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DEVELOPMENT AND STRUCTURAL ANALYSIS OF PRECAST RIBBED WALLS AND SLABS PRODUCED WITH STEEL SLAG AGGREGATE CONCRETE: AN APPROACH TO SUSTAINABLE MODULAR CONSTRUCTION

DESENVOLVIMENTO E ANÁLISE ESTRUTURAL DE PAREDES E LAJES NERVURADAS PRÉ-MOLDADAS PRODUZIDAS COM CONCRETO DE AGREGADO SIDERÚRGICO: UMA ABORDAGEM PARA A CONSTRUÇÃO MODULAR SUSTENTÁVEL

DESARROLLO Y ANÁLISIS ESTRUCTURAL DE PAREDES Y LOSAS NERVADAS PREMOLDEADAS PRODUCIDAS CON CONCRETO DE AGREGADO SIDERÚRGICO: UN ENFOQUE PARA LA CONSTRUCCIÓN MODULAR SOSTENIBLE

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ABSTRACT

Essentially, everything known about civil construction, everything that has evolved over time regarding construction methods, everything we use to build the structures indispensable to our existence, has always been linked to the direct consumption of non-renewable raw materials, the uninterrupted generation of waste harmful to the environment and to humankind itself, wasted time, and always related to unhealthy conditions resulting from the sum of these events. Going against this traditional script, a product was developed whose research, from the beginning, focused on promoting an efficient, environmentally sound, economically viable, and strategically applicable solution aimed at directly impacting the timeline, cost, and efficiency of the construction process using concrete based on steelmaking aggregate. This is how the ribbed wall was developed. This product consists of

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using a geometric strategy to compose a reinforced concrete element whose manufacturing versatility guarantees diversification for the most complex structural models, adapting to the most diverse types of projects and layouts, and is also logistically viable due to the simplicity of its manufacturing process. The variability necessary to guarantee the versatility and adaptability of this constructive element is directly related to the specific application of each of the projects that will be built with this product, since by altering the FCK (compressive strength) and the distribution strategy of the steel reinforcement, a controlled variation in the resistance capacity of the walls and ribbed slabs is obtained, with the maximum possible span to date being 6 m free.

Keywords: Civil Construction. Ribbed Wall. Efficiency. Economy. Steelmaking Aggregate.

RESUMO

Essencialmente tudo que se conhece de construção civil, tudo que se evoluiu no progressivo do tempo no tocante a método construtivo, tudo que utilizamos para construção de nossas estruturas indispensáveis ao funcionamento que a nossa existência exige, sempre esteve ligado ao consumo direto de matéria-prima de fonte não renovável, geração ininterrupta de rejeitos nocivos ao ambiente ao próprio homem, desperdício de tempo e sempre relacionado a condições insalubres recorrentes do somatório destes eventos. Seguindo na contramão desse tradicional roteiro, desenvolveu-se um produto cuja pesquisa desde o princípio, esteve focada em promover a busca eficiente, ambientalmente correta, economicamente viável e estrategicamente aplicável cujo objetivo era o de gerar interferência direta no prazo, no custo e na eficiência da prática do processo construtivo fazendo uso de concreto a base de agregado siderúrgico. Desta forma foi desenvolvida a parede nervurada. Esse produto consiste na utilização de uma estratégia geométrica para a composição de um elemento de concreto armado cuja versatilidade de fabricação nos garante a diversificação para os mais complexos modelos estruturais, adequação aos mais diferentes tipos de projetos e layouts, sendo também, logisticamente viável devido à simplicidade do seu processo de confecção. A variabilidade necessária para garantir a versatilidade e adaptabilidade desse elemento construtivo está diretamente relacionada à aplicação específica de cada um dos projetos que se construirão com esse produto, uma vez que alterando o FCK e a estratégia de distribuição da armadura de aço, obtém-se uma variação controlada na capacidade de resistência das paredes e lajes nervuradas, sendo o vão máximo possível até o momento de 6 m livres.

Palavras-chave: Construção Civil. Parede Nervurada. Eficiência. Economia. Agregado Siderúrgico.

RESUMEN

Esencialmente, todo lo que se conoce sobre construcción civil, todo lo que ha evolucionado con el tiempo en cuanto a método constructivo, todo lo que utilizamos para construir nuestras estructuras indispensables para el funcionamiento que nuestra existencia exige, siempre ha estado vinculado al consumo directo de materias primas de fuentes no renovables, generación ininterrumpida de residuos nocivos para el ambiente y para el propio hombre, desperdicio de tiempo y siempre relacionado con condiciones insalubres resultantes de la suma de estos eventos. Yendo en contra de este guion tradicional, se desarrolló un producto cuya investigación desde el principio estuvo enfocada en promover una solución eficiente, ambientalmente correcta, económicamente viable y estratégicamente aplicable, cuyo objetivo era generar interferencia directa en el plazo, el costo y la eficiencia de la práctica del proceso constructivo haciendo uso de concreto a base de agregado siderúrgico. De esta forma se desarrolló la pared nervurada. Este producto consiste en la utilización de una

estrategia geométrica para la composición de un elemento de hormigón armado cuya versatilidad de fabricación garantiza la diversificación para los más complejos modelos estructurales, adaptándose a los más diferentes tipos de proyectos y layouts, siendo también logísticamente viable debido a la simplicidad de su proceso de confección. La variabilidad necesaria para garantizar la versatilidad y adaptabilidad de este elemento constructivo está directamente relacionada con la aplicación específica de cada uno de los proyectos, ya que alterando el FCK y la estrategia de distribución de la armadura de acero, se obtiene una variación controlada en la capacidad de resistencia de las paredes y losas nervuradas, siendo el vano máximo posible hasta el momento de 6 metros libres.

Palabras clave: Construcción Civil. Pared Nervurada. Eficiencia. Economía. Agregado Siderúrgico.

1 INTRODUCTION

Essentially, everything known about civil construction, everything that has evolved over time regarding construction methods (Teixeira and Carvalho, 2005), everything we use to build the structures indispensable to the functioning that our existence demands, has always been linked to the direct consumption of raw materials from non-renewable sources, the uninterrupted generation of waste harmful to the environment and to humankind itself, the waste of time, and always related to unhealthy conditions resulting from the sum of these events (Firjan, 2014). Following the discrepant routine of the dilemma of human existence, which produces what is established as essential for the moment, these processes generate harmful conditions for future moments.

As an undeniable result of this routine, we have steelmaking aggregate, a material originating from the steelmaking slag treatment process and a waste product of steel manufacturing. In Brazil, between 70 and 170 kg of steelmaking slag is produced, thus reproducing millions of tons of this material (Terninum, 2022).

Commonly used for asphalt sub-base, various soil fillings, paving substrate, and as a direct object of diverse research aimed at new applications of the product in civil construction as an agricultural corrective, concrete, cement, among others. Considering the physicochemical analyses, granulometric structure and geometric advantages of its structure, a mix design for application in concrete was developed with the purpose of composing a structural element (reinforced concrete).

Contemporary civil construction increasingly consumes prefabricated cementitious elements for a wide variety of constructions in our daily work. Reinforced concrete panels are used in various models, shapes, and sizes with diverse geometric applications for their intended purposes.

The construction industry is one of the largest consumers of natural resources on the planet, extracting approximately 40 billion tons of raw materials annually (MEHTA; MONTEIRO, 2014). Simultaneously, it is estimated that buildings are responsible for approximately 30% of CO_2 emissions and 40% of solid waste generated worldwide (JOHN *et al.*, 2018). This scenario imposes an urgent need to adopt construction practices that reconcile technical performance, economic viability, and environmental responsibility.

In Brazil, the steel industry produces approximately 8 million tons of steelmaking slag annually, a byproduct generated during the steel refining stage (TSUTIYA *et al.*, 2017). Although some of this material is destined for low value-added applications—such as paving

and landfills—a significant portion is still deposited in industrial landfills, occupying usable space and representing an environmental liability. Technical literature shows that steelmaking slag has a mineralogical composition rich in dicalcium silicates (C_2S), calcic ferrites, and free calcium and magnesium oxides, giving it potential for use as an aggregate in concrete (CHATTERJEE, 2017; GUMIERI, 2014). However, the presence of free CaO and MgO can induce late volumetric expansions, requiring the application of aging or carbonation techniques for dimensional stabilization (LIM *et al.*, 2019).

In parallel, prefabricated modular construction has been gaining prominence as an alternative to conventional masonry, providing shorter construction times, reduced material waste, and greater quality control in a factory environment (SILVA *et al.*, 2021). Among modular systems, ribbed slabs and walls stand out for combining low self-weight with high flexural rigidity, thanks to the geometric optimization of their cross-sections. This behavior allows spanning up to 6 meters without the need for intermediate beams, simplifying assembly logistics and reducing steel and concrete consumption (ABNT, 2014).

This article is situated within the context of the circular economy, proposing the integration between the steel production chain and civil construction through the development of precast ribbed panels produced with steelmaking aggregate concrete. The central objective is to demonstrate, from material, structural, economic, and environmental perspectives, the technical viability of this solution, contributing to the decarbonization of the construction sector and the valorization of industrial waste.

1.1 JUSTIFICATIVA

This product, which is called a ribbed wall, consists of using a geometric strategy to compose a reinforced concrete element whose manufacturing versatility guarantees diversification (Niemeyer, 2002) for the most complex structural models, adapting to the most diverse types of projects and layouts, and is also logistically viable due to the simplicity of its manufacturing process (Niemeyer, 2002). The versatility of the ribbed wall allows for adequate adaptation to different types of projects regardless of their layouts or number of floors. This is due to the use of simple variations in the combination of steel mesh and the FCK of the mix, producing ideal pieces for each type of project, currently having a maximum capacity to span up to 6 m.

According to (Aecweb, 2021), the growth in consumption of precast reinforced concrete in Brazil is (58.3%), and strategic innovations regarding this material are growing

exponentially as the market reacts positively to the consumption of materials that speed up the construction processes of the most diverse projects. Regardless of the model, manufacturing method, or characteristics, the use of precast reinforced concrete elements in contemporary civil construction is established as a viable alternative.

2 LITERATURE REVIEW

2.1 MATERIALS ENGINEERING: CHARACTERIZATION AND STABILIZATION OF STEELMAKING SLAG

Steelmaking slag is a non-metallic byproduct composed mainly of calcium silicates (C_2S and C_3S), calcium ferrites (C_2F), aluminates, and free oxides of calcium (CaO) and magnesium (MgO). Its chemical composition varies according to the type of steelmaking (LD, electric arc furnace) and the desulfurization process employed (CHATTERJEE, 2017). The typical particle size ranges from coarse sand to crushed stone, with a specific gravity between 2.8 and 3.2 g/cm³, higher than that of natural aggregates (NEVILLE, 2016).

The main technical limitation to the use of slag as aggregate lies in the reactivity of free CaO and MgO, which, upon hydration, form hydroxides with a volume increase of up to 100%, potentially causing cracking and disintegration of the concrete (GUMIERI, 2014). To overcome this phenomenon, strategies such as the following are adopted:

- Natural aging: exposure to open air for a minimum period of 90 days, with periodic humidification, promoting slow hydration of oxides;
- Accelerated carbonation: controlled exposure to CO_2 in carbonation chambers, transforming $Ca(OH)_2$ into stable $CaCO_3$ and reducing porosity (LIM *et al.*, 2019);
- Washing and sieving: removal of fines rich in free CaO.

SANTOS *et al.* (2020) demonstrated that concrete produced with electric arc furnace slag subjected to aging for 120 days showed compressive strength greater than 30 MPa at 28 days, without evidence of deleterious expansion in accelerated tests (immersion in water at 70 °C). SOUZA *et al.* (2019) add that durability in aggressive environments (freeze-thaw cycles, sulfate attack) is maintained as long as the free oxide fraction is less than 6% by mass.

2.2 CIVIL ENGINEERING AND ARCHITECTURE: MECHANICAL BEHAVIOR OF RIBBED SECTIONS

Ribbed slabs and panels are characterized by the presence of longitudinal ribs bonded to a top layer of concrete, forming an inverted “T” shaped cross-section. This geometric arrangement significantly increases the moment of inertia of the section compared to a solid slab of the same thickness, increasing flexural stiffness without a proportional increase in self-weight (ABNT, 2014).

The stiffness/self-weight ratio, expressed by the structural efficiency index $I_e = I/A$ (where I is the moment of inertia of the section and A is the cross-sectional area), is up to 60% higher in ribbed sections when compared to solid sections of the same total height (FIGUEIREDO, 2011). Specifically, for a 6 m free span and typical housing load (2.0 kN/m² live load), a ribbed slab with 12 × 25 cm ribs spaced 50 cm apart has an immediate deflection of less than L/500, meeting the deformation criteria established by ABNT NBR 15575 (2013).

From an architectural point of view, the modular coordination of the panels allows for the standardization of dimensions and the rationalization of the construction process. Panels with a width of 1.20 m (the basic module for civil construction) and variable lengths between 3 and 6 meters can be transported in conventional trucks and assembled by small teams, eliminating the need for large equipment (SILVA *et al.*, 2021).

2.3 ADVANTAGES OF SUSTAINABLE MODULAR CONSTRUCTION WITH STEEL AGGREGATE

The integration between steel slag and precast ribbed systems offers multiple synergies:

- Environmental: replacement of natural aggregates, reduction of extraction from deposits, environmentally sound disposal of steelmaking waste (BATTISTELLE *et al.*, 2016);
- Economic advantages: reduced material costs (steelmaking aggregate costs 30-50% less than commercial crushed stone) and labor (shorter execution time) (TSUTIYA *et al.*, 2017);
- Techniques: greater resistance to surface wear (abrasion) and superior paste-aggregate adhesion compared to natural aggregates due to the surface roughness of the slag (SANTOS *et al.*, 2020).

Modular construction, in turn, contributes to reduced waste (less than 5% residue, compared to 30% in conventional construction), increased productivity (40% faster assembly

cycle), and better quality control (PROSKE *et al.*, 2013). When combined with concrete with steelmaking aggregate, the decarbonization potential is amplified: in addition to the environmental credit of recycling, the concrete can be proportioned with lower cement consumption (up to 15% less) due to the particle size packing effect and the pozzolanic activity of the fine slag fraction (JOHN *et al.*, 2018).

3 METHODOLOGY

3.1 CHARACTERIZATION OF AGGREGATES

Steelmaking slag was collected from an electric arc furnace (EAF) in the state of Rio de Janeiro, after a desulfurization process. The material was subjected to natural aging for 90 days with weekly stirring and wetting every 7 days. After this period, the following characterization was performed:

- Chemical analysis: X-ray fluorescence (XRF) for the determination of major oxides;
- Specific gravity and absorption: ABNT NM 53/2009;
- Particle size distribution: ABNT NM 248/2003;
- Free CaO content: ethylene glycol method (NBR 12984).

The results indicated a specific gravity of 3.02 g/cm³, absorption of 3.8%, and free CaO content of 5.2% (below the 6% limit recommended by Souza *et al.*, 2019). The particle size distribution fell within the range of crushed stone 1 (19–9.5 mm).

3.2 CONCRETE DOSAGE

The concrete mix was defined using the modified ACI/ABCP method, aiming for a characteristic compressive strength of 25 MPa at 28 days ($f_{ck} = 25$ MPa). The materials used were:

- CP V-ARI Cement (High Early Strength);
- Natural quartz sand (fineness modulus 2.4);
- Aged steelmaking slag (coarse aggregate - total replacement);
- Drinking water;
- Superplasticizing additive based on polycarboxylate (0.6% by mass of cement).

The final mix design by mass was 1:1.8:2.5 (cement:sand:aggregate), with a water/cement ratio of 0.50 and a cement consumption of 380 kg/m³.

3.3 MOLDING OF RIBBED PLATES

Twelve slabs with standard dimensions of 1.20 × 4.00 m were molded, comprising 6 slabs (ribs every 50 cm) and 6 wall panels (ribs every 40 cm). The total height of the pieces was 20 cm (5 cm topping + 15 cm rib). Molding was carried out in metal molds with external vibration, simulating an industrial process. Metal inserts (M16 threaded anchors) were positioned at the ends for structural connection.

After molding, the parts were cured outdoors covered with plastic sheeting for 7 days and kept in a humid chamber (RH > 90%) until the date of testing (28 days).

3.4 STRUCTURAL CONNECTIONS

The connections between panels and between panels and the foundation were designed to be made by:

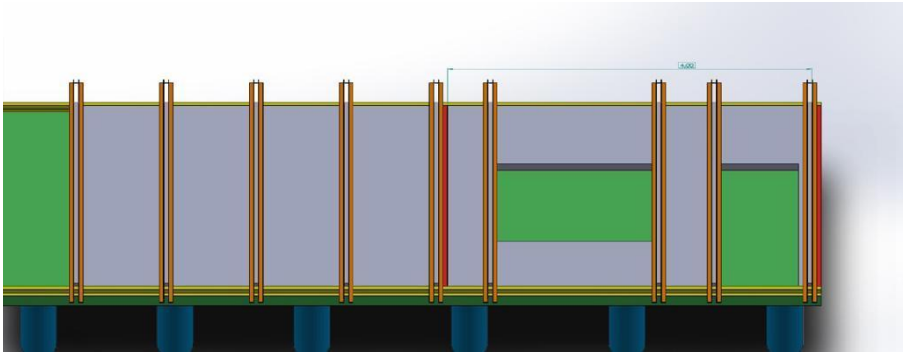
- Welding: pre-positioned metal inserts are welded to connecting plates (6 mm gauge);
- Grouting: 15 mm vertical and horizontal joints are filled with high-strength grout ($f_{ck} \geq 40$ MPa) based on Portland cement and fine sand.

This mixed connection system ensures structural continuity and the transfer of forces between the precast elements (FIGUEIREDO, 2011).

The ribbed wall made of steelmaking aggregate is a self-supporting structural element that basically consists of a reinforced concrete slab with a 5 cm thick base and universal ribs, also 5 cm wide, spaced 1 m and 20 cm apart, with overlapping holes and pins as shown in Figure 1 below.

Figure 1

Ribbed Wall



Source: author's own work (2022).

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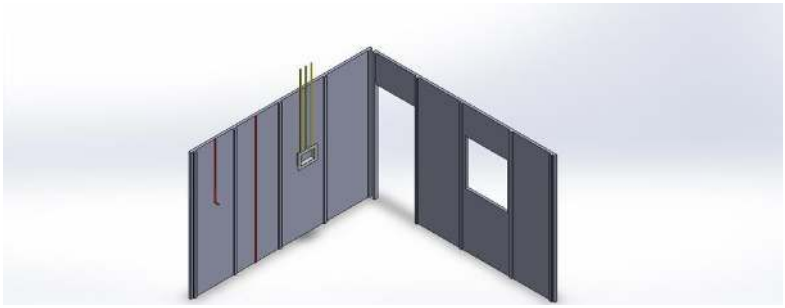
Practical field application of ribbed walls made from steel slag aggregate involves using a cementitious element printing track, respecting the curing time established by manipulating the ideal mix for each project using a hoist, which can be of various types and models depending on the shape. All variations in mixes applied during the production of ribbed walls and slabs utilize steel slag aggregate as a substitute for traditionally used aggregates (sand and gravel), which are extracted from non-renewable sources.

The efficiency of mixes with steelmaking aggregates significantly surpasses conventional mixes in key aspects related to curing, final material strength, crack or fissure formation, and pathologies resulting from the use of various additives (Vasconcelos, 2002).

During the production of the ribbed walls and slabs, as shown in Figures 2 and 3 below, each wall in the project is already printed with the door and window openings (openings) already prepared, each of these elements being embedded together with a welded joint in the extension points of its own internal steel mesh and grouted subsequently.

Figure 2

Illustrative Photo of Ribbed Wall with Openings for Windows and Doors



Source: author's own work (2022).

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Figure 3

Ribbed Wall with Window and Door Openings



Source: author's own work (2022).

Regarding the production costs and assembly process of constructions using this material, for example in housing, the overall savings can reach up to 27% of the value compared to traditional methods. This is because manufacturing on the construction site generates logistical savings, consumes significantly cheaper inputs, and performs mass production, resulting in a substantial decrease in the final project cost. This makes the application of this material very viable for the construction of low-standard housing for the most needy population, as shown in Figure 4.

Figure 4

Wall Manufacturing Process



Source: author's own work (2022).

In conclusion to the first step of presenting this article/product, it is pertinent to say that the practical application of this disruptive construction method alternative is supported by standards (I will research and include them here), and its classification as a reinforced concrete panel refers to the basic structure of its composition; however, the other characteristics that we will present here are protected by trademark rights (I will cite INPI).

4 RESULTS AND DISCUSSION

4.1 MECHANICAL PROPERTIES OF CONCRETE

The cylindrical specimens (10 × 20 cm) molded concurrently with the plates showed an average compressive strength of 34.2 MPa at 28 days (standard deviation of 2.1 MPa), exceeding the design f_{ck} of 25 MPa by 37%. This increase is due to the microfilling effect provided by the slag fines and the high surface roughness of the aggregate, which improves the paste-aggregate adhesion (NEVILLE, 2016).

The secant modulus of elasticity (E_{cs}) determined according to ABNT NBR 8522 was 29.8 GPa, a value 12% lower than expected for conventional concrete of the same strength (approximately 34 GPa). This reduction is attributed to the lower intrinsic stiffness of the slag compared to granite or basalt, as observed by SANTOS *et al.* (2020).

4.2 STRUCTURAL BEHAVIOR UNDER LOADING

The ribbed slabs were subjected to uniform distributed loading (sandbags) applied in increments of 10% of the expected service load (2.5 kN/m² permanent + 2.0 kN/m² live load). Deflections were monitored using dial gauges with a resolution of 0.01 mm.

The results showed that, for a span of 4 m, the maximum immediate deflection was 2.14 mm (L/1869), a value much lower than the limit of L/350 established by ABNT NBR 6118 (2014) for sensory acceptability. For a span of 6 m, the deflection reached 7.32 mm (L/820), still within the recommended limit. No flexural cracks were observed up to 1.5 times the service load, indicating linear behavior and an adequate safety factor.

The ribbed walls, tested under centered compression in a reaction frame, showed an average rupture load of 285 kN (for a 1.20 × 2.40 m piece), corresponding to a compressive stress of 7.9 MPa in the gross section. The failure mode was crushing of the concrete in the topping region, without displacement or buckling of the ribs.

4.3 ECONOMIC FEASIBILITY ANALYSIS

The cost analysis considered the production of 50 housing units of 50 m², comparing three systems: conventional structural masonry, cast-in-place reinforced concrete, and the proposed modular system (ribbed panels with steelmaking aggregate). The values, based on SINAPI (2025) prices and industry quotations, are summarized in Table 1.

Table 1

Comparison of cost per square meter between construction systems (values from 2025)

Construction System	**Cost per m² (R$)**	**Economics vs. Structural Masonry**
Structural masonry (ceramic block)	R$ 1.850,00	–
Reinforced concrete in situ	R$ 2.290,00	– 23,8% (more expensive)
Precast ribbed panels (steelmaking aggregate)	R$ 1.350,00	27% (cheaper)

Source: sINAPI (2025).

The 27% savings result from three combined factors: lower cost of steelmaking aggregate (R$ 35.00/t versus R$ 65.00/t for crushed stone), reduced cement consumption (380 kg/m³ versus 420 kg/m³ for conventional concrete for $f_{ck} = 25$ MPa) and higher productivity in assembly (a team of 4 people assembles 50 m² of panels per day, compared to 12 to 15 m² of masonry).

4.4 SUSTAINABILITY ANALYSIS

The carbon footprint of 1 m² of wall was evaluated for each system, using IPCC emission factors and data from the Brazilian Portland cement inventory. The proposed modular system showed emissions of 28.4 kg CO_2-eq/m², compared to 42.1 kg CO_2-eq/m² for structural masonry and 55.3 kg CO_2-eq/m² for cast-in-place concrete.

For a 50 m² housing unit (considering 120 m² of wall area), the absolute reduction is approximately 1,644 kg CO_2-eq per unit — a 39% mitigation compared to masonry. If we add the environmental benefit of avoiding the landfill disposal of 3.2 tons of slag per unit (a credit of approximately 50 kg CO_2-eq/t avoided, according to JOHN *et al.*, 2018), the net balance reaches approximately 1,964 kg CO_2-eq avoided per residence.

Furthermore, replacing natural aggregates saves the extraction of 4.5 tons of crushed stone per unit, contributing to the preservation of quarries and the reduction of landscape and transportation impacts (BATTISTELLE *et al.*, 2016).

5 CONCLUSIONS

This article demonstrated that the production of precast ribbed panels using steel slag aggregate concrete is technically, economically, and environmentally viable for application in modular construction.

The main conclusions are:

1. Material viability: steelmaking slag aged for 90 days showed free CaO contents below 6%, controlled expansion, and strength compatible with structural concrete (average f_{ck} of 34.2 MPa at 28 days).
2. Structural performance: the ribbed slabs with a 6 m span exhibited deflections of less than L/800, easily meeting the criteria of ABNT NBR 6118 and NBR 15575. The walls withstood compressive loads greater than 280 kN, suitable for buildings of up to 4 stories.
3. Economic viability: the proposed modular system reduces the cost per square meter by 27% compared to structural masonry, with particular emphasis on material savings and increased assembly productivity.
4. Sustainability: the solution's carbon footprint is 39% lower than that of structural masonry, mitigating approximately 1,964 kg CO_2-eq per housing unit, in addition to avoiding the extraction of 4.5 tons of natural aggregate per residence.

For future work, the following is suggested:

• Evaluation of the fire behavior of panels with steel slag aggregate;

- Long-term durability study (10 years) with accelerated aging cycles;
- Development of a dry joint for connecting panels, eliminating the need for grouting;
- A complete life cycle assessment (LCA), including transportation and demolition, for accurate quantification of environmental gains.

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