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## Electrochemical characterisation of novel screen-printed carbon paste electrodes for voltammetric measurements

MILAN SÝS<sup>1</sup>, ELMORSY KHALED<sup>2</sup>, RADOVAN METELKA<sup>1</sup> and KAREL VYTRÁS<sup>1\*</sup>

<sup>1</sup>Department of Analytical Chemistry, Faculty of Chemical Technology, University of Pardubice, Studentská 573, 532 10 Pardubice, Czech Republic and <sup>2</sup>Microanalysis Laboratory, National Research Centre, 33 El Bohouth St., Dokki, Giza, 12622 Egypt

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**Abstract:** This work is focused on the homemade screen-printed carbon paste electrode containing basically graphite powder (or glassy carbon powder), poly(vinylbchloride) (PVC) and paraffin oil. It compares the electrochemical properties of conventional carbon-based electrodes and prepared screen-printed carbon paste electrodes towards  $[\text{Fe}(\text{CN})_6]^{3-}/[\text{Fe}(\text{CN})_6]^{4-}$  and quinone/hydroquinone redox couples. Significant attention is paid to the development of the corresponding carbon inks, printing and the surface characterisation of the resulting electrodes by the scanning electron microscopy. An optimization consisted of the selection of the organic solvent, the optimal content of the used polymer with the chosen paste binder, appropriate isolation of electric contact, etc. Very similar properties of the prepared screen-printed electrodes, containing only corresponding carbon powder and 3 % PVC, with their conventional carbon paste electrode and glassy carbon-based electrodes, were observed during their characterisation. Screen-printed electrodes, with the pasting liquid usually provided satisfactory analytical data. Moreover, they can be used in the flow injection analysis and could undoubtedly replace the carbon paste grooved electrodes. It can be assumed that certain progress in the development of electrode materials was achieved by this research.

**Keywords:** carbon paste; carbon ink; screen printed electrodes; redox couples; cyclic voltammetry.

### INTRODUCTION

Since the eighties of the last century, all scientific community is well informed on the carbon paste electrodes (CPEs).<sup>1–3</sup> CPEs can be defined as a heterogeneous mixture of a conductive carbon powder and a liquid binder which is pressed into the cavity of the electrode holder with an electric contact. The most distinct advantage of CPEs is a possibility of the bulk modification and the

\* Corresponding author. E-mail: karel.vytras@upce.cz  
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renewing surface by the simple pushing out of carbon paste and polishing with wet filter paper. The carbon paste usually has different physical properties from solid electrode materials due to lipophilic character of the liquid binder which links together the individual carbon particles.<sup>4,5</sup> Moreover, the hydrophobic character of carbon paste can be useful for the accumulation of many significant analytes which exhibit lipophilic properties.<sup>6,7</sup>

Unmodified CPEs difference is only based on the types of used carbon powder and lipophilic binder. These CPEs can be simply modified by the mixing of corresponding carbon paste with some specific components such as carbon nano-materials,<sup>8,9</sup> surfactants,<sup>10</sup> metal oxide powders,<sup>11,12</sup> organic dyes,<sup>13</sup> biomolecules and tissues, etc.<sup>14,15</sup> Electrochemical measurements at CPEs are usually realized in the common batch configuration.

An application of CPEs in the flow injection analysis (FIA) is more complicated than for compatible screen-printed carbon electrodes (SPCEs) due to the bulky electrodes holders and the small flow cell.<sup>16</sup> To the best of our knowledge, this problem was resolved by the development of groove electrodes (GrEs) as a new type of CPEs.<sup>17</sup> Unfortunately, the restoration of GrE surface is lengthier than the simple replacement by the another SPCE because the preparation of the GrE includes many necessary steps such as the careful removing of the old paste from the electrode, the addition of the new carbon paste, tamping into the groove, the rubbing of the excess paste on a clean filter paper and polishing of the electrode surface.

This contribution is focused on the preparation of the CPE in the planar arrangement and could be applied in FIA. For this reason, it was necessary to find a way to immobilize the carbon paste on the ceramic platform. An idea is based on the previous knowledge of the preparation of home-made carbon inks<sup>18,19</sup> when an organic solvent is evaporated at room temperature and the resulting carbon paste is deposited onto the ceramic platform by the low amount of binding polymer.

The optimization of the screen-printed electrodes preparation is described in details. For the sake of comparison with the conventional variants of CPEs, the electrodes presented here are characterized by the ohmic resistance,<sup>20</sup> the scanning electron microscopy (SEM), and the cyclic voltammetry of  $[\text{Fe}(\text{CN})_6]^{3-}/[\text{Fe}(\text{CN})_6]^{4-}$  and the quinone/hydroquinone redox couples.

## EXPERIMENTAL

### *Apparatus*

All electrochemical measurements were performed using the conventional three electrode system consisting of screen-printed and carbon paste electrodes as working, Ag/AgCl/ $3.0 \text{ mol dm}^{-3}$  KCl as reference (all potentials in the paper are expressed *vs.* this electrode) and platinum wire as counter electrode, immersed into the voltammetric glass cell and connected to the modular electrochemical system Metrohm Autolab (Utrecht, The Netherlands). Scan-

ning electron microscopy (SEM) for the characterization of developed SPCPE was done at Vega3 SB (Tescan, Czech Republic). The freshly printed electrodes were dried in dryer Memmert (Schwabach, Germany). The printing of carbon ink on ceramic platform (10 mm×40 mm) was performed using the screen-printer machine (UL 1505 A, Tesla, Czech Republic).

#### *Reagents and chemicals*

Poly(vinyl chloride) (PVC) as polymer substance was obtained from Sigma–Aldrich. Different kinds of lipophilic binders, such as paraffin wax (PW; Sigma–Aldrich) vaseline (VA; Sigma–Aldrich), silicone oil (SO; Sigma–Aldrich), paraffin oil (PO; Merck) and polypropylene (PP; Spolana Neratovice, Czech Republic), were tested as eventually suitable pasting liquids for the preparation of carbon ink and carbon pastes. Two types of carbon powders were used for the preparation of carbon inks, and for the corresponding conventional carbon pastes which are presented in the upcoming sections.

Hydroquinone and  $K_4[Fe(CN)_6]$  of *p.a.* grade were purchased from Sigma–Aldrich. Potassium chloride and hydrochloric acid (35 %) were provided by Lach-Ner, Czech Republic. Ultrapure water with electric resistivity  $\sim 18.3 M\Omega\text{ cm}$  (Milli-Q system, Millipore) was used to prepare supporting electrolyte solutions as well as a stock solution of ferrocyanide. All other chemicals were used with analytical grade purity.

#### *Preparation of screen-printed electrodes*

Screen-printed electrodes were prepared as described in the previous paper dealing with potentiometric sensors.<sup>18</sup> Principally, the carbon-based ink was printed onto a ceramic substrate and then an organic solvent was evaporated either at laboratory conditions during whole day or in an oven at 60 °C for two hours. The resulting carbon paste was kept on a ceramic platform by a low content of sticky polymer. The corresponding home-made carbon inks were prepared by mixing of 3 g spectroscopic graphite powder (8 g glassy carbon powder) with 5 g polyvinylchloride (PVC) solution (3 mass %) in pure cyclohexanone and paraffin oil (PO, 10 mass %; relative to the portion of used powder). The compositions of these carbon inks was optimized as explained in following paragraphs.

#### *Commercial working electrodes*

For comparison, two types of the completely different commercial carbon-based electrodes were also used, namely a SPCE type 150 from DropSens (Spain), a SPCE based on commercial carbon ink (type C10903P14) from Gwent Group (United Kingdom) and a solid glassy carbon electrode (GCE; Metrohm, Czech Republic). Before each measurement, the mentioned commercial GCE had to be polished using wet  $Al_2O_3$  powder of particles size 1.0  $\mu\text{m}$  and washed by deionized water. Other electrodes were for single use only.

#### *Preparation of conventional carbon paste electrodes*

CPE and GCPE<sup>21,22</sup> were prepared by the mixing of 0.450 g spectroscopic graphite powder CR-2 type (Maziva, Týn nad Vltavou, Czech Republic) or 0.045 g of glassy carbon (GC) powder Sigradur-G type (HTW Meitingen, Germany) with 0.05 g of PO in a ceramic mortar for 15 min. Homogenous carbon pastes were pushed into the individual Teflon piston holders with the conductive electric wires for the electric contact with the potentiostat. The surfaces of carbon paste electrodes were polished using the wet filter paper.

#### *Procedure*

All electrochemical experiments were performed at room temperature using 0.01 mol  $\text{dm}^{-3}$  HCl and 0.1 mol  $\text{dm}^{-3}$  KCl (pH 2.05) as a supporting electrolyte. Electrochemical characterization of screen-printed electrodes – compared with the conventional carbon-based elec-

trodes – was realized by the cyclic voltammetry (CV) in  $1 \times 10^{-3}$  mol dm $^{-3}$  K $_4$ [Fe(CN) $_6$ ] and  $5 \times 10^{-4}$  mol dm $^{-3}$  hydroquinone under following conditions: potential range from  $-0.5$  to  $1.0$  V, potential step,  $5.0$  mV, and scan rate ( $v$ ),  $50$  mV s $^{-1}$ .

## RESULTS AND DISCUSSION

Comments on selection of solvents, paste liquid and isolation, as well as on the effects of paraffin oil content and carbon layer thickness are given in Supplementary material to this paper.

### *Effect of PVC amount in carbon ink*

The satisfied immobilization of the carbon-based layer on some solid platforms (ceramic, glass or Teflon $^{\text{®}}$  plates) is not possible without using a polymer, which makes a carbon ink sufficiently sticky and mechanically stable, after evaporation of used organic solvent. In potentiometry, the favoured PVC was frequently used for preparation of the ion selective electrodes. Although electrically non-conducting, its high ohmic resistance ( $R$ ) is principally acceptable. $^{23}$

Contrary to that, in the voltammetric arrangement, the high ohmic resistance of a working electrode is usually a cause of a very high background current of voltammetric curves and thus, the electrochemical properties of final sensors become significantly worse.

As it is apparent from Fig. 1, the conductivity of sensors exponentially decreases with the increasing amount of PVC in the carbon ink. For example, the values of ohmic resistance were attained about  $2.0$  k $\Omega$  for SPCE and  $3.0$  k $\Omega$  for SPGCE with  $8\%$  PVC content, but values a little bit higher than  $200$   $\Omega$  were observed for the electrodes with  $3\%$  content of PVC in graphite powder-based electrodes. It was found that the PVC content cannot be lower than  $3$  mass % because the dried carbon layer did not hold on the ceramic plate. This phenomenon is more evident when glassy carbon powder is used (due to its geometric shape beads). Thus, the value of  $3\%$  PVC content was chosen as optimum.

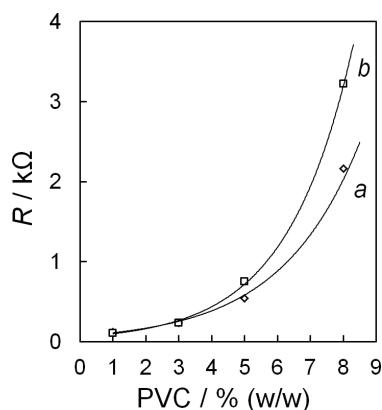


Fig. 1. Dependence of the ohmic resistance on different amount of PVC in SPCE (a) and SPGCE (b).

An explanation can be found just in the different structure of the used carbon powders; balls of glassy carbon (spherical particles with a distribution of 5–20  $\mu\text{m}$ ) and the sheets of spectroscopic graphite powder type CR-2 (diameter of particle size less than 2  $\mu\text{m}$ ). The homogenous distribution of PVC is much better in combination with the bigger carbon particles of glassy carbon. Therefore, the beads of glassy carbon are uniformly covered by the thin layer of PVC, if its 8 % content is used. Otherwise, this amount of PVC is not sufficient to cover every small particle of the graphite powder. For that reason, ohmic resistance of SPCEs was lower than that of SPGCEs with the same content of nonconducting PVC.

As a reference, the value (arithmetic mean) of ohmic resistance about 400  $\Omega$  was found for five samples of commercially available screen-printed carbon electrodes marketed by DropSens. According to such observations, SPCEs or SPGCEs with 3 % PVC content can be modified by some amount of a pasting liquid. This is important for the development of CPEs in planar arrangement (using ceramic platforms) looking like conventional SPCEs, because in voltammetric measurements, the small increase of ohmic resistance, caused by the presence of pasting liquid, can still be tolerated.

#### *Structures of screen-printed electrodes*

In contrast with the SPCEs based on PVC, the structures of conventional CPEs are already known.<sup>23</sup> The carbon particles occupy the closest arrangement, where an individual particle is entirely surrounded by the others. The structures of SPCPE surfaces are very close to their analogues of conventional CPEs but the individual carbon particles are arranged in thin layers. The confirmation is displayed in Fig. 2. The different structure is evident from SEM of GCPE (Fig. 2A) in comparison with SPGCE (Fig. 2B).

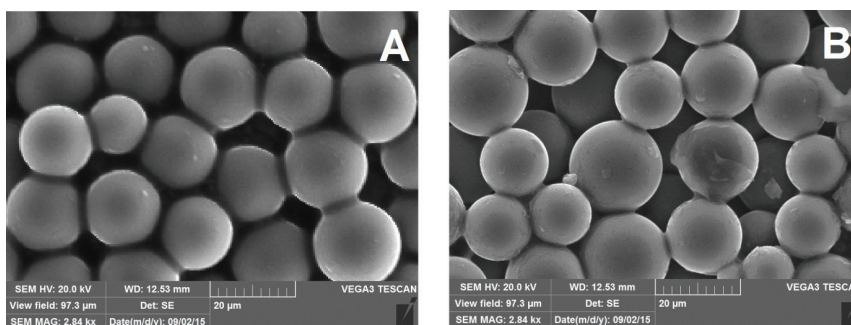


Fig. 2. SEM image of GCPE (A) and SPGCE (B) surface structure.

The spherical arrangement of glassy carbon beads provides better conductivity than planar configuration. Moreover, relative permittivities ( $\epsilon_r$ ) differ also significantly (2.1 for PO, 4.5 for PVC). It results in an increase of ohmic resist-

ance from *ca.* 10  $\Omega$  of conventional GCPE to *ca.* 250  $\Omega$  of SPGCE, containing 3 mass % PVC.

#### *Physicochemical properties of electrodes*

The SPCEs based on carbon powder and PVC are very stable mechanically and the carbon layer cannot simply be removed from the ceramic platform by manual wiping. It must be taken into consideration, especially from the viewpoint of their practical application in flow systems. Owing to specific properties of PVC, they are also chemically resistant.<sup>24</sup>

Unfortunately, the electrodes containing PO are usually susceptible to mechanical damage, similarly to conventional CPEs. On the other hand, the SPCEs created from commercial inks may also be easily scratched. Because PW is more viscous than PO, the electrodes containing PW as a pasting liquid are more stable than the electrodes mentioned above. However, it is important to mention that the electrochemical properties of PW-based SPEs were not satisfactory.

It was confirmed that all of the SPCEs are suitable for electrochemical measurements in common aqueous electrolytes such as buffers, solutions of salts, strong inorganic acids or bases. Moreover, electrodes based on glassy carbon powder are resistant to aggressive aqueous-organic mixtures; when tested by immersion into 60 % acetone for 2 h, no differences in their behaviour were observed.

#### *Voltammetric studies*

Generally, the polarization capability of a working electrode is defined by their practical application in faradaic measurements. Thus, polarization study can be seen as an initial step of the development of the SPCEs characterisation. The resulting potential ranges are determined by the limit values of cathodic ( $E_{c,lim}$ ) and anodic potential ( $E_{a,lim}$ ), which are totally different depending on the supporting electrolyte used, especially on its pH value.

Various supporting electrolytes were selected at the same concentrations (0.1 mol dm<sup>-3</sup>) to cover the whole pH range and linear sweep voltammetric (LSV) measurements at SPGCPE in common buffers were done. In addition, these measurements were carried out also, in solutions of strong inorganic acids and bases (see Fig. 3).

Fundamentally, the value of  $E_{c,lim}$  decreases with the increasing pH values of supporting electrolytes. For example, values of  $E_{c,lim}$  about -0.4 V for HNO<sub>3</sub> solution (pH 1.05) and -1.4 V for NaOH solution (pH 12.5) were observed. Otherwise, the values of  $E_{a,lim}$  are typically higher for acidic solutions (1.3 V; HCl) than for the alkaline ones (0.6 V; NaOH). The SPCPE provides similar results (not shown), which are typical for the carbon-based working electrodes.<sup>24</sup>

The voltammetric behaviour of a conventional CPEs and their screen-printed analogues described here, was examined with  $[\text{Fe}(\text{CN})_6]^{3-}/[\text{Fe}(\text{CN})_6]^{2-}$  and quin-

one/hydroquinone redox systems. Corresponding SPEs were always compared with their conventional analogues in which the identical carbon powders were used. Because the mentioned sensors differed in surface sizes, the current responses obtained during voltammetric measurements are presented as current density ( $j$ ).

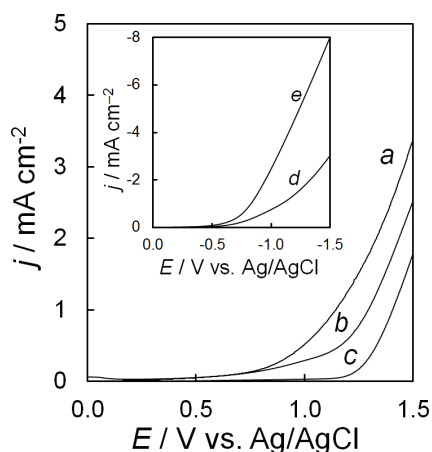


Fig. 3. LSV at SPGCPE in  $0.1 \text{ mol dm}^{-3}$  NaOH (pH 12.5; a), ammonia buffer (pH 9.2; b), HCl (pH 1.1; c) acetate buffer (pH 4.5; d) and  $\text{HNO}_3$  (pH 1.05; e); scan rate  $50 \text{ mV s}^{-1}$ .

As shown in Fig. 4, the comparison of SCPEs with the corresponding conventional paste electrodes is documented by the representative cyclic voltammograms (CVs) of  $\text{K}_4[\text{Fe}(\text{CN})_6]$ , obtained at these sensors based on graphite powder (Fig. 4A) and glassy carbon (Fig. 4B).

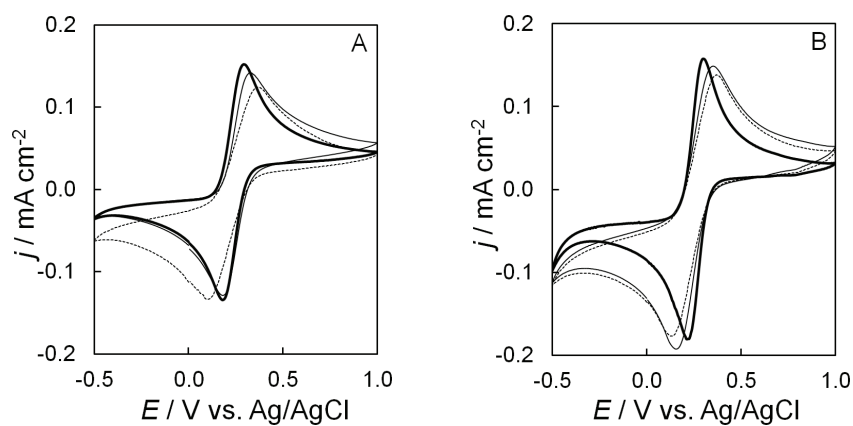


Fig. 4. CVs of  $1 \times 10^{-3} \text{ mol dm}^{-3}$   $\text{K}_4[\text{Fe}(\text{CN})_6]$  at conventional GCPE (thick), SPGCPE (thin) and SPGCPE (dashed line): A) and conventional CPE (thick), SPCE (thin) and SPGCPE (dashed line); B) measured in  $0.1 \text{ mol dm}^{-3}$  KCl and  $0.01 \text{ mol dm}^{-3}$  HCl at scan rate  $50 \text{ mV s}^{-1}$ .

Resulting shapes of presented cyclic voltammograms obtained at SPEs (thin lines) are very similar to those recorded with their analogues of the conventional

CPE and GCPE types (thick lines). Any content of PO in the carbon ink causes the peak broadening (dashed lines).

To compare electrochemical behaviour of the developed screen-printed CPEs with their conventional analogues, the measurements in  $[\text{Fe}(\text{CN})_6]^{3-}/[\text{Fe}(\text{CN})_6]^{4-}$  were preferred.<sup>25</sup> It is evident that the conventional paste-based sensors (both CPE and GCPE) provide better analytical data than their screen-printed analogues. In Table I, the values of peak separation potential ( $\Delta E_p$ ) are presented. These values for all working electrodes were higher than 59 mV, expected for the Nernstian one-electron transfer. It should be stated that the results obtained are typical for the heterogeneous electrode materials. It is caused by slower kinetics of partial electrode reactions due to the presence of hydrophobic PO. Fortunately, the ratio of cathodic/anodic peak current responses  $|I_{\text{red}}/I_{\text{ox}}|$  was always close to 1.

TABLE I. Comparison of various carbon electrodes at  $[\text{Fe}(\text{CN})_6]^{4-}/\text{Fe}(\text{CN})_6]^{3-}$  redox couple

Electrode	Composition	$\Delta E_p / \text{mV}$	$ I_{\text{red}}/I_{\text{ox}} $
CPE	CR-2; 10 % PO	110	1.06
SPCE	CR-2; 3 % PVC	190	1.24
SPCPE	CR-2; 10 % PO; 3 % PVC	240	1.28
GCE	Solid glassy carbon	140	1.15
GCPE	GC; 10 % PO	130	0.90
SPGCE	GC; 3 % PVC	160	0.92
SPGCPE	GC; 10 % PO; 3 % PVC	280	1.08

A scan rate study of the each prepared SPCE was done for closer characterisation. Scan rate varied from 20 to 300  $\text{V s}^{-1}$  and cyclic voltammograms were recorded and compared mutually (SPCE with SPCPE and SPGCE with SPGCPE). The corresponding cyclic voltammograms obtained at SPCEs based on glassy carbon powder are shown in Fig. 5. A linear relationship between the peak current density (both anodic and cathodic) and the square root of the scan rate

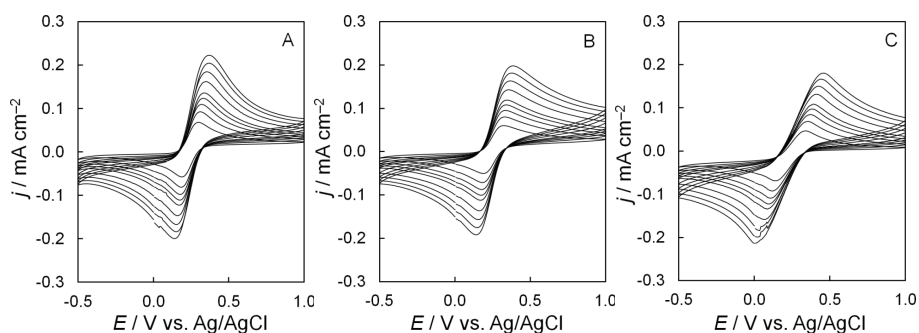


Fig. 5. Cyclic voltammograms for  $1 \times 10^{-3} \text{ mol dm}^{-3} \text{ K}_4[\text{Fe}(\text{CN})_6]$  in  $0.1 \text{ mol dm}^{-3} \text{ KCl}$  and  $0.01 \text{ mol dm}^{-3} \text{ HCl}$ , at conventional GCPE (A), SPGCE (B) and SPGCPE (C). Scan rates: 20, 40, 60, 80, 100, 150, 200, 250 and  $300 \text{ mV s}^{-1}$ .



demonstrated that the process is controlled by diffusion. Parameters of the individual equations of the linear regressions ( $k$ ; slope and  $q$ , intercept) with corresponding correlation coefficients ( $R^2$ ) are presented in Table II.

TABLE II. Parameters of equations obtained at various carbon electrodes under scan rate study

Sensor	$j$ (anodic)			$j$ (cathodic)		
	$k$ mA cm <sup>-2</sup> (mV s <sup>-1</sup> ) <sup>-1/2</sup>	$q$ mA cm <sup>-2</sup>	$R^2$	$k$ mA cm <sup>-2</sup> (mV s <sup>-1</sup> ) <sup>-1/2</sup>	$q$ mA cm <sup>-2</sup>	$R^2$
CPE	0.477	0.019	0.9999	-0.434	-0.015	0.9988
SPCE	0.404	-0.013	0.9996	-0.410	0.021	0.9994
SPCPE	0.372	-0.022	0.9970	-0.348	-0.021	0.9997
GCPE	0.376	0.016	0.9980	-0.345	-0.012	0.9989
SPGCE	0.338	0.012	0.9999	-0.346	-0.002	0.9999
SPGCPE	0.325	0.003	0.9990	-0.357	-0.020	0.9990

As it is evident from the data obtained experimentally, all prepared screen-printed electrodes are polarized slower than the conventional paste analogues; SPCPE and SGCPE exhibited twice higher values of  $\Delta E_p$ . A little higher sensitivity towards  $K_4[Fe(CN)_6]$  was observed for the electrodes prepared from the spectroscopic graphite powder, than for glassy carbon-based electrodes.

It is important to note that no exceptionally different values of calculated slopes were found. Moreover, the values of the intercept were very low. These facts indicate the good electrochemical properties of the developed electrodes which are comparable with the conventional CPEs. In measurements with all electrodes, the observed values of the background current responses were usually not higher than 1.0  $\mu A$ . Generally, the developed SPCEs, fortified by 10 mass % PO, provided worse analytical data than their conventional analogues. Anyway, they are still beneficial in the case of their application for measurements in the flow systems where they can replace GrEs.<sup>17</sup>

Using the repetitive cyclic voltammetry of the  $K_4[Fe(CN)_6]$ , the satisfactory repeatability of peak current responses at all kinds of prepared SPCEs was observed for five repetitions which was comparable with the corresponding conventional CPEs. The highest value of the standard relative deviation (RSD) was calculated for SPCPE (about 0.8 %).

It was also necessary to check if it is possible to prepare five identical screen-printed carbon electrodes containing 3 % PVC and 10 % PO (optimum composition), for example. From a total amount of seven pieces prepared, two SPCPEs failed. In 1.0 mmol dm<sup>-3</sup>  $K_4[Fe(CN)_6]$  with 0.1 mol dm<sup>-3</sup> KCl and 0.01 mol dm<sup>-3</sup> HCl, the remaining five electrodes provides nearly constant anodic current response of the average value about 22.26 $\pm$ 0.75  $\mu A$  ( $\pm$ 3.4 %).

In addition, the behaviour of the developed SPEs was compared with their commercial variants as well (see Figs. 6 and 7). This comparison was carried out

using cyclic voltammetry of the quinone/hydroquinone redox couple. The solid glassy carbon electrode (GCE) from Metrohm and also the conventional GCPE were chosen for comparison with SPGCE (Sigradur-G powder with 3 % PVC). Similarly, the SPCE based on the commercial carbon ink (type C10903P14) from Gwent Group (United Kingdom) and the conventional CPE were used for comparison with the developed SPCE (CR-2 graphite powder with 3 % PVC content).

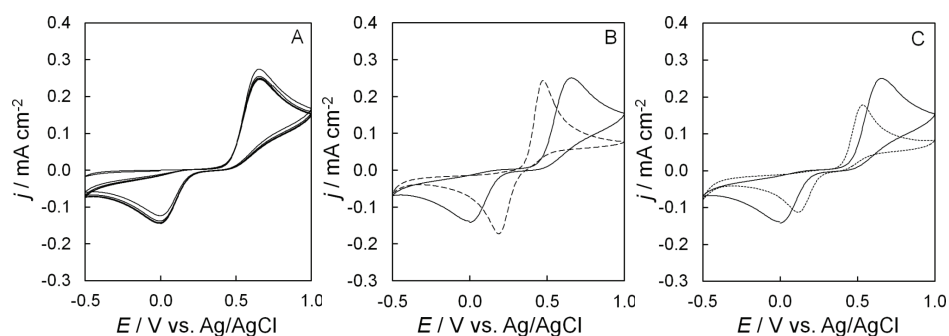


Fig. 6. Repetitive cyclic voltammograms of  $5 \times 10^{-4} \text{ mol dm}^{-3}$  hydroquinone at SPGCE (solid line; A). Its comparison with conventional GCPE (dashed line; B) and commercial solid GCE (dotted line; C). All shown measurements were performed in  $0.1 \text{ mol dm}^{-3}$  KCl and  $0.01 \text{ mol dm}^{-3}$  HCl at  $50 \text{ mV s}^{-1}$ .

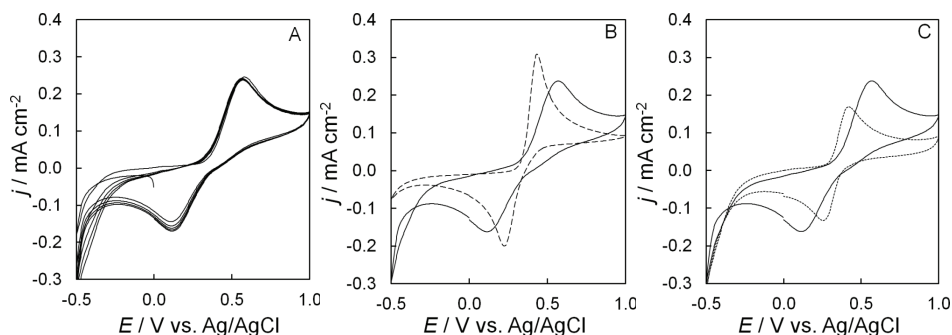


Fig. 7. Repetitive cyclic voltammograms of  $5 \times 10^{-4} \text{ mol dm}^{-3}$  hydroquinone at SPCE (solid line; A). Its comparison with conventional CPE (dashed line; B) and commercial SPE (dotted line; C). All shown measurements were performed in  $0.1 \text{ mol dm}^{-3}$  KCl and  $0.01 \text{ mol dm}^{-3}$  HCl at  $50 \text{ mV s}^{-1}$ .

Very satisfactory repeatability of peak current responses was obtained at both kinds of PVC electrodes (see voltammograms A in Figs. 6 and 7) using the repetitive cyclic voltammetry ( $n = 5$ ). Unfortunately, SPCEs based on PVC provided worse electrochemical properties than the conventional paste electrodes in most cases. This fact is documented by voltammograms B in Figs. 6 and 7 (for example, values of  $\Delta E_p$  were usually higher than 200 mV at PVC electrodes). In comparison with the commercial carbon electrodes, they provided higher peak

current responses (voltammograms C in Figs. 6 and 7) due to larger electrode surfaces. This increase is probably caused by paste character of these PVC electrodes.

#### CONCLUSION

The electrochemical experiments carried out in the present study showed that the both types of screen-printed electrodes, containing only corresponding carbon powder and PVC, can be successfully applied in voltammetric measurements because they provide nearly identical electrochemical properties as their conventional analogues. A choice of the supporting electrolyte which is used only depends on the solubility of PVC and PO.

Their surfaces cannot be simply restored as in the case of conventional carbon paste electrodes but they could undoubtedly replace the carbon paste "groove electrodes" mentioned in the introduction. It is also important to mention that the screen-printed CPEs or GCPEs can be used for the accumulation of many important chemical substances, such as surfactants, lipophilic vitamins, some alkaloids, steroid hormones, etc., because of the presence of lipophilic pasting liquids. Evidently, they could be suitable for the development of many analytical methods based on the extractive stripping voltammetry and could provide better analytical parameters than costly electrodes based on carbon nanoparticles.<sup>26</sup> It is also evident that the screen-printed electrode composited from glassy carbon powder and PVC can undoubtedly replace the commercial solid GCE because the SPGCE is mechanically and chemically stable and its ohmic resistance is low.

It can be assumed that SPCEs fortified by some content of PO up to 10 mass % can be used as widely as conventional CPEs due to the similar electrochemical properties. The similar memory effects, known at conventional CPE and GCPE, were also observed at SPEs containing only 3 % PVC and CR-2 or Sigradur powders. However, SPCEs with low content of PO provided a little bit higher memory effect, fortunately not higher than the 1.5 % hydroquinone oxidation peak current response.

The preparation of carbon inks at laboratory conditions brings many benefits, from which the largest one is the known composition of mixtures. This is a way to develop the more sophisticated sensors of the screen-printed type for various classes of compounds. This will be the aim of the further research.

#### SUPPLEMENTARY MATERIAL

Details about production of screen-printed electrodes are available electronically at the pages of journal website: <http://www.shd.org.rs/JSCS/>, or from the corresponding author on request.

ИЗВОД  
 ЕЛЕКТРОХЕМИЈСКА КАРАКТЕРИЗАЦИЈА НОВИХ ШТАМПНИХ ЕЛЕКТРОДА ОД  
 УГЉЕНИЧНЕ ПАСТЕ ЗА ВОЛТАМЕТРИЈСКА МЕРЕЊА

MILAN SÝS<sup>1</sup>, ELMORSY KHALED<sup>2</sup>, RADOVAN METELKA<sup>1</sup> и KAREL VYTRÁS<sup>1</sup>

<sup>1</sup>*Department of Analytical Chemistry, Faculty of Chemical Technology, University of Pardubice, Studentská 573, 532 10 Pardubice, Czech Republic, u* <sup>2</sup>*Microanalysis Laboratory, National Research Centre, 33 El Bohouth St., Dokki, Giza, 12622 Egypt*

Рад се бави лабораторијски направљеним штампаним електродама на бази угљеничне пасте које садрже прах графита (или прах стакластог угљеника), поливинил-хлорид (PVC) и парафинско уље. Активност ових електрода за редокс реакције  $[\text{Fe}(\text{CN})_6]^{3-}/[\text{Fe}(\text{CN})_6]^{4-}$  и хинон/хидрохинон је упоређена са активношћу електрода од угљеничне пасте које су припремљене на конвенционалан начин. Посебна пажња је посвећена развоју одговарајућих угљеничних суспензија за штампу, самом процесу штампања и карактеризацији површине добијених електрода, скенирајућом електронском микроскопијом. У оптимизацију је спадао избор органског растварача, количина коришћеног полимера са изабраним везивним средством, погодан начин изолације електричног контакта, итд. У испитивањима је уочено веома слично понашање припремљених штампаних електрода које су садржале само одговарајући угљенични прах и 3 % PVC и конвенционалне електроде од угљеничне пасте, или оне на бази праха стакластог угљеника. Штампане електроде припремљене са везујућом течносту су углавном давале задовољавајуће резултате анализе. Штавише, оне се могу користити у проточним анализама са ињектовањем и несумњиво могу заменити електроде од угљеничне пасте у форми жљеба. Може се претпоставити да ће овај рад допринети развоју електродних материјала за електроде намењене аналитичким техникама.

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