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International Review of Mechanical Engineering (I.RE.M.E.), Vol. 13, N. 11
ISSN 1970 - 8734 November 2019

# Crack-Tip Opening Displacement Behavior Based on Energy Partitioned Work of Fracture Technique on Ultraviolet-Irradiated Mordenite Zeolite-High Density Polyethylene Composites

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**Abstract** – *Crack-tip opening displacement (CTOD) has been widely used to measure the fracture toughness of materials. Based on the energy partitioned work of fracture concept, CTOD behavior is able to describe in more depth the characteristics of mechanical fracture of materials. This study aims to investigate the CTOD behavior in the ultraviolet (UV) irradiated zeolite-HDPE composites. The annealed double-edge notched tension (DENT) shape composite was exposed in UV radiation environment for 50, 100, 150 and 200 hours at a constant temperature of 60°C and atmospheric pressure. The DENT specimens are subjected tensile loaded according to ESIS protocol. CTOD was analyzed based on the concept of partitioned work of fracture. The results show that at the yielding and crack initiation stage, the CTOD value begins to increase when the displacement has passed the 0.5 mm value. At the crack propagation stage, the range of CTOD and displacement values are shorter with increasing duration of UV radiation. At the same crack extension, the CTOD value decreases by increasing the duration of UV radiation.* 

***Keywords****: Crack Tip Opening Displacement, Displacement, Crack Extension, Load, Behavior*

## Nomenclature

| | |
|---|---|
| *CTOD* | Crack-Tip Opening Displacement |
| *CTOA* | Crack-Tip Opening Angle |
| *UVR* | Ultra Violet Radiation |
| $CTOD_y$ | Crack-tip opening displacement at crack initiation |
| $CTOD_n$ | Crack-tip opening displacement at crack propagation |
| $w_f$ | Specific total work of fracture |
| $w_y$ | Specific work required for yielding and crack initiation |
| $w_{np}$ | Specific work for necking and crack propagation |
| $\ell$ | Ligament length |
| $\delta$ | Displacement |
| $\delta_b$ | Displacement at break |
| $\delta_0$ | Crack opening displacement |
| $\delta_p$ | A plastic contribution of extension |
| $\delta_y$ | Displacements for yielding and crack initiation |
| $\delta_n$ | Displacements for for crack propagation. |
| $\delta_{0y}$ | The values of crack opening displacement for yielding |
| $\delta_{0n}$ | The values of crack opening displacement for crack propagation |
| $\delta_{py}$ | Plastic contribution of extension for yielding |
| $\delta_{pn}$ | Plastic contribution of extension for crack propagation |
| $F$ | Load |
| $F_f$ | Flow of stress |
| $K$ | Strength coefficient |
| $\psi$ | Positive material constant |
| $a$ | Initial crack |
| $\Delta a$ | Crack extension |
| $D$ | Parameter for scalar damage variable |
| $D_i$ | Initial damage |
| $w$ | Specimen width |
| $q,R$ | Positive parameter |

## I. Introduction

The application of polymer products especially implemented under sunlight continues to increase. Therefore the polymer stability under UV radiation is a major concern for many researchers. Advanced exposure to UV radiation can speedily accelerate polymer degration. UV degradation generates permanent changes in the chemical structure affected the properties of the polymer and reduces its valuable life. The absorption of UV radiation causes the low energy needed to break chemical bonds which are a crucial case for photodegradation [1]-[4]. Many researchers have reported that polymers are degraded due to exposure to ultraviolet light [5]-[7], so that their mechanical strength decreases [8]-[11]. In terms of the protection of ultraviolet degradation, it has been reported that zeolite is able to resist the degradation of polymers from ultraviolet radiation [12]. In previous studies conducted by Purnomo and co workers [13]-[15], data related to the effects of UV radiation on degradation of high density polyathelene


https://doi.org/10.15866/ireme.v13i11.17584

(HDPE) could not be found. This is unfortunate because the data is very important especially to provide protection for the degradation and fracture toughness of material.

Fracture toughness is used as a parameter of material resistance to crack growth. The value of fracture toughness is used as a primary consideration in material characterization [16], [17].

Therefore, the evaluation of fracture toughness is a very important and interesting field in the development of fracture mechanics methods. Crack-tip opening displacement (CTOD) and Crack-tip opening angle (CTOA) are parameters used in fracture mechanics [18], [19]. The CTOD is well accepted as a parameter for resistance to crack propagation. For resistance to crack extension, the resistance curve model can be considered as a function of crack size in terms of limiting amounts of crack growth [20], [21]. So crack extension as a function of driving force fracture. However, for crack raise greater than the material thickness, the most appropriate criterion for toughness characterization is the CTOA which can be accurately applied to characterize material fracture resistance which experiences stable crack growth [22]-[24]. In the last decade, CTOA parameters were widely used to explain fracture behavior in stable crack propagation [25]-[29]. The CTOD concept is proposed by Wells [30] as a technique fracture parameter and is equivalent to a stress intensity factor K or *J*-Integral. As a material resistance parameter for crack propagation, CTOD has been widely used in materials undergoing plastic deformation before fractures occur which are characterized by strain at the end of the notch.

The CTOD is a displacement vector at the crack-tip which is regarded as the sweep strength for crack propagation [31], [32]. The CTOD assessment is applied for opening crack which propagates along a certain direction associated with the initial crack axis. Moreover, the material structure in the zone in which the CTOD value evaluated will be assessed as one of the considerate variables [33], [34]. Kelly and White [35] have reported that UV radiation in polyethylene notched accelerates failure at the crack tip. As a result, the crack opening displacement (COD) developed faster as well as the strain rate.

It was also reported that the effect of the direction of UV irradiation had no significant effect. Based on the energy partitioned work of fracture, CTOD can be obtained in two states of the fracture stage, namely when the crack is initiated and the crack propagation stage.

Therefore, it is important to conduct a study aimed to investigate the behavior of CTOD at both stages of the fracture. This study aimed to investigate the CTOD behavior based on the energy partitioned work of fracture on UV-irradiated zeolite-HDPE composites.

This paper depicts an analysis of the CTOD behavior in two conditions, namely at the stage of yielding/crack initiation on both notch-tip and the crack propagation stage until both cracks-tip meets in the middle of the ligament length. The CTOD analysis is associated with crack extension and ligament length. Its behavior due to the duration of UV radiation and the evolution of the crack zone are also presented based on recordings when the loading occurred. Eventually, the relationship between CTOD and crack extension of composites was presented based on the video observation.

The rest paper is divided into three sections. Section I describes the methods include the preparation of various test samples, mechanical tests, and how to analyze the behavior of CTOD based on the energy partitioned work of fracture approach. In Section II, the results and discussion are presented. At the earlier of this section, the fracture behaviors of UV-irradiated material related to the pattern of the relationship between load and displacement are presented. The COD value is described through the relationship between displacement and ligament length in crack initiation and crack development phase. This section also describes the CTOD of both crack initiation and crack propagation phase of UV-irradiated materials in different time durations. Section III explains the conclusions of this work and the future work plan.

## II. Method

### *II.1. Materials and Manufacture*

This study was carried out on the mordenite zeolite-HDPE composite. Natural mordenite zeolite rocks that have been converted into powder act as reinforcement.

Commercial HDPE pellets that act as matrices are changed in the form of powder through a mechanical process. Each powder material is sifted so that it is smaller than 90 microns and 100 microns for zeolite and HDPE, respectively. The zeolite-HDPE composite specimen in the form of a double-edge notch tension (DENT) (50×80×3 mm) was formed by injection molding technique at 160 °C barrel temperature with a holding time of 10 minutes. The notch is initially formed with mold and then sharpened with the fresh razor blade so that the ligament length varies between 9-14 mm.

DENT specimens were given heat treatment with a heating rate of 1 °C/min to reach 90 °C. The temperature is held for 4 hours and then cooled with a cooling rate of 1 °C/min until it reaches ambient temperature (27 °C). Composite specimens were exposed in UV-irradiated environments from UV lamps with constant radiation intensity of 92 µW/cm$^2$ for 50, 100, 150 and 200 hours.

The irradiation process is maintained at temperatures of 55-60 °C at atmospheric pressure with a relative humidity level of 90%.

### *II.2. Mechanical Test*

The UV-Irradiated zeolite-HDPE composites in the form of DENT were subjected a tensile load on a universal tensile machine with a constant cross-head speed of 2 mm/min based on test parameters for the essential work of fracture technique in quasi-static conditions. When the load starts to be applied until the total fracture occurs so that the specimen is divided into two different parts, the Sony Handycamp was employed to record the evolution of the ligament length zone, especially at the notch-tip region. An experimental setup of mechanical test was shown in Fig. 1.

### *II.3. Crack Tip Opening Displacement Measurement*

Based on energy partitioning work of fracture approach, the total of fracture work can be divided into two components of the work for ligament yielding (crack initiation) and tearing work (crack propagation) as express by Equation (2) [36]-[38]:

$$w_f = w_y + w_{np} \tag{1}$$

where $w_y$ is the work required for yielding and crack initiation while $w_{np}$ is the work for necking and crack propagation. Crack opening displacement was measured based on the concept of energy partitioned work of fracture in DENT testing of quasi-static conditions as proposed by Hashemi and O'Brien [39]:

$$\delta_b = \delta_0 + \delta_p \ell \tag{2}$$

where $\delta_b$ is the displacement at break, $\delta_0$ = COD, and $\delta_p$ is a plastic contribution of extension. Based on the energy partitioned work of fracture technique, Equation (2) can be divided into two different equations namely equations (3) and (4) which show displacements for yielding and crack initiation ($\delta_y$) and for crack propagation ($\delta_n$), respectively:

$$\delta_y = \delta_{0y} + \delta_{py} \ell \tag{3}$$

$$\delta_n = \delta_{0n} + \delta_{pn} \ell \tag{4}$$

where $\delta_y$ and $\delta_n$ are displacements for yielding and crack propagation, respectively, while, $\delta_{0y}$ and $\delta_{0n}$ are COD values for yielding and crack propagation, respectively.

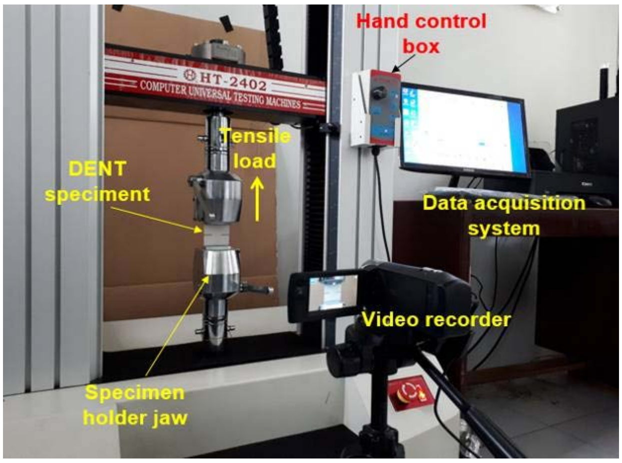



Fig. 1. Experimental setup for mechanical tests

## III. Results and Discussion

Applied load-displacement curves for 0UVR (a), 50UVR (b), 100UVR (c), 150UVR (d), and 200UVR (e) composites with a UV exposure duration of 0, 50, 100, 150, and 200 hours, respectively, are shown in Figs. 2.

The displacement for the yielding stage was started from the beginning of loading until the crack is initiated. The shape and radius of the crack tip have an effect on the crack initiation created in the smaller length scales. From the observation, the cracks were initiated at the peak of the curve (Figs. 2). The next step is the crack propagation that ends when the two crack tip meets in the middle of the ligament length. This phenomenon is shown by the sharp drop in the curve until the direction of the curve is almost horizontal (Figs. 2). The tail of curve indicates the surface layer of matrix has not to break even though end path of specimens has broken.

The relationship between displacement and ligament length at the crack initiation and propagation stage is shown in Figs. 3. Displacement, as shown in Figs. 2 and 3, determined since loading starts until cracks are initiated at the tip of the notch marked by changes in direction at the top of the curve (crack initiation stage) until the cracks meet in the middle of the ligament length (crack propagation stage). The small COD value in the crack propagation stage is confirmed by the profile curve δ-ℓ as shown in Figs. 3.

It is clearly shown that cracks propagate very quickly by small displacements. Increasing the duration of UV radiation shortens the displacement, which means the crack propagation speed increases. This phenomenon indicates that after the crack has been initiated, the crack propagation only requires a small enough energy to overcome the crack resistance of the material. This phenomenon is similar to previous work [40]-[42]. The CTOD value as shown in Fig. 4 is obtained based on the relationship of displacement and ligament length as shown in Figs. 3. It is clearly shown in Fig. 4 that the COD value of crack initiation decreases with increasing duration of UV-irradiation. However, an interesting phenomenon was observed in COD on crack propagation on 100UVR, 150UVR, and 200UVR irradiated-specimens.

Their COD value shows a constant even tends to increase even though the value remains below the 0UVR and 50UVR composites. This phenomenon is thought to be the effect of heating 60 $^{o}$C during the UV radiation process.

The relationship between CTOD and displacement in various irradiated composites is shown in Figs. 5. In general, CTOD at the crack initiation stage increases at a displacement value greater than 0.5 mm (Fig. 5(a)). The 0UVR composite has the greatest CTOD value when the crack at the notch tip is initiated. Increasing the duration of UV radiation in the composite causes a decrease in the CTOD value at notch-tip. The CTOD value at the crack propagation stage as shown in Fig. 5(b) shows that the 0UVR composite has the longest range of displacements and CTOD values.

The value-range decreases further with increasing composite duration exposed to UV light. This phenomenon indicates that an increase in the duration of UV radiation causes (i) an increase in notch-tip sensitivity to initiate cracks by changes in CTOD values, and (ii) an increase in crack propagation acceleration.

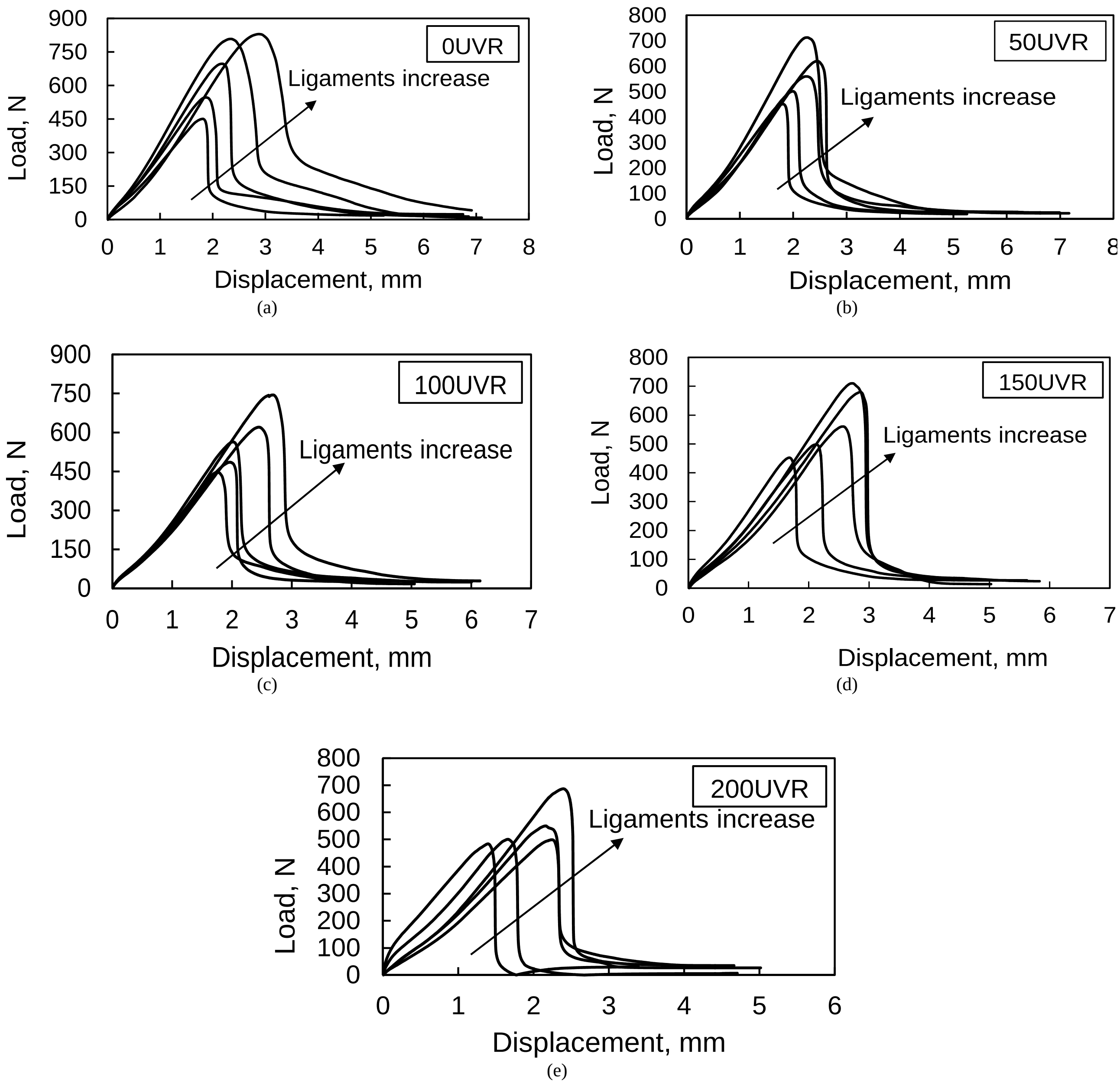
In case of the small value of COD and deformation at the notch-tip of the DENT, it can be elucidated by using saturation expression and power law [43]-[45] at a constant temperatures. Load ($F$) is a displacement function ($\delta$) and can be expressed in mathematical form as follows:

$$F = (1-D)\left\{F_f\left[1-\exp(-\psi\delta)\right]+K\delta\right\} \tag{5}$$

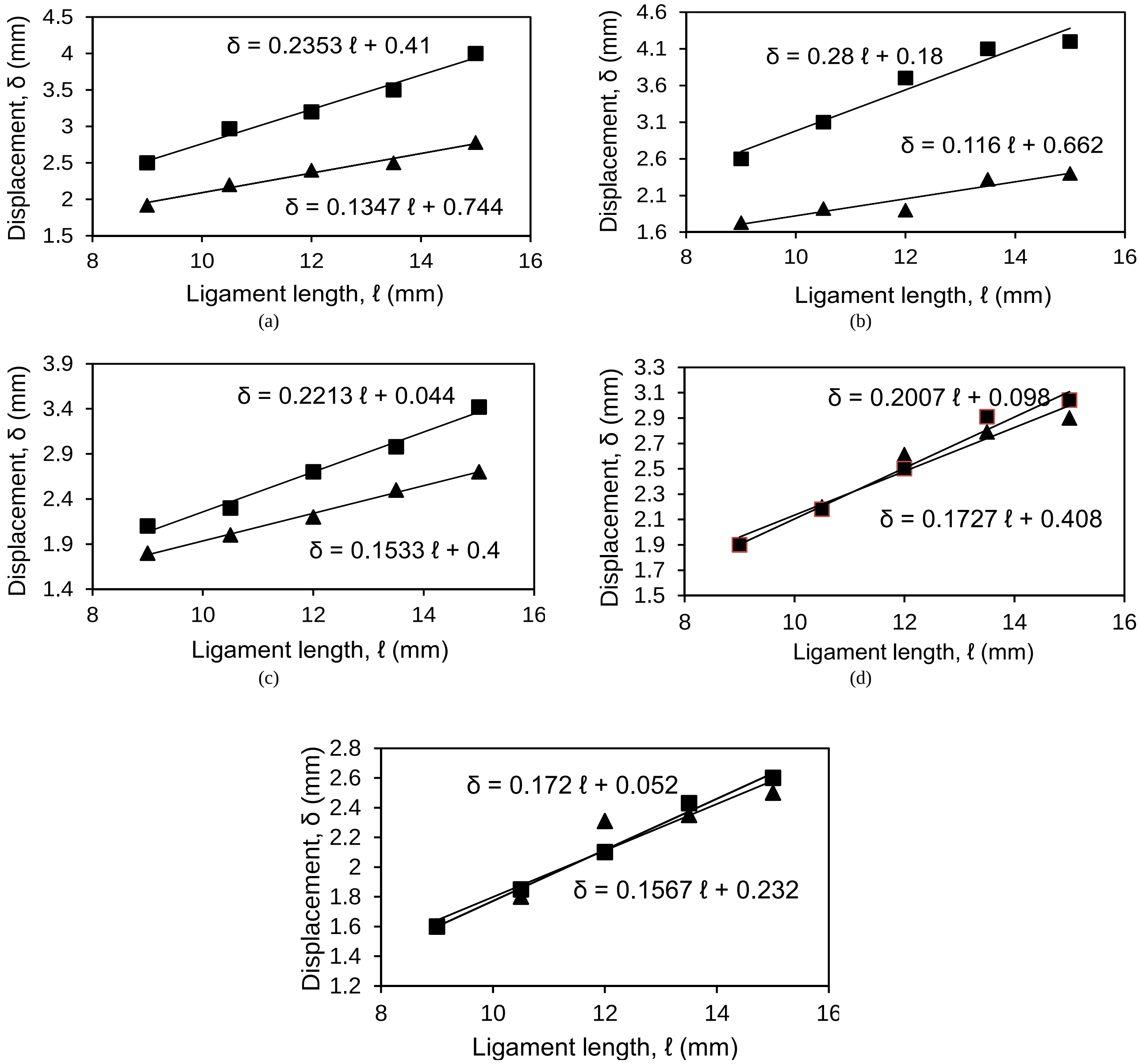
where $F_f$, $K$, and $\psi$, are the flow of stress, the strength coefficient, and the positive material constant. The $D$ parameter in (5) is the scalar damage variable expressed in the formula below [27]:

$$D = \frac{2(a+\Delta a)}{w} \tag{6}$$

where the value of $D$ ranges from initial damage ($D_i$) value and 1. The parameter $a$ is the initial crack length, and $\Delta a$ is the crack extension. Parameters $D_i$ are evaluated on unloading conditions in relation to parameters $a$ and $w$, $D_i$=2$a$/$w$ [43], [44], [27]. The evolution of cracks in the end area of the notch during loading of the quasi static condition is shown in Fig. 6.




Figs. 2. The curve of load against displacement for 0UVR (a), 50UVR (b), 100UVR (c), 150UVR (d), and 200UVR (e) composites with a UV exposure duration of 0, 50, 100, 150, and 200 hours, respectively




Figs. 3. The $\delta$ vs. $\ell$ curve for irradiated zeolite-HDPE with time duration of UV exposure of 0 hours (a), 50 hours (b), 100 hours (c), 150 hours (d) and 200 hours (e); ▲ shows the value of the yielding or crack initiation, while ■ shows the value of crack propagation

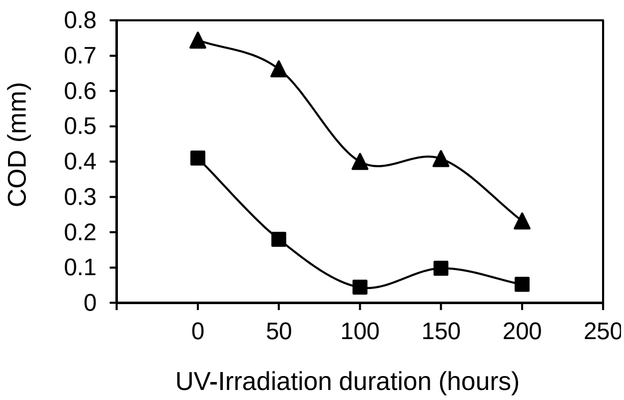
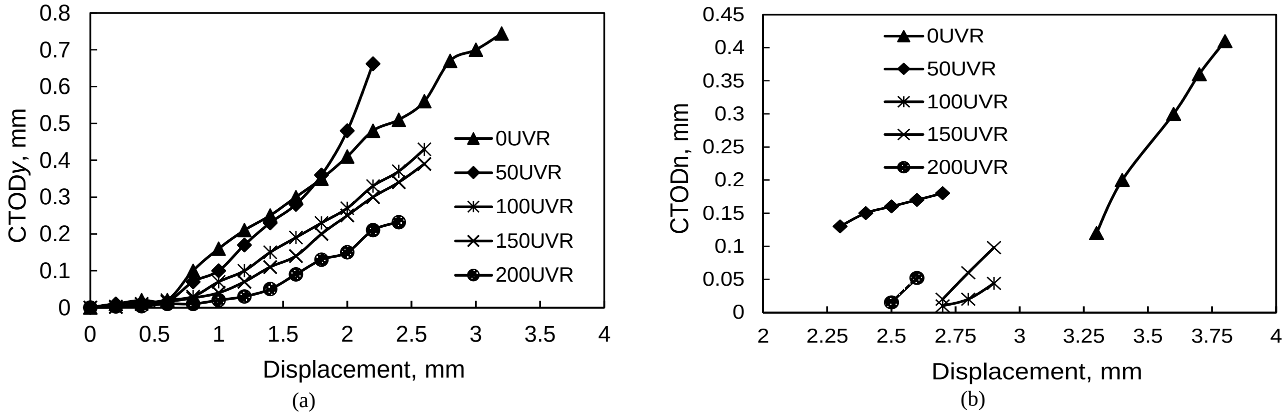



Fig. 4. COD curve at various durations of UV-Irradiation. ▲ shows COD at the crack initiation, while ■ shows COD at the crack propagation stage




Figs. 5. Crack tip opening displacement against displacement at the crack initiation (a) and crack propagation stage (b)

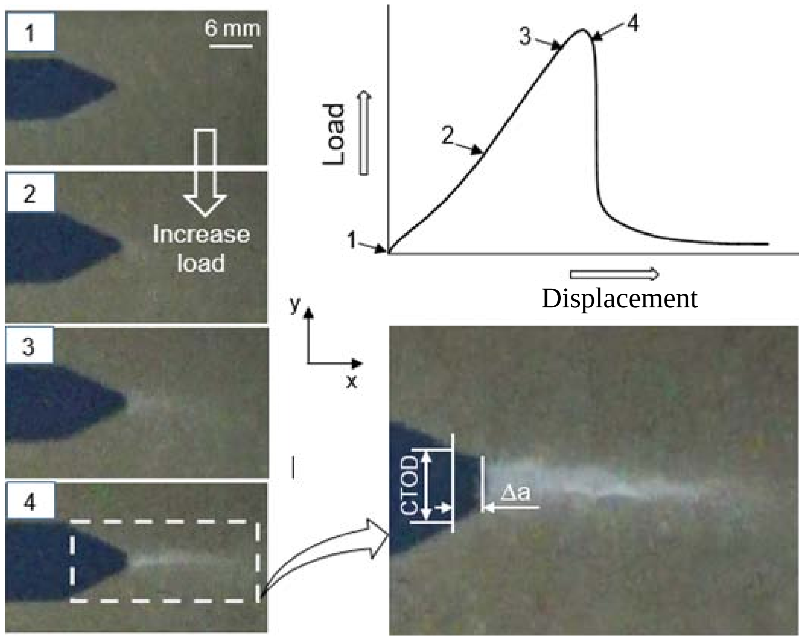
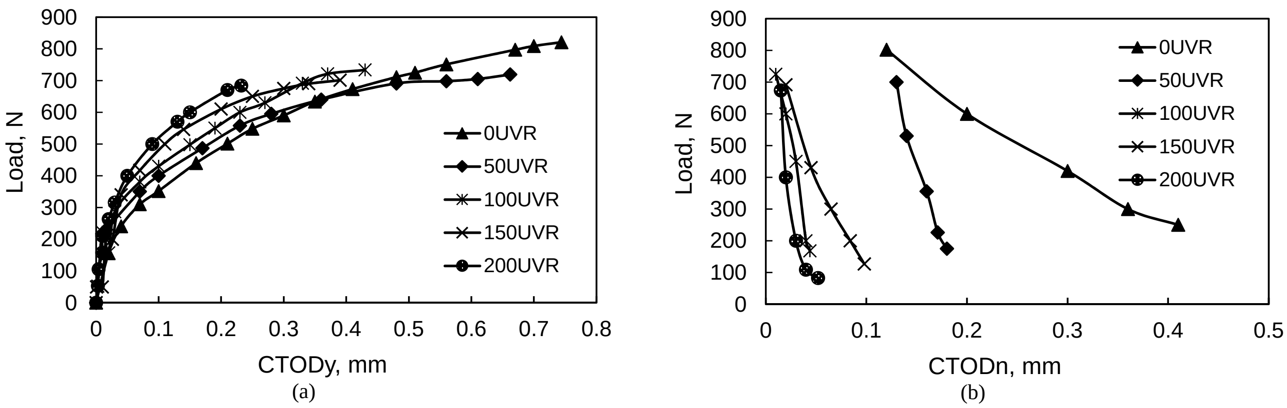
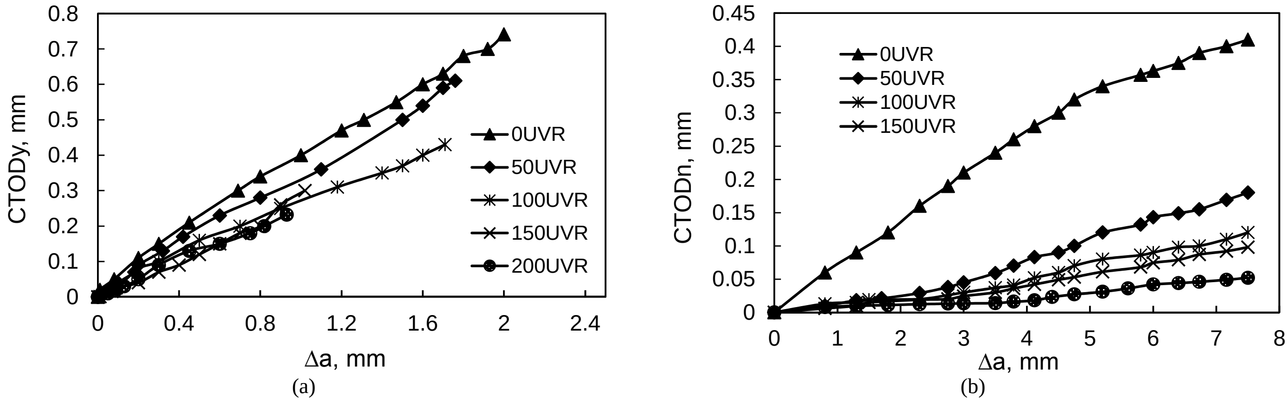



Fig. 6. Evolution of crack zone during loading condition




Figs. 7. Load - CTOD curve ($\ell$ = 15 mm) for various duration of UV exposure




Figs. 8. CTOD - Δ*a* curve of composites for various duration of UV exposure

It is clearly seen that the crack extension (Δ*a*) increases by increasing displacement. Therefore, it can be determined by the approach [27], [46]:

$$\Delta a = q\left(\frac{\delta}{a}\right)^{R} \quad (7)$$

where *q* and *R* are positive parameters. In tests, all specimens underwent the same evolution of cracks at notch-tip. Fig. 6 shows the evolution of the crack zone near the notch tip in the 200UVR specimen. It was clearly seen that the tip of the notch getting blunted by increasing the load. The crack extension is close to zero (Δ*a*=0) until the load increases around 2 (Load-displacement curve in Fig. 6). However, Δ*a* > 0 when the load increases near the peak of the curve (points 3 and 4 at Fig. 6). The relationship of the applied load to CTOD in various UV exposure is shown in Figs. 7 ($\ell$ = 15 mm). In the same load, the CTOD value in the yielding stage is smaller by increasing the UV exposure duration (Fig. 7(a)). The load in the 0UVR composite shows a delay to increase (Figs. 7) even though it has the largest displacement (Figs. 5) so that it has the largest CTOD range. The CTOD for crack initiation in 0UVR composites is greatest compared to others. In other words, the duration increases of UV irradiation reduces CTOD values. In the crack propagation stage, load and CTOD decrease sharply after the crack was initiated (Fig. 7(b)). The shortcoming in the post-peak load reaction is correlated with the fast crack propagation for slight increases in CTOD [47]. All composites tested, the CTOD related load changes in different ligament length showed similarity in behavior as shown in Figs. 7. The load - Δ*a* curve in the yielding stage in the different specimens tested is shown in Fig. 8(a) while the crack propagation state is shown in Fig. 8(b). It is clearly shown that the CTOD value increases with increasing Δ*a*. In addition, the load - Δ*a* curve is almost linear. This phenomenon is similar to previous studies [29], [48] even though it was carried out on different materials and methods. Increasing the duration of UV radiation decreases the CTOD value. The high increase in value by a slight increase in CTOD (Fig. 8(b)) indicates that cracks propagate rapidly by a slight increase in crack opening displacement. In other word, there is a common tendency that higher propagation rates are related to high CTOD values. Mode I (crack opening) tests enforce critical cleavage stresses on bonded joints near the notch-tip as an attractive phenomenon in order to restrict the fracture propagation rate due to the load increase monotonically caused crack propagation initiates [49]-[51].

## IV. Conclusion

The aim of this work was to evaluate the CTOD of UV-irradiated zeolite-HDPE composites. The CTOD behavior based on the energy partitioned work of fracture has been well described in relation to displacements, crack extension, and the evolution of cracks at the notch tip region. Commonly, the CTOD value decreases by increasing the UV-radiation duration of the composite.

The CTOD value and load (when the crack initiation occurs) is reduced by the increase in the duration of UV radiation. In situ video instrument monitoring for the time of the test confirmed that the failure of the specimens happened subsequent to ligament yielding.

The ligament underwent full yielding at the maximum load prior to crack propagation. The composites were also studied in load-displacement behavior base on tensile load by universal tensile machine. The load-displacement curves can be used to evaluate the suitability of using the essential work of fracture approach. Future work is planned to investigate the effect of coupling agent (e.g. the use of HDPE modified).

Moreover, it is also planned to use natural fibers like silk fiber as a reinforcement of modified zeolite-HDPE composite to manufacture a material with defined fiber orientation to verify our idea on a larger scale.

## Acknowledgements

The authors acknowledge to the Ministry of Research, Technology and Higher Education of the Republic of Indonesia for financial support in this work.

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