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DEVELOPMENT OF SMART SHAPE MEMORY POLYMERS FOR ENVIRONMENTALLY FRIENDLY PACKAGING MATERIALS

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This article discusses the development of smart shape-memory polymers for use in eco-friendly packaging materials, as well as materials capable of changing properties under pH, such as shape, swelling, and color, opening up opportunities for reusability, self-healing, and waste reduction. The paper presents the operating principles, classification, and application examples of these materials. It also describes the polymer systems being studied, based on PVA/CMC/PEG, which form films and hydrogels with an optical response to pH and moderate thermal sensitivity. The materials exhibit low solubility, controlled swelling, and change color or fluorescence depending on the pH of the environment. The study reflects the author's long-term vision for the development of a "polymer revolution" aimed at creating sustainable, adaptable, and safe materials for the future.

Keywords: Smart polymers, shape memory, PVA, CMC, PEG, pH sensitivity, temperature sensitivity, hydrogels, packaging materials, sustainability

Main part

1.Definition and introduction

Smart polymers are a class of materials capable of changing their physicochemical properties (color, fluorescence, volume, permeability, or swelling ratio) in response to external stimuli such as temperature, pH, ionic strength, light, or redox conditions. Their key feature is their adaptability—their ability to respond to environmental changes without the need for electronics or external power.

The primary mechanisms of operation of such systems involve dynamic changes in the conformation of polymer chains and the rearrangement of intermolecular interactions. This provides the material with reversible behavior: for example, the ability to maintain a temporary shape and return to its original form upon heating or changes in acidity.

The materials under study, based on polyvinyl alcohol (PVA), carboxymethyl cellulose (CMC), and polyethylene glycol (PEG), form hybrid structures—films and hydrogels—with optical pH response and moderate thermal sensitivity. These

systems exhibit low solubility and controlled swelling, making them promising for the creation of self-adaptive packaging materials and sensor coatings.

An advantage of the selected systems is their compatibility with aqueous chemistry and biodegradable components, paving the way for the development of safe and environmentally friendly solutions. Laboratory studies have confirmed the optical response to changes in pH, and quantitative fluorescence calibration and stability analysis are underway.

Potential future applications include:

– Indicator labels for smart packaging;

– Adaptive agrohydrogels for arid regions;

– Polymer "sponges" for oil spill containment;

– Biomedical devices, subject to chemical and safety certification.

Despite the early testing stage, the obtained results confirm the potential of the developed systems as a basis for future smart materials combining functionality, environmental friendliness, and technological adaptability.

2. Materials and Methods

The study was conducted on polymer composites based on PVA (polyvinyl alcohol), CMC (carboxymethyl cellulose), and PEG. The systems formed films and hydrogels designed to evaluate the optical response to pH and temperature-sensitive properties.

PVA served as the primary film-forming agent, providing transparency and barrier properties. CMC served as a hydrophilic matrix, regulating swelling and ionic crosslinking through interaction with GA (glutaraldehyde). PEG served as an internal modifier and plasticizer, increasing flexibility and reducing brittleness of the samples.

Three types of crosslinkers were used to control the network structure:

borate (boric acid, pH 8-9) dynamic bridges between PVA chains;

covalent (glutaraldehyde) crosslinkers were used only at the research stage with subsequent washing. Fluorescein was used as an indicator, providing a visible and fluorescent pH response. The indicators were introduced through an ethanol or glycerol carrier for uniform distribution.

3.Results and Discussion

The fabricated samples demonstrated stable formation of transparent, homogeneous films and hydrogels. All compositions exhibited low solubility and controlled swelling in aqueous and slightly acidic media. Optical analysis revealed a pronounced pH-dependent response: a hue shift and a change in fluorescence intensity were observed when moving from acidic to alkaline conditions.

Moderate thermosensitivity was confirmed, manifested by changes in segment mobility and water binding upon heating. The hydrogels demonstrated good

mechanical reversibility and retained their structure after several swelling-drying cycles.

This work is currently undergoing active laboratory testing, and all conclusions are considered preliminary. The composition is being refined to improve photostability, flexibility, and biocompatibility.

4.Development Prospects and Case Studies

Short-term (1–3 months)

Creation of external indicator labels and demonstration prototypes without product contact.

Development of educational sensory models and microfluidic tests.

Medium-term (3–9 months)

Replacement of glutaraldehyde with safe crosslinkers

Introduction of barrier laminations, encapsulation of indicators, migration and photostability control.

Long-term (9–18+ months) — Key Case Studies of the PolyNova Project

PolyNova SmartPack — a freshness indicator film for food products.

Reacts to pH changes associated with spoilage by changing color.

The goal is to reduce write-offs by 15–20% and increase consumer confidence.

PolyNova HealFilm — a medical hydrogel shell with pH and thermal response for packaging pharmaceuticals and dressings. The goal is passive sterility monitoring and the ability to self-seal minor defects.

PolyNova SensorNet — sensor elements based on PVA/CMC/PEG networks, integrated into packaging or monitoring devices.

The goal is passive contaminant detection and air or water quality assessment without electronics.

The development of smart shape-memory polymers based on PVA/CMC/PEG demonstrates high potential for use in eco-friendly packaging materials. The systems exhibit controlled swelling, optical response, and thermal sensitivity, making them promising for indicator and sensor applications.

Preliminary results confirm the feasibility of creating hybrid architectures with tunable properties; however, further optimization of the cross-linking chemistry, stabilizers, and barrier coatings is required. In the long term, the PolyNova project aims to develop a platform of "smart" biodegradable materials capable of combining functionality, environmental safety, and adaptability.

This work lays the foundation for a future "polymer revolution," where materials not only serve as a shell but become an active element in the sustainable interaction of humans, technology, and the environment.

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ЭКОЛОГИЯЛЫҚ ТАЗА ҚАПТАМА МАТЕРИАЛДАРЫНА АРНАЛҒАН АҚЫЛДЫ ПІШІНДІ ЕСТЕ САҚТАУ ПОЛИМЕРЛЕРІН ӘЗІРЛЕУ

Цой Ратмир

Бұл мақалада экологиялық таза қаптама материалдарында қолдануға арналған ақылды пішінді жадты полимерлерді, сондай-ақ pH жағдайында пішін, ісіну және түс сияқты қасиеттерді өзгерте алатын материалдарды әзірлеу, қайта пайдалану, өзін-өзі қалпына келтіру және қалдықтарды азайту мүмкіндіктерін ашады. Мақалада осы материалдардың жұмыс принциптері, жіктелуі және қолданылу мысалдары келтірілген. Сондай-ақ, pH-ға оптикалық жауап беретін және орташа термиялық сезімталдығы бар пленкалар мен гидрогельдерді түзетін PVA/CMC/PEG негізінде зерттелетін полимерлік жүйелер сипатталған. Материалдар төмен ерігіштікке, бақыланатын ісінуге және қоршаған ортаның pH-на байланысты түсін немесе флуоресценциясын өзгертуге ие. Зерттеу автордың болашақ үшін тұрақты,

бейімделгіш және қауіпсіз материалдарды жасауға бағытталған «полимерлік революцияны» дамытуға арналған ұзақ мерзімді көзқарасын көрсетеді.

Кілт сөздер: Ақылды полимерлер, пішінді жад, PVA, CMC, PEG, pH сезімталдығы, температураға сезімталдық, гидрогельдер, қаптама материалдары, тұрақтылық

РАЗРАБОТКА УМНЫХ ПОЛИМЕРОВ С ПАМЯТЬЮ ФОРМЫ ДЛЯ ЭКОЛОГИЧНЫХ УПАКОВОЧНЫХ МАТЕРИАЛОВ

Цой Ратмир

В данной статье рассматривается разработка интеллектуальных полимеров с эффектом памяти формы для использования в экологичных упаковочных материалах, а также материалов, способных изменять свойства в зависимости от pH, такие как форма, набухание и цвет, что открывает возможности для повторного использования, самовосстановления и сокращения отходов. В статье представлены принципы действия, классификация и примеры применения этих материалов. Также описываются исследуемые полимерные системы на основе ПВС/КМЦ/ПЭГ, которые образуют пленки и гидрогели с оптической реакцией на pH и умеренной термочувствительностью. Материалы демонстрируют низкую растворимость, контролируемое набухание и изменение цвета или флуоресценции в зависимости от pH окружающей среды. Исследование отражает долгосрочное видение автора относительно развития «полимерной революции», направленной на создание устойчивых, адаптивных и безопасных материалов будущего.

Ключевые слова: интеллектуальные полимеры, память формы, ПВС, КМЦ, ПЭГ, pH-чувствительность, температурная чувствительность, гидрогели, упаковочные материалы, устойчивое развитие