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Effect of Ultraviolet Radiation on the Physical and Mechanical Properties of Polymer Matrix

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Abstract: In recent years, the use of polymer concrete have become a promising choice in outdoor applications such as repair concrete structures, beams and slabs of small cross section and coating of railway sleepers, is subjected to degradation caused by photochemical reactions from solar ultraviolet (UV) radiation. Any small damage in polymer matrix can be detrimental to the overall mechanical performance of the structure as it binds and transfers load to the reinforcement. This paper deals with the effect of UV radiation on the physical and mechanical properties of epoxy resin based polymer matrix. Seven different mixes containing filler materials from 0 to 60% with an increment of 10% were exposed to UV radiation using accelerated laboratory testing. Specimens were subjected to 2000 hours of UV radiation by Xenon 2200 watt air cooled lamp in the sunset XLS chamber and subsequently weighed, examined by microscope and mechanically tested. Surface degradation in the form of discoloration were observed by microscopic observation. It was found that, the loss of specimen’s weight decreased with the increase of filler materials in the mix. Significant decrease of flexural strength were observed in the mixes containing filler volume up to 20%. However, no reduction of flexural strength were noticed for the higher filler (≥ 30% filler) containing mixes indicating the filler can helps to preserve the structural performance by absorbing or blocking UV radiation before it reaching the chromophores in polymer matrix.

Keywords: epoxy resin, polymer matrix, ultraviolet radiation, physical and mechanical properties.

1. Introduction

The use of polymer concrete in outdoor structures such as bridge decking, pavement overlays, hazardous waste containers, waste water pipes and composite railway sleepers [1-3] are commonly exposed to ultraviolet (UV) radiation. UV radiation is found highly damaging to organic polymeric materials [4]. The solar UV radiations absorbed by the polymer are responsible for photolytic, photo-oxidative, and thermo-oxidative reactions that can degrade the polymer [5]. This photo-oxidative reaction reduces the molecular weight and makes the polymer brittle. Therefore, a special attention need to be provided for the application of polymer matrix in such kind of infrastructures. The wavelengths of UV radiation that reaches the earth’s surface are ranged from 290 nm to 400 nm and most of the polymers have bond dissociation energies in that range of wavelength [6]. The UV ray caused by sunlight frequently combined with atmospheric oxygen, moisture, temperature, wind-borne abrasives, freeze-thaw and other environmental factors, and their photo-oxidative degradation can break the polymeric chains [6]. Due to photo-oxidation, the polymer matrix greatly affected by UV radiation and its effect on the physical and mechanical properties are essential to investigate for their widespread applications. Unfortunately, so far, a very limited research have been conducted on the performance of polymer matrix under UV radiation.

The effect of UV radiation are usually confined to the top few microns of the surface [6] that can reduce the mechanical properties which results in embrittlement, discoloration and an overall reduction in its physical and electrical properties [7]. This effect is severe for transparent polymer that allows UV ray to break the molecular bond of structure [8]. To reduce the transparency of epoxy resin, a non-transparent filler such as fly ash can be added. In contrast with the traditional concept of using fly ash as filler, this study incorporates two other filler materials, a fire retardant filler and hollow microsphere to improve the fire and shrinkage performance, respectively. However, the addition of filler can reduce the mechanical strength of polymer matrix as the flexural strength of polymer primarily depends on the amount of resin, the more resin in the mix- the more strength is.

The effect of different UV exposure time (500, 1000 and 1500 hrs) on fibre reinforced polymer composites have been studied by Yan et al. [9]. They found the deterioration of tensile and flexural properties after 1500 hrs of UV exposure. Chin et al. [10] investigated the UV radiation on thin polymer films that was exposed to a 1000 watt xenon arc source for 1200 hrs at 30 °C in an Oriel solar simulator. They observed surface oxidation results surface erosion and cracking for both vinyl ester and iso-polyester samples.
Peng et al. [11] studied the accelerated weathering on polypropylene composites reinforced with wood flour, lignin and cellulose at different loading levels from 0 to 960 hrs. They observed large cracks and delamination of polypropylene layer after 960 hrs of UV exposure. Cao et al. [12] investigated the degradation of polymer coating systems under 2000 hrs of UV exposure. The present study decided to expose the polymer matrix under UV radiation up to 2000 hours to achieve the more reliable results.

The lack of comprehensive knowledge on the effect of UV radiation on epoxy polymer matrix restricts their applications to the practicing civil engineers and designers. This paper explore some aspects related to physical and mechanical properties of polymer matrix under UV radiation and contributes to the scientific knowledge in the field.

2. Materials and Method

2.1 Materials

The materials employed in this investigation were epoxy resin and light-weight filler. Epoxy provides a high level of bonding properties compare to the traditional paste style glue. Generally two components of resin are required to get the gluing properties and need to be mixed together before use. In this study, two main components of the epoxy resin were DGEBA type (Part-A) and an amine based curing agent (Part-B). Epoxy resins are blended, filled, or modified with reactive and nonreactive components. It is then necessary to adjust the concentration of the curing agent to cure only the portion of the mix that is reactive. The resin producer furnishes the Epoxy Equivalent Weight (EEW) of 190 gm for Part-A and Amine Hydrogen Equivalent Weight (AHEW) of 60 gm for Part-B. To make the resin mix reactive, one equivalent weight quantity of amine curative will require for one equivalent weight quantity of an epoxy resin. Therefore, 32 gm of Part-B is required to react with 100 gm of Part-A, and otherwise it will not work properly.

Resin is the most expensive ingredients in polymer matrix and to minimise the cost and improving durability light weight filler materials were added in the mix. Three different filler materials such as Fire Retardant Filler (FRF), Hollow Microsphere (HM) and Fly Ash (FA) were mixed together by a certain percentage to get the effective filler mix. The mixing formulation of these three filler materials was established after several trial mixes. The fire retardant used is non-toxic and has low abrasiveness, acid resistance, chemically inertness, electric arc resistance and smoke suppression properties. On the other hand, hollow microspheres can contribute in reducing weight, controlling shrinkage, increasing thermal insulation of the polymer matrix. The by-product fly ash can improve the performance of matrix by resisting UV and reducing permeability of water and aggressive chemicals.

![Figure 1. Polymer matrix ingredients and specimens casting.](image-url)
2.2 Method

The addition of UV absorbers or UV stabilizers into the polymer is one of the best methods for protecting polymeric matrix against UV radiation [7]. In this study, filler materials were incorporated as UV absorbers for targeting the absorption of UV light and dissipating the absorbed energy harmlessly. The specimens were cast in plastic cups (Fig. 1b). Seven different mixes were prepared with an increment of 10% filler by volume starting from pure resin mix (0% filler) to the mix with 60% filler content. The detail mixing proportions are given in Table 1.

Table 1. Details of mixing proportion.

<table>
<thead>
<tr>
<th>Identity of mix</th>
<th>Mix-1</th>
<th>Mix-2</th>
<th>Mix-3</th>
<th>Mix-4</th>
<th>Mix-5</th>
<th>Mix-6</th>
<th>Mix-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Resin/Filler  (by volume)</td>
<td>100/0</td>
<td>90/10</td>
<td>80/20</td>
<td>70/30</td>
<td>60/40</td>
<td>50/50</td>
<td>40/60</td>
</tr>
<tr>
<td>Resin Part A, (gm)</td>
<td>124</td>
<td>112</td>
<td>100</td>
<td>87</td>
<td>75</td>
<td>62</td>
<td>50</td>
</tr>
<tr>
<td>Part B, (gm)</td>
<td>40</td>
<td>36</td>
<td>32</td>
<td>28</td>
<td>24</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>Filler (FRF+ HM+ Fly Ash), (gm)</td>
<td>0</td>
<td>30</td>
<td>59</td>
<td>89</td>
<td>119</td>
<td>148</td>
<td>178</td>
</tr>
</tbody>
</table>

Specimens were demolded in the next day of casting and cut it to a nominal dimension of 80 × 10 × 10 mm using machine. The initial flexural properties of the specimens were determined and recorded before exposed to the UV radiation. The effect of UV can be determined either by accelerated laboratory testing or actual outdoor exposure. The latter is obviously time consuming method and therefore accelerated laboratory testing was conducted. UV-chambers basically consist of a UV-light source(s) and a specimen rack. A variety of artificial light sources including carbon arc lamps, xenon arc lamps, fluorescent sun lamps and mercury lamps can be used to simulate the natural sunlight. However, xenon arc and fluorescent lamps are the two most popular UV-sources for photo-degrading materials that can emit a similar type of harmful radiation [5]. In this study, specimens were subjected to 2000 hours of UV radiation by xenon 2200 watt air cooled lamp in the sunset XLS chamber. The exposure was carried out in an ambient atmosphere where the temperature was varied between 22 to 24 °C, with a relative humidity between 30 to 50%. After the specified time, the specimens were taken out from the UV chamber and subsequently weighed, examined by microscope and mechanically tested. Flexural test of the affected samples were conducted under three-point bending (Fig. 2b) set-up and compared the results with unaffected one.

(a) ultraviolet chamber

(b) bending test of polymer matrix

Figure 2. Bending test of the UV affected samples.

3. Results and Discussion

The polymer matrix usually generate heats while mixing two resins together and the maximum temperature was generated in the mix containing 0% filler. The addition of filler can absorb heat and maintain the temperature to the comfortable range for working. The physical properties in terms of
discolouration, depth affected by UV and loss of weight, and mechanical properties in terms of bending strength were examined once the samples were removed from the UV chamber.

### 3.1 Physical properties

The mixes containing high resin or low filler (Mix 1 to mix 3) were severely affected by UV and surface degradation in the form of discolouration were observed by microscopic observation (Fig. 3 a-c). The discolouration is due to interaction between epoxy molecules on the exposed surface and the photons from UV radiations results in photo-oxidative reactions that alter the chemical structure [13]. No significant changes in colour were noticed for the mix having filler 30% or more (Fig. 3 d-g). It is noted that the Mix-1 which contains 100% resin or 0% filler is more transparent than the other mixes. This transparency is due to the physical properties of resin and the addition of filler can increase the darkness in the succeeding mix because the colour of fly ash which is grey or light dark in nature. Significant improvements were observed in 30% filler mix. Therefore, it can be concluded that the mix containing filler less than 30% is more prone to UV radiation. No significant variations were observed in the higher filler content mix (Mixes 4 to 7) because the darkness of filler can block the UV ray and protect the samples from physical and mechanical degradation. However, a minor changes in surface roughness were also visible by naked eye for all UV exposed specimens.

![Figure 3. Discoloration of UV affected samples after UV exposure.](image)

The weight of the specimens were measured immediately after taken out from UV chamber. As the UV lamp focused the specimens from the top, the top surface of the specimens were mostly affected by the UV light [14]. The loss of specimen’s weight per unit UV exposed area was determined and it was found that the loss of weight follows a decreasing trend with the increase of filler in the mix (Fig. 4a). The highest loss of weight was found 50 gm/m² in 0% filler mix (Mix-1) and it decreased to 27 gm/m² for 60% filler mix (Mix-7). The loss was found more for the mix containing 0 to 20% filler and suddenly decreased from 45 gm/m² to 35 gm/m² when the filler increased from 20% to 30%. This sudden drop is expected because the depth of the specimen affected by UV for 20% filler mix was found significantly higher than 30% filler mix (Fig. 5b) and consequently the expulsion of moisture was higher. Moreover, the improvement rate is quite slow from 30 to 60% filler mix. The percentage loss of weight based on the initial weight of the specimens (before UV exposure) shown in Figure 4(b). It was also found that the loss of weight decreased from 0.37% to 0.15% with the increase of filler from 0 to 60%. This result is somewhat comparable with the loss of weight of carbon fibre reinforced epoxy composites after 500 hrs of UV exposure studied by Kumar et al. [13] where they found an average loss of 0.27%. The decrease of weight loss is due to the gradual improvement of UV resisting properties with the increase of filler which can protect the samples from deterioration.
The affected depth of the specimens due to UV light were measured using electronic microscope. There was a clear distinction of colours between the affected and unaffected layers (Fig. 5a). The affected depth was found higher for the mix containing filler up to 20%. The maximum depth was measured 4.58 mm for 0% filler mix and it was slightly decreased to 4.45 mm for 20% filler mix. However, a sudden decrease of the affected depth was found when the mix contained 30% filler (Fig. 5b). This indicates, the transitional polymer matrix that has superior resistance to UV radiation contains filler between 20 and 30%. The affected depth was gradually decreased from 1.11 to 0.40 mm for the mix having filler from 30 to 60%. Overall, the addition of filler in the epoxy polymer matrix can increase the resistance against UV radiation as the fillers block the penetration of UV thus only the resin near the surface is affected.

### Figure 4. Loss of weight of polymer matrix after 2000 hours of UV exposure.

3.2 Mechanical properties

The flexural strength of the UV unaffected group of specimens were measured before placing the identical second group in UV chamber. After 2000 hours of UV exposure, the flexural strength of the second group of samples were measured using three point bending test. To ensure the effect of UV on flexural strength, the specimens were placed in the testing machine in such a way that the UV affected side subjected to tension in bending. Results were compared with the unaffected samples and observed a significant
reduction of flexural strength up to 48% for zero filler mix (Mix-1). The reduction of strength was found 34
and 32% for the mixes containing filler volume of 10 and 20% respectively (Mix-2 and Mix-3). The
reduction of strength due to the effect of UV should not be more than 10% in outdoor application [15], thus
the mixes containing filler up to 20% is vulnerable to UV. However, no reduction of flexural strength were
noticed for the higher filler containing mixes indicating the filler can help to preserve the structural
performance by absorbing or blocking UV radiation before it reaching the chromophores in polymer matrix
(Fig. 6).

![Figure 6. Effect of UV radiation on flexural strength of polymer matrix.](image_url)

Surprisingly, a slight increase of the flexural strength was found in the UV affected mix containing filler
volume from 30 to 60%. It is previously mentioned that the effect of UV is only significant for the mix
having filler less than 30% and no major change in colour was observed for the mix containing 30 to 60%
filler (Fig. 3). Therefore, the slight increase of strength is probably due to the age of UV specimens which
was at least 2000 hours (in-chamber period) longer than the unaffected samples.

4. Conclusions

In this paper, the effect of UV radiation on some of the physical and mechanical properties of epoxy
polymer matrix was studied by accelerated UV weathering. Microscopic observation was performed to
analyse the change of colour and measuring the affected depth of the specimens under the effect of UV
radiation. The loss of weight and the reduction of flexural strength was compared with unaffected
samples. Some conclusions drawn from the investigation are listed as follows:

1. Significant surface degradation in terms of discoloration was observed in the mix containing filler
up to 20%. However, no noticeable change in colour were found for the mixes containing 30 to
60% filler. The increase of filler reduces the transparency of the mix that can increase the UV
resistance.

2. Specimens were affected up to a maximum depth of 4.58 mm when the mix contained pure resin
without filler. A slight improvement was observed up to 20% filler mix (affected depth 4.45 mm).
However, the addition of 30% filler can significantly improve the UV resisting properties as the
affected depth drastically reduced to 1.11 mm indicating the transition polymer matrix containing
filler between 20 and 30%. A minor variation was observed among 30 to 60% filler mix.

3. The loss of specimen’s weight per unit UV exposed area decreased from 50 gm/m² to 27 gm/m²
or 0.37 to 0.15% with the increase of filler from 0 to 60%. However, the loss of weight suddenly
decreased from 45 gm/m² to 35 gm/m² or 0.29 to 0.21% when the filler increased from 20 to 30%.
This is due to the significant improvement of UV resistance by the later when comparing with the
former.
4. Reduction of flexural strength was observed for the UV exposed specimens containing filler from 0 to 20%. However, the addition of filler from 30 to 60% can protect the polymer matrix from mechanical degradation by improving the UV resisting performance.

5. **Acknowledgement**

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6. **References**


