ABSTRACT

Purpose: To evaluate the production of concrete from the partial replacement of Portland cement with petroleum catalyst residue (RC), generated in large quantities by the petrochemical industries, and the addition of polyethylene glycol 400 (PEG 400), with an emphasis on investigating its mechanical properties and durability, considering the technological, scientific and environmental aspects.

Theoretical framework: Oil catalyst waste is generated in significant quantities and is classified as non-inert due to its metal ion content, so there is a need to investigate new disposal methods. The use of RC as partial substitute for Portland cement, with the addition of PEG 400 (self-curing agent), was investigated for the production of non-conventional concrete. The waste has pozzolanic activity, enabling improvements in mechanical properties when added to the cement matrix. PEG 400 has properties that can make concrete more effective in terms of water absorption, hydration heat and workability. The search for sustainability leads to research into new construction materials in order to preserve natural resources and reduce environmental impact. The concrete developed can be lower cost and more durable, without any loss of structural strength.

Method/design/approach: The use of RC was investigated with partial substitutions of 2%, 5%, 10% and 20% in relation to the total mass of Portland cement for the manufacture of concrete and the addition of polyethylene glycol 400 (PEG 400) as a self-curing agent. The void ratio, water absorption by capillarity and immersion, specific masses and pozzolanicity index of the waste were investigated. Mechanical and morphological characterization tests were also carried out on the concretes developed.

Results and conclusion: The compressive strength of concrete produced with 2% RC in relation to the total mass of cement and 1.5% PEG 400 increased by 18.3% compared to conventional concrete. An increase in the amount of residue caused a reduction in concrete strength. The sample with 1.5% PEG 400 obtained better workability in
the fresh state, which may be due to the polymer acting as a self-healing agent. The images obtained by scanning electron microscopy showed that the samples containing 2% added RC had lower porosity. The study showed that the waste can be used satisfactorily in civil construction and the implementation of this new process can reduce global warming and the scarcity of mineral resources, taking sustainability into account.

Research implications: This work contributes to a sustainable circular economy with a new process for using petroleum catalyst waste, with pozzolanic characteristics, in cementitious materials.

Originality/value: The results will be promising for the use of petroleum catalyst waste and polyethylene glycol in the production of environmentally sustainable concrete.

Keywords: Oil Catalyst Residue, Concrete, Polyethylene Glycol, Self-Healing Agent, Sustainability.

CONCRETO SUSTENTÁVEL PRODUZIDO COM RESÍDULO DE CATALISADOR DE PETRÓLEO E POLIETILENO GLICOL COMO AGENTE DE AUTOCURA

RESUMO

Objetivo: Avaliar a produção de concreto a partir da substituição parcial do cimento Portland pelo resíduo de catalisador de petróleo (RC), gerado em elevada quantidade pelas indústrias petroquímicas, e adição de polietilenoglicol 400 (PEG 400), com ênfase em investigar sua propriedade mecânica e de durabilidade, considerando os aspectos tecnológico, científico e ambiental.

Referencial teórico: Resíduos de catalisador de petróleo são gerados em quantidades significativas e classificados como não inertes devido ao seu teor de íons metálicos e, sendo assim, há necessidade de se investir novos métodos de disposição. Foi investigado para a produção de concreto não convencional, o uso do RC, como substituinte parcial do cimento Portland, com a adição de PEG 400 (agente de autocura). O resíduo apresenta atividade pozzolânica, possibilitando melhorias de propriedades mecânicas quando adicionado à matriz cimentícia. O PEG 400 possui propriedades que podem tornar o concreto mais eficaz quanto à absorção de água, ao calor de hidratação e à trabalhabilidade. A busca pela sustentabilidade conduz à investigação de novos materiais de construção, a fim de preservar os recursos naturais e reduzir o impacto Ambiental. O concreto desenvolvido pode apresentar um menor custo e maior durabilidade, sem perdas de resistência estrutural.

Método/desenho/abordagem: Foi investigado o uso de RC com substituições parciais de 2%, 5%, 10% e 20%, em relação à massa total de cimento Portland, para a fabricação de concreto e a adição de polietilenoglicol (PEG 400) como agente de autocura. Foram pesquisados o índice de vazios, a absorção de água por capilaridade e por imersão, as massas específicas e o índice de pozolanicidade do resíduo. Foram realizados ainda, ensaios de caracterização mecânica e morfológica dos concretos desenvolvidos.

Resultados e conclusão: A resistência à compressão do concreto produzido com 2% de RC, em relação à massa total de cimento, e 1,5% de PEG 400 teve um aumento de 18,3% em relação ao convencional. Um aumento na quantidade do resíduo causou uma redução na resistência do concreto. A amostra com adição de 1,5% de PEG 400 obteve uma melhor trabalhabilidade no estado fresco, o que pode ser evidenciado pelo polímetro atuar como agente de autocura. As imagens obtidas por microscopia eletrônica de varredura constataram que as amostras contendo 2% de adição de RC apresentaram menor porosidade. O estudo evidenciou que o resíduo pode ser utilizado de forma satisfatória na construção civil e a implementação deste novo processo pode reduzir o aquecimento global e a escassez de recursos minerais, levando em conta a sustentabilidade.

Implicações da pesquisa: Este trabalho contribui para uma economia circular sustentável com um novo processo do uso do resíduo de catalisador de petróleo, com características pozzolânicas, em materiais cimentícios.

Originalidade/valor: Os resultados serão promissores para a utilização do resíduo de catalisador de petróleo e o polietilenoglicol na produção de concreto ambientalmente sustentável.

Palavras-chave: Resíduo de Catalisador de Petróleo, Concreto, Polietilenoglicol, Agente Autocura, Sustentabilidade.
1 INTRODUCTION

Trying to meet the goals of the 2030 Agenda for sustainable development and reduce the consumption of non-renewable resources, scientists are increasingly seeking the use of non-conventional materials in cement products. In the 21st century, the construction industry, one of the sectors that most generates impacts, faces several global challenges associated with growing concerns about the environment. This sector poses several issues due to its final operations, including extensive natural resource consumption, improper disposal practices, CO₂ emissions, slow adaptation, waste production among others. (Leite et al., 2023; Pupin et al., 2022)

Environmental conservation has been a global concern since natural resources are not infinite, and nature is incapable of absorbing the excessive production of waste (Freita et al., 2016). In this scenario of search for innovative products, researchers investigate materials to be incorporated into concrete, such as waste from the oil cracking industry, vegetable fibers, rice husk ash, sugarcane bagasse, as well as various types of polymers (Huang et al., 2023; Akid et al., 2021; Rostami et al., 2020; Gu and Ozbakkaloglu, 2016; Asim et al., 2021; Kajaste and Hurme, 2016).

The petroleum catalyst residue, generated in Brazil by petrochemical industries in high quantities of approximately 400 thousand tons per year, originates from fluidized bed catalytic cracking units that convert heavy gas oils into lighter hydrocarbons during the refining process (Almeida et al., 2020). The physical-chemical-mineralogical characteristics of the waste and its potential use in the civil construction sectors have attracted the attention of investigators (Asim et al., 2021). RC is a thin material with pores around 4nm, consisting of silica (55.7 wt%) and alumina (37.2 wt%), and a minor amount of oxides of La (3.20 wt%), Ti (0.5 wt%), Na (1.1 wt%), Mg (1.0 wt%), plus some traces of the oxides of V (0.5 wt%), K (0.5 wt%) and S (<0.5 wt%) (Almeida et al., 2018).

The composition of RC presents similarities with pozzolanic materials such as fly ash and silica fume that are within the parameters established by ASTM C618 (2022) for use in concrete. Borrachero et al. (2021) cite that the residue has excellent pozzolanic reactivity due to the high content of reactive silica and alumina. A study conducted by Castellanos et al. (2016) investigated the use of adding this material in concrete, mentioning that 10% of RC increased the compressive and flexural strengths of the composite by approximately 15% and 30%, respectively. Phenomena such as carbonation can be crucial for the appearance of pathologies in constructions. Anwar and Emarah (2020) evaluated the resistance to chloride attack in concrete containing mixtures of 15 and/or 25% fly ash and 5 and/or 10% silica fume. For all samples studied, the results showed a lower percentage of soluble chloride than the reference concrete.

The literature cites the addition of polyethylene glycol 400 (PEG 400) as a chemical agent responsible for the self-healing of concrete due to its ability to retain a greater amount of water in the cement pores for adequate hydration in the material (Singh, 2021). The self-healing concrete produced with PEG 400 mitigates the problems related to the lack of water for cement hydration, in addition to improving the mechanical properties of the material, such as compressive and tensile strength, when compared to conventional concrete. The addition of PEG 400 is a viable solution for concrete with good structural performance and for construction
applications in places with low water availability. Jamle and Mandiwal (2018) report that in the manufacture of concrete, water is essential for cement hydration and for the curing process. Self-curing additive aids water retention and minimizes evaporation on concrete surface (Magudeaswaran et al., 2023). Although concrete is the most widely used structural material in the world, a curing method that does not rely on the addition of water is still being investigated by researchers (Malathy et al., 2020; Madduru et al., 2020; Kulkar and Muthadhi, 2020).

In this context, the research aims to investigate the use of petroleum catalyst residue as a partial substitute for Portland cement in the production of concrete with the addition of PEG 400. Polyethylene glycol possesses characteristics that can improve the concrete’s properties regarding water absorption, hydration heat, physical and chemical strengths, and workability. The pursuit of sustainability leads to the investigation of new construction materials to preserve natural resources, reduce environmental impact, and enable the production of low-cost materials with better performance and durability.

2 MATERIALS AND METHODS

2.1 Materials

The concrete samples were produced using Portland cement CPII-E-32 from the company TUPI (MG/Brazil) with a specific mass of 3.10 g/cm³. The petroleum catalyst residue was supplied by Petrobras S.A. (MG/Brazil). The fine aggregate used was of artificial origin with a medium granulation, and the coarse aggregate was crushed gneiss type 0, with a maximum characteristic diameter of 9.5 mm and a specific mass of 2.94 g/cm³. Polyethylene glycol (PEG 400), 1.5% in relation to the total mass of the cement, was provided by Neon Comercial (SP/Brazil) and has a specific mass at 20ºC of 1.11 g/cm³.

2.2 Concrete Production

To produce concrete, a dosage of 1:2:3:0.55 (cement: fine aggregate: coarse aggregate: water) was used, following the methodology developed by Abreu et al. (2020). Specimens with six different dosages were produced. Each sample was properly identified as conventional concrete (CC), concrete with the addition of 1.5% PEG 400 (CP), concrete with the addition of 1.5% PEG 400 and replacement of the cement mass by RC at levels of 2 %, 5%, 10% (CPRC2.0%, CPRC 5.0% and CPRC 10.0%) and concrete with 20% replacement of RC by cement mass without PEG 400 (CRC20%). The dosages of materials for specimens of the concrete produced are shown in Table 1.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cement (g)</th>
<th>Fine aggregate (g)</th>
<th>Coarse aggregate (g)</th>
<th>Water (mL)</th>
<th>PEG 400 (mL)</th>
<th>RC (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>662.07</td>
<td>1299.25</td>
<td>1948.87</td>
<td>357.29</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>CP</td>
<td>640.85</td>
<td>1299.25</td>
<td>1948.87</td>
<td>357.29</td>
<td>8.78</td>
<td>0.00</td>
</tr>
<tr>
<td>CPRC2.0%</td>
<td>627.85</td>
<td>1299.25</td>
<td>1948.87</td>
<td>357.29</td>
<td>8.78</td>
<td>12.99</td>
</tr>
<tr>
<td>CPRC5.0%</td>
<td>608.36</td>
<td>1299.25</td>
<td>1948.87</td>
<td>357.29</td>
<td>8.78</td>
<td>32.48</td>
</tr>
<tr>
<td>CPRC10.0%</td>
<td>575.38</td>
<td>1299.25</td>
<td>1948.87</td>
<td>357.29</td>
<td>8.78</td>
<td>64.96</td>
</tr>
<tr>
<td>CRC20.0%</td>
<td>519.70</td>
<td>1299.25</td>
<td>1948.87</td>
<td>357.29</td>
<td>0.00</td>
<td>129.93</td>
</tr>
</tbody>
</table>

Source: own authorship.
To produce concrete, the aggregates were mixed together with the RC and the cement. Then, PEG 400 mixed with water was incorporated into the system. The materials were mixed until obtaining a mixture with a homogeneous appearance (Figure 1a and 1b) and molded into cylindrical specimens with dimensions of 10 x 20 cm, following the procedures established by NBR 5738 (2019). After 24 hours, the specimens were demolded and transferred to a curing tank with an alkaline aqueous solution (Ca(OH)\(_2\), 0.3 mol/L).

![Figure 1. Addition of concrete components (a) and after mixing (b). Source: own authorship.](image)

### 2.3 Characterization Tests

The material underwent various tests to characterize it regarding its chemical, physical, mechanical, and morphological properties. In its fresh state, tests for consistency were carried out using the slump cone test (ABNT, 2020) and the determination of specific mass (ABNT, 2018).

After 28 days of curing, tests were carried out to determine water absorption, voids ratio and specific mass (ABNT, 2019), determination of water absorption by capillarity (ABNT, 2020) and resistance to axial compression (ABNT, 2018) using a MFL Systeme hydraulic press with a load of 0.45 ± 0.15 MPa/s.

It was also investigated the process of chloride ion penetration by sprinkling silver nitrate (AgNO\(_3\)) on the test specimens. For this test, the Italian standard UNI 7928 (1978) was used as a reference. This standard evaluates the formation of white precipitate when AgNO\(_3\) is sprinkled on concrete and in the presence of light, indicating that the sample with a whitish color is contaminated and that the layer of passivation may be deteriorated (Rocha and Ibarra-Vilanueva, 2020; Lyra and Monteiro, 2020). Thus, an aqueous solution of AgNO\(_3\) with a concentration of 0.1 M was sprinkled on the fractured concrete parts, cut into slices (50 mm in height and 100 mm in diameter). After a period of 10 minutes, the penetration depths of chlorides identified by a white precipitate of silver chloride were measured on the surface of the sample. Seven measurement values were obtained, starting from the center at 10 mm intervals.

Finally, the scanning electron microscopy (SEM) test was carried out using the Hitachi TM 4000 Plus microscope on the concrete samples to evaluate the material morphology, weld lines, blend interfaces, cracks, irregular surfaces, porosity, and other features.

### 3 RESULTS AND DISCUSSION

#### 3.1 Characteristics of Cement and Aggregates used for the Production of Concrete

Table 2 shows the characteristics of Portland cement with the addition of blast furnace slag, CPII E32, used both in conventional and in the concretes evaluated with petroleum catalyst residue and PEG 400 (ABNT, 2022; ABNT, 2019; ABNT 2018).
Sustainable Concrete Produced with Petroleum Catalyst waste and Polyethylene Glycol as a Self-Healing Agent

Table 2. Characteristics of Portland cement.

<table>
<thead>
<tr>
<th>Cement</th>
<th>Unit Mass</th>
<th>Specific mass</th>
<th>Fineness Modulus (200 sieve)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPII-E-32</td>
<td>1,10</td>
<td>3,10</td>
<td>2,5</td>
</tr>
</tbody>
</table>

Source: own authorship.

The physical properties of fine and coarse aggregates for the production of concrete can be seen in Tables 3 and 4.

Table 3. Fine aggregate characterization tests.

<table>
<thead>
<tr>
<th>Specific mass (g/cm³)</th>
<th>Unit mass (g/cm³)</th>
<th>Compacted bulk density (g/cm³)</th>
<th>Content of powdery materials (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.67</td>
<td>1,12</td>
<td>1.68</td>
<td>2.12</td>
</tr>
</tbody>
</table>

Source: own authorship.

Table 4. Coarse aggregate characterization tests.

<table>
<thead>
<tr>
<th>Aggregate</th>
<th>Specific mass/density of dry aggregate (g/cm³)</th>
<th>Specific mass/density of saturated surface dry aggregate (g/cm³)</th>
<th>Bulk density (g/cm³)</th>
<th>Water absorption (%)</th>
<th>Compacted bulk density (g/cm³)</th>
<th>Loose Bulk Density (g/cm³)</th>
<th>Content of powdery materials (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gnaissae</td>
<td>2.54</td>
<td>2.53</td>
<td>2.52</td>
<td>0.40</td>
<td>1.57</td>
<td>1.57</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Source: own authorship.

The average particle size of coarse and fine aggregates (ABNT, 2022) was determined. The particle size curve of natural average sand and type 0 gneiss aggregate can be seen in Figure 2a and 2b, respectively. The maximum characteristic dimension of the fine aggregate was 2.4 mm, and the fineness modulus of the aggregate is 2.17 mm, similar to the work developed by Scheifer and Callejas (2021).

For coarse aggregate, the sieve with the highest percentage of retained materials was the one with a mesh size of 6.3 mm (Figure 2b) in accordance with Estolano et al. (2017). This characterized the coarse aggregates in crushed stone 0 with dimensions ranging between 4.5 and 9.5 mm. The tests were based on ABNT NBR 16917 (2021), ABNT NBR 16972 (2021) and ABNT NBR 16973 (2021) standards.

Figure 2. Grain size distribution of fine aggregate (a) and coarse aggregate (b).

Source: own authorship.
3.2 Consistency of the Concrete Produced

The rheology of concrete produced in the fresh state was analyzed using the slump test, as specified in NBR 16889 (2020) and NBR 9833 (2018). Table 5 illustrates the results obtained.

Table 5. Results of the consistency tests of the concrete produced.

<table>
<thead>
<tr>
<th>Dosage</th>
<th>Water/binder ratio</th>
<th>Addition of PEG 400</th>
<th>Slump test (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>0.55</td>
<td>-</td>
<td>120 ± 10</td>
</tr>
<tr>
<td>CP</td>
<td>0.55</td>
<td>1.5%</td>
<td>140 ± 10</td>
</tr>
<tr>
<td>CPRC2%</td>
<td>0.55</td>
<td>1.5%</td>
<td>135 ± 5</td>
</tr>
<tr>
<td>CPRC5%</td>
<td>0.55</td>
<td>1.5%</td>
<td>135 ± 5</td>
</tr>
<tr>
<td>CPRC10%</td>
<td>0.55</td>
<td>1.5%</td>
<td>120 ± 10</td>
</tr>
<tr>
<td>CRC20%</td>
<td>0.55</td>
<td>-</td>
<td>120 ± 5</td>
</tr>
</tbody>
</table>

Source: own authorship.

Based on the consistency results, it was found that all concrete produced in the fresh state showed good workability for molding the test specimens. However, the CP sample showed greater consistency in the fresh state, which is probably due to the hygroscopic characteristic of PEG400, making it convenient to reduce the water/cement content, in agreement with Singh (2020). PEG400 is soluble in water and other organic solvents, such as aromatic hydrocarbons, which contributes to the good water retention in concrete mixes, adhesives, binders, and welding fluxes using this polymer.

By increasing the RC content, the consistency decreased and there was an increase in water absorption rates, as the RC grains are finer than those of Portland cement (50 - 150µm), which provides a higher water-to-cement ratio. An increase in the porosity of the concrete was also observed. According to the classification of the International Union of Pure and Applied Chemistry (IUPAC), the catalyst residue can be considered as mesoporous because it is in the range of pore diameters from 2 to 50 nm (Almeida et al., 2017). As explained by Le et al. (2021), the incorporation of CR in concrete causes a need to add an extra alkaline liquid to maintain workability similar to conventional concrete samples.

3.3 Determination of Water Absorption, Void Ratio and Specific Mass

It was observed that for most samples, the greater the amount of CR, the greater the percentage of water absorption (Figure 3a) and the greater the voids index (Figure 3b). The CPRC 20% sample showed higher values of water absorption rate and voids index. It is likely that there will be an increase in the total pore volume of concrete, which may interfere with the mechanical strength of the material (Estolano et al., 2017). As mentioned by Givi et al. (2011), the addition of fine particles such as RC may require the consume of more water as a result of more C–S–H gel formation in the early ages of moist curing.

During the cement hydration process, primary chemical reactions take place, leading to the production of C-S-H (calcium silicate hydrate), which promotes concrete crystallization and the formation of calcium hydroxide. Additionally, a byproduct (free lime) is produced, which can coat the available pores inside the concrete, impeding water movement within the composite (Lothenbach et al., 2016).
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The increase in the RC content favored a small reduction in the dry, saturated, and real specific masses compared to conventional concrete (Figure 4). It is likely that the incorporation of RC, as it has a smaller granulometry than that of Portland cement and, therefore, a greater specific surface area, favors the hydration reaction and a higher water/cement ratio. The reduction of specific masses would lead to a denser cementitious matrix.

3.4 Absorption of Water by Capillarity

The dosages of concrete with the addition of PEG 400 1.5% (CP) showed a lower absorption by capillarity in all time intervals evaluated in relation to the reference sample (CC), as shown in Figure 5. This happens because PEG 400, agent of self-healing, reduces the use of water in concrete and controls water evaporation during the hydration process (Singh, 2020). The sample with 10% RC replacement content showed low absorption rates compared to conventional concrete. That can be explained, most likely, by the chemical composition of the waste, which has a high percentage of silica (SiO2), 53.66%, in its composition with a faujasite crystalline structure, as described by Almeida et al. (2020). According to Deboucha et al. (2017), water absorption by capillarity is reduced as the content of pozzolanic materials increases. This happens because the capillary pores are filled by the formation of a secondary C-S-H gel due to the pozzolanic reaction that favors the reduction in the capillary absorption coefficient of the cementitious composite in relation to the reference sample. The presence of PEG 400 also favors the results, since this component makes it difficult for water to rise (Herki et al., 2022).
3.5 Resistance to Axial Compression

The concrete sample containing 2% RC replacement and 1.5% PEG 400 (CPRC2%) obtained a higher compressive strength value (15.67 MPa) compared to the reference sample (12.80 MPa), as well as CPRC5% (13.33 MPa) and CPRC10% (13.16 MPa) samples, as shown in Figure 6. According to Lothenbach et al. (2016), the addition of moderate amounts of SiO\(_2\), a substance that is present in greater quantity in the waste, leads to the consumption of Portlandite. If a higher percentage of SiO\(_2\) is added, the excess SiO\(_2\) will react with the CSH. The pozzolanic reaction occurs between silica fume and calcium oxide, producing additional CSH in many of the voids around hydrated cement particles, compounds that fill the space previously occupied by water and dissolving cement particles (Ahmed et al., 2019).

The additional C-S-H (calcium silicate hydrate), resulting from the increase in active silica, provides the concrete not only with better compressive and flexural strength but also a denser matrix, especially in areas that would have remained with small voids susceptible to the possible ingress of harmful substances (Lothenbach et al., 2016). However, it is observed that there is a maximum content of RC that can be incorporated into the concrete for these properties to improve. Thus, the addition of up to 2% of the waste provides an increase in the material's strength of up to 22%. After this percentage, the higher the RC content, the lower the axial compression strength of the unpacked samples. The CPRC20% sample showed lower strength than the reference. This result confirms that having an additional amount of high-silica waste with high porosity can favor the formation of a more porous composite. Researchers report that the compressive strength of hardened concrete samples produced with RC is reduced due to the presence of a large number of voids compared to the conventional sample (Le et al., 2021; Yu et al., 2021).

As water plays an important role throughout the useful life of concrete, since it is an essential component in mixing, hardening, and curing, it was decided to add PEG 400 with the proposal of aiding the internal curing of the material under study. For this purpose, the aim was to provide additional moisture distributed throughout the concrete matrix, which often does not occur in the conventional curing process. Curing can take place markedly on the surface of the material (Gopinadhan et al., 2018). Water in the curing of concrete maintains a satisfactory moisture content to achieve the desired mechanical properties, improving the microstructure of
the material and, consequently, improving its performance and durability. The results indicate that the petroleum catalyst residue can favor an increase in the resistance to axial compression and that the PEG 400 can significantly contribute to the concrete curing process.

Figure 6. Average axial compressive strength of the different experimental mixtures studied. Source: own authorship.

3.6 Scanning Electron Microscopy (SEM)

The microstructural analyzes of the concrete specimens with some study dosages were carried out (Figure 7). The CC reference sample (Figure 7a) appears to be more porous than CPRC2% (Figure 7b). CR particles are clearly seen in images of concrete in the hardened state, as they are quite round in shape (Fig 8b). The images of samples with the incorporation of 20% of residue, CPRC20%, reveal that the particles are strongly grouped, as also observed in the work developed by Malaiskiene et al. (2021) It is likely that the total porosity of the CPC20% sample is increased with the incorporation of the residue due to the RC having a porous structure, which reduces the resistance. However, the concrete containing 20% of the residue still has good durability and compact microstructure (Huang et al., 2023).

Figure 7. Microstructure images obtained by SEM of concrete samples CC (a); CPRC 2% (b); and CRC 20% (c). Source: own authorship.
4 CONCLUSIONS

The residue from petroleum catalyst, considered non-inert, can cause environmental pollution if not properly disposed of. The development of concrete using materials with pozzolanic properties, as well as self-polymerizing additives, allows meeting sustainability commitments. Concrete samples with the addition of polyethylene glycol 400 (1.5%) and the use of petroleum catalyst residue as a partial replacement for Portland cement proved to be efficient in several parameters. The sample with polymer addition showed a high yield stress and viscosity compared to the others, probably due to the hygroscopic characteristic of PEG 400. As the content of RC increased, the consistency of the concrete decreased, which is due to the fact that the residue has a high specific surface area, allowing for a higher water consumption for the hydration reactions of the material.

The compressive strength of the sample containing 2% RC and 1.5% PEG 400 (15.67 MPa) was 18% higher than the conventional one (12.80 MPa), which can probably be explained by the fact that the residue has a smaller granulometry than Portland cement, allowing a greater hydration reaction speed, leading to a faster formation of hydrated calcium silicate (C-S-H) and thus favoring the resistance property of the concrete. However, an increase in catalyst residue caused a reduction in the compressive strength of concrete, which may be related to the increase in porosity. With a larger volume of pores, concrete has a greater potential to absorb water, thereby affecting the material's mechanical strength. Furthermore, the excess amount of waste favors greater water absorption. Excess water for the hydration reaction remains in the concrete pores, which contributes to reduced strength. The microstructural analysis corroborates the results presented in the tests of porosity, void index, and capillary water absorption, showing that as the percentages of residue in the concrete increased, the material could become more porous, as RC is a porous material, and its specific mass decreased. Nonetheless, the concrete containing the residue has good durability and compact microstructure.

The new composite developed can provide low-cost concrete structures and provide an alternative application for petroleum catalyst residue.

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