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Assessment of Hectorite/Spring Water Hydrogels as Wound Healing Products †

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Abstract: Wound healing treatments continue to be a medical challenge, since complications usually lead to chronicization and comorbidities. Natural inorganic ingredients such as clays have been demonstrated to exert useful activities in this regard. Hectorite is a smectite clay with desirable rheology due to its layered structure and remarkable swelling capacity. These properties make it an appropriate excipient for semisolid systems. Nonetheless, the biocompatibility of natural hectorite has been scarcely addressed; the majority of studies centered on synthetic or functionalized hectorites. The aim of this study was to prepare and characterize a hectorite/spring water hydrogel. The hectorite clay mineral was subjected to a solid-state characterization, while the hydrogel (HTgel@10) was evaluated in terms of rheology, pH and in vitro biocompatibility and wound healing. Results demonstrated that the hectorite possessed a remarkable purity (84% w/w of hectorite), very similar to that of similar pharmaceutical excipients. HTgel@10 showed a non-Newtonian, viscoplastic to pseudoplastic profile and a stable pH for 12 months. In vitro tests reported that the hectorite and the HTgel@10 were biocompatible (cellular viability ≥ 70%). Specifically, the hectorite used in this study was more biocompatible toward fibroblasts than Veegum® HS. The in vitro wound healing test revealed that HTgel@10 was able to favor the wound closure. Therefore, hectorite/spring water hydrogels could be considered as potential wound healing formulations with remarkable stability and safety.

Keywords: inorganic hydrogel; hectorite; biocompatibility; wound healing; rheology

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1. Introduction

Clay minerals are widely used in pharmacy due to their versatile physicochemical characteristics, both as actives and excipients. Among all these properties, their swelling capacity is significantly useful in the preparation of semisolid systems, since they are able to form gel-like structures when dispersed in water.

Today, the wound healing process continues to be a challenge for medicine, since complications usually lead to chronicization and comorbidities. Clay minerals have been demonstrated to exert useful activities in this regard [1]. In fact, recent studies have demonstrated that hydrogels formed by fibrous clay minerals and natural spring water were able to induce in vitro wound healing process by affecting both the mobility and the proliferation of fibroblasts [2,3]. In line with these studies, the biocompatibility and

wound healing effects of hectorite/spring water hydrogels have been assessed. Hectorite is a smectite clay mineral with a layered structure. Normally, smectite clay minerals possess desirable rheology properties due to their layered structure and remarkable swelling capacities [4–6], which makes them perfect ingredients in the formulation of semisolid systems. Nonetheless, the biocompatibility of hectorite natural clay mineral has been scarcely addressed. The majority of studies deal with synthetic hectorite-like clay minerals or functionalized natural hectorite [7–13].

The aim of this study was to prepare and fully characterize a hectorite/spring water hydrogel as a wound healing formulation. Apart from a full solid-state characterization of the clay mineral, rheology, pH and in vitro biocompatibility and wound healing (scratch assay) were performed.

2. Experiments

2.1. Materials

A purified clay mineral sample, commercialized as Pangel HT-11 (abbreviated as HT from now on) was used in this study as a solid phase. It was kindly gifted by TOLSA (Madrid, Spain). Medicinal waters from Alicún de las Torres spring source (ALI) were used.

2.2. Solid State Characterization of Hectorite

X-ray powder diffraction (XRPD) and oriented aggregates of HT were performed by means of a PANalytical diffractometer (X'Pert Pro). The randomly oriented mounts diffractograms were analyzed with CuKα radiation (45 kV and 40 mA) from 4 to 70°2θ (0.008°2θ step size, 9.73 s as scan step time). Bruker® S4 Pioneer equipment was used for the X-Ray fluorescence analysis (XRF). In this occasion, an Rh anode X-ray tube was used, operating at 60 kV and 150 mA.

Shimadzu (mod. TGA-50H) calorimeter was used to perform thermogravimetric analysis (TGA), equipped with a vertical oven and a precision of 0.001 mg. The experiments were performed in 30–950 °C range, in atmospheric air (50 mL/min) and a heating rate of 10 °C/min. Differential scanning calorimetry (DSC) was performed with a Mettler Toledo (DSC1) apparatus equipped with an FRS5 sensor. DSC analysis was performed from 26 °C to 400 °C at 10 °C/min in atmospheric air (50 mL/min).

High-resolution transmission electron microscopy (HR-TEM) was carried out with a FEI TITAN G2 microscope, equipped with Super-X silicon drift windowless energy-dispersive X-ray spectroscopy (EDX) detector. HT was dispersed in ethanol and subjected to ultrasounds prior to its deposition onto a TEM carbon grid (300 mesh). Elemental analysis of the samples was obtained working with a scanning transmission electron microscopy (STEM) with a high angle annular dark field (HAADF) detector.

2.3. Hectorite Hydrogel Formulation

Consequently, hydrogels were prepared by dispersing 25 g of HT in 225 mL of ALI, thus obtaining two types of hydrogels, abbreviated as HTgel@10. The turbine high-speed agitator was equipped with a high-traction stirrer head of square mesh working at 8000 rpm for 10 min. The resultant semisolid formulation was preserved in polyethylene containers in static conditions at room temperature.

2.4. Hydrogel Characterization

2.4.1. Rheology and pH Stability

Rheological characterization of HTgel@10 was performed by a controlled rate viscometer (Thermo Scientific HAAKE, RotoVisco 1) equipped with a plate/plate combination (Ø 20 mm serrated PP20S sensor system). Flow curves were obtained at constant temperature of 25 °C (±0.5 °C) from 70–800 s^{-1}. The rheological characterization (flow curves, apparent viscosities and hysteresis loops) was performed just after their preparation (0D)

and after 48 h (2D), 1, 2, 6 and 12 months (1M, 2M, 6M and 12M). Six replicates were obtained for each sample.

Stability of the HTgel@10 was also monitored through pH, which was studied by a pH-meter Crison pH25+ equipped with a semisolid electrode (5053T). Eight replicates were collected for each sample.

2.4.2. Biocompatibility and Wound Healing Studies

The biocompatibility of HT and HTgel@10 was studied by 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) test. Normal human dermal fibroblasts (NHDFs, PromoCell GmbH) were grown in Dulbecco's modified Eagle medium (DMEM, Sigma Aldrich® Merck), supplemented with 10% fetal bovine serum (FBS, Euroclone), 200 IU/mL penicillin and 0.2 mg/mL streptomycin (PBI International, I). Cultures were kept at 37 °C in a 5% CO_2 atmosphere with 95% of relative humidity and cells were seeded with a density of 10^5 cells/cm^2. HT and HTgel@10 were put in contact with cells for 24 h at 1000, 500, 50 and 5 μg/mL. Eight replicates were assessed for all samples and for the control. After 24 h, the surnatant was withdrawn and replaced by 50 μL of MTT diluted in growth medium (final MTT concentration = 2.5 mg/mL) for 3 h. The absorbance was assayed at 570 nm by means of an ELISA plate reader (Imark Absorbance Reader, Bio-rad), 655 nm of reference wavelength. Cell viability was calculated with respect to the viability of the control.

The in vitro wound healing studies were performed in Petri μ-Dish$^{35\ mm,\ low}$ (Ibidi, Giardini), fibroblasts cultured in the same conditions described for MTT. After cell confluence, the silicone inserts were removed and the cells were put in contact with HT and HTgel@10 (50 μg/mL of clay mineral) diluted in DMEM.

3. Results and Discussion

3.1. Solid State Characterization of Hectorite

XRPD of HT showed the typical diffraction pattern of hectorite together with other minor mineral phases (Figure 1). According to the reflections of the diffractogram, feldspar, quartz and calcite are some of the impurities present in the HT sample.

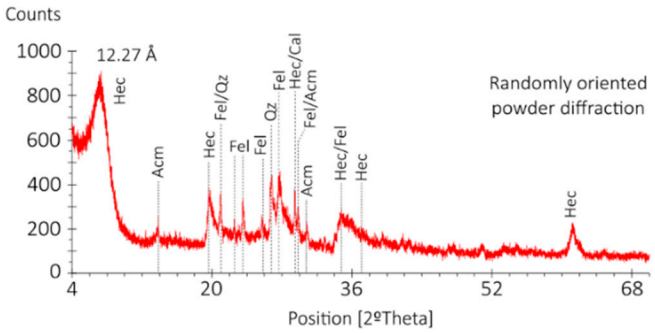

Figure 1. X-ray powder diffraction (XRPD) of Pangel HT-11 (HT). Mineral phases identified are included in the diffractogram. Hec: hectorite; Acm: acmite; Fel: potassium feldspar; Cal: calcite.

Oriented mounts (Figure 2) confirmed that the main mineral phase was a smectite since the d001 basal reflection of air-dried diffractogram (14.12 Å) expanded to approximately 16.86 Å with ethylene glycol and then collapsed at 9.72 Å when heated at 550 °C. The combination of XRPD and XRF results (Table 1) made possible the quantification of minor mineral phases. The Si/Mg ratio confirmed that phases such as quartz and feldspar were present, the main one identified by XRPD. Moreover, 5% of calcite was calculated in agreement with the amount of CaO together with the calcite reflections on the diffractogram (3.03 Å, Figure 1). Values of iron (Table 1) and reflections at 6.39 and 2.98 Å showed the presence of acmite mineral (8%).

Table 1. XRF results of hectorite. The loss of ignition (LOI) value accounted for a 9.4% w/w.

Oxides	Amount (%)	Oxides	Amount (%)
SiO_2	53.19	CaO	3.09
Al_2O_3	8.39	Na_2O	5.60
Fe_2O_3	3.42	K_2O	2.83
MnO	0.05	TiO_2	0.37
MgO	13.38	P_2O_5	0.12

Potassium feldspar accounted for 7% (reflections at 3.78 and 3.45 Å) and quartz accounted for 4%. Finally, homoionic, sodium hectorite accounted for 76%. No hectorite monograph is included in the main pharmacopoeias. The most similar pharmaceutical grade clay mineral with which it could be compared is bentonite ("magnesium aluminum silicate" in USP32-NF27 [14] or "aluminum magnesium silicate" in Ph. Eur. 10th [15]). In comparison with pharmaceutical grade bentonites, such as Veegum® HS (85% of montmorillonite (MMT)), the pureness of HT is rather high, making it quite acceptable for cosmetic use.

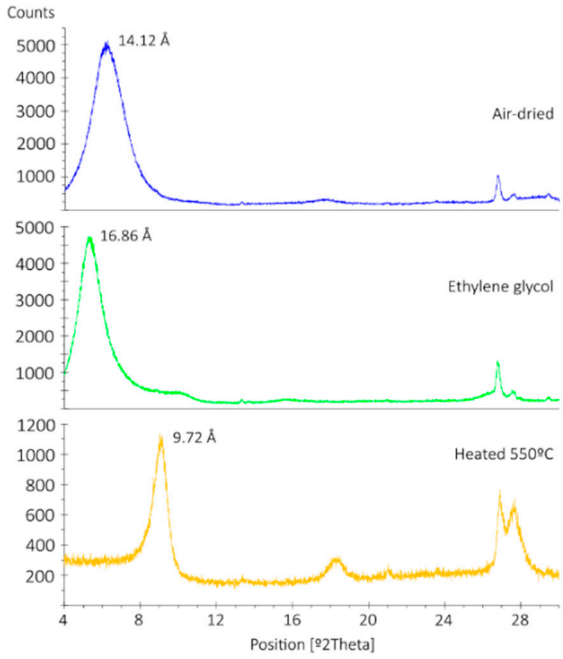

Figure 2. X-ray oriented mounts of HT (air-dried, ethylene glycol and sample heated at 550 °C).

TGA and DSC curves of HT are plotted in Figure 3. The first weight loss in TGA corresponded to free water associated with HT (from 30 to 139 °C). This event coincided with the DSC endothermic peak at 109 °C. Loss of drying for bentonite in the main pharmacopoeias is defined to be between 5 and 15% of weight [14–16], a parameter accomplished by HT. Weight loss from 140 to 576 °C is ascribed to bound water I and II [17,18]. Dehydroxylation of hectorite happened between 580 and 687 °C and accounted for 1.6% of mass loss (Figure 3B).

HR-TEM confirmed the mineralogical composition. The major part of the HT sample corresponds to Figure 4A, in which typical smectite morphology and composition were detected [19–21]. Potassium feldspar crystals were also detected, as is shown by the presence of K and Al in Figure 4B. In this image, the feldspar crystal is surrounded by hectorite, which explains the detection of Mg and Na in the spectrum. The proportion of Si, Fe and Na of the crystal analyzed in Figure 4C corresponds with the presence of acmite. Spectrum 1 (Figure 4D) is in agreement with the presence of calcite. The spherical morphology of calcite has been previously reported for vaterite [22,23]. The presence of traces

of fibrous clay minerals (sepiolite or palygorskite) was also confirmed. A fine, subtle acicular crystal is located to the right of the calcite crystals (spectrum 2, Figure 4D), whose analysis revealed a proportion of Si, Mg and Al in agreement with sepiolite or palygorskite [2]. The cuboid-shaped crystals in Figure 4D,E were identified as rutile [24], which justified the amount of titanium in XRF (Table 1). By the same token, the presence of P_2O_5 corresponded to apatite traces (Figure 4F). According to XRF, rutile and apatite accounted for approximately 0.4% and 0.3% w/w in HT, respectively.

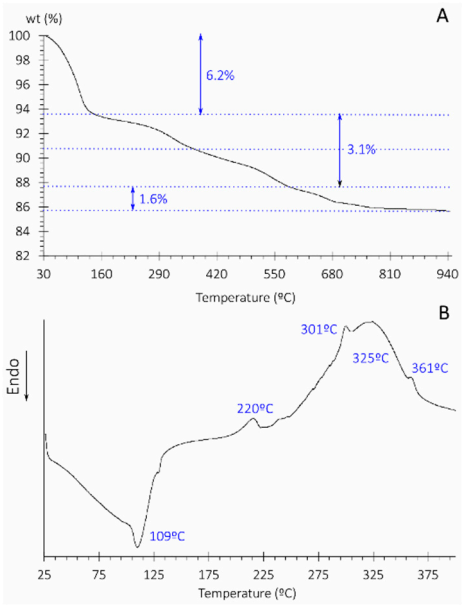

Figure 3. (**A**) Thermogravimetric analysis (TGA) and (**B**) differential scanning calorimetry (DSC) analysis of hectorite.

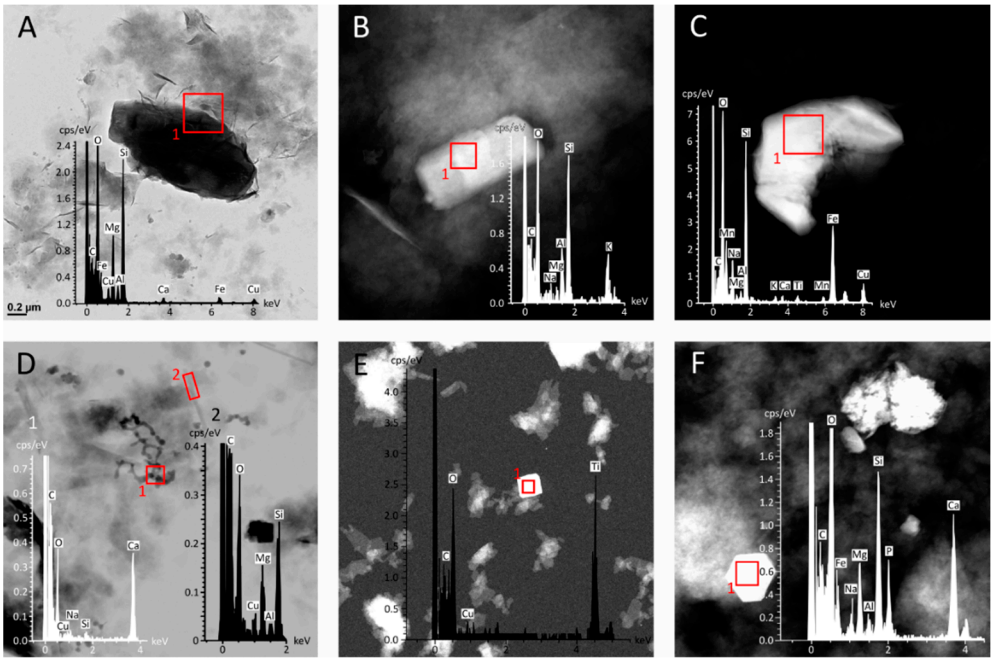

Figure 4. High-resolution transmission electron microscopy (HR-TEM) microphotographs of different mineral phases identified in HT sample together with their corresponding energy-dispersive X-ray spectroscopy (EDX) analysis. (**A**) hectorite smectite (major part of HT); (**B**) potassium feldspar mixed with hectorite; (**C**) acmite crystal; (**D**) calcite and sepiolite mixed with hectorite; (**E**) rutile crystal; (**F**) apatite mixed with hectorite. Images B to F were obtained in scanning transmission electron microscopy (STEM) mode.

3.2. Rheology and pH

Full rheological characterization of HTgel@10 is shown in Figure 5. The hydrogel showed non-Newtonian viscoplastic flow curves that evolved toward pseudoplastic as time passed [5,6,25]. As such, 12M HTgel@10 showed thixotropic hysteresis loops with a characteristic bulge in the upper curve known as spur value that represents a structural breakdown at low shear rates [26]. The apparent viscosity increased with time, as can be seen in Figure 5. It is accepted that hectorite disk-like particles are more elongated than those of montmorillonite (MMT), which favors higher swelling capacities [27,28]. This fact was confirmed since smaller shear stresses were reported for MMT suspensions at the same solid concentration [29] than HTgel@10. The expansion of the electrical double layer of HT particles prevents the formation of a "house-of-cards" network [30]. Therefore, the individually dispersed suspension makes the particles freely flow under stress conditions without forming defined hysteresis loops (0D, 1D, 1M). Thixotropic hysteresis loops appeared from 2M onwards. After 12M, the shear stresses decreased with increasing shear rates, something that could be ascribed to a reduction of the electrical double layer of HT particles, thus allowing the formation of a three-dimensional structure that breaks down under stress.

The pH of the HTgel@10 was alkaline and was maintained for 12 months, thus indicating that the formulation was chemically stable. As can be seen in Table 2, it slightly reduced at the beginning (especially during the first two days due to hydrogel stabilization) and then maintained around 9.8.

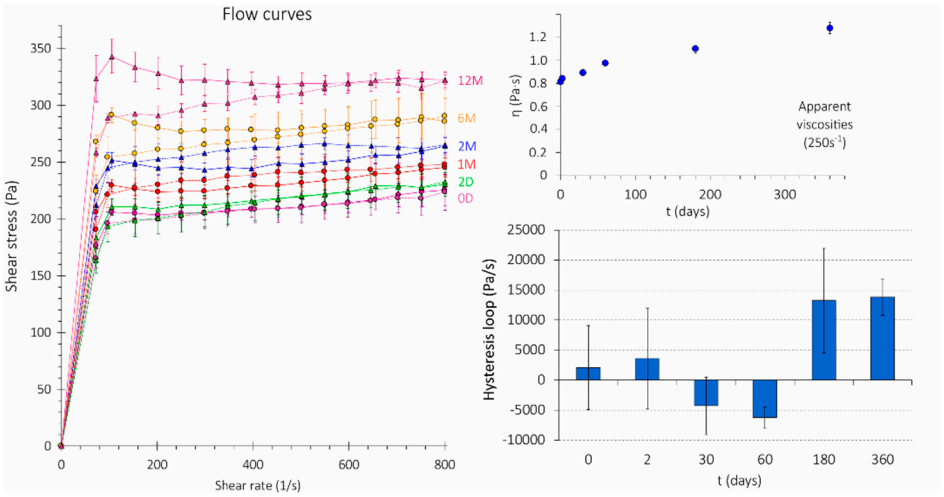

Figure 5. Flow curves, apparent viscosities and hysteresis loops of HTgel@10 (mean values ± s.d.; n = 6 in all cases).

Table 2. Monitoring of HTgel@10 hydrogel.

	0D	2D	30D	2M	6M	12M
pH	10.25 ± 0.013	10.15 ± 0.039	9.96 ± 0.011	9.88 ± 0.013	9.66 ± 0.024	9.88 ± 0.039

3.3. Biocompatibility and Wound Healing

In vitro biocompatibility results of HT and HTgel@10 are reported in Figure 6 (left). Viability (%) was found to be higher than 70% in all cases, which indicates the absence of drastic cellular cytotoxicity within 24 h. Significant differences between 1000 μg/mL and growth medium (GM) were found, though the hydrogel reported slightly higher biocompatibility. The precipitation of clay particles over cells could be the cause of reduced cellular viability. Nonetheless, Veegum HS® was reported to compromise Caco-2 viability from 160 μg/mL of clay (viability ≈ 50%) [31]. HT was demonstrated to be more biocompatible than Veegum HS® (Figure 6, left) [9,11–13,32]. In view of the MTT results, 50 μg/mL

was selected as the concentration to evaluate wound healing (Figure 6, right). This test revealed that HTgel@10 delivered better results than pure HT. That is, after 48 h, the wound gap in HT sample was bigger than in HTgel@10 and GM, thus indicating that the semisolid formulation did not interfere with the wound healing process.

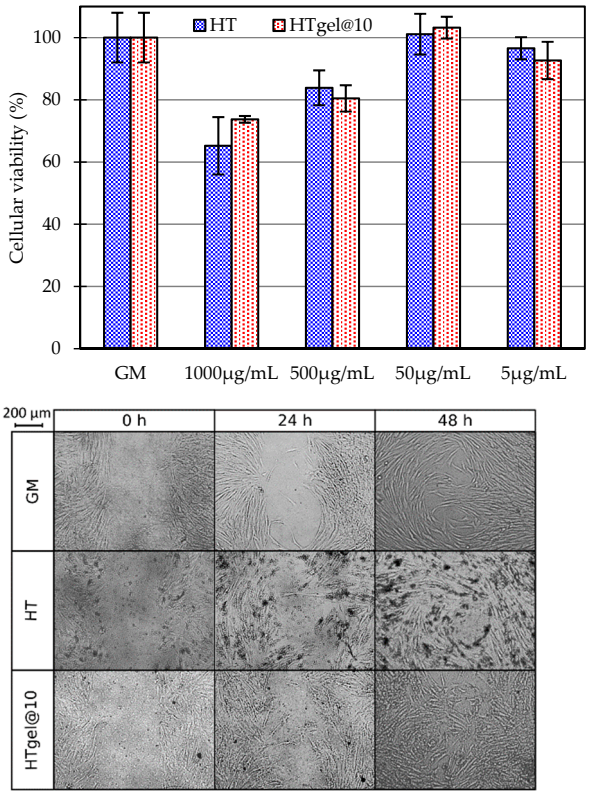

Figure 6. 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) test (**left**) (mean values ± s.e.; n = 8) and wound healing results (**right**). The wound healing was evaluated by using samples at 50 μg/mL. Microphotographs were taken with an inverted optical microscope.

4. Conclusions

In conclusion, the present study demonstrated that the hectorite used in this study could be considered as a pharmaceutical grade excipient in view of its purity, rheological properties and dermal biocompatibility. In fact, this clay is able to form stable hydrogels in a natural spring water with potential wound healing activity, according to the in vitro tests.

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Conflicts of Interest: The authors declare no conflict of interest.

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