Performance of aged cement–polymer composite immobilizing borate waste simulates during flooding scenarios

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ABSTRACT

An advanced composite of cement and water extended polyester based on the recycled Poly(ethylene terephthalate) waste was developed to incorporate the borate waste. Previous studies have reported the characterizations of the waste composite (cement-polymer composite immobilizing borate waste simulates) after 28 days of curing time. The current work studied the performance of waste composite aged for seven years and subjected to flooding scenario during 260 days using three types of water. The state of waste composite was assessed at the end of each definite interval of the water infiltration through visual examination and mechanical measurement. Scanning electron microscopy, infrared spectroscopy, X-ray diffraction and thermal analyses were used to investigate the changes that may occur in the microstructure of the waste composite under aging and flooding effects. The actual experimental results indicated reasonable evidence for the waste composite. Acceptable consistency was confirmed for the waste composite even after aging seven years and exposure to flooding scenario for 260 days.

Keywords, Radioactive borate waste; long-term; immobilization; immersion

1. INTRODUCTION

The main component of liquid waste concentrates generated from the pressurized water reactor is boric acid (H₃BO₄). Such reactors generate about 50,000 gallons of the boric acid evaporator bottom yearly. Boric acid waste is mostly neutralized by using sodium hydroxide and then concentrated by evaporation. The resulted borate slurry should be immobilized usually in cement, polymer, bitumen or cement-polymer composites [1-3].

Long-term resistivity of solidified radioactive waste forms is a major area of research in the radioactive waste management intending to minimize the
back release of hazardous materials which could be occurring at environmental impacts during the disposal period. Instead of simulating the extreme climatic and other conditions by using accelerated aging test, real time observations could be applied to imitate the real aging of the final waste form for several years under different natural conditions.

Radioisotope Department, Egyptian Atomic Energy Authority has developed a system of using cement-water extended polyester based on the recycled poly (ethylene terephthalate) (PET) waste for incorporating borate waste simulates to improve the mechanical and chemical characterizations of solidified radioactive waste form. Our previous publications concerned with the characterization of the final waste form after 28 days curing period [3-5].

The current work aiming at studying the performance of cement-polymer composite [Portland cement (PC) and the recycled Poly(ethylene terephthalate)] incorporated borate waste simulates, which aged for 7 years. The aged waste form was immersed into three types of water for 260 days. The stability of the final waste product was assessed at the end of definite interval times through visual evaluation in addition to mechanical integrity. Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), thermal analyses and Fourier Transmittance Infra-Red (FT-IR) were performed at different immersion periods to characterize the changes in the microstructure of the immobilized waste form due to aging and immersion impacts.

2. MATERIALS AND METHODS

2.1. Preparation of cement-polymer composite waste form

The unsaturated polyester (UP), based on the glycolysis of PET waste is prepared by mixing the shredded soft drink bottles with propylene glycol and diethylene glycol, and then the products of this glycolysis process are reacted with maleic anhydride and adipic acid. Styrene monomer, in turn, is added to the resulting UP at a ratio 40 : 60 wt.:wt. % to give styrenated polyester (SP). On the other hand, water extended polyester (WEP) is obtained by dispersing 20% of distilled water containing 0.2 mmol/g diethanolamine into 80% of the obtained SP. Finally, the waste composite is obtained by premixing 3% by weight of WEP with hydrated cement paste immobilizing 4% by weight borate waste simulates of chemical composition reported in Table 1.
The hydrated cement paste was prepared by mixing of locally manufactured Portland cement of the chemical composition presented in Table 2 with water at w/c ratio equal to 0.40 related to the weight of cement. The obtained waste composite slurry is poured into polyethylene molds and agitated vigorously by hand to keep the WEP suspended in the cement paste. The waste composite was allowed to set and hard for 28 days and left to age for seven years at room temperature (30±5°C). More details for the preparation of the UP, WEP, and the waste composite were fully described in previous work [6]. At the end of aging time, well standing monolithic cylindrical blocks of final waste form are obtained and subjected to immersion process.

2.2. Immersion process

The worst scenario, flooding in the repository environment, was simulated in the laboratory by statically immersing the 7 years aged cured cylindrical solid specimens of the waste composite in each of the three different types of leachant namely, tap, ground and sea water. The analyses of some ions of an interest present in the three types of water are represented in Table 3 successively. After predetermined immersion periods, chosen solid blocks were separated from the immersion media then weighted and subjected to a compressive strength evaluation and other experimental investigations.

Table (1): Chemical composition of the simulated borate waste solution concentrates (g/l)

<table>
<thead>
<tr>
<th></th>
<th>NaOH</th>
<th>H₃BO₃</th>
<th>Na₂SO₄</th>
<th>Na₂HPO₄·12H₂O</th>
<th>NaCl</th>
<th>Fe₂(SO₄)₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration</td>
<td>29</td>
<td>180</td>
<td>30</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table (2): The chemical compositions of Portland cement in percent

<table>
<thead>
<tr>
<th></th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>K₂O</th>
<th>SO₃</th>
<th>Insoluble residues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage</td>
<td>19.84</td>
<td>4.74</td>
<td>4.0</td>
<td>61.01</td>
<td>2.5</td>
<td>0.6</td>
<td>2.4</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Table (3): The concentrations of some interested ions in tap, ground and sea water

<table>
<thead>
<tr>
<th>Leachant</th>
<th>pH</th>
<th>K⁺</th>
<th>Na⁺</th>
<th>Mg²⁺</th>
<th>Ca²⁺</th>
<th>Cl⁻</th>
<th>SO₄²⁻</th>
<th>HCO₃⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap water</td>
<td>6.90</td>
<td>0.08</td>
<td>1.07</td>
<td>1.2</td>
<td>1.4</td>
<td>0.77</td>
<td>0.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Ground water</td>
<td>7.20</td>
<td>23</td>
<td>149</td>
<td>13</td>
<td>74</td>
<td>137</td>
<td>317</td>
<td>272</td>
</tr>
<tr>
<td>Sea water</td>
<td>7.93</td>
<td>8.4</td>
<td>652.6</td>
<td>96.9</td>
<td>28.06</td>
<td>496.9</td>
<td>60.8</td>
<td>183</td>
</tr>
</tbody>
</table>
Compressive strength measurements were carried out for 3-5 blocks with height 6.0±0.2 cm and diameter 3.10±0.05 cm using Ma-Test Measuring Machine E-159 SP, Italy. To follow up the internal changes that could be take place in the aged waste composite blocks at the end of immersion period, X-ray diffraction and infrared analysis were performed. For X-ray diffraction examinations, Phillips-1390 type diffractometer, with Cu Kα-radiation and Ni filter was used. On the other hand, Schimadzu DTA-50 and TGA-50H were used for thermal analyses, where the powder samples were heated by 10°C/min. up to 1100°C using □-Al2O3 as a reference material. Absorption bands characterizing the hydration process of different waste form specimens were studied by utilizing Infrared Phillips-Pu 9700 spectrophotometer using KBr pellets. For studying the particle morphology and mass microstructure, Jeol JXA-840A Electron Probe Microanalyzer (Japan) was employed with stage magnification up to 2500x. The actual pretreatment and preparation consisted only of gold plating of the dry samples in S150A Sputter Coater Edwards (England) before the examination.

3. RESULTS AND DISCUSSION

The need of long-term efficient protection for final radioactive waste form in terms of the biosphere and hence man towards the radiological hazardous is considered mandatory. That need requires certain formal, mechanical and internal microstructural stability achievement.

3.1. Mineralogical changes

XRD analyses were performed using the powder pattern method while the patterns were measured in the 2θ diffraction ranges from 0°C to 60°C. XRD patterns of the 7 years aged final waste form (FWF) before the immersion process are shown in Fig. 1 and characterized by the peaks of one of the main hydrated cement products, namely portlandite [(CH) Ca(OH)2] [7]. These peaks are detected at 2θ≈ 18.2°, 34.6° and 47.7°. On the other hand, the second main hydration product of calcium silicate hydrate (CSH) is mostly amorphous phase and hardly detected by the XRD analysis. In the diffractgram (Fig. 1), some larnite [(L) (l 2CaSiO4)] could be demonstrated at 2θvalues ≈ 32.5°, 32.9° and 41.6° Calcite [(CC) (CaCO3)] was also detected at 2θ≈ 23.3°, 29.6°, 39.6° and 47.7°. Quartz component of the cement has been differentiated nearly at 2θ≈ 26.7° while traces of gypsum can be detected at 2θ values around 10.7° and 31.3°. It is worth mentioning that, the diffratogram of 7 years aged FWF has the main peaks comparable to that for 28 days FWF samples [3,5]. These
observations could be long-established that the proposed cement-PET composite can immobilize up to 4% borate waste and withstand aging without striking mineralogical changes.

By applying the flooding scenario, some differences could be observed in the XRD patterns of 7 years aged FWF exposed to three leachants for 260 days and reported as following:

The peaks associated to the presence of C-H in the samples after the immersion in tap water are similar to that for the non-immersed FWF and lower for specimens immersed in sea and ground water (Fig. 1). The decrease in portlandite contents during the immersion process could be referring to the increasing contents of gypsum and/or calcite fractions in the final waste form.

It is known that Ca(OH)$_2$ is less stable in a gypsum environment (sea and ground water) than C-S-H phases, but due to their low degree of crystalinity in the water as previously stated, it is hardly to detect. Therefore, during the immersion process, some pozzolanic reactions may result in replacement of C-H by C-S-H [8]. However, it should be notified that these results can be confirmed through the forward scanning electron microscopy examination.

The increasing of calcite content in the moisture environment could be explained on the basis of larnite or portlandite reactions with the surrounding carbon dioxide [9]. This could be thermodynamically illustrated by the following reactions when the equilibrium is shifted towards the formation of CaCO$_3$.

$$\text{CaSiO}_4 (s) + \text{CO}_2 (g) \rightarrow \text{CaCO}_3 (s) + \text{SiO}_2 (s) \quad (1)$$
$$\text{Ca(OH)}_2 (s) + \text{CO}_2 (g) \rightarrow \text{CaCO}_3 (s) + \text{H}_2\text{O} (l) \quad (2)$$

Fig.(1): XRD patterns of 7 years aged cement–polymer composite immobilizing 4% borate waste simulate before and after immersion in three types of water for 260 days
Therefore, during the flooding event at disposal site including the aged final waste form, part of the decrease in the larnite content could be referred to the progress in carbonation reaction [10]. Similar trend was reported by Kuusik et al. [11]. It could be noticed in Fig. 1 the decrease of larnite peaks for the immersed blocks accompanying with an increase of the calcite peak’s intensity.

The coexistence or increase in gypsum content (peak at $2\theta \approx 10.7^\circ$) for final waste form samples immersed in sea and ground water, in combination with the decrease in portlandite (peaks at $2\theta \approx 18.2^\circ$, $34.6^\circ$ and $47.7^\circ$) leads to the conclusion that C-H is most probably reacted with magnesium sulfate (present in sea and ground water) to form CaSO$_4$ according to the following reaction:

$$\text{Ca(OH)}_2(s) + \text{MgSO}_4(\ell) + 2\text{H}_2\text{O}(\ell) \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O}(s) + \text{Mg(OH)}_2(s) \quad (3)$$

Peaks of ettringite in the immersed blocks appeared at high intensities of $2\theta$ around $9.2^\circ$ and $34.6^\circ$ and clearly observed for samples dipped in sea and ground water. The principal chemical process of ettringite formation through gypsum is reported [12] as the following equation (4):

$$3\text{CaO} \cdot \text{Al}_2\text{O}_3(s) + 3(\text{CaSO}_4 \cdot 2\text{H}_2\text{O})(s) + 26\text{H}_2\text{O}(\ell) \rightarrow 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 32\text{H}_2\text{O}(s) \quad (4)$$

Collectively, and based on the XRD analyses, it could be stated that the aged FWF of proposed cement–polymer composite immobilizing borate waste simulate exposed to flooding process in three types of water for different periods exhibited some mineralogical changes summarized in the formation of ettringite and gypsum especially for the samples dipped into sea and ground water. In addition, an increase in calcite formation is accompanying with the decrease in portlandite and larnite contents. Even, with these changes, the cemented waste form showed acceptable visual and mechanical stabilities.

3.2. FT-IR analysis

FT-IR spectroscopy was performed to identify the chemical groups specified to the FWF and to confirm the speculated changes that may occur for aged final waste forms before and after its statically immersion in various types of water for 260 days. The obtained spectra are represented in Fig. 2. OH group referring to the hydroxyl of portlandite is appeared as a small band near 3770 cm$^{-1}$. This band disappeared for the samples immersed in both sea and ground water, which confirming the data previously obtained by using XRD indicating that a great part of C-H was consumed in C-S-H phases, gypsum and calcite formations. The strong bands at about 3440 cm$^{-1}$ may be attributed to water
molecules formed or absorbed by the cement-polymer composite. Weak bands adjacent to 2925 cm\(^{-1}\) and 2850 cm\(^{-1}\) are attributed to the stretching vibration of -CH\(_2\) groups while a shoulder band at \(\approx 1795\) cm\(^{-1}\) may be describing the vibration of the organic –C=O in the polymer moiety. Furthermore, for samples dipped in sea and ground water, H\(_2\)O and OH stretching vibration absorption bands near to 1650 cm\(^{-1}\) may be generated from the formed ettringite (Fig. 2). The bands near vicinity of 1420 cm\(^{-1}\) is corresponding to the strong asymmetric stretching vibration of CO\(_3^{2-}\) and also sharp peaks at 875 cm\(^{-1}\) are due to out of a plane bending vibration of CO\(_3^{2-}\). S-O vibration beak related to the formation of ettringite appeared near to 1120 cm\(^{-1}\). It is worth to mentioning that, these bands could be specified for the immersed samples only.

The little bit shift accompanying to asymmetric stretching vibration of SiO\(_4^{2-}\) at 920-970 cm\(^{-1}\) could be attributed to its polymerization during C-S-H formation. On the other hand, Si-O out of a plane bending vibration and Si-O in a plane bending vibration appeared in the ranges of 560-520 cm\(^{-1}\) and 460-420 cm\(^{-1}\) respectively. However, due to the low polymer content in the composite (4%) and overlapping of the major polymer bands with the bands assigned with the hydrated aged cement phases, the characterization bands of the polymer could be hardy detected.

Generally, FT-IR analyses can be used to corroborate the data obtained from the XRD analyses which mainly concerning with the formation of ettringite due to the immersion in various water media. Furthermore, it should be notified in the spectrograms that the presence of all chemical groups assigned for the FWF even after aging process and immersion in different water media for 260 days could be taken as a stability indication for the candidate cement-polymer composite to encapsulate the radioactive borate waste.
Fig.(2): IR spectroscopy of 7 years aged cement–polymer composite immobilizing 4% borate waste simulate before and after immersion in three types of water for 260 days

3.3. Thermal Analysis

Differential thermal analysis (DTA) and thermogravimetry (TG) are valuable tools for evaluating the nature of the aged cement-polymer composite immobilizing borate waste simulates before and after their exposure to immersion in different water media. Fig. 3 shows that all DTA thermograms exhibited similar trends. The studied samples are characterized by the following four major zones [10,11]:

Endothermic peak presents near 125°C and describes the dehydration process of hygroscopic water and also from ettringite, gypsum and C-S-H phase.

The pyrolysis of the organic polymer moiety in the composite could be identified by an exothermic peak located nearly around 335°C.

Endothermic peak at about 490°C characterized the dehydroxylation of portlandite formed during the hydration of cement components.

The decarbonation of calcites formed during aging and immersion periods is detected as an endothermic peak displayed at about 776-792°C.
Fig.(3): DTA and TG of 7 years aged cement–polymer composite immobilizing 4% borate waste simulate before and after immersion in three types of water for 260 days

On the other hand, TG curves of the aged final waste forms before and after exposing to the flooding are represented also in Fig. 3. These TG curves would be divided into four major parts according to the different reactions as following:

*- 30 – 112 °C is due to loss of water from C-S-H and other calcium hydrate in addition to that water absorbed by the samples.

*- 112 – 353 °C is according to the weight loss attributed to the different stages of C-S-H and gypsum dehydration and polymer pyrolysis.

*- 353 – 550 °C is tending to dehydroxylation of portlandite and dehydration of some silica hydrates.

550 – 1099 °C is related to decarbonation of calcite as well as calcium and silica interactions.
The deterioration in the final waste form may be estimated basing on calculating the mass losses. The mass loss depending on thermal analysis was applied to evaluate the performance of the aged cement-polymer composite incorporating 4% borate waste simulates after water flooding scenario for 260 days.

Table 4 represented portlandite percentages, calcite contents and the total mass loss as a function of immersion in the three leachants.

**Table (4): Mass loss based on the thermogravimetric analysis of aged cement-polymer composite incorporating 4% borate waste simulate due to the immersion in different water composition**

<table>
<thead>
<tr>
<th>Temperature range, °C</th>
<th>Non-immersed</th>
<th>Immersed in tap water</th>
<th>Immersed in ground water</th>
<th>Immersed in sea water</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-112</td>
<td>1.7</td>
<td>3.8</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>470</td>
<td>4.1</td>
<td>3.6</td>
<td>2.8</td>
<td>2.05</td>
</tr>
<tr>
<td>&gt;750</td>
<td>3.4</td>
<td>3.8</td>
<td>4.8</td>
<td>5.1</td>
</tr>
<tr>
<td>Total mass loss</td>
<td>19.9</td>
<td>27.3</td>
<td>28.4</td>
<td>28.4</td>
</tr>
</tbody>
</table>

Ca(OH)$_2$ contents in the studied waste forms were calculated according to the following equation:

$$\text{Ca(OH)}_2\text{ content, }% = \frac{\text{WL}_{\text{Ca(OH)}_2} \times \text{Mwt. of Ca(OH)}_2}{\text{Mwt. of H}_2\text{O}}$$

Where $\text{WL}_{\text{Ca(OH)}_2} \%$ is the mass loss during the dehydroxylation of portlandite and calculated from TG curves according to the method described by Tylor and Turner [13].

Mwt of Ca(OH)$_2$ and Mwt of H$_2$O represent the molecular weights of Ca(OH)$_2$ and H$_2$O respectively.

The increase of mass loss at first zone (30-112°C) as well as the total mass loss for the specimens immersed in water for 260 days comparing to the low values for non-immersed one could be referred to the water formed or absorbed during the immersion process. On the other hand, the mass losses near 470°C and greater than 750°C was noted and could be referred to the decrease in portlandite content due to the immersion process accompanied with a parallel increase in the calcite content. The diminish in C-H content and the escalation in calcite percentages could be identified by the carbonation process of the portlandite in the presence of surrounding carbon dioxide as previously illustrated in equation (1). Thermal analysis confirmed the results reached from
XRD and FT-IR analyses, which described the changes took place in the internal structure of the proposed cemented waste form.

3.4. Scanning Electron Microscopy (SEM)

The internal microstructures and morphology of the aged cement-polymer composite incorporating borate waste simulate before and after immersion in various water types are represented in Fig. 4 and Fig. 5, respectively. Fig. 4 shows the plate like crystals of Ca(OH)$_2$, which found in parallel towards each other, and they are almost undistorted (Fig. 4-a). The crystals are arranged in some sort of stack. The polymer films stretched and covered the C-S-H phases (Fig. 4-b), giving them a more smooth texture. Fig. 4-c and Fig. 4-d exhibit pronounced randomly oriented calcite crystals.

At the end of the immersion period for the aged final waste form in various leachants, abundant C-S-H phases coated by thin polymer film were detected (Fig. 5-a). The thin polymer film is also observed around the needle like structure of ettringite that assumed to be recrystallized inside the final waste form holes due to the immersion in sea and ground water (Fig. 5-b). Even after 260 days of immersion process, polymer was detected between Ca(OH)$_2$ crystals and may act as a gene bonding for the crystals together. In addition, a large amount of ettringite crystals is distributed in between. It is worthwhile mention that, the solubility of the ettringite is much lower than that of portlandite and hence the former is predominant in the immersed samples (Fig. 5-c).

Gypsum crystals could be distinguished for final waste forms immersed in sea and ground water due to their measurable contents of sulfate ions (Fig 5-d). Furthermore, this figure showed the gluing action of the polymer. Gypsum and ettringite are known by causing expansion in the cement-polymer composite immersed in ground or sea water and accordingly, some internal cracks could be present, (Fig. 5-b). The compressive strength could be decreased due to the expansion cracks in the final waste forms while the similar trend was described by Thokchom et al. [14]. The data reached through SEM confirmed the adequate performance of the proposed cement-polymer composite based on the recycled PET waste to incorporate the borate waste up to 4% even for long time and under flooding effect for 260 days.
Fig. (4): scanning electron photomicrograph of the internal microstructure of 7 years aged cement-polymer composite incorporating borate waste simulate.

Fig. (5): scanning electron photomicrograph of the internal microstructure of 7 years aged cement-polymer composite incorporating borate waste simulate and immersed in different leachants for 260 days.
3.5. Visual Appearance

Aged cement-polymer composite incorporating borate waste simulate did not show any changes in its shape and remained structurally intact without visible cracks even after immersion in the three types of leachants for 260 days. Specimen’s surfaces received white deposits throughout the water exposure period while rare and minimum white deposits are appeared in case of tap water. On the other hand, the maximum deposits were observed on the blocks dipped in sea water. These deposits are coming powdery and harden with time. The typical images of such structural formations are shown in Fig. 6, which revealed the photographs of the specimens after 260 days exposures to different water types tap (a), ground (b) and sea (c), respectively.

(a) Immersion in tap water  (b) Immersion in ground water  (c) Immersion in sea water

Fig. (6): The 7 years aged cement-polymer composite incorporating borate waste simulate after immersion in different leachant for 260 days

3.6. Mechanical durability

Much attention has been paid to study the long-term performance of cement-polymer composite from the point of view of durability related to mechanical characterizations. Fig. 7 represents the variation in compressive strength values of the aged final waste form specimens immersed in different water compositions. After 260 days of water exposure, the specimens exhibited a decrease in their mechanical durability through fluctuations in strength. The samples immersed in both sea and ground water showed greater fluctuations in strength compared to that dipped in tap water. Loss of strength could be attributed to the formation of gypsum and ettringite in the pores of specimens [14]. However, it is worth mentioning that the candidate cement-polymer composite immobilizing the borate waste simulate has compression strength greatly exceed the value specified by the Nuclear Regulatory Commission.
(NRC) technical position paper for stabilized low-level radioactive waste forms even after 7 years aging and nearly 260 days of immersion in different compositions of water [15].

![Graph](image)

Fig. (7): Compressive strength of specimens immersed in different water compositions

**CONCLUSION**

The long-term characterization of cement–polymer composite immobilizing the borate waste simulates was evaluated by the real aging time observations (7 years) of the final waste form exposed to flooding scenario conditions for 260 days. The finding indicates that cement–recycled PET composite retained their structure without deformation for nearly 7 years in ambient conditions and immersion in aqueous media for 260 days. The candidate cement–polymer composite is indeed compromise between investment cost and long-term matrix durability. The former is based on the cheap materials used [e.g. cement material, recycled poly(ethylene terephthalate)] while the latter as established on ease of workability and legitimate experimental results. As well as the fact that inorganic-organic composite possessed acceptable mechanical integrity, it was also specified by low processing temperature and ease of fabrication.
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أداء متراكم الإسمنت - البوليمر المتقدم والحاوي لعوامل نفايات البناء خلال سيناريو الغمر
سمير باشا إسكندر و طلعت عبد الله بومي و حسان الدين مصطفى صالح
قسم النظائر المشعة - مركز البحوث النووية، هيئة الطاقة الذرية، مصر

تم تطوير متراكم الإسمنت مع البولي إستير المائي المحضر من مخلفات البولي ايثيلين تيرفالات المعاد تدويرها في وحدة الكيمياء غير العضوية التطبيقية بيئة الطاقة الذرية وذلك لاحتواء عوامل نفايات البناء.

ولقد تناولت أبحاث الوحدة المشتركة سابقا خصائص المنتج النهائي لعوامل نفايات المذكورة في مرحلة ما بعد التصليح لمدة 28 يوم من الخلط. أما هذا البحث يتناول دراسة خصائص المنتج بعد التقادم لمدة 7 أعوام ثم تعرضه لسيناريو الغمر المائي لمدة 210 يوم في أوساط مائية مختلفة. وتم تقييم المنتج النهائي لعوامل نفايات في نهاية مراحل زمنية مختلفة من سيناريو الغمر المائي عن طريق الاختبار العيني والقياسات الميكانيكية. وكذلك فقد تم دراسة المنتج تحت المجهر الإلكتروني والأشعة السينية والأشعة تحت الحمراء والتحليل الحراري وذلك لمتابعة أي تغيرات قد تطرأ على الشكل النهائي المقدم خلال الفترات المختلفة من الغمر المائي وأنشئ النتائج العملية الفعالة وحسن أداء المتراكم المقترح كمادة حاوية لعوامل نفايات البناء رغم التقادم لمدة 7 سنوات وخلال سيناريو الغمر المائي لمدة 260 يوما.