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# Influence of the nature of the porous confining network on the sorption, diffusion and mechanical properties of hydrogel IPNs

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ABSTRACT

Two series of amphiphilic hydrogels of various compositions were prepared by sequentially interpenetrating two polymer networks, a poly(2-hydroxyethyl acrylate) (PHEA) network inside either a macroporous matrix of poly(methyl methacrylate) (PMMA) or a macroporous poly(ethyl acrylate) (PEA) network. In both cases poly(2-hydroxyethyl acrylate) (PHEA) served as network II, and the firstly formed porous network was a hydrophobic homonetwork, PMMA or PEA, that conferred mechanical strength to the hydrogel. In order to obtain hydrogels with high hydrophilic content, the first network was prepared in the presence of a solvent, thus yielding a macroporous network. The two families of IPNs thus obtained were: (net-PMMA)-ipn-(net-PHEA) and (net-PEA)-ipn-(net-PHEA), with a PHEA content ranging from 36% to 87% and from 64% to 94%, respectively. The novelty of the work consisted in comparing the effect of using as the first macroporous network a polymer which is glassy at room temperature (PMMA) and another of the same family (PEA) but which is in the rubber state at room temperature. Swelling studies showed that the specific equilibrium water content of PHEA falls from 1.6 for pure (unconfined) PHEA to values that range from 0.4 to 1, for the (net-PMMA)-ipn-(net-PHEA), whereas in the second IPNs family, the equilibrium water uptake of PHEA phase is, at least, the same as that of the pure PHEA (in some cases it is greater). This means that the expansion of the PHEA phase is not restricted by the confining hydrophobic component when this last is in the rubber state at room temperature. Whereas for the first IPNs the mechanical properties significantly increased (storage modulus at 37 °C from 0.25 to 2.5 GPa) compared with those of pure PHEA (25.12 MPa), little if any reinforcing effect was observed in the second type of IPNs. This is due to the fact that the glass transition of the PEA network takes place at a lower temperature than that of PHEA, so both components are in the rubbery state at room temperature. Both series behave differently also in dynamic water sorption experiments: the rigid PMMA network hinders the diffusion of water, yielding lower values of the apparent diffusion coefficients. By contrast, with the PEA polymer as network I this diffusion is similar to that of the pure PHEA homonetwork.



## 1. Introduction

Hydrogels are hydrophilic polymer networks which can absorb a large amount of water but are insoluble due to the fact that their molecules are cross-linked forming a network. The biocompatibility of hydrogels has attracted the

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interest as biomaterials for many applications, such as drug and cell carriers and as matrices for repairing and regenerating a wide variety of tissues and organs [1]. Hydrogels are also used to encapsulate cells both "in vivo" and "in vitro", separating them from their biological neighbourhood but at the same time allowing for a suitable transport of nutrients and waste products of the cells metabolism. Their tuneable swelling capacity allows controlling the kinetics of diffusion in drug delivery systems. One of the disadvantages that hydrogels have is that their mechanical properties are usually weak, especially when swollen with high amounts of water. This drawback can be overcome by using interpenetrating polymer networks, IPNs. These are systems formed by two or more polymer networks, chemically independent but spatially interpenetrated [2–4]. IPNs usually present phase separation to different degrees; true interpenetration at a molecular scale only takes place in a few cases of miscible polymer pairs (and even in this case it is further hindered by the network connectivity, that still decreases mixing entropy with respect to blending chain polymers) or when compatibility is forced by a high cross-linking density [5]. The morphology of an IPN depends on the chemical kinetics of the network formation and on the physical kinetics of the phase separation, both processes proceeding under non-equilibrium conditions [3,4,6]. One of the most interesting aspects of IPNs is that, due to the absence of chemical bonding between the component polymers, many properties of the initial networks are inherited by the IPNs, which converts IPNs in a perfect combination of properties needed for many applications. For example, in the case of IPNs used as drug delivery systems, the interpenetration of two components, one of them hydrophilic and the other hydrophobic, can slow drug release rates. This happens because the hydrophobic part limits the swelling degree of the hydrophilic network [7]. In tissue engineering applications, it has been found that a moderate hydrophobic character of the polymeric surfaces leads to more favourable cell responses than pure hydrophobic or hydrophilic substrates [8]. Pérez Olmedilla et al. [9] found that alternating, phase separated, hydrophilic and hydrophobic nanodomains showed the best results for human chondrocytes culture in a series of surfaces with similar chemical compositions.

In this work we have prepared hydrophobic/hydrophilic IPN hydrogels, produced by sequential polymerization. The first network, the hydrophobic one, has a confining effect on the second network, the hydrophilic one, as it hinders its expansion when swollen in water. In IPNs systems obtained by this sequential method the amount of network II that can be incorporated into network I is not arbitrary, but is limited by several factors (polymer affinity, degree of cross-linking of network I). In order to have greater amounts of network II incorporated into our IPNs the first network was polymerized in the presence of an amount of a good solvent. In this way a macroporous network was obtained, that can lodge a larger network II phase within the pores and thus enables to increase the hydrophilic content of the IPN. When the second network is also polymerized in the presence of a good solvent, a macroporous hydrogel is obtained. The literature records different methods to obtain porous polymers, such as porogen leaching [10,11], foaming [12], fiber processing [13] to be cited only some, and, in the field of polymer networks from the synthesis of semi-IPNs, the pores can be generated by dissolving the non cross-linked network [14,15].

Some aspects of the confinement effect of the hydrophobic phase on the hydrophilic phase were treated in a previous paper [16]. In the present work our objective is to study the influence of the rigidity at room temperature of the first network on the hydrogel properties. With that purpose in mind, we chose two different macroporous hydrophobic polymer networks, poly(methyl methacrylate), PMMA, and poly(ethyl acrylate), PEA, as the first component network of the IPNs, and poly(2-hydroxyethyl acrylate), PHEA, as the hydrophilic component. PHEA is a widely used polymer, because of its good hydrophilicity [17,18], in very different fields of applications [19–21]; compared to the more frequently used poly(2-hydroxy ethyl methacrylate) (PHEMA), PHEA seems a better option for the case of simulating the mechanical properties of soft tissues without loosing water sorption capacity [22].

The difference in the glass transition temperatures of dry PMMA (around 110 °C) and dry PEA (−10 °C approximately) means that, at room temperature, the first polymer is in the glassy state, while the second is in the rubber-like state. In this work, we study how this fact affects the mechanical properties, the equilibrium water sorption, and the water transport properties of the resulting hydrogels.

## 2. Experimental

### 2.1. Materials

Monomers of ethyl acrylate, EA, (99% purity), methyl methacrylate, MMA, (99% purity), 2-hydroxyethyl acrylate, HEA, (99% purity), and ethyleneglycol dimethacrylate, EGDMA, (98% purity) were purchased from Sigma–Aldrich. Benzoin (98% purity) was used as an ultraviolet light initiator and supplied by Scharlau. The diluents employed to produce macroporous polymer networks were ethanol (Sigma–Aldrich 99.5% pure), methanol (Scharlau, synthesis grade) and ethyl acetate (Sigma–Aldrich 99.8%). All chemicals were used as received without further purification.

### 2.2. Synthesis of the interpenetrating polymer networks

Two families of IPNs were prepared, differing in the chemical nature of the first component network: (net-PMMA)-ipn-(net-PHEA) and (net-PEA)-ipn-(net-PHEA). The IPNs were synthesized in a sequential way. To prepare the first family of IPNs, a series of porous poly(methyl methacrylate), PMMA, sponges was prepared by polymerizing MMA monomer with a 1 wt.% of EGDMA as cross-linking agent, a 0.2 wt.% of benzoin as photoinitiator (relative to monomer weight) and different amounts of ethyl acetate as diluent: 30, 40, 50, and 60 wt.% relative to the monomers/solvent mixture. Polymerization took place at room temperature under ultraviolet radiation, at a wavelength of 300–460 nm, for 24 h between two glass plates. Low molecular weight substances of the resulting porous net-