Effects of the induced micro- and meso-porosity on the single site density and turn over frequency of Fe-N-C carbon electrodes for the oxygen reduction reaction

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1. Introduction

It is nowadays well recognized that the commercialization of proton-exchange membrane fuel cells (PEMFCs) is highly hindered by the cost of the cathode side catalyst layer which is commonly manufactured using Pt/C. For this reason, great efforts have been and continue to be made in order to find alternatives [1]. The two main classes of material that have been explored for the oxygen reduction reaction (ORR) are low-content Pt catalysts and Platinum Group Metals (PGM)-free catalysts. The first route aims at producing highly active and durable (layer stability and poisoning resistance) catalysts in order to reduce the amount of Pt needed to run the cell efficiently and to improve the life of the devices [2]. Different approaches have been adopted, e.g. creation of Pt alloys with transition or late earth metals [1,3–6] and/or by engineering of nanoparticles (NPs) size and shape [7,8], focusing also on the interaction with the support, commonly pristine or doped carbon [9–11]. The second PGM-free route aims at finding materials with good activity and durability based on cheap and earth-abundant metals. Within the PGM-free group, the metal-nitrogen-doped (M-N-C) materials have emerged as the most promising candidate [12–15] due to the low cost [16,17] and their performances which are slowly approaching those of Pt-based materials, in particular in alkaline environment [18]. Among all M-N-C materials, Fe-N-C has become the most studied and promising system due to the good activity and stability if compared with other metal center like Co, Mn, or Zn [19]. However, the nature of the active sites in these catalysts is still under debate [20–22]; in addition, the role of the support, of the doping precursor and of the synthesis condition on the final system in term of activity and type of sites formed still have to be fully rationalized.

Combining multiple spectroscopic technique and DFT computational analysis [22–24] it is progressively emerging that the main active sites in Fe-N-C materials are the FeNx centres with the assistance of C-N functionalities (such as pyrrolic, pyridinic and graphitic nitrogen) and, perhaps through other co-catalyst centres such as Fe/FeOx or less likely FeOx NPs encapsulated by few layers of N-doped carbon that could change the local electronic density [23,25–31]. Such evidences were confirmed both by comparison of similar catalysts made with and without iron addition, but also by specifically poisoning the metal sites [32] with different chemical moieties like CN−, SCN− [21,33], NO [34], CO [35], NO2 [36], the last two also allowing quantitative analysis.

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https://doi.org/10.1016/j.apcatb.2021.120068
Received 16 November 2020; Received in revised form 5 February 2021; Accepted 13 February 2021
Available online 28 February 2021
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A carbonaceous pre-synthesized support or metal-doped carbon materials prepared starting from nitrogen-based chelating centers or metal complexes are the building blocks for some recent catalysts [37, 38]. Other synthetic strategies start from very cheap precursors, e.g. biomass, waste plastic or polymers, that allow formation of different porous supports, even with nitrogen or sulphur doping [17,39,40]. An example of a recently developed strategy is to use metal-organic framework (MOF) highly porous structures (namely a zinc based one, ZIF-8) as precursors of C and N to selectively form M-N₄ centres and, at the same time, obtaining highly accessible active sites [22,41,42]. It turns out that the M-N₄ structure is maintained even after the pyrolytic step, which is a standard procedure adopted for these types of material [43]. Multi-step synthesis is another important approach that considers a double thermal treatment interspersing an acid wash for the removal of inorganic species. This synthetic protocol is proven to be useful for increasing activity thanks to the opening of porous structure clogged by inorganic species, yielding a higher density of accessible sites [44–46]. This last approach will be also adopted in this work.

One common feature of all these approaches is the attention to specific surface area and porous structure of the support (micro-, meso- and macropore ratio) because these are fundamental for the formation of metal-nitrogen active sites, and for the transport of reactants and products [47,48]. Regarding the last aspect, the present study aims at understanding and confirming the role of micro- and mesopore on catalytic sites formation. In particular, controlled activation treatment has been performed on a commercial carbon black with low surface area (S ~ 60 m² g⁻¹) in order to progressively raise the surface area (and the pore volume). This, in turn, is expected to enhance the catalytic site density and site accessibility. The importance of micropores has been already singled out [49,50], where the combination of several techniques was employed to locate the presence of Fe-N₄ sites in micropores and mesopores. However, the systematic variation of the catalyst textural properties and the determination of the site density by an innovative NO-stripping technique allowed us to attain a direct evidence of how site density and turn over frequency of a Fe-N-C catalyst are connected with micro and mesopore volume and surface area. A detailed physico-chemical and electrochemical characterization was carried out to relate morphological properties of the support with the final activity of the catalysts.

2. Experimental

2.1. Activation treatments

The setup for the activation treatments consisted of a tubular furnace (Carbolite, with a quartz tube Ø = 25 mm) flanged at both sides to control the inner atmosphere. The outlet flange was connected to the purging line directed to a scrubber, whereas the inlet flange was connected to a syringe pump (Phenomenex) and was actioned after purging the entrance of the oven. The syringe pump was used as working electrode, a graphite rod was used as counter-electrode and a homemade RHE as reference electrode prepared according to literature [5]. The RRDE tip was used as working electrode, a graphite rod was used as counter-electrode and a homemade RHE as reference electrode prepared before each experiment according to literature [5]. It consists in a spiral Pt wire settled to the closed end of a capillary glass tube filled with the electrolyte solution in which H₂ was directly electrogenerated at the Pt wire via chronoamperometric technique until half of the spiral was filled with gas.

The materials activity was investigated on a thin catalyst layer loaded on GC surface via drop-casting after the preparation of an ink made approximately of a 9:1 mixture of water, an organic solvent (acetonite and THF) and Naion (mcat/mnaion solution ~ 1:1). To obtain a good dispersion the ink was sonicated both in a bath and probe sonicator. The loading was chosen to be 0.6 mg cm⁻² as used in previous work [17], other loadings were also tested as discussed later in the text (see also Fig. S6).

All the materials were initially activated in Ar-purged electrolyte with extensive CV cycling at 200 mV s⁻¹ until a stable current was observed. In ORR tests, O₂ was bubbled inside the electrolyte solution for at least 30 min. The number of transferred electron (n) was reached, the nitrogen flow was replaced by a flow of CO₂ of 100 sccm. The pristine CB was treated for a period in the range 1–9 h (hereafter referred as CBCO₂-W where W = treatment time in hour), and then cooled down to ambient temperature with a 50 sccm N₂ flow. To evaluate the role of temperature, other treatments have been carried out at 850 °C and 1050 °C maintaining a constant exposure time of 5 h. These last samples were named as CBCO₂-5-Y (where Y is the temperature in °C).

All the obtained samples were vibro-milled (Retsch MM 400, 10 mL, and 5 mL steel jars with steel balls) obtaining a micrometric powder to facilitate further treatments or characterization.

2.2. Synthesis of Fe-N-C materials

Iron(II)-phenanthroline chloride (hereafter referred to as Fe(Phen)₂Cl₂), was synthesized from anhydrous FeCl₃ and 1,10-phenanthroline in ethanol according to literature (see SI for specification) [17]. The synthesis of Fe-N-C catalysts were carried out as follow: 200 mg of CB or the activated carbon and 222 mg of Fe(Phen)₂Cl₂ (equivalent to the 2% molar of iron compared to the molar amount of carbon) was vibro-milled at 18, 20 and 25 Hz for 1 h (20 min. for each frequency in ascending order), then heated at 900 °C in a tubular furnace (Carbolite, with a quartz tube Φ = 25 mm) for 2 h under nitrogen-hydrogen atmosphere (9% H₂ in the mixture, HG 2400 Claind) and eventually cooled down to ambient temperature under pure nitrogen flow. The resulting powder was vibro-milled and then washed at reflux in 100 mL 1 M solution of H₂SO₄ for 3 h at 100 °C under continuous stirring and then filtered and rinsed with at least 0.5 L of milli-Q water and finally dried in oven at 40 °C overnight. After the acid leaching, the powder was vibro-milled a second time and then heated again at 900 °C as described before. The resulting powder, labelled as FNCB1-X, FNCBCO₂-W or FNCBCO₂-5-Y (where X and W are the treatment time in min. and hours, respectively and Y is the temperature treatment) are the final catalyst. The sample obtained from the non-treated CB was labelled as FNCB. This procedure allows to obtain more or less 200 mg of catalyst. The catalysts were vibro-milled another time before electrochemical test with the same settings listed above. Other iron molar percentage were also prepared, i.e.1% and 4%, which however resulted in less active ORR catalysts with respect to the 2% molar one (Fig. S2).
determined by RRDE linear sweep voltammetry according to the following equation (Eq. 1):
\[
n = \frac{4|i_d|}{|i_b| + |i_a|}\frac{4}{N}
\]

where \(i_d\) is the current recorded at disk, \(i_b\) the current recorded at ring and \(N\) is the collection efficiency, which is equal to 0.25 (determined by performing RRDE measurement in the presence of K\(_2\)Fe(CN)\(_6\) in 0.5 M K\(_2\)SO\(_4\) electrolyte) \([51]\). With the last analysis it is also possible to evaluate the percentage of hydrogen peroxide (Eq. 2) produced at the working electrode:

\[
\%_{\text{H}_2\text{O}_2} = 100 \frac{4 - n}{2} = \frac{100 - 2|i_b|}{N|i_a| + |i_a|}
\]

Other parameters of interest are the peak potential \(E_p\) derive from the CV recorded in oxygen saturated electrolyte at 5 mV s\(^{-1}\), the half-wave potential \(E_{1/2}\), and the limiting current density \(j_{\text{lim}}\) determined from LSV analysis at 2 mV s\(^{-1}\) and 1600 rpm. The mass-transport corrected kinetic current density at a selected potential was calculated according to Eq. (3).

\[
j_i,E = j_{\text{lim}} - j_k = j_{\text{lim}} - j_k\]

where \(j_k\) is the current density at the selected potential \(E = 0.8\) V vs RHE.

To evaluate the catalysts site density, nitrite (NO\(_2\)) poisoning and electrochemical stripping were performed following the procedure described by Malko et al. \([36]\). This procedure allows the selective poisoning of Fe-N\(_x\) site and the site density is determined by measuring the charge of NO reductive stripping during a CV measurement. The site density measurements were performed on a thin layer of catalyst deposited on a GC (RDE, PINE Research 2020 Plus instrument). Specific surface area of the samples was determined with a FEI TECNAI G2 instrument operating at 100 kV.

3. Result and discussion

\[\text{3.1. Carbon supports activation and characterization}\]

The Super P\textsuperscript{®} Conductive CB was chosen as starting carbon material because of the relatively low surface area (66 m\(^2\) g\(^{-1}\)) and a comparable micropore and mesopore area (Table 1). The CO\(_2\) activation treatment was carried out at 950 °C from 1 h to 9 h obtaining a burn-off of about 25 %, which is reasonable considering that the starting material has a medium-high degree of graphitization (see Raman analysis later in the text) \([54,55]\). The isotherms obtained by physisorption of N\(_2\) at 77.3 K for samples treated with CO\(_2\) at different exposure times are reported in Fig. 1 while data are listed in Table 1. The isotherms change from a hybrid I-IL type with a very small hysteresis for the pristine CB sample, indicating a starting material made of macropore with a small amount of micro and mesopore, to isotherms with H3/H4 type hysteresis for the activated CBs (Fig. 1a). The growing of initial uptake at low relative pressure indicates an evolution of micro and mesopore (Fig. 1d), whereas the steep uptake at high relative pressure indicate that also macropores are evolving. The appearance of this type of hysteresis is also related to slit-shaped pores, supporting the choice of the DFT model \([56,57]\). The characteristic hysteresis closure at relative pressure of about 0.45 is generally due to cavitation \([57]\).

The effect of carbon dioxide activation is generally described as an opening of narrow micropores followed by widening due to the reaction C + CO\(_2\) → 2CO enhanced by the oxidizing behavior of CO\(_2\) in the 800–1000 °C range of temperature \([58–60]\). The actual mechanism is not well understood, and the phenomenon could occur in different steps; furthermore the surface chemistry of the CB (oxygen and hydrogen content) can impact on the reactivity \([61]\) and the actual flow of CO\(_2\) can impact on the final result. Usually, for high temperature a low flow is

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Textural properties and elemental analysis of activated CB supports.</th>
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<tr>
<td>CB &amp; CBSt-10 &amp; CBSt-20 &amp; CBSt-30 &amp; CBSt-60 &amp; CBCO(<em>{2})(</em>{1}) &amp; CBCO(<em>{2})(</em>{5}) &amp; CBCO(<em>{2})(</em>{9}) &amp; CBCO(<em>{2})(</em>{10}) &amp; S-5 &amp; S-950</td>
<td></td>
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<tr>
<td>%C</td>
<td>98.75</td>
</tr>
<tr>
<td>%H</td>
<td>0.17</td>
</tr>
<tr>
<td>%O</td>
<td>1.66</td>
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<tr>
<td>(m^2) g(^{-1})</td>
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</tr>
<tr>
<td>(m^2) g(^{-1})</td>
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<tr>
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<tr>
<td>(V_{max}) cm(^3)</td>
<td>0.137</td>
</tr>
<tr>
<td>(V_{max}) cm(^3)</td>
<td>0.204</td>
</tr>
<tr>
<td>(S)</td>
<td>5</td>
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</table>

\[a\] elemental analysis by CHNS elemental analyser.  
\[b\] QSDFT slit method 0.5–40 nm.  
\[c\] pore width < 2 nm.  
\[d\] obtained by applying Gurvitsch law at \(p/p^* \approx 0.98\).
preferable [62]. In our case it was possible to observe a general evolution of the surface area (Fig. 1a–b), initially due to the evolution of micropore that for longer treatment is also accompanied by the development of mesoporosity and macroporosity.

Increasing CO$_2$ treatment time produces a linear evolution of surface area (~260 m$^2$ g$^{-1}$ for 9 h) with a slightly preferential evolution of micropore accompanied by an evolution of mesopore due to a widening effect (Fig. 1d,g). Fig. 1d report the evolution of pore dimensions and it is evident that the CO$_2$ treatment mostly increases the pore volume while keeping the pore diameter almost unchanged. This can be explained considering either the opening of new pores or the elongation of those already existing. To accelerate the activation process, CO$_2$ treatment at higher temperatures were also carried out. As expected, the carbon support surface area increases upon increasing the treatment temperature (from 850$^\circ$C up to 1050$^\circ$C) while the treatment duration was kept constant at 5 h (Fig. 1b). The isotherm of sample treated at 1050$^\circ$C shows a more pronounced H3/H4 type hysteresis. This result is in line with the endothermic nature of the reaction, which is actually one of the reasons why steam and CO$_2$ are preferred for activation instead of air [54]. Also, in this case pore diameters change only slightly, whereas the pore volume increases consistently (Fig. 1e).

Therefore, CO$_2$ is also generated in situ (behaving as an activating agent), so explaining why a broader pore distribution is expected with this treatment. What it is indeed observed is a slightly preferential widening of mesopore of various dimension, in particular for the longer treatment (60 min) and a consistent gain in volume. Nevertheless, a peak around 2–3 nm arises, probably due to the opening of existing pore of 2–3 nm in the pristine CB, as visible in the histogram in Fig. 1f. This confirms that both opening and widening/elongation effects are present. From Fig. 1i, it is clear that the micro, meso and total surface areas increase almost linearly with the time of exposure. It is important to stress that the steam treatment is much more effective at 950$^\circ$C than at 800$^\circ$C as evidenced in Fig. 1m, where the effect of time exposure is also reported. Furthermore, steam treatment is much more effective than the CO$_2$ one, since almost the same textural values are obtained with a high temperature are reported in Fig. 1c. The isotherms evolve from a hybrid I-I type of CB with a very small hysteresis to a pronounced H3/H4 hysteresis loop of CBSt-60, which indicates an evolution of micro and to a more extent of mesopore as observed also for the CO$_2$ treatments. The action of steam is generally described as different when compared with that of CO$_2$. In fact, a general enlargement of existing pores is expected leading to larger pore size distribution. However in this case more reaction could be involved: [63]

\[
\begin{align*}
C + H_2O &\rightarrow H_2 + CO \\
C + 2H_2O &\rightarrow 2H_2 + CO_2 \\
C + CO_2 &\rightarrow 2CO \\
CO + H_2O &\rightarrow CO_2 + H_2
\end{align*}
\]

The N$_2$ adsorption isotherms for the samples activated with steam at high temperature are reported in Fig. 1c. The isotherms evolve from a hybrid I-I type of CB with a very small hysteresis to a pronounced H3/H4 hysteresis loop of CBSt-60, which indicates an evolution of micro and to a more extent of mesopore as observed also for the CO$_2$ treatments. The action of steam is generally described as different when compared with that of CO$_2$. In fact, a general enlargement of existing pores is expected leading to larger pore size distribution. However in this case more reaction could be involved: [63]
min steam treatment compared to a 9 h CO₂ treatment at the very same temperature.

Summarizing we were able to prepare different CB supports starting from a low surface area one, where a significant and fast improvement in pore volume is achieved with steam, while with CO₂ a more controlled evolution is possible. Fig. 1n and p show the relation between time of treatment and micropore-mesopore volume and surface ratio (pore width 0.5 ± 40 nm) for CBs treated with both steam and carbon dioxide. In addition, Fig. 1o shows the same relation but considering the effect of increasing temperature in CO₂ treatment. The two trends appear to be similar for both steam and CO₂ treatments, where an initial growing of micropore is reasonably caused by opening of new pore, while longer treatment brings a plateau meaning that new pores are formed but also existing pores are widened or elongated (Fig. 1n and p). The enhancement of the temperature of the CO₂ treatment seems also to affect mostly the micropore evolution (Fig. 1o). The apparent discordance between volume ratio and surface ratio is certainly a consequence of the geometry of pores and their dimension: larger pores have a smaller surface to volume ratio. It is worth noting that for the whole set of data, micropore volume increases linearly with micropore area, whereas a second order relation links the mesopore volume with the mesopore surface area. This can be explained considering that both steam and CO₂ treatments leads to an elongation of the pore rather that their widening. Conversely the action of both treatments on mesopore is to both enlarge and elongate the pre-existing pores. We mention here that also a slit/cylindrical adsorption branch model gives a good fit with a similar distribution (Fig. S1). Probably some deeper cylindrical pores or wedge-like shaped pores might form, but obviously we do not know the actual shape considering that the synthesis is not done with a templating agent and that the type of measurement gives only an average description. Considering these things and looking at some literature works [64,65], we chose to maintain the same model (slit) for all samples. Elemental analysis showed no significant changes in carbon support composition, with the sole exclusion of the anomalous CBSt-10. It is our impression that CBSt-10 contains a higher content of oxygen and that the steam treatment produces an increased number of oxygen functional groups, which form at the beginning of the treatment and are oxidized to CO₂ after prolonged treatments.

In order to evaluate the possible effects of degree of graphitization, Raman characterization was also performed on all samples (Fig. 2a). The spectra were deconvoluted with 5 bands (Fig. 2b) in the region between 1100 and 1700 cm⁻¹ [66-69] as described in Table S1 after a normalization relative to the G band peak (namely to the Raman shift around 1600 cm⁻¹ for which the maximum intensity is recorded [70]). In the region between 2200 and 3200 cm⁻¹, 2 or 3 bands were used to deconvolute the spectrum according to Sadezky et al. [68] This spectral region is generally called the graphene/graphene oxide region because at least two distinct bands similar to those of graphene oxide are observed in materials such as CB (Fig. 2a). The similarity comes from the aromatic region with non-oxidized benzene rings and the regions containing C–OH, epoxide and double bonds [68,71-73]. We do not report the deconvoluted data because no evident trend was observed. No
particular changes were neither observed in \( I_D/I_G \) ratio or in G band position upon steam treatment (Fig. 2c and f), only a slight change in graphene/graphene oxide band in the region 2400 \( \div \) 3000 cm\(^{-1}\) was observed when comparing CBSt-60 with the pristine CB. More evident changes were observed for carbon dioxide treatment (Fig. 2d,e), in particular the \( I_D/I_G \) ratio and the G band position slightly changed (Table S2), though without a clear trend, and the evident the decreasing grows by one order of magnitude on going from 0.1 % in FNCB to 1.06 % in FNCBSt-30 and to 0.9 % for FNCBCO around 1% of nitrogen is the maximum obtainable with these support bizarre to see that the most porous sample of each set shows a small effect of different initial amounts on the resultant catalyst ORR activity. It is noteworthy that the formation of Fe particles, subsequently removed by acid treatment of surface nitrogen (Table 2). This is reasonable assuming that in the untreated support shallow pores are present, while in more porous sample some nitrogen could be confined inside pores undetectable by XPS but still electrochemically accessible. For this reason, we retain that XPS measurements are helpful to characterize different nitrogen sites in non-porous samples, while it has some limits to determine bulk N sites in highly porous samples, in particular when the nitrogen content is too

3.2. Synthesis and characterization of Fe-N-C catalysts from CB activated supports

All the Fe-N-C catalysts where prepared by thermal treatment of activated CBs and Fe(Phen)Cl\(_2\) at 900 °C according to a procedure described in the experimental section.

The optimal amount of iron-phenanthroline used for the formation of Fe-Nx active sites in the final catalyst was defined by evaluating the effect of different initial amounts on the resultant catalyst ORR activity. The selection was made by adopting CB-Co5-9 and four different Fe (Phen)Cl\(_2\) molar concentrations i.e. 0, 1, 2 and 4 %mol. According to the elemental analysis reported in Table S3, the maximum amount of nitrogen was obtained for the 2% sample. The LSV for ORR measurements and the correlation between the iron percentage and activity are reported in Fig. S2: the sample with 2% of iron shows the best compromise between activity and precursor quantity. In fact, the 4% sample was only slightly better in term of activity, but considering that a similar activity slightly better in term of activity, but considering that a similar activity would in turn change the amount of Fe-N sites. It is noteworthy that the FeNx sample, which has the lowest content of bulk nitrogen according to the elemental analysis, has on the other hand the highest concentration of surface nitrogen (Table 2). This is reasonable assuming that in the untreated support shallow pores are present, while in more porous sample some nitrogen could be confined inside pores undetectable by XPS but still electrochemically accessible. For this reason, we retain that XPS measurements are helpful to characterize different nitrogen sites in non-porous samples, while it has some limits to determine bulk N sites in highly porous samples, in particular when the nitrogen content is too...
low. Regarding this last aspect other considerations are done later when showing the electrocatalytic results.

The C 1s peak was also examined (Fig. 4b) to evaluate the sp<sup>2</sup>/sp<sup>3</sup> ratio and the superficial graphitization degree. The main carbon components at BE between 284.2–284.4 eV is attributed to C-sp<sup>2</sup>. At higher BE (285.4 eV), the peak represents the sp<sup>3</sup>C–C bond. There is also a substantial amount of carbon bound to nitrogen or/and to oxygen: peaks at BEs higher than 286.4 eV are due to carbon species bound to oxygen (C=O, O–C=O, O–C(O)=O) or oxygen and nitrogen (C–N=O, N–C=O). The peak at 291.1 eV is due to shakeup satellite (π-π*). [77–80] No evident changes have been observed from the C 1s high-resolution core-level XPS spectra of different samples activated in steam or CO<sub>2</sub>, but a slight increment of sp<sup>2</sup> accompanied by a decrement of sp<sup>3</sup> is clearly visible (Fig. 4c) when the CBs were activated in CO<sub>2</sub> at different temperatures. All deconvolution data are reported in Tables S3 and S4.

### 3.3. Electrochemical characterization of Fe-N-C catalysts

In Fig. S5a,c, we report a representative example of the voltammetric behavior of FCBSt-30 and FCBCO<sub>2</sub>-5 in Ar-saturated electrolyte, respectively. The other catalysts show very similar behavior. In all cases, the voltammetric background shows a couple of peaks between 0.5 V ad 0.7 V RHE, which could be attributed to the reversible Fe<sup>3+</sup>/Fe<sup>2+</sup> and/or to a quinone/hydroquinone redox couples [13,81,82]. The samples obtained from activated CBs are also characterized by a higher capacitive current with respect to the pristine one, ascribable to the increased active surface area. In oxygen-saturated electrolyte, a very intense and
narrow peak appears at around 0.75 V$_{\text{RHE}}$ (scan rate at 5 mV s$^{-1}$) which is not present in the background and is assigned to the ORR process (Fig. S5b,d). The peak potential shifts, as expected, with the variation of the scan rate, pointing out the irreversibility of the ORR reaction. Fe-N-C catalysts derived from steam activated CBs were further characterized by RRDE measurement (Fig. 5a). It clearly appears that the $E_{1/2}$ shifts to more positive value passing from FN CB to FNCBSt-60, while there is a diminution of the limiting current ($i_{L}$). The first effect can be attributed to an increase of the site density or simply an increase of the accessible sites, that allows ORR at lower overpotential. If we rely on the fact that passing from FN CB to FNCBSt-60, pyridinic and pyrrolic functional groups increase as pointed out by XPS analysis, the ORR mechanism probably follows a 2 $\times$ 2 e-$^{-}$ pathway. This would explain also why the limiting current density is lower with respect to that expected for a 4 e-$^{-}$ pathway, and this is even more evident for the activated Fe-N-Cs. Such a difference could be related to the relatively higher loadings used for the RRDE analysis (0.6 mg cm$^{-2}$) resulting in a thicker catalyst layer which might hinder the H$_2$O$_2$ release. Fig. S6a reports the voltammetric behavior of FNCBCO$_{26}$ for different catalysts loading. It is evident the increase in capacitive current with the catalyst loading when CV are recorded in Ar purged electrolyte, while in oxygen saturated electrolyte the increase in capacitive current with the catalyst loading when CV are recorded in Ar purged electrolyte, while in oxygen saturated electrolyte $E_k$ (peak potential) shifts to more positive potential and $i_k$ (peak current) increases in module increasing the catalysts loading. From RRDE measurements, the quantity of hydrogen peroxide produced (Fig. 6b,c) are proportional to the loading meaning that the reduction pathway is not a pure 4e-$^{-}$ and for higher loading some hydrogen peroxide is trapped in the material and could be further reduced to water [83]. Therefore, when a highly porous carbon is used, H$_2$O$_2$ is not further reduced to H$_2$O, but it is released from the electrode layer.

The histograms in Fig. 5b show two other important parameters for evaluating the ORR performance, namely kinetic current $j_k$ and $E_{1/2}$ half-wave potential. The latter increases from 0.6 V$_{\text{RHE}}$ to 0.654 V$_{\text{RHE}}$ and $j_k$ from 0.16 to 0.50 A g$^{-1}$ (3 times higher) passing from the FN CB to the activated FNCBSt-60. Fig. 5c shows that the Tafel slope (around $-$100 mV dec$^{-1}$) does not significantly change within this set of materials and the right-shift is caused by the increment of kinetic current. Fig. 5d shows that the number of transferred electron and the quantity of hydrogen peroxide is similar for all the samples, around 3.90 and 5% at 0 V$_{\text{RHE}}$, respectively. The explanation of this improvement in activity must be searched in variation of morphology and chemistry of the samples. As reported in Fig. 5e and f, the almost linear correlation between both $E_{1/2}$ as well as $j_k$ with the microporous surface (that grows linearly with treatment time as reported in Fig. 1) is rather clear. In the first instance, this should be attributed to a higher percentage of the sole Fe-N$_x$ (not necessarily the density per unit of area) that are preferentially formed in the micropores, but from our XPS analysis this correlation is not straightforward at all.

If we rely on the XPS deconvolution, the reported improvement is only explainable by considering the overall increase of the pyridinic, pyrrolic and Fe-N$_x$ centers. All the sites are able to catalyze the ORR to water via either the 4e$^{-}$ pathway or the 2 $\times$ 2 electron pathway. In the latter case, reducing hydrogen peroxide before leaving the catalyst layer. In other word, the highest surface area, and in particular the higher micropore surface area, brings a preferential nitrogen functionalization to create C–N (pyridinic, pyrrolic) and Fe-N$_x$ instead of graphitic and iminic groups, so the improvement in activity is related to a higher percentage content of groups that effectively catalyze ORR (Fig. 5g and h). An alternative explanation could be that indeed the content of Fe-N$_x$ sites grows with micropores content but the XPS deconvolution is not enough sensitive to appreciate such difference because of the low N content and the very narrow BE range of the different species, resulting in a misinterpretation of pyridinic or pyrrolic nitrogen contribution with respect to Fe-N$_x$ [26,84].

The evolution of the electrochemical behavior and catalytic activity versus ORR is similar also for the Fe-N-C catalysts prepared from CO$_2$ activated carbon (Fig. 6). The LSV recorded from CB samples, treated at different CO$_2$ exposure times, exhibit a well-defined plateau, with the sole exclusion of FNCBCO$_2$-9. It is evident that $E_{1/2}$ becomes more positive passing from FN CB to FNCBCO$_2$-5 (Fig. 6a), so that it results even more positive than the steam activated samples. This is not simple to explain because no evident differences emerge from the N$_2$ adsorption isotherms or from Raman analysis (see section 3.1). However, it is possible that CO$_2$ treatment leads to a wider network of interconnected pores and hindered the diffusion. To evaluate this possibility, a very short steam treatment (equal as previously described) has been done on FNCBCO$_2$-5-1050 showing unfortunately a completely loss of activity (Fig. S7), where the elemental analysis confirmed the complete loss of nitrogen.
(Table S5). This result is anyway interesting because it could indicate that the nitrogen functionalization is almost restricted on the surface. Also for the CO\textsubscript{2} activated Fe-N-C catalysts, a correlation between \(E_{1/2}\) or \(j_k\) with the nitrogen content is evident (Fig. 6c and f), but it was not possible to discriminate whether this would be due to the increasing of the sole Fe-N\textsubscript{x} sites with respect to the pyrrolic and pyridinic sites or vice versa, as XPS analysis indicated. Among other common techniques used for characterizing Fe-N-C, \(^{57}\)Fe Mössbauer Spectroscopy is surely a powerful tool to characterize Fe-N\textsubscript{x} bearing materials. However, as this technique is sensitive to \(^{57}\)Fe, which is \(\approx 2\%\) of natural iron, this aspect excludes its application to materials with a low load of natural Fe (usually lower than 1–2 \% in weight, expressed as Fe\textsubscript{2}O\textsubscript{3}) as in the present case and also require to be prepared in larger amount.

Another option to quantify the number of Fe-N\textsubscript{x} sites relies on the electrochemical nitrite stripping developed by Malko et al. \cite{36,85,86}. This method is based on the selective interaction of Fe-N\textsubscript{x} sites with...
probe molecule NO₂, NO or NH₂OH [see reference above] which reversibly binds to the Fe center as nitrosyl at mildly acidic pH value of 5.2. When the catalyst layer is poisoned, there is an excess of cathodic charge, \(Q_{\text{strip}}\), which can be related to the gravimetric site density according to the formula:

\[
\text{MSD} \left( \text{mol sites g}^{-1} \right) = \frac{Q_{\text{strip}} \left( \text{C g}^{-1} \right)}{n_{\text{Fe}} F \left( \text{C mol}^{-1} \right)}
\]

where \(n_{\text{Fe}}\) is the number of electrons associated with the reduction of one adsorbed nitrosyl per site to NH₃.

What we expected to observe was an increment in sites density due to the increment of micro and mesopores and probably an increment in TOF which would justify the increment in activity. The activity in terms of kinetic current is given by the expression:

\[
j_k = F \cdot \text{TOF} \cdot \text{MSD}
\]

where \(F\) is the Faraday constant, TOF is the turnover frequency of Fe-Nₓ sites and MSD the gravimetric active sites density. So, an active catalyst could be obtained either from a high turnover frequency or a high accessibility to sites.

An example of the obtained electrochemical curves is reported in Fig. 7, while the full collection of data are reported in Table 3. A clear reductive current is evident in Fig. 7a due to nitrite stripping, as highlighted by the difference between the two curves (Fig. 7b). The diminution in activity at 0.8 \(V_{\text{RHE}}\) (0.309 vs. SCE) is clear from LSV and Tafel plots (Fig. 7c and d). The recovered LSV, i.e. the LSV recorded after the NO stripping, shows that most of the activity is recovered but there is a diminution in current at higher overpotential. This could be caused by some sites that are permanently poisoned or more probable due to a time-dependent catalyst degradation. It is worth noting that the shape of LSV are stretched compared with LSV in Fig. 5 probably due to the effect of electrolyte or lower catalyst loading (0.2 mg cm\(^{-2}\)) used for the nitrite stripping versus 0.6 mg cm\(^{-2}\) employed for all the other electrochemical measurements.

It is interesting to observe that according to NO-stripping findings, the site density increases almost linearly both with respect to micropore surface area and volume (but also for mesopores). This outcome is in disagreement with the XPS findings. Therefore, increasing the activation treatment both in terms of time and temperature favored the subsequent formation of Fe-Nₓ sites. A more porous network allows higher functionalization, whereas a more open structure entails a higher accessibility to sites and as a consequence, a global higher site density (Fig. 8a). Carbon dioxide treatment seems to be more effective than steam treatment. Clearly, this last reasoning does not consider that the subsequent functionalization with Fe-Nₓ sites is in any case limited by the capability of fixing Fe-Nₓ while not changing the textural properties.

For the CO₂ sets, it appears that the activated samples move along a single isocurves, indeed these sample are in general more active but some for a higher SD and others for higher TOFs. In fact, passing from FNCB to FNCBCO₂⁻ the activity increases because TOF increases, whereas FNCBCO₂⁻ moves up to higher SD value but to lower TOF. This is in accordance with the observation that micropore gets longer easier than they are widened, so that the formation of Fe-Nₓ can indeed increase. However, if this is not followed by a suitable increase of volume/area of mesopore, the active sites remain hardly reachable which could lead to lower TOFs. Also, CO₂ treatments allows an increase of iron active site utilization touching the 14.72 % in FNCBCO₂⁻ h-1050 (Table 3). Therefore, also in this case we can claim that CO₂ activation involve the formation of a more open and accessible structure where allowing better access of electrolyte to the active sites.

Fig. 8d compares the model samples prepared in this work with benchmark samples used in Primbs at al. work, which represent the state of the art Fe-N-C materials for ORR. [12] Primbs paper evaluated in depth the Fe surface site densities and TOF values and compared the same set of Fe-N-C catalysts using in situ nitrite reduction and ex situ CO cryo adsorption. It is clear that the carbon activation with CO₂ and

### Table 3

<table>
<thead>
<tr>
<th>Electrochemical data determined by RRDE measurements in 0.5 M H₂SO₄ and NO stripping in 0.5 M acetate buffer at pH 5.2.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{\text{C-2, \text{Ag}}^{1}}) V</td>
</tr>
<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>FNCB</td>
</tr>
<tr>
<td>FNCBSt-10</td>
</tr>
<tr>
<td>FNCBSt-20</td>
</tr>
<tr>
<td>FNCBSt-30</td>
</tr>
<tr>
<td>FNCBSt-60</td>
</tr>
<tr>
<td>FNCBCO₂⁻¹</td>
</tr>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>FNCBCO₂⁻₅₉₅₀</td>
</tr>
<tr>
<td>FNCBCO₂⁻₁₀₅₀</td>
</tr>
</tbody>
</table>

\(^a\) vs. RHE.

\(^b\) Error are reported as standard deviation of multiple measurements.

\(^c\) at 0.8 V vs. RHE.

\(^d\) at 0.0 V vs. RHE.

\(^e\) difference in kinetic current before and after poisoning (0.5 M acetate buffer at pH 5.2) at 0.309 V vs. SCE (0.8 vs RHE).
steam leads to a more open structure, which in the end resemble preferentially to the behavior of UNM or Pajarito powder (PAJ), i.e. the catalysts with specific textural properties induced by the hard template synthesis. This apparently means that increasing the micro and mesopore surface and volume helps preferentially the enhancement of TOF than the SD. To increase the SD as in CNRS and ICL catalysts, it is necessary to change the type of Fe-Nx precursor that must be able to efficiently pin the active sites avoiding the clogging of micro and mesopores.

Regarding the increase of TOF we can make more insightful consideration by considering the sole steam sets. If we plot the change in kinetic activity with stripping charge (or site density), we see that there is good straight-line dependence, but the intercept is not zero (Fig. 8e). This hold strongly with steam sets material although this effect is not so strong for the CO2 treated material possibly because of the interaction of NO2 with other iron species such as Fe2O3 even if Fe2O3 was not detected...
by XRD or XPS analysis. This appears to suggest that there are a given number of sites that are “inactive” for the ORR, or alternatively we overestimate the stripping charge by a constant amount for all catalysts (that amount is 0.667 C g⁻¹ based on the intercept) and we should ignore those sites – i.e. we should subtract the “inactive” sites from the total sites:

\[ Q_{\text{orp,corr}} = Q_{\text{orp}} - 0.667 \text{ C g}^{-1} \]

If we correct the site densities and TOF (Table S6) and we plot against the microporous surface area (valid also for the volume) which is one of the main parameters that differentiate these materials, we see that a new description is possible, the increment in activity is mainly due to SD increment and the TOF is oscillating around an average value of 3.11 ± 0.39 electron sites⁻¹ s⁻¹ (Fig. 8f,g). Looking at the slope (8.11 ±10¹⁵ sites m⁻²) of red fitting in Fig. 8b, it is possible to estimate the average distance of sites, using the expression:

\[ d = \frac{1}{\sqrt{\text{slope}}} \]

Which gives about 11 nm of average distance between two sites. The same effect, as said, is not evident on CO₂ stripping allowed to characterize the electrochemical accessible site density of Fe-Nₐ centres showing that the improvement in activity is both caused by an increment in site density and turnover frequency. The percentage of iron active for ORR that can be counted by nitrite poisoning with Fe(Phen)₃Cl₂. All the activated supports give higher activity if compared with the pristine one, where the steam treatment allows to obtain a faster evolution of pore and a good improvement in activity (three time higher kinetic current at 0.8 V). It was established that standard XPS analysis leads to not fully precise interpretation of N 1s spectrum since it is difficult to single out the contribution of the Fe-Nₐ components with respect to the pyridinic and pyrrolic one especially when the nitrogen content is low (< 1). It was also demonstrated that nitrite stripping allowed to characterize the electrochemical accessible site density of Fe-Nₐ centres showing that the improvement in activity is both caused by an increment in site density and turnover frequency. The percentage of iron active for ORR that can be counted by nitrite poisoning with respect the total amount of iron determined by XPS increases from 2.65 in FNCB to 11.01 % and to 14.74 in FNCBS60 and FNCBCO2-5-1050, respectively, confirming that steam and CO₂ treatments help in opening up the structure, allowing deposition of more sites and a better access to sites. This is in good agreement with evolution of micro and mesopore in the support indicating the importance pore structure in carbon precursor, in particular the role of micro and mesopore is important either in site formation and/or site accessibility. It is however important to stress that microporosity should be accompanied with adequate mesoporosity to prevent flooding and capillary

4. Conclusion

In this work, the effect of activation of CB, namely a controlled evolution of micro and mesopores content was carried out in order to study the influence of carbon support on site formation and activity in Fe-N-C catalysts prepared by thermal treatment of activated carbons with Fe(Phen)₃Cl₂. All the activated supports give higher activity if compared with the pristine one, where the steam treatment allows to obtain a faster evolution of pore and a good improvement in activity (three time higher kinetic current at 0.8 V). It was established that standard XPS analysis leads to not fully precise interpretation of N 1s spectrum since it is difficult to single out the contribution of the Fe-Nₐ components with respect to the pyridinic and pyrrolic one especially when the nitrogen content is low (< 1). It was also demonstrated that nitrite stripping allowed to characterize the electrochemical accessible site density of Fe-Nₐ centres showing that the improvement in activity is both caused by an increment in site density and turnover frequency. The percentage of iron active for ORR that can be counted by nitrite poisoning with respect the total amount of iron determined by XPS increases from 2.65 in FNCB to 11.01 % and to 14.74 in FNCBS60 and FNCBCO2-5-1050, respectively, confirming that steam and CO₂ treatments help in opening up the structure, allowing deposition of more sites and a better access to sites. This is in good agreement with evolution of micro and mesopore in the support indicating the importance pore structure in carbon precursor, in particular the role of micro and meso pore is important either in site formation and/or site accessibility. It is however important to stress that microporosity should be accompanied with adequate mesoporosity to prevent flooding and capillary

![Figure 9](image-url)
condensation effects into micropores when passing to test the electrode material in a full MEA.

CRediT authorship contribution statement


Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The research leading to these results has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 779366, CRESCENDO. This Joint Undertaking receives support from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 108 (2009) 1623-1639.

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Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.apcatb.2021.120068.

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