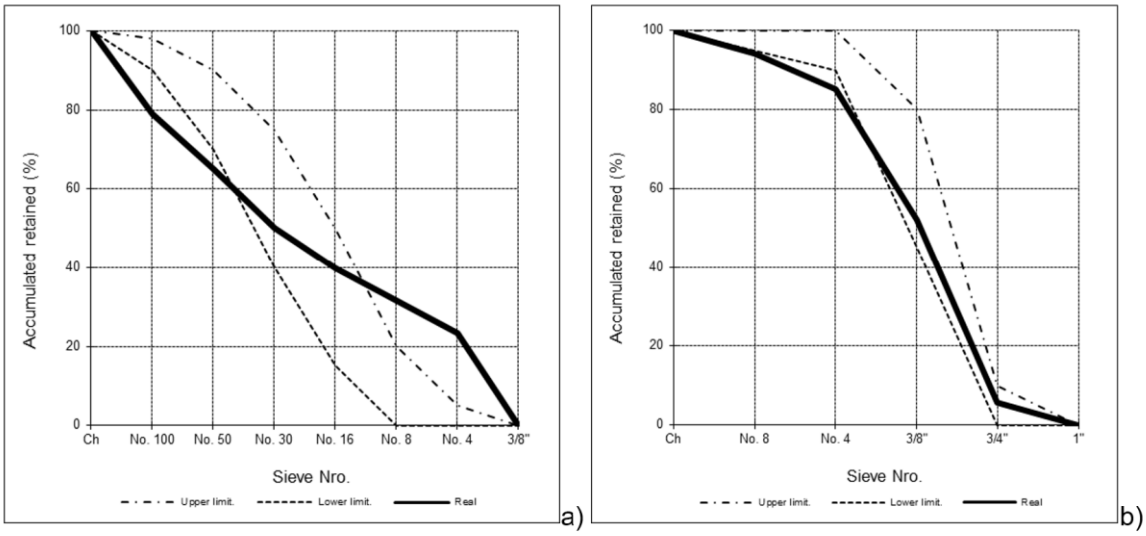


Fig. 1 -Particle size distribution of the aggregates used, a) Fine aggregate, b) Coarse aggregate

2.2. *EXPERIMENTAL DESIGN*

A 2x2 factorial design with randomized blocks was adopted:

Factors:

- Type of cement (4 levels: LC3, ECOPlanet, Cement HPH 1 y 2).
- Target strength (2 levels: 20 MPa and 30 MPa).
- Replicates: 3 samples per combination (total: 24 samples).
- Randomization: Manufacture in random order to minimize environmental biases.

For the 20 MPa concrete, the same dosage of the construction company contracted by Habitat was used. In addition, a second batching was produced for 30 MPa concrete recommended by the Holcim team. During the manufacture of the concrete, care was taken to ensure that the conditions of all the mixtures with different types of cement were the same (same type of aggregate and dosage). Table 3 shows the proportions used.

Table 3- Dosage used in the manufacture of concrete (1 m^3)

Sample	**Proportion**	**Cement (kg)**	**Fine aggregate (kg)**	**Coarse aggregate (kg)**	**Water (kg)**	**w/c**	**Ambient temp. (°C)**	**Concrete Temp. (°C)**
Cement HPH 1	1-5-6	327	751	901	190	0.58	27	22
Cement HPH 2	1-5-6	327	751	901	206	0.63	30	25
CPC 30 ECOPlanet (Holcim)	1-5-6	327	751	901	177	0.54	23	23
CPC 30 Fuerte Mas (Holcim LC3)	1-5-6	327	751	901	203	0.62	24	23
Sample	**Proportion**	**Cement (kg)**	**Fine aggregate (kg)**	**Coarse aggregate (kg)**	**Water (kg)**	**w/c**	**Ambient temp. (°C)**	**Concrete Temp. (°C)**
Cement HPH 1	1-2 1/2 -4 1/2	452	519	933	226	0.5	20	19
Cement HPH 2	1-2 1/2 -4 1/2	452	519	933	226	0.5	23	20
CPC 30 ECOPlanet (Holcim)	1-2 1/2 -4 1/2	452	519	933	226	0.5	24	24
CPC 30 Fuerte Mas (Holcim LC3)	1-2 1/2 -4 1/2	452	519	933	244	0.54	24	24

2.3. TESTS

In the manufacture of the concrete this was evaluated in fresh and hardened condition. The tests performed were:

- In fresh condition: Slump [16], occluded air [17] and Determination of setting time using the Holcim Heat equipment, SGI-CITEC-SDL-PR-059.
- In hardened state: Compressive strength in 10x20 cm cylinders [18].
- A durability study protocol was also carried out on specimens prepared with the concretes produced. The tests are briefly described below
- Chloride permeability (ASTM 1202): The PROOVE'it system is used to evaluate the resistance in concrete to chloride ion ingress by determining how easy it is to force chlorides into saturated concrete by applying an electrical potential across a test specimen in accordance with AASHTO T 277 or ASTM 1202. This is known as the “Coulomb Test” or the “Rapid Chloride Permeability Test (RCPOT)”. During the test, the total past load is determined and used for the classification of the concrete according to the criteria shown in Table 4, proposed by Whiting.

Table 4- RCPOT Ranges [19]

Passed load (Coulombs)	**Chloride Ion Permeability**
>4.000	High
2.000-4.000	Moderate
1.000-2.000	Low
100-1.000	Very Low
<100	Insignificant

- Surface resistivity: This test is performed with the resipod, an instrument that is designed to measure the electrical resistivity of concrete or rock using the Wenner probe principle. A current is applied to two outer probes and the potential difference between the two inner probes is measured. The current is carried by ions from the liquid in the pores. The calculated resistivity depends on the distance between the sondes[20], [21], [22], [23]. The interpretation of the results is made taking the following reference:

Table 5- Interpretation of resistivity levels [24]

Electrical resistivity	**Interpretation criteria**
p>200 kΩ.cm	Low corrosion risk
200>p>10 kΩ.cm	Moderate corrosion risk
P<10 kΩ.cm	High corrosion risk

- Nordtest NT Build 492: The test consists of subjecting a cylindrical concrete specimen to an electric potential applied axially through it, forcing the chloride ions present in the external solutions to migrate towards the interior of the specimen. Once the penetration distance has been measured, the non-steady-state chloride migration coefficient (Dnssm) can be calculated. The interpretation of the results is carried out by taking the following reference (See Table 6)

Table 6- Nordtest NT Build 492 Data Ranges.

Chloride migration	**Dnssm (×10−12 m2/s)**
Very low	0–3.5
Low	3.5–6.75
Moderate	6.75–10.5

3. RESULTS

3. 1. PROPERTIES IN THE FRESH STATE

The results of the slump test using the Abrams Cone (Figure 2) indicate that the concretes made with conventional CPC 30 cement and CPC 30 Fuerte Mas (LC3) for strengths of 20 MPa show comparable behavior, with no significant differences. This suggests that partial substitution of traditional cement with alternative materials such as LC3 does not adversely affect workability in this strength range. However, in 30 MPa concretes, a slight decrease in slump is observed when using cements incorporating calcined clays (CPC 30 Fuerte Mas). Despite this reduction, all values remain within the range specified by the standard [16] for fluid consistency concretes, which guarantees their adequate workability on site.

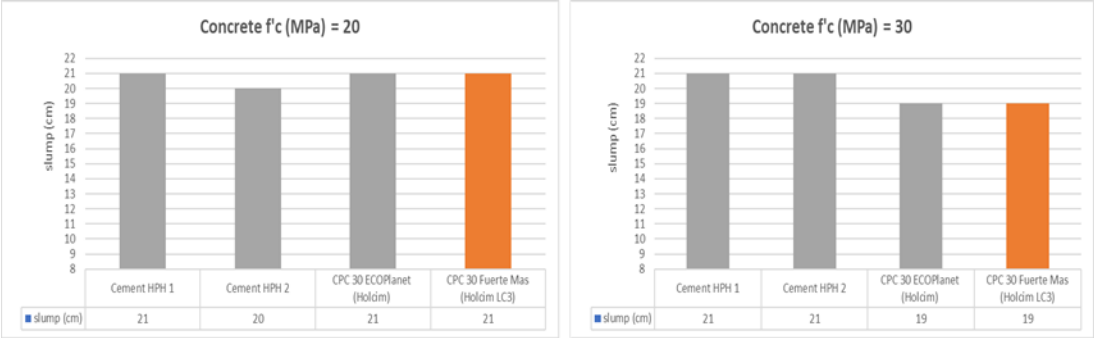


Fig. 2- Abrams Cone Test Results

The measurement of occluded air in fresh concrete (Figure 3) shows no significant variations among the evaluated mixes. However, a more detailed analysis of the concretes made with Holcim's CPC 30 ECOPlanet cement reveals specific values that require closer attention. For the 30 MPa mix, the incorporated air content was measured at 1.3%, placing it slightly below the recommended limit of 1.5%. In contrast, the 20 MPa mix achieved an air content of 1.7%, placing it within the optimal range (1.5 – 3.0%). This variability suggests that while the ECOPlanet cement formulation designed to reduce the carbon footprint without compromising rheological properties [5] generally favors adequate air content, its performance could be influenced by the specific mix design, such as aggregate gradation or paste volume, which would explain the lower value in the 30 MPa mix.

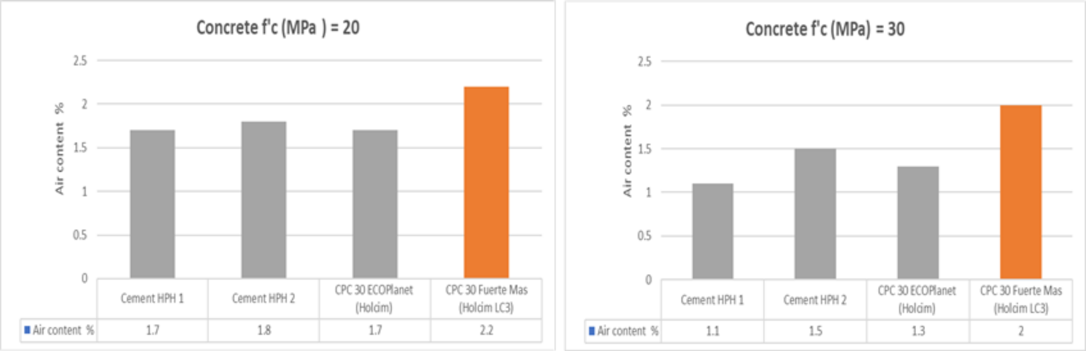


Fig. 3- Measurement of occluded air in concrete

The setting times (Figure 4) show notable differences when using cements with calcined clays (CPC 30 Fuerte Mas). These concretes have a slower setting time compared to traditional concretes, together with a lower release of hydration heat. This phenomenon is beneficial for durability, as it reduces the risk of thermal cracking in massive structural elements, such as slabs or foundations [25]. The extended setting time also allows a larger window for surface finishing in adverse weather conditions.

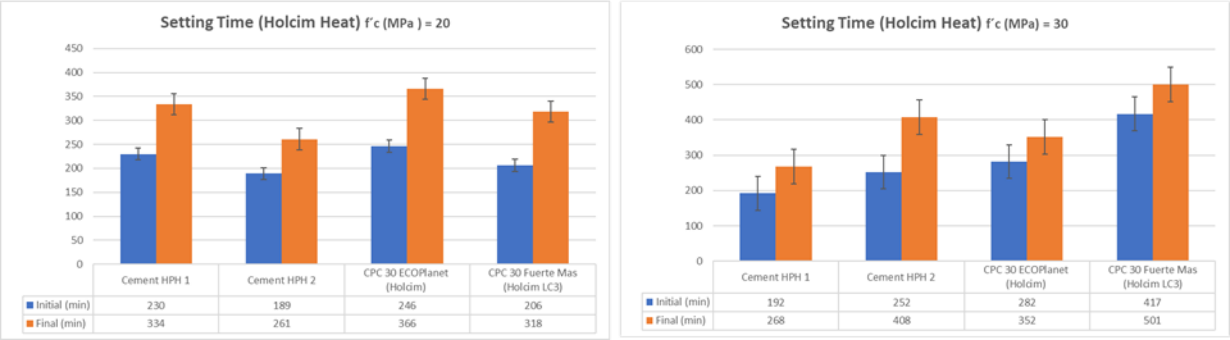


Fig. 4- Measurement of setting time in concretes

The results demonstrate that the use of cements with calcined clays (LC3) and ECOPlanet does not compromise the fundamental properties of fresh concrete, complying with regulatory standards. In addition, the variations observed, such as lower slump in higher strength concretes and prolonged setting, reflect technical adaptations that can optimize the performance of the material in specific applications, prioritizing durability and sustainability without sacrificing quality.

3.2. MECHANICAL STRENGTH

The compressive strength results of the evaluated concretes (Figure 5.), under NMX-C-083-ONNCCE-2014, 2014, show a differentiated behavior according to age and type of cement used. The main results are detailed below:

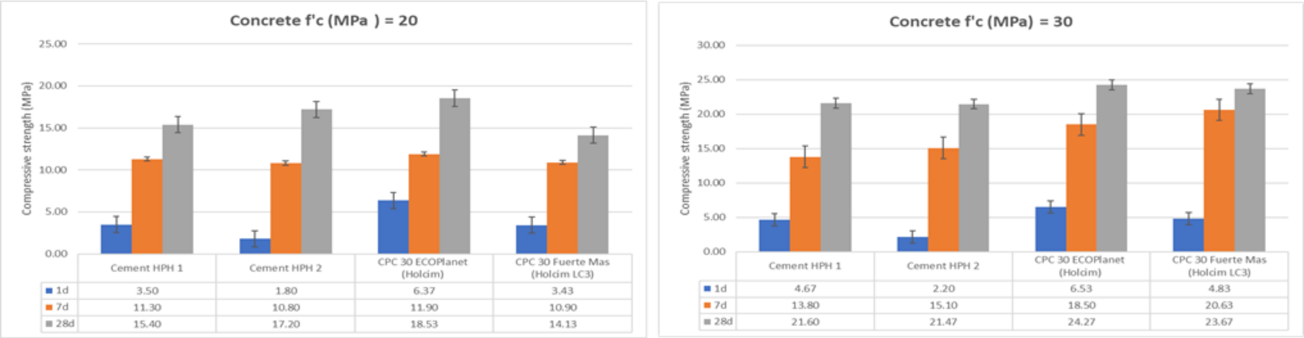


Fig. 5- Strength values in concrete

Strength at early ages (24 hours and 7 days):

- Concretes designed for 30 MPa, made with cement including calcined clays (CPC 30 Fuerte Mas Holcim LC3), presented the highest strength values at 7 days. This behavior suggests an early strength gain, possibly associated with the activation of calcined clays, which accelerate hydration reactions.
- However, none of the concretes evaluated reached the minimum requirements established (20 MPa and 30 MPa for the specified ages).

Strength at 28 days:

- At 28 days, the CPC 30 Fuerte Mas Holcim LC3 concrete matched the strength of CPC 30 ECOplanet Holcim. However, both failed to meet the minimum required values (20 MPa and 30 MPa) established for this age. The quality of aggregates, identified as a critical factor, did not comply with Mexican standards. Aggregates with high porosity, contamination, or inadequate gradation reduced compaction and final strength.
- The proposed mix designs also failed to ensure the expected quality, highlighting the need to adjust material proportions in future designs.

The evaluated concretes, including variants with calcined clays (CPC 30 Fuerte Mas Holcim LC3) and eco-friendly alternatives (CPC 30 ECOplanet Holcim), did not achieve the required strength values (20 MPa and 30 MPa) at any of the analyzed ages (24 h, 7, and 28 days). Although the calcined clay concrete showed better early-age performance (7 days), its strength plateaued at 28 days, matching ECOplanet. Substandard aggregate quality and improper mix designs were the primary causes of these results.

3.3. DURABILITY INDICATORS

3.3.1. CHLORIDE PERMEABILITY (ASTM 1202)

The results in Figure 6 show that concretes made with CPC 30 Fuerte Mas cement (incorporating calcined clays) have a permeability to chlorides classified as low to very low, with values between 100-2000 Coulombs. A direct decrease in permeability is observed in cements with calcined clays. This is attributed to the formation of a denser microstructure, where the calcined clays act as supplementary material, reducing the connectivity of the capillary pores and limiting the penetration of chloride ions. This behavior is critical in environments exposed to chlorides, such as marine areas, where low permeability delays reinforcement corrosion [26].

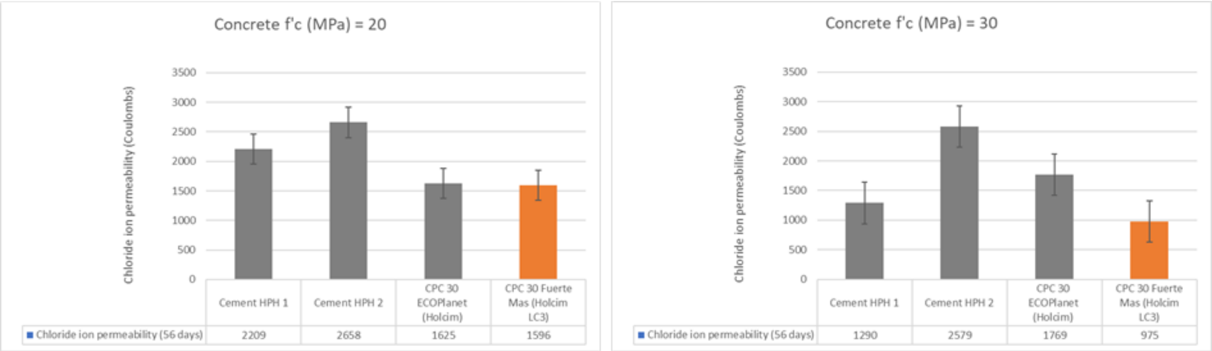
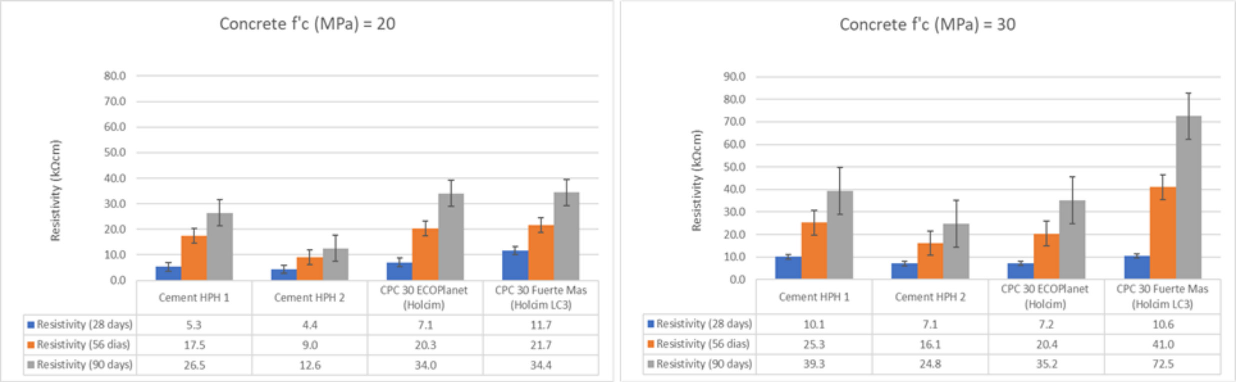


Fig. 6- Rapid Chloride Permeability Values according to ASTM 1202

3.3.2. ELECTRICAL RESISTIVITY

Fig. 7 reveals that the mixes with CPC 30 Fuerte Mas reach the highest resistivity values (10 – 72 kΩ-cm at 96 days), being classified as low corrosion risk. In contrast, conventional cements (1 and 2) show lower resistivities, associated with higher corrosion risk. High resistivity indicates a reduction in ion mobility within the concrete, which hinders electrochemical corrosion processes. The improvement in this property with calcined clays is due to the refinement of porosity and the formation of additional hydrated phases, such as aluminates and silicates[27].



Concrete f'c (MPa) = 20

	Cement HPH 1	Cement HPH 2	CPC 30 ECOPlanet (Holcim)	CPC 30 Fuerte Mas (Holcim LC3)
■ Resistivity (28 days)	5.3	4.4	7.1	11.7
■ Resistivity (56 dias)	17.5	9.0	20.3	21.7
■ Resistivity (90 days)	26.5	12.6	34.0	34.4

Concrete f'c (MPa) = 30

	Cement HPH 1	Cement HPH 2	CPC 30 ECOPlanet (Holcim)	CPC 30 Fuerte Mas (Holcim LC3)
■ Resistivity (28 days)	10.1	7.1	7.2	10.6
■ Resistivity (56 dias)	25.3	16.1	20.4	41.0
■ Resistivity (90 days)	39.3	24.8	35.2	72.5

3.3.3. CORRELATION BETWEEN PERMEABILITY AND RESISTIVITY

Fig. 8 shows an inverse correlation between chloride permeability and resistivity- samples with lower permeability (CPC 30 Fuerte Mas) exhibit higher resistivity. This relationship is explained by the dense and poorly connected microstructure, which restricts both chloride flux and ionic conduction. Previous studies support that a reduction in pore size and connectivity simultaneously improves both properties, increasing the durability of concrete [28].

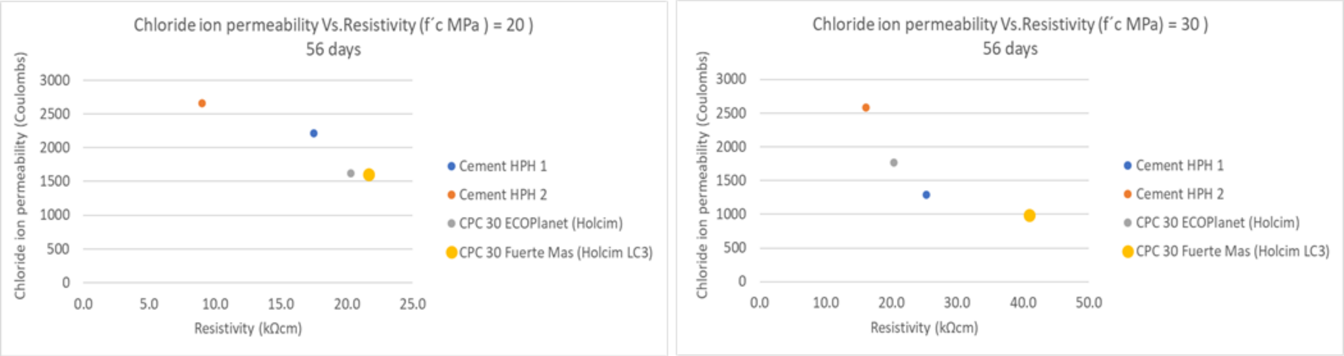
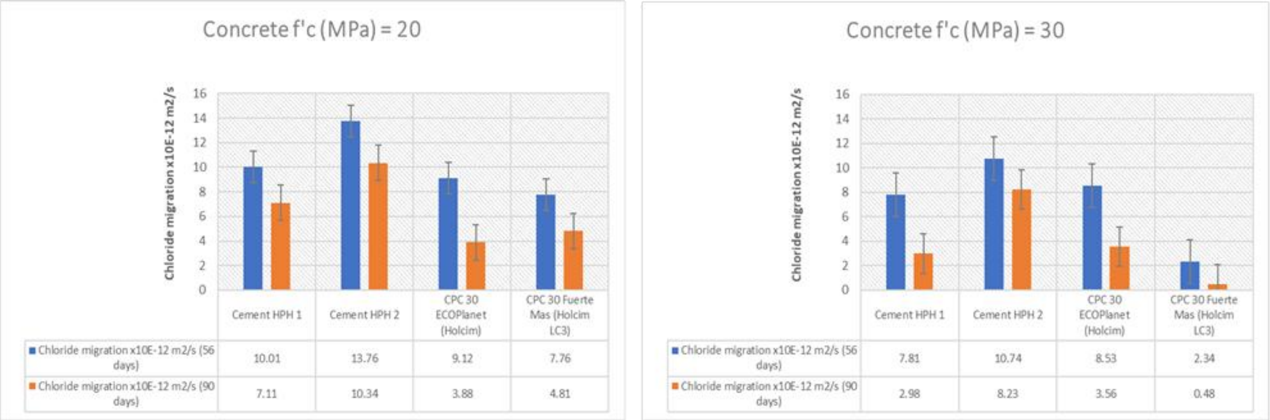


Fig. 8 -Contrast between Chloride permeability and Resistivity

3.3.4. CHLORIDE MIGRATION

Fig. 9 shows that concretes with CPC 30 Fuerte Mas exhibit non-steady-state chloride migration values of 0-3.5×10-^{12} m^2/s, classified as very low. In comparison, conventional cements (1,2) show values of 6.75-10.5×10-^{12} m^2/s, considered moderate. This confirms that calcined clays effectively inhibit the entry and migration of chlorides by creating a dense microstructure with discontinuous porosity, which forces the ions to follow tortuous paths[29].



Concrete f'c (MPa) = 20

	Cement HPH 1	Cement HPH 2	CPC 30 ECOPlanet (Holcim)	CPC 30 Fuerte Mas (Holcim LC3)
■ Chloride migration x10E-12 m2/s (56 days)	10.01	13.76	9.12	7.76
■ Chloride migration x10E-12 m2/s (90 days)	7.11	10.34	3.88	4.81

Concrete f'c (MPa) = 30

	Cement HPH 1	Cement HPH 2	CPC 30 ECOPlanet (Holcim)	CPC 30 Fuerte Mas (Holcim LC3)
■ Chloride migration x10E-12 m2/s (56 days)	7.81	10.74	8.53	2.34
■ Chloride migration x10E-12 m2/s (90 days)	2.98	8.23	3.56	0.48

Fig. 9- Chloride migration values in concretes

3.3.5. CORRELATION BETWEEN CHLORIDE MIGRATION AND RESISTIVITY

As in the previous cases, the samples with calcined clays show lower chloride migration and higher resistivity (Figure 10), confirming that a refined porous structure simultaneously improves both properties. Previous studies support that reduction in pore size and connectivity increases durability [30].

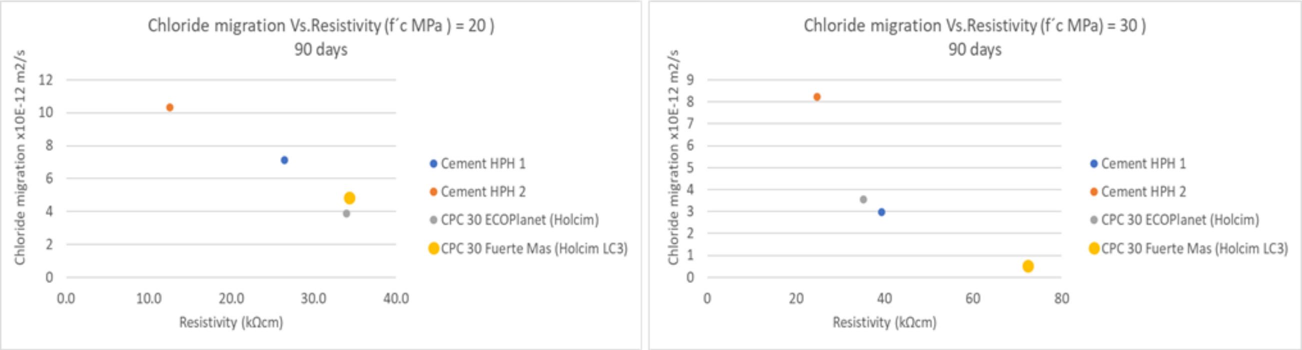


Fig. 10- Chloride migration vs. resistivity

CPC 30 Fuerte Mas cement, incorporating calcined clays, demonstrates superior performance in durability:

- Reduced chloride permeability (100-2000 Coulombs), ideal for marine environments.
- High resistivity (10-72 kΩ-cm), minimizing the risk of corrosion.
- Very low chloride migration ($0\text{-}3.5\times10^{-12}$ m^2/s), compared to moderate values in conventional cements.

The inverse correlations between permeability/resistivity and migration/resistivity underline the key role of a dense microstructure in inhibiting corrosive processes. These findings are aligned with research highlighting the use of supplementary materials (calcined clays) to optimize the microstructure of the cement [31].

3.4. IMPACT OF NON-STANDARD AGGREGATES ON THE RESULTS

The results of the study evidence that the use of non-standard aggregates (those non-compliant with NMX-C-111-ONNCCE-2018, 2018 had a significant impact on the properties of LC3 concrete. Their key effects are discussed below:

3.4.1. INFLUENCE ON WORKABILITY AND MECHANICAL STRENGTH

- **High water demand and high w/c ratio:** Aggregates presented an out-of-specification grain size distribution (Figure 1), with high fines content and irregular particles. This increased the water demand to achieve workability, raising the water/cement (w/c) ratio to 0.63 (Table 3). As pointed out by [32], poorly graded aggregates generate voids in the concrete matrix, reducing mechanical strength. This explains why the samples did not reach the required design strength (Figure 5), despite using LC3, which in controlled studies [33] equals Portland in strength.
- **Slump reduction:** Calcined clays in LC3 increase the specific surface area of cement, which normally reduces workability. However, in this case, the non-standard aggregates exacerbated this effect, limiting the slump to minimum acceptable values (Figure 2).

3.4.2. EFFECTS ON DURABILITY

- **Permeability and resistivity:** Despite the deficient aggregates, LC3 (specifically CPC 30 Fuerte Más) showed low permeability to chlorides (100-2000 Coulombs, Figure 6) and high electrical resistivity (10-50 kΩcm, Figure 7). This is attributed to the ability of calcined clays to densify the concrete matrix, reducing pore connectivity [5]. However, under normative conditions, these values could be further improved, as demonstrated by Garces-Vargas et al., 2024 in studies with standardized aggregates.

3.4.3. SPECIFIC TECHNICAL RECOMMENDATIONS

Non-standardized aggregates, such as those used in this study, present critical challenges for concrete quality. Their irregular grain size, high fines content and angular texture affect workability, strength and durability. Technical recommendations for builders and regulators are proposed below:

For Builders:

1. **Aggregate Processing:**

- **Screening and Grading:** Implement mobile screening equipment to separate out-of-standard particles (e.g. vibrating screens). This allows adjusting the granulometric curve to the ranges of Mexican regulations (NMX-C-111-ONNCCE-2018, 2018).
- **Aggregate Washing:** Reduce fines content (<75 µm) by water washing, especially in sand, to minimize water demand and improve compaction.
- **Source Mixing:** Combine aggregates from different quarries or add commercial aggregates (e.g. crushed gravel) to compensate for deficiencies in shape or size.

1. **Dosage Adjustments:**

- **Modify Proportions:** Test alternative mix designs (e.g. 1-4-5 instead of 1-5-6) to balance workability and strength, considering the angular shape of the aggregates.

1. **On-site Quality Control:**

- Perform rapid tests for particle size and fines content prior to each batch of concrete.
- Monitor consistency with Abrams cone.

For Regulators:

1. **Standardization Policies:**

- Require NMX-C-111(NMX-C-111-ONNCCE-2018, 2018) certification for aggregates in public projects, including in rural contexts.
- Promote the creation of local aggregate processing centers, subsidized by state governments, to guarantee access to standardized materials.

1. **Training and Dissemination:**

- Develop practical guidelines for the use of non-standardized aggregates, including protocols for adjusting dosages and compaction techniques.
- Implement workshops with engineers and site managers on the management of LC3 and local aggregates, emphasizing water and additive control.

1. **Sustainable Incentives:**

- Award subsidies or green certifications to projects that combine LC3 with processed aggregates, aligned with SDG 9 and 11.
- Establish partnerships with universities or NGOs to validate low-cost aggregate processing technologies (e.g. manual screens, washing systems with water recycling).

3.5. COMPARISON WITH PREVIOUS STUDIES: MECHANICAL STRENGTH MATCHES AND DURABILITY ADVANTAGES OF LC3

The results show that LC3 cement achieved mechanical strengths comparable to Portland cement at early ages and similar to 28 days, despite the limitations imposed by the non-standard aggregates. These observations are in line with key results from the literature (see Table 6).

Table 6- Comparison with Previous Studies

Parameter Evaluated	Results of the Current Study	Coincidences with Previous Studies	Differences/Context
Mechanical Resistance	- Similar strength to Portland at 28 days (Figure 5). - - Higher strength at 7 days in LC3 (30 MPa concrete).	- [5]: LC3 equals Portland at 28 days. - [12]: Pozzolanic reaction improves early strength.	- The use of non-standard aggregates increased the water/cement ratio and limited the mechanical strength. - [34]: With standardized aggregates, optimum strengths are achieved.
Chloride Permeability	- Low" to 'very low' values (100-2000 Coulombs) in LC3 (Figure 6).	- [7]: LC3 reduces permeability due to dense matrix. - [35]: C-A-S-H blocks chloride ions.	- Non-standardized aggregates did not significantly affect the permeability advantage.
Electrical Resistivity	- Moderate (10-72 kΩ cm), low corrosion risk (figure 7)	- [27]: High resistivity linked to low porosity. - [6]: LC3 reduces effective porosity.	- Lower values than in studies with standardized aggregates, but still superior to Portland.
Aggregate Impact	- Non-normalized aggregates increased w/c ratio and limited mechanical strength.	- [32]: Poorly graded aggregates reduce strength. - [34]: Standardized aggregates optimize LC3	- Unlike other studies, where standardized aggregates were used, this work faced challenges due to irregular grain size.

LC3 cement confirmed its potential to match Portland cement in mechanical strength (under controlled conditions) and surpass it in durability, as reported in the literature. Similarities with previous studies validate its technical efficacy, while differences related to the decrease in compressive strength highlight the importance of standardizing local materials. The advantages in durability (low permeability and high resistivity) were maintained even with deficient aggregates, supporting its suitability for projects in aggressive environments.

3.6. PRACTICAL IMPLICATIONS: RECOMMENDATIONS FOR BATCHING ADJUSTMENTS AND STANDARDIZATION OF LOCAL MATERIALS.

Dosage adjustments: Review aggregate proportions and adjust the proportion of fine and coarse aggregates according to their actual grain size (e.g., reduce fines if there is excess) to minimize voids in the matrix and improve compaction. Conduct pilot tests with modified dosages (e.g., 1-4-5 instead of 1-5-6) to balance strength and workability.

Standardization of Local Materials: Aggregate quality control: Implement mandatory granulometric and water absorption tests, aligned with NMX-C-111-ONNCCE-2018, to ensure technical compliance.

4. CONCLUSIONS

1. LC3 cement demonstrated mechanical strength comparable to Portland cement at early ages (7 days) and similar at 28 days, despite the limitations imposed by non-standard aggregates. Its ability to densify the concrete microstructure significantly reduced chloride permeability (100-2000 Coulombs) and increased electrical resistivity (10-72 kΩ-cm), improving durability in aggressive environments.
2. However, aggregates with irregular grain size and high fines content increased water demand (w/c ratio up to 0.63), limiting the final mechanical strength and evidencing the need for dosage adjustments.
3. The substandard quality of the local aggregates (non-standard grain size distribution, excess fines and angular particles) negatively affected the workability, compaction and strength of the concrete. This underscores the importance of standardizing local materials to maximize the potential of LC3.
4. Aggregate standardization and technical training are pillars for scaling up LC3. Strategies such as screening, washing, and batching adjustments can mitigate the limitations of local materials, while public policies can ensure access in marginalized regions.
5. The use of LC3 reduces CO_2 emissions associated with cement production by up to 40%, aligning with SDGs 9 (Industry and Innovation) and 11 (Sustainable Cities). Its greater durability also extends the useful life of structures, minimizing resource consumption in maintenance and reconstruction.
6. In summary, LC3 is positioned as a viable and sustainable alternative to traditional cement in social housing projects, provided that it is complemented by improvements in the quality of local materials and construction practices. Its adoption would not only reduce the environmental footprint of the construction sector, but also promote more resilient structures in regions exposed to adverse climatic conditions.

5. ACKNOWLEDGEMENTS

The authors express their gratitude to the collaboration of Habitat for Humanity Mexico and Holcim, Center of Technological Innovation for Construction (CITEC) for providing all the necessary facilities to carry out this study.

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