CWRU DSCI351-351M-451: EDA of PET Degradation

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Contents

4.1.2.1 Degradation of Polyester Films

- This is a Materials Data Science Study
- A Journal Article by Gok
- Is located in 3-readings folder of your class repo
  – "Gok et al. - 2017 - Predictive models of poly(ethylene-terephthalate).pdf"
- And the data set is summarized in 2-class/data
  – "PetDegr-DataFrameColumnDefinitions.pdf"

4.1.2.2 Study Design and Protocol

4.1.2.2.1 Samples

Three PET grades used in this study are

- Unstabilized PET: Melinex 454 (3 mil)
- UV stabilized PET: Tetoron HB3 (2 mil)
- Hyrolytically stabilized PET: Mitsubishi 8HL1 (5 mil)

4.1.2.2.2 Exposures

Four different acceleated weathering exposures were applied:

Exposure	Condition
Continuous UVA	Constant exposure of 1.55 W/m^2 at 340nm at 70°C
ASTM G154-4 and 4 hours of condensing humidity at 50°C in the dark	Cyclic exposure of 8 hours of UVA light at 1.55 W/m^2 at 340nm at 70°C
Damp Heat	Constant exposure 85°C / 85% RH exposure per IEC 61215
Humidity Freeze	Cyclic exposure of 70°C / 85% RH and -40°C per IEC 61215

4.1.2.2.3 Evaluations

Three evaluation techniques are:

- $L^*a^*b^*$ color, Yellowness index (YI) and Haze (%) measurements using Hunterlabs UltrascanPro
- Optical absorbance measurements (abs) using Cary 6000i with DRA
- IR spectra measurements using Agilent 630 FTIR with Diamond ATR

4.1.2.3 Raw Data

An example of raw spectra that comes right out of the instrument

- Note the saturation of Absorbance for wavelengths below 300 nm

4.1.2.3.1 Raw Data

An example of raw spectra that comes right out of the instrument

- Note the saturation of Absorbance for wavelengths below 300 nm

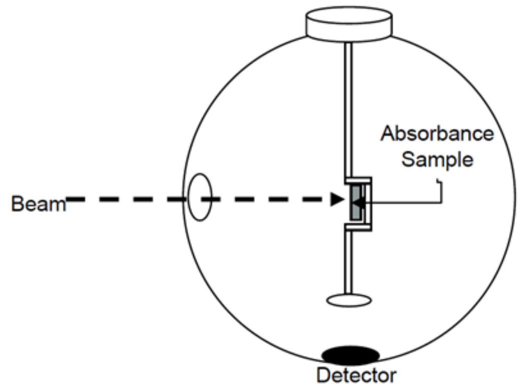


Figure 1: Figure

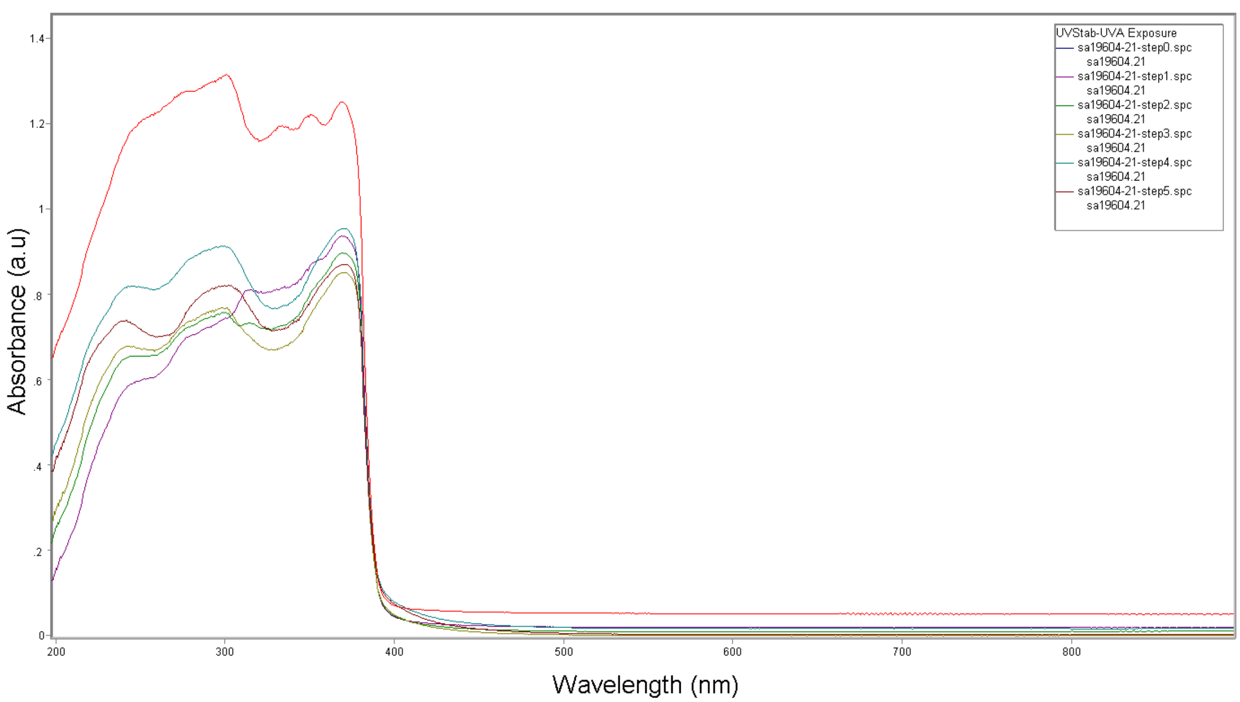


Figure 2: Figure. Note that the absorbance saturates for wavlengths < approx. 400 nm

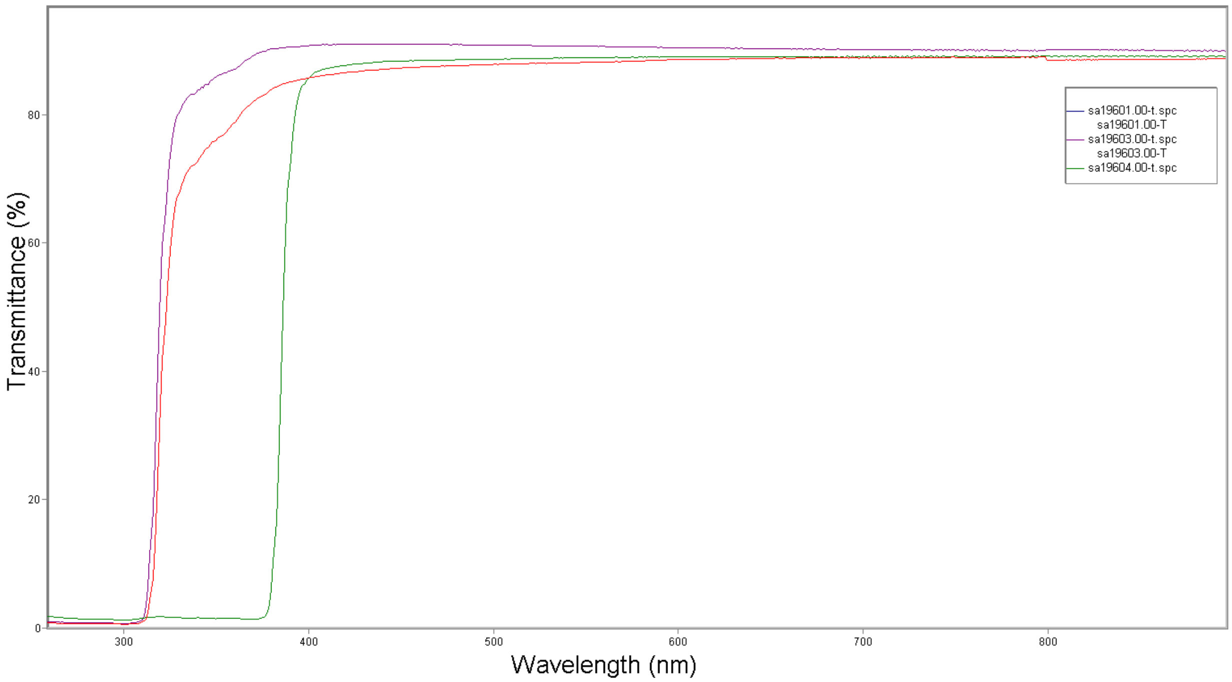


Figure 3: Figure

4.1.2.3.2 Raw Data

An example of raw spectra that comes right out of the instrument

- Note the saturation of Absorbance for wavelengths below 300 nm

4.1.2.4 Processing Data

- Absorbance is first normalized to thickness (abs/cm)
  - Then zero correction is applied between 600 and 800 nm
- Average Induced absorbance to dose is calculated from corrected **abs/cm**
  - Negative IAD is photobleaching
  - Positive IAD is photodarkening

$\frac{Abs}{cm} per \frac{GJ}{m^2} = aIAD = \frac{Abs_i(\lambda) - Abs_0(\lambda))}{Dose_i - Dose_0}$

4.1.2.4.1 Point-in-Time Data

Single values are extracted from spectra

- YI and Haze are already obtained directly from instruments

Single abs/cm values are extracted from spectra at specific wavelengths

- Fundamental absorption edge at ~300 nm

- Features associated with UV stabilizer at 335 nm, 350 nm, and 370 nm

- Optical density at 400 nm related to yellowing
- Single aveIAD values are also extracted at the same wavelengths

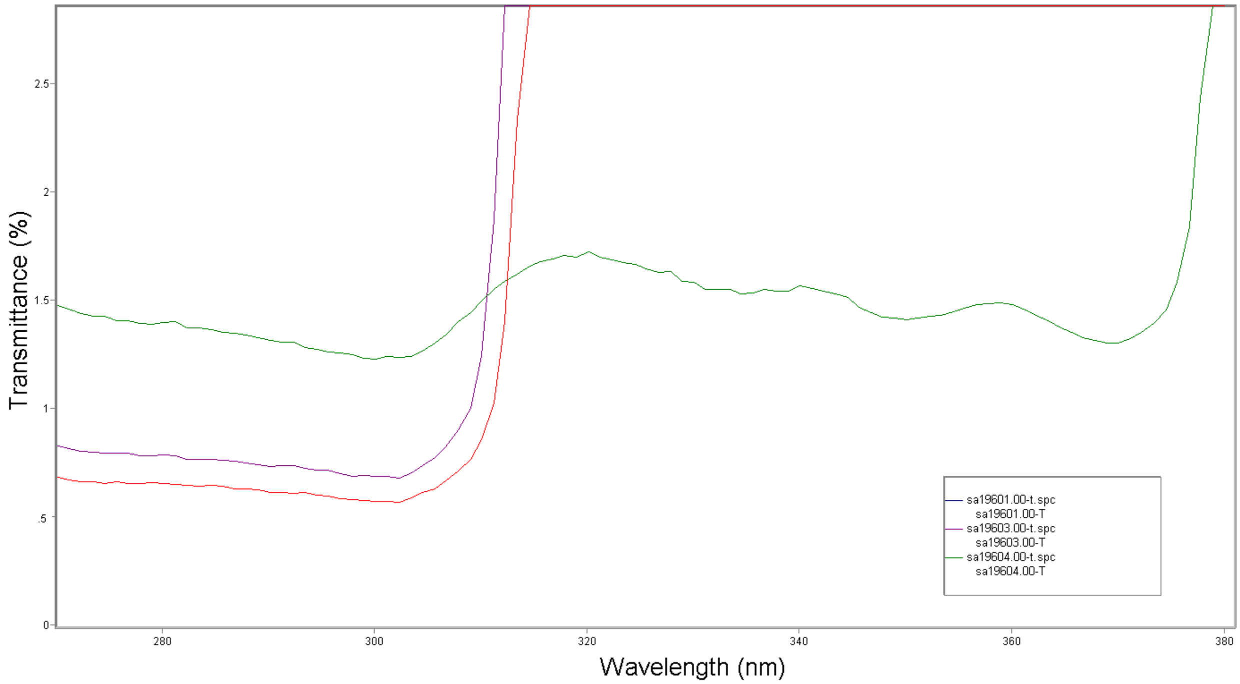


Figure 4: Figure

4.1.2.4.2 Point in Time Data

Single values are extracted from spectra

- Zero absorbance correction applied for FTIR between 4000-3500 cm^{-1} to remove offset
  - Single IR peak heights are extracted at specific wavenumbers
    - 714 cm^{-1} and 1017 cm^{-1} for out of plane and in plane vibration of benzene
    - 872 cm^{-1} and 1341 cm^{-1} for CH_2 rocking and wagging of glycol
    - 1093 cm^{-1}, 1251 cm^{-1}, and 1716 cm^{-1} for ester C=O stretching
  - Due to shifts in peak position, maximum data point is pulled as the single data point in some range for the corresponding peaks
    - i.e., for the 1716 cm^{-1} data point, the maximum between 1700 cm^{-1} and 1730 cm^{-1} is extracted.

4.1.2.5 Data Structure Build the data frame for analysis

All data put together in one data frame

- Samples entered as rows and variables as columns:
  - Sample and exposure information (type, time and step size, irradiation and dose content, etc.)
  - Cyclic exposure conditions (rate of change from one state to another) for further modelling purposes
  - Spectral information, point in time, extracted from spectra
  - Spectra from UV-Vis (abs/cm) and IR also included.

4.1.2.5.1 Data Structure

Introducing data frame:

```
dat <- read.csv("../2-class/data/PetDegr-DataFrame-v05-singles.csv")
names(dat)
```

```
##  [1] "Rowkey"   "Sample"   "Material" "Thick"    "Exposure" "Time"
##  [7] "Step"     "Irrad"    "Pdose"    "L"        "a"        "b"
## [13] "YI"       "Haze"     "abs300"   "abs335"   "abs345"   "abs350"
## [19] "abs370"   "abs400"   "iad300"   "iad335"   "iad345"   "iad350"
## [25] "iad370"   "iad400"   "ftir1716" "ftir1409" "ftir1341" "ftir1251"
## [31] "ftir1093" "ftir1017" "ftir872"  "ftir714"
```

4.1.2.5.2 Data Structure

```r
str(dat)
```

```
## 'data.frame':    405 obs. of  34 variables:
##  $ Rowkey  : Factor w/ 405 levels "sa19601.00-step0",..: 1 2 4 7 11 16 22 28 34 36 ...
##  $ Sample  : Factor w/ 90 levels "sa19601.00","sa19601.01",..: 1 2 3 4 5 6 7 8 9 10 ...
##  $ Material: Factor w/ 3 levels "HydStab","Unstab",..: 1 1 1 1 1 1 1 1 1 1 ...
##  $ Thick   : num  0.0125 0.0125 0.0125 0.0125 0.0125 0.0125 0.0125 0.0125 0.0125 0.0125 ...
##  $ Exposure: Factor w/ 5 levels "Baseline","CyclicQUV",..: 1 3 3 3 3 3 3 3 4 4 ...
##  $ Time    : int  0 0 0 0 0 0 0 0 0 0 ...
##  $ Step    : int  0 0 0 0 0 0 0 0 0 0 ...
##  $ Irrad   : num  NA 0 0 0 0 0 0 0 0 0 ...
##  $ Pdose   : num  NA 0 0 0 0 0 0 0 0 0 ...
##  $ L       : num  94.8 95.1 95.1 95.1 95.1 ...
##  $ a       : num  0 0 0 0 0 0.01 0.01 0.01 0.02 0 ...
##  $ b       : num  0.79 0.75 0.73 0.73 0.74 0.75 0.74 0.76 0.74 0.74 ...
##  $ YI      : num  1.5 1.42 1.39 1.38 1.4 1.44 1.42 1.44 1.42 1.4 ...
##  $ Haze    : num  3.8 0.8 1 1.4 0.9 0.9 1.2 1.3 2.4 1.8 ...
##  $ abs300  : num  NA 71.6 95.4 91.2 71.7 ...
##  $ abs335  : num  NA 4.62 5.44 5.5 4.6 ...
##  $ abs345  : num  NA 3.33 4.06 4.12 3.44 ...
##  $ abs350  : num  NA 3.1 3.76 3.74 3.09 ...
##  $ abs370  : num  NA 1.46 2.02 2.02 1.47 ...
##  $ abs400  : num  NA 0.302 0.648 0.685 0.312 ...
##  $ iad300  : num  NA NA NA NA NA NA NA NA NA NA ...
##  $ iad335  : num  NA NA NA NA NA NA NA NA NA NA ...
##  $ iad345  : num  NA NA NA NA NA NA NA NA NA NA ...
##  $ iad350  : num  NA NA NA NA NA NA NA NA NA NA ...
##  $ iad370  : num  NA NA NA NA NA NA NA NA NA NA ...
##  $ iad400  : num  NA NA NA NA NA NA NA NA NA NA ...
##  $ ftir1716: num  0.585 0.622 0.604 0.481 0.448 ...
##  $ ftir1409: num  0.186 0.189 0.188 0.164 0.156 ...
##  $ ftir1341: num  0.21 0.216 0.212 0.185 0.177 ...
##  $ ftir1251: num  0.621 0.663 0.643 0.522 0.491 ...
##  $ ftir1093: num  0.582 0.619 0.602 0.503 0.477 ...
##  $ ftir1017: num  0.391 0.408 0.399 0.353 0.342 ...
##  $ ftir872 : num  0.409 0.429 0.418 0.37 0.358 ...
##  $ ftir714 : num  0.871 0.933 0.903 0.793 0.77 ...
```

4.1.2.5.3 Data Structure

Introducing data frame:

```r
head(dat)[1:8]
```

```
##             Rowkey     Sample Material  Thick Exposure Time Step Irrad
## 1 sa19601.00-step0 sa19601.00  HydStab 0.0125 Baseline    0    0    NA
```

```
## 2 sa19601.01-step0 sa19601.01  HydStab 0.0125 DampHeat    0    0     0
## 3 sa19601.02-step0 sa19601.02  HydStab 0.0125 DampHeat    0    0     0
## 4 sa19601.03-step0 sa19601.03  HydStab 0.0125 DampHeat    0    0     0
## 5 sa19601.04-step0 sa19601.04  HydStab 0.0125 DampHeat    0    0     0
## 6 sa19601.05-step0 sa19601.05  HydStab 0.0125 DampHeat    0    0     0
```

```
tail(dat)[1:8]
```

```
##               Rowkey     Sample Material Thick   Exposure Time Step Irrad
## 400 sa19604.13-step6 sa19604.13   UVStab 0.005 FreezeThaw 1008    6  0.00
## 401 sa19604.14-step6 sa19604.14   UVStab 0.005 FreezeThaw 1008    6  0.00
## 402 sa19604.20-step6 sa19604.20   UVStab 0.005     HotQUV 1008    6  1.55
## 403 sa19604.21-step6 sa19604.21   UVStab 0.005     HotQUV 1008    6  1.55
## 404 sa19604.27-step6 sa19604.27   UVStab 0.005  CyclicQUV 1008    6  1.55
## 405 sa19604.28-step6 sa19604.28   UVStab 0.005  CyclicQUV 1008    6  1.55
```

4.1.2.6 Data Subsetting

Since we have three different materials

```
library(dplyr)
```

```
##
## Attaching package: 'dplyr'

## The following objects are masked from 'package:stats':
##
##     filter, lag

## The following objects are masked from 'package:base':
##
##     intersect, setdiff, setequal, union
```

```
unstab <- filter(dat, Material == 'Unstab')
# unstab <- dat[which(dat$Material=="Unstab"), ]

uvstab <- filter(dat, Material == 'UVStab')
# uvstab <- dat[which(dat$Material=="UVStab"), ]

hystab <- filter(dat, Material == 'HydStab')
# hystab <- dat[which(dat$Material=="HydStab"), ]
```

You can also use "subset" function to subset your data

```
unstab.dh2 <- subset(dat, Material == "Unstab" & Exposure == "DampHeat")

uvstab.hq2 <- subset(dat, Material == "UVStab" & Exposure == "HotQUV")

hystab.ft2 <- subset(dat, Material == "HydStab" & Exposure == "FreezeThaw")
```

4.1.2.6.1 Data Subsetting

Since we have four different exposures

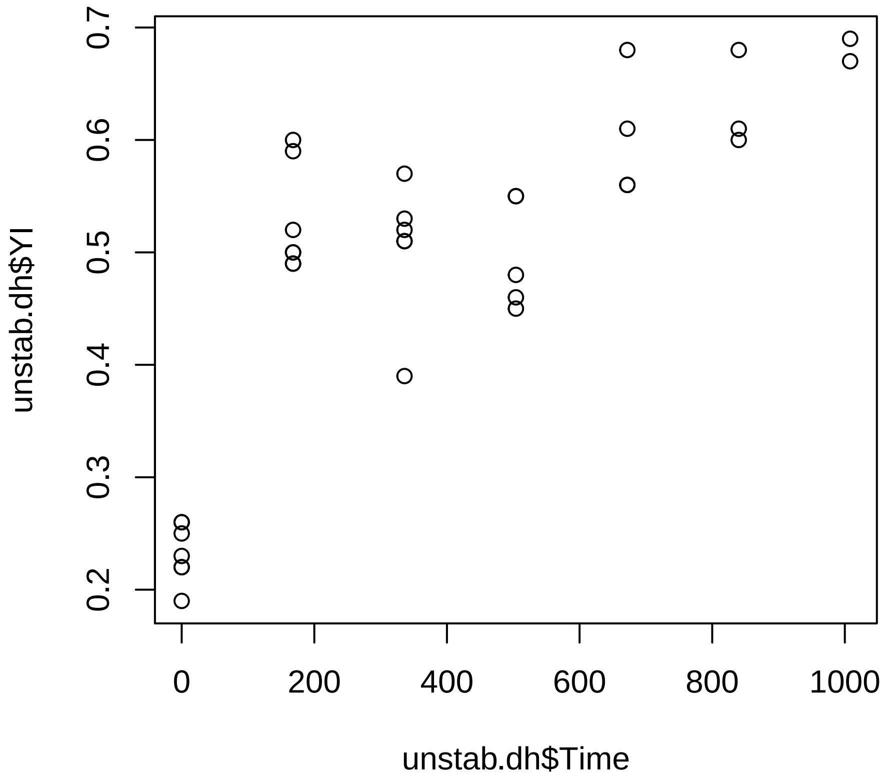
```
# Exposures for Unstabilized

unstab.dh <- filter(unstab, Exposure == "DampHeat")
unstab.ft <- filter(unstab, Exposure == "FreezeThaw")
```

```r
  unstab.hq <- filter(unstab, Exposure == "HotQUV")
  unstab.cq <- filter(unstab, Exposure == "CyclicQUV")
  # unstab.dh <- unstab[which(unstab$Exposure=="DampHeat"), ]
  # unstab.ft <- unstab[which(unstab$Exposure=="FreezeThaw"), ]
  # unstab.hq <- unstab[which(unstab$Exposure=="HotQUV"), ]
  # unstab.cq <- unstab[which(unstab$Exposure=="CyclicQUV"), ]

# Exposures for UV stabilized

  uvstab.dh <- filter(uvstab, Exposure == "DampHeat")
  uvstab.ft <- filter(uvstab, Exposure == "FreezeThaw")
  uvstab.hq <- filter(uvstab, Exposure == "HotQUV")
  uvstab.cq <- filter(uvstab, Exposure == "CyclicQUV")
  # uvstab.dh <- uvstab[which(uvstab$Exposure=="DampHeat"), ]
  # uvstab.ft <- uvstab[which(uvstab$Exposure=="FreezeThaw"), ]
  # uvstab.hq <- uvstab[which(uvstab$Exposure=="HotQUV"), ]
  # uvstab.cq <- uvstab[which(uvstab$Exposure=="CyclicQUV"), ]

# Exposures for UV stabilized

  hystab.dh <- filter(hystab, Exposure == "DampHeat")
  hystab.ft <- filter(hystab, Exposure == "FreezeThaw")
  hystab.hq <- filter(hystab, Exposure == "HotQUV")
  hystab.cq <- filter(hystab, Exposure == "CyclicQUV")
  # hystab.dh <- hystab[which(hystab$Exposure=="DampHeat"), ]
  # hystab.ft <- hystab[which(hystab$Exposure=="FreezeThaw"), ]
  # hystab.hq <- hystab[which(hystab$Exposure=="HotQUV"), ]
  # hystab.cq <- hystab[which(hystab$Exposure=="CyclicQUV"), ]
```

4.1.2.7 Simple Plotting with base graphics, "Plot", Function

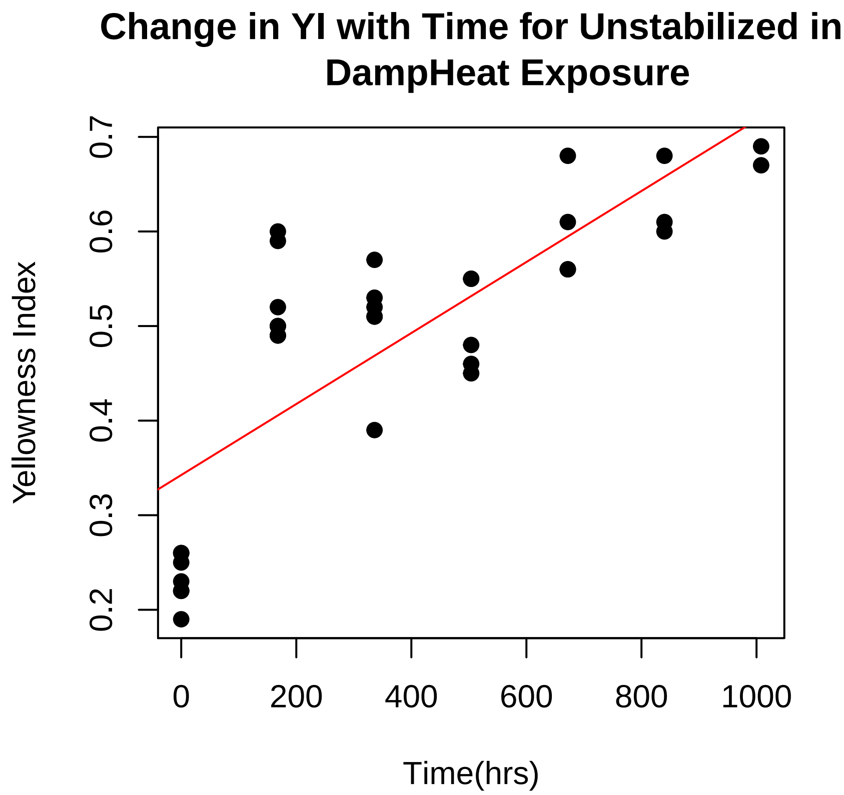
Let's plot YI as a function of Time for Unstabilized in DampHeat exposure

```r
  plot(unstab.dh$Time, unstab.dh$YI)
```



4.1.2.7.1 Simple Plotting with "Plot" Function

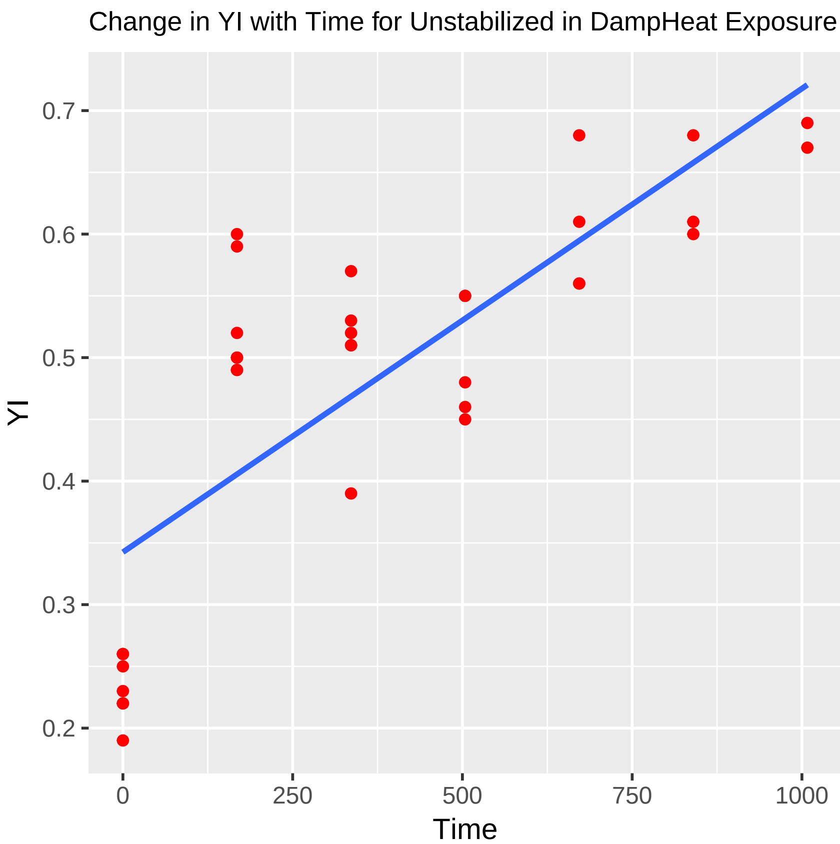
```
plot(unstab.dh$Time, unstab.dh$YI, main = "Change in YI with Time for Unstabilized in
     DampHeat Exposure", xlab = "Time(hrs)", ylab = "Yellowness Index", pch = 19)
abline(lm(unstab.dh$YI~unstab.dh$Time), col = "red")          # Regression line (YI~Time)
```



An example of plotting from the main dataframe.

- This is a cleaner way of organizing and plotting data
- as it does not depends on a large number of environmental dataframes.

```
library(ggplot2)

dat %>%
  filter(Material == "Unstab" & Exposure == "DampHeat") %>%
  ggplot(aes(x = Time, y = YI)) +
  geom_point(color = 'red', pch = 19) +
  geom_smooth(method = 'lm', se = FALSE) +
  labs(xlab = "Time(hrs)", ylab = "Yellowness Index", title = "Change in YI with Time for Unstabilize
  theme(plot.title = element_text(size = 10))
```

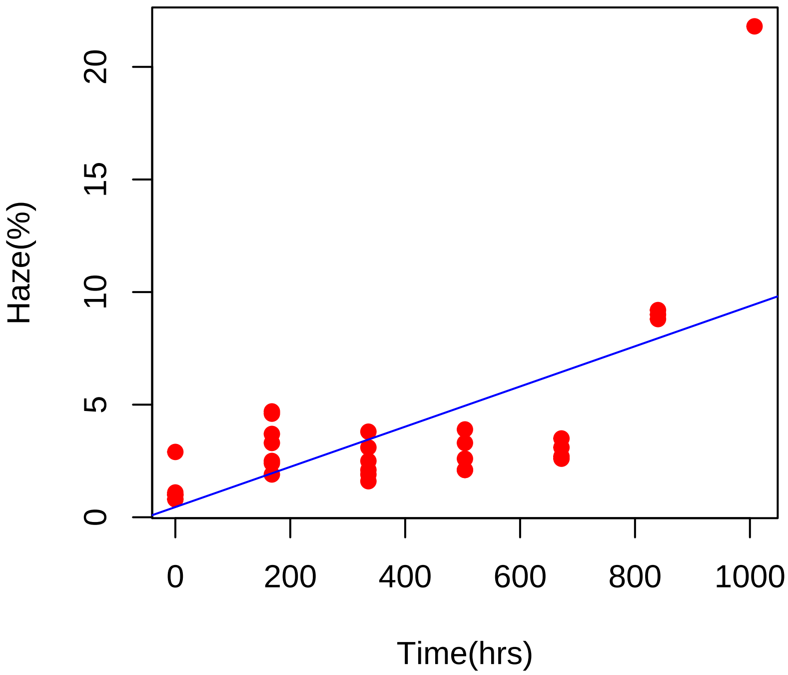


4.1.2.7.2 Simple Plotting with "Plot" Function

Another example: Plot of haze as a function of Time for Hydstab in CyclicQUV

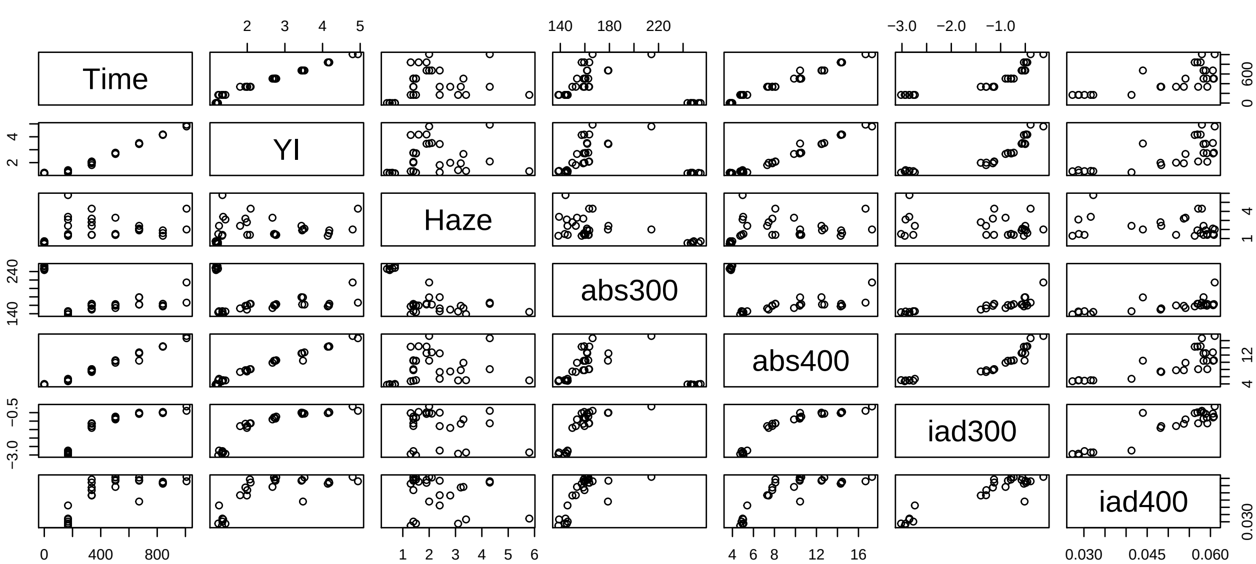
```
plot(hystab.cq$Time, hystab.cq$Haze, main = "Change in Haze with Time for Hyd. stabilized in CyclicQU

abline(lm(hystab.cq$Haze~hystab.cq$Time), col = "blue")         # Regression line (YI~Time)
```

in Haze with Time for Hyd. stabilized in CyclicQL



4.1.2.8 Pairwise plots

```
pairs(~Time+YI+Haze+abs300+abs400+iad300+iad400,
      data = uvstab.hq, main = "Pairwise plot for UVstabilized in HotQUV Exposure")
```



4.1.2.8.1 Pairwise plots

```
ggpairwise <- ggpairs(uvstab.hq[,c(6,13,14,15,20,21,26)], title = "Pairwise plot with correlation coe
```

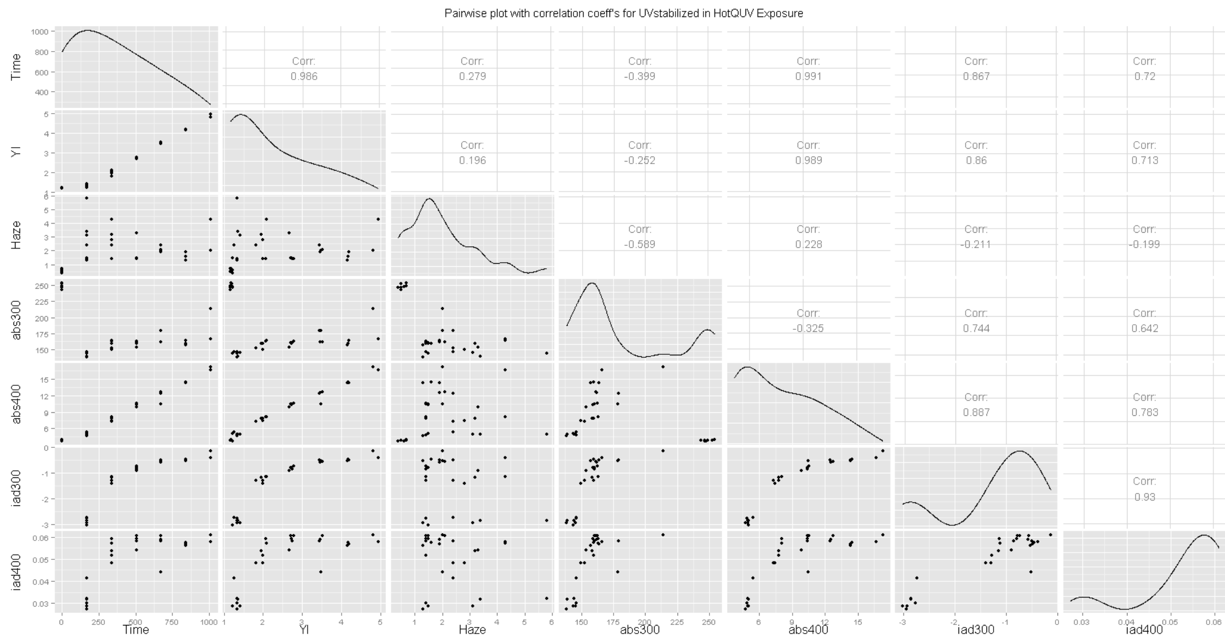


Figure 5: Figure

4.1.2.9 Plotting with "ggplot" function for advanced plots

```
library(ggplot2)
??ggplot2

# if (!require("bear")) install.packages("bear");
# library(bear)   # bear package no longer exists
# ??bear

# if (!require("plotrix")) install.packages("plotrix");
# library(plotrix)
# ??plotrix


# SummarySE function for standard error
# have to rework this to get the standard error with either plotrix of
# unstab.yi <- std.error(unstab::YI, measurevar="YI", groupvars=c("Time", "Exposure"))
# unstab.haze <- std.error(unstab, measurevar="Haze", groupvars=c("Time", "Exposure"))

# ggplot of unstabilized-YI

# eda <- ggplot(unstab.yi, aes(x=Time, y=YI, group=Exposure, colour=Exposure)) +
#   geom_errorbar(aes(ymin=YI-se, ymax=YI+se),
#                 colour="black", size=1, width=5) +
#   geom_line(size=1) +
#   geom_point(size=3, shape=21, fill="black") +
#   theme_bw() +
#   #geom_text(aes(label=N, hjust=1, vjust=2)) +
#   #scale_y_continuous(limits=c(0, 10)) +
#   ggtitle(paste("Change in Yellowness Index (YI) with Time")) +
#   xlab("Time (hrs)") +
```

```
#   ylab("Yellowness Index") +
#   theme(legend.position = c(0.25,0.80), legend.title = element_blank(),
#         legend.text = element_text(size=13, face="bold"),
#         legend.key = element_blank(), axis.text=element_text(size=13,face="bold"),
#         axis.title=element_text(size=13,face="bold"),
#         plot.title=element_text(size=13,face="bold"))
```

4.1.2.9.1 Plotting with "ggplot" function for advanced plots

```
# print(eda)
```

4.1.2.10 Standard deviation, standard error, and 95% confidence interval

Subsetting data for baseline measurements for each material type

```
# Subset data for time zero

  unstab.0 <- filter(dat, Material == "Unstab" & Time == "0")
  uvstab.0 <- filter(dat, Material == "UVStab" & Time == "0")
  hystab.0 <- filter(dat, Material == "HydStab" & Time == "0")

# unstab.0 <- subset(dat, Material=="Unstab" & Time=="0")
# uvstab.0 <- subset(dat, Material=="UVStab" & Time=="0")
# hystab.0 <- subset(dat, Material=="HydStab" & Time=="0")
```

Just as an example

```
  head(unstab.0)[1:8]
```

```
##              Rowkey      Sample Material  Thick Exposure Time Step Irrad
## 1 sa19603.00-step0 sa19603.00   Unstab 0.0075 Baseline    0    0    NA
## 2 sa19603.01-step0 sa19603.01   Unstab 0.0075 DampHeat    0    0     0
## 3 sa19603.02-step0 sa19603.02   Unstab 0.0075 DampHeat    0    0     0
## 4 sa19603.03-step0 sa19603.03   Unstab 0.0075 DampHeat    0    0     0
## 5 sa19603.04-step0 sa19603.04   Unstab 0.0075 DampHeat    0    0     0
## 6 sa19603.05-step0 sa19603.05   Unstab 0.0075 DampHeat    0    0     0
```

4.1.2.10.1 Standard deviation, standard error, and 95% confidence interval

For yellowness index measurement for each material

```
# For YI at Time=0 for unstabilized
# unstab.yi.unc <- summarySE(unstab.0, measurevar="YI", groupvars="Time")
# print(unstab.yi.unc)

# For YI at Time=0 for UVstabilized
# uvstab.yi.unc <- summarySE(uvstab.0, measurevar="YI", groupvars="Time")
# print(uvstab.yi.unc)

# For YI at Time=0 for Hyd.stabilized
# hystab.yi.unc <- summarySE(hystab.0, measurevar="YI", groupvars="Time")
# print(hystab.yi.unc)
```

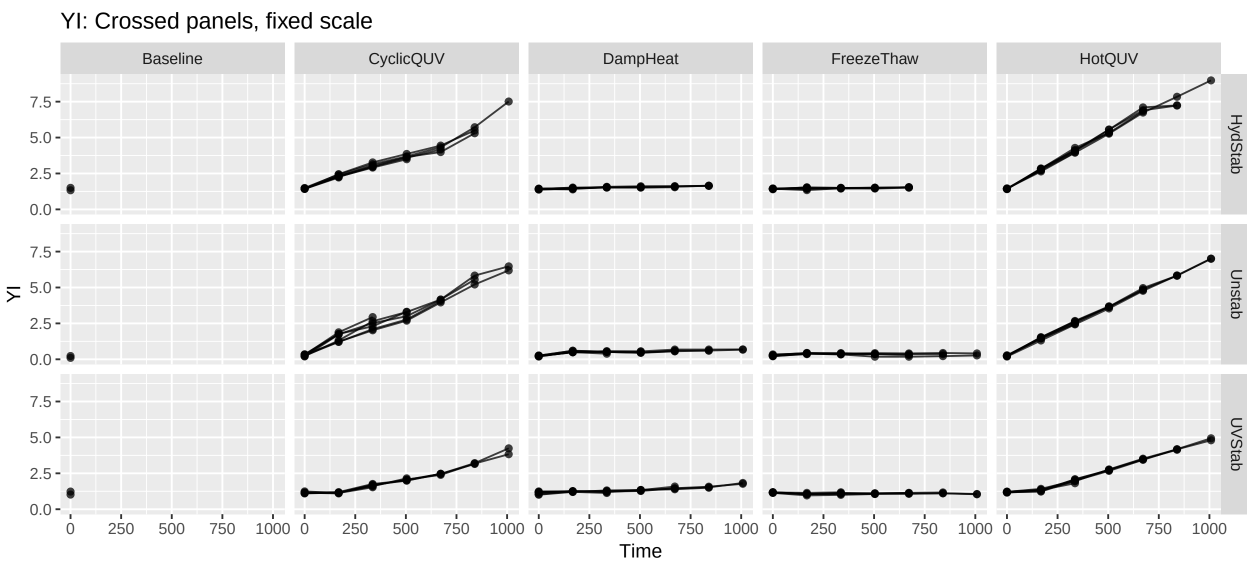
4.1.2.10.2 Standard deviation, standard error, and 95% confidence interval

For haze measurement for each material

```
# For Haze at Time=0 for unstabilized
# unstab.haze.unc <- summarySE(unstab.0, measurevar="Haze", groupvars="Time")
# print(unstab.haze.unc)

# For Haze at Time=0 for UVstabilized
# uvstab.haze.unc <- summarySE(uvstab.0, measurevar="Haze", groupvars="Time")
# print(uvstab.haze.unc)

# For Haze at Time=0 for Hyd.stabilized
# hystab.haze.unc <- summarySE(hystab.0, measurevar="Haze", groupvars="Time")
# print(hystab.haze.unc)
```

4.1.2.11 Exploratory Data Analysis

```
ggplot(dat, aes(x = Time, y = YI, group = Sample)) + geom_point(alpha = 0.75) +
geom_line(alpha = 0.75) + facet_grid(Material ~ Exposure) + ggtitle("YI: Crossed panels, fixed scale")
```



4.1.2.11.1 Exploratory Data Analysis

```
ggplot(dat, aes(x = Time, y = Haze, group = Sample)) + geom_point(alpha = 0.75, na.rm = FALSE) +
geom_line(alpha = 0.75) + facet_grid(Material ~ Exposure) + ggtitle("Haze: Crossed panels, fixed scal
```

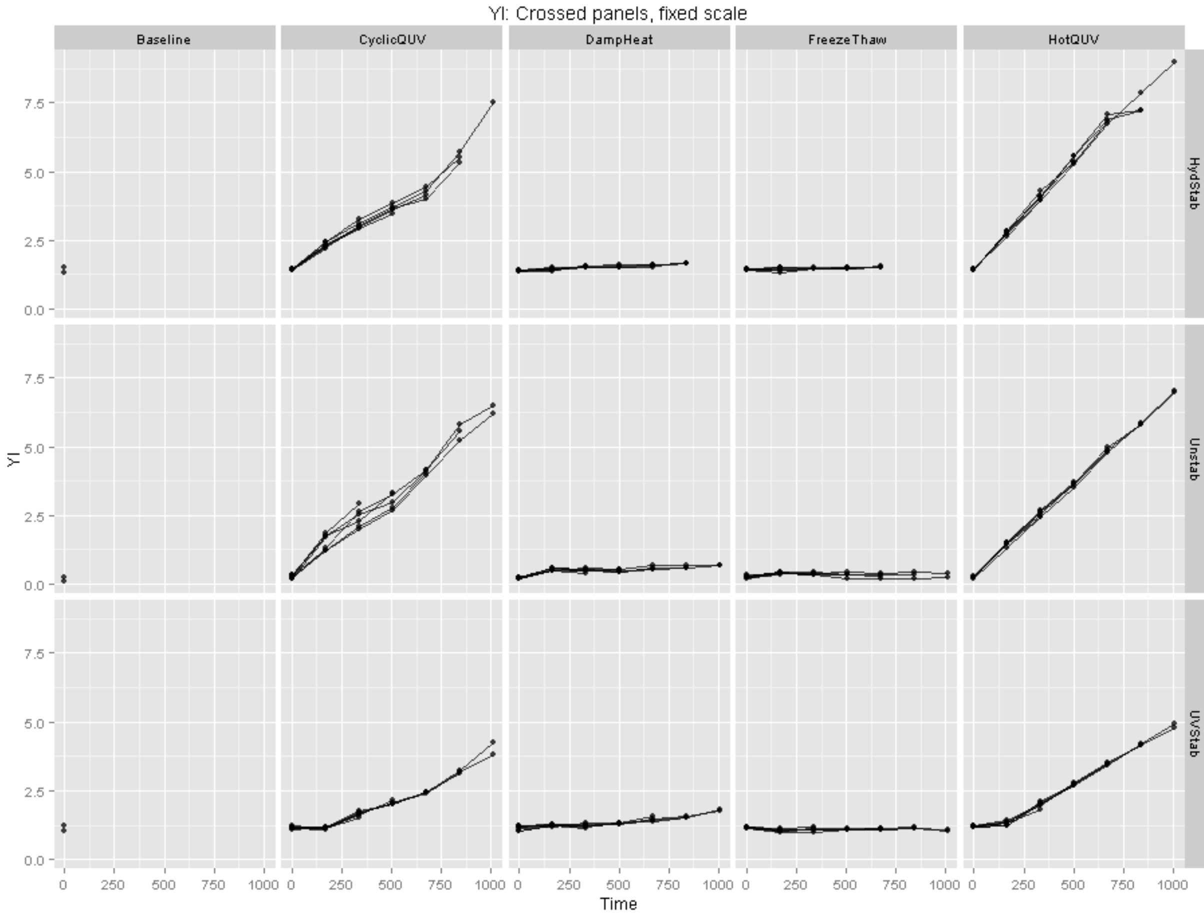
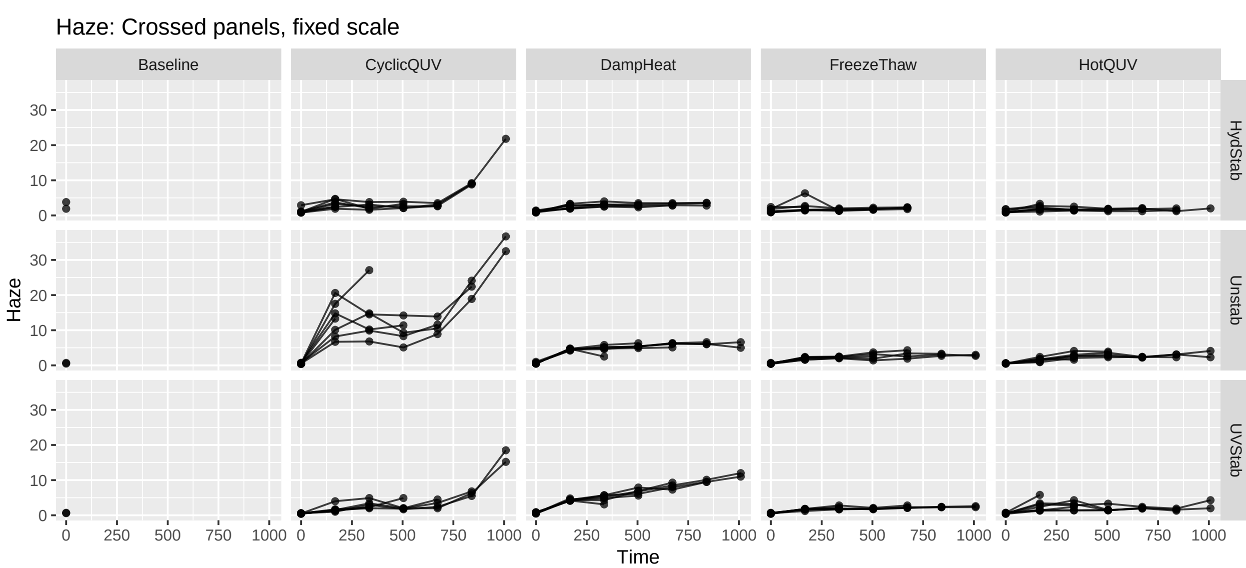


Figure 6: Figure



4.1.2.12 Exploratory Data Analysis

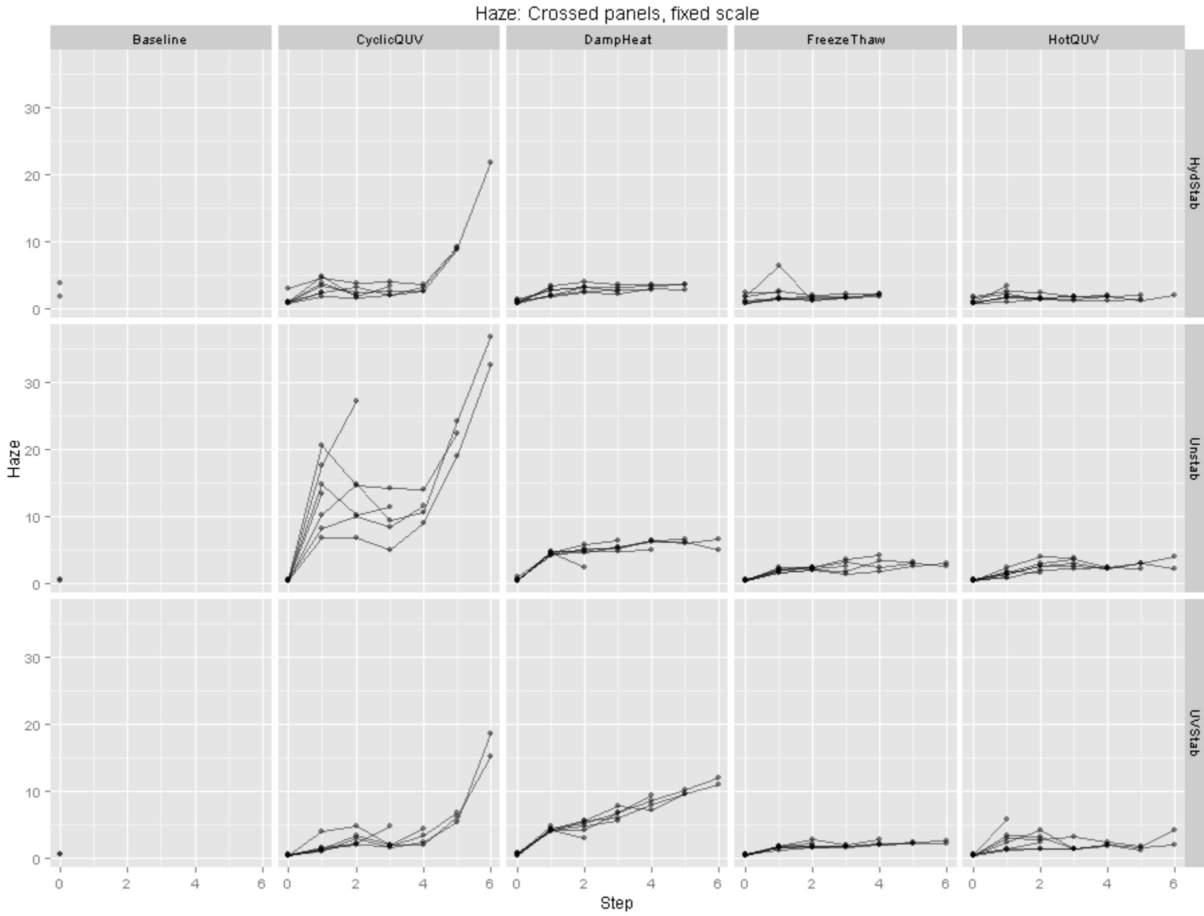


Figure 7: Figure

4.1.2.13 Exploratory Data Analysis

4.1.2.14 Comments

Very useful to

- identify outliers
- Look for trends and change points
- compare different materials and exposures
- Observe sample and measurement variability

4.1.2.15 Exploratory Data Analysis

Absorbance at 300 nm and 400 nm for Unstabilized PET

4.1.2.15.1 Exploratory Data Analysis

IAD at 300 nm and 400 nm for Unstabilized PET

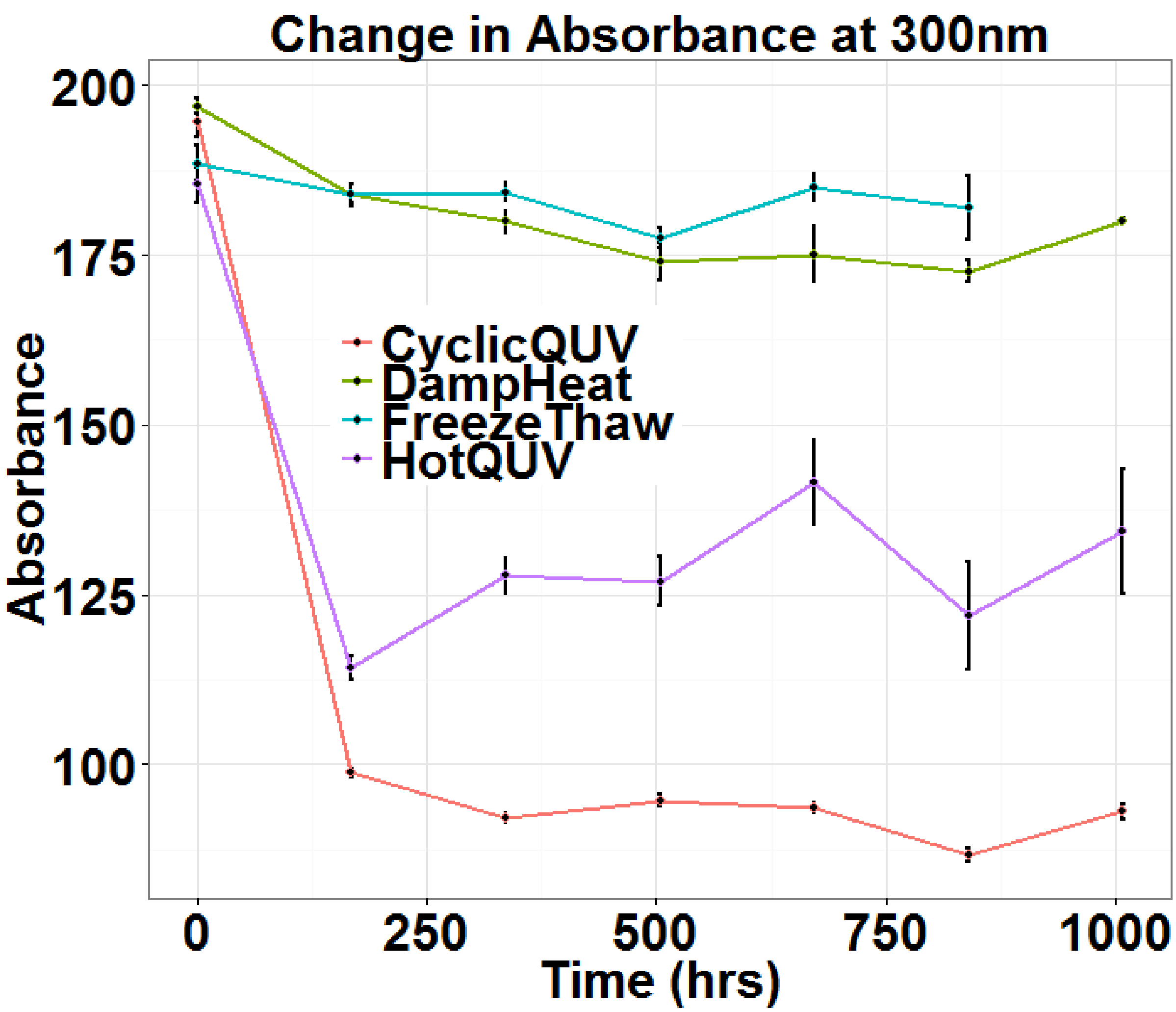


Figure 8: Figure

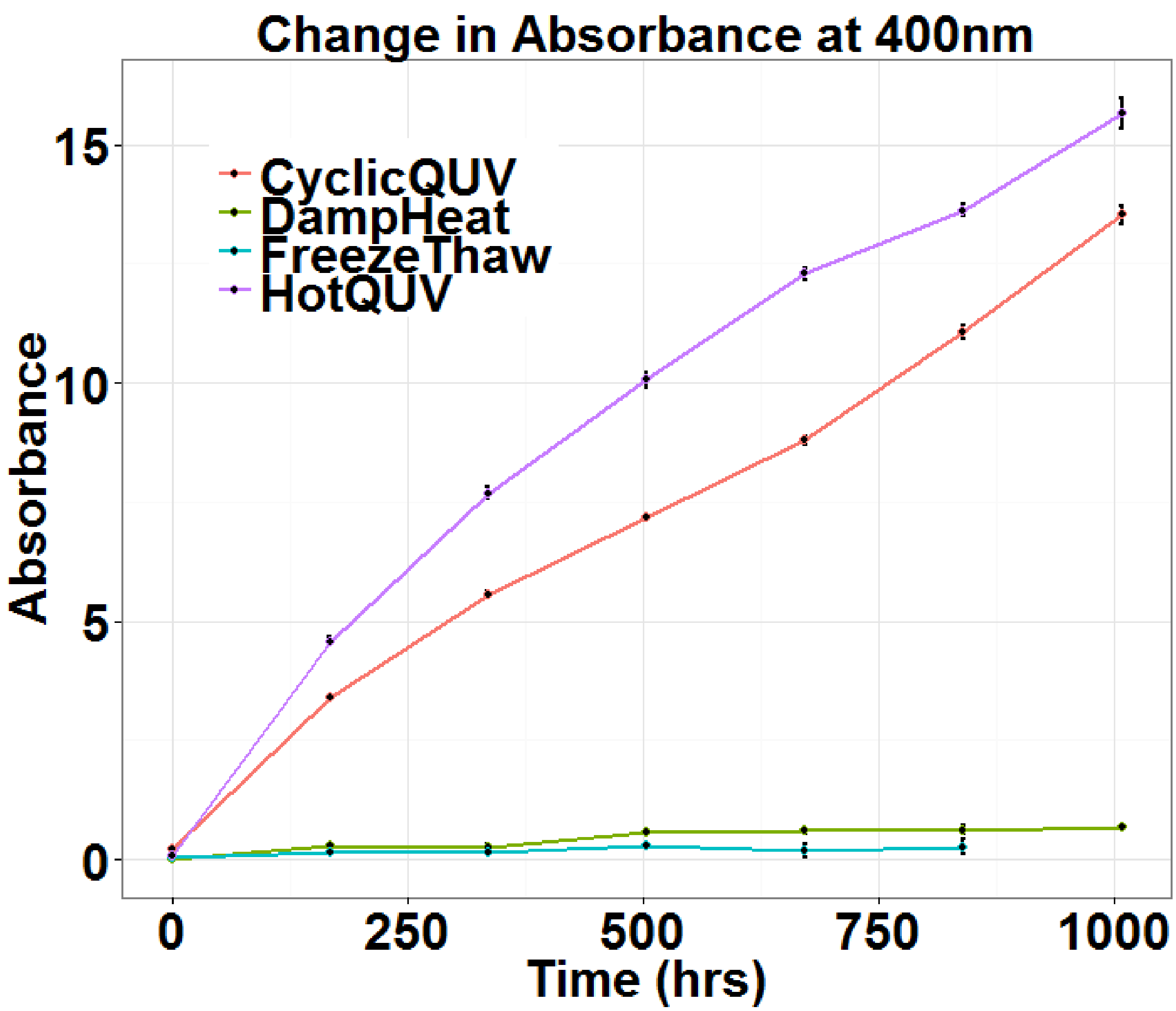
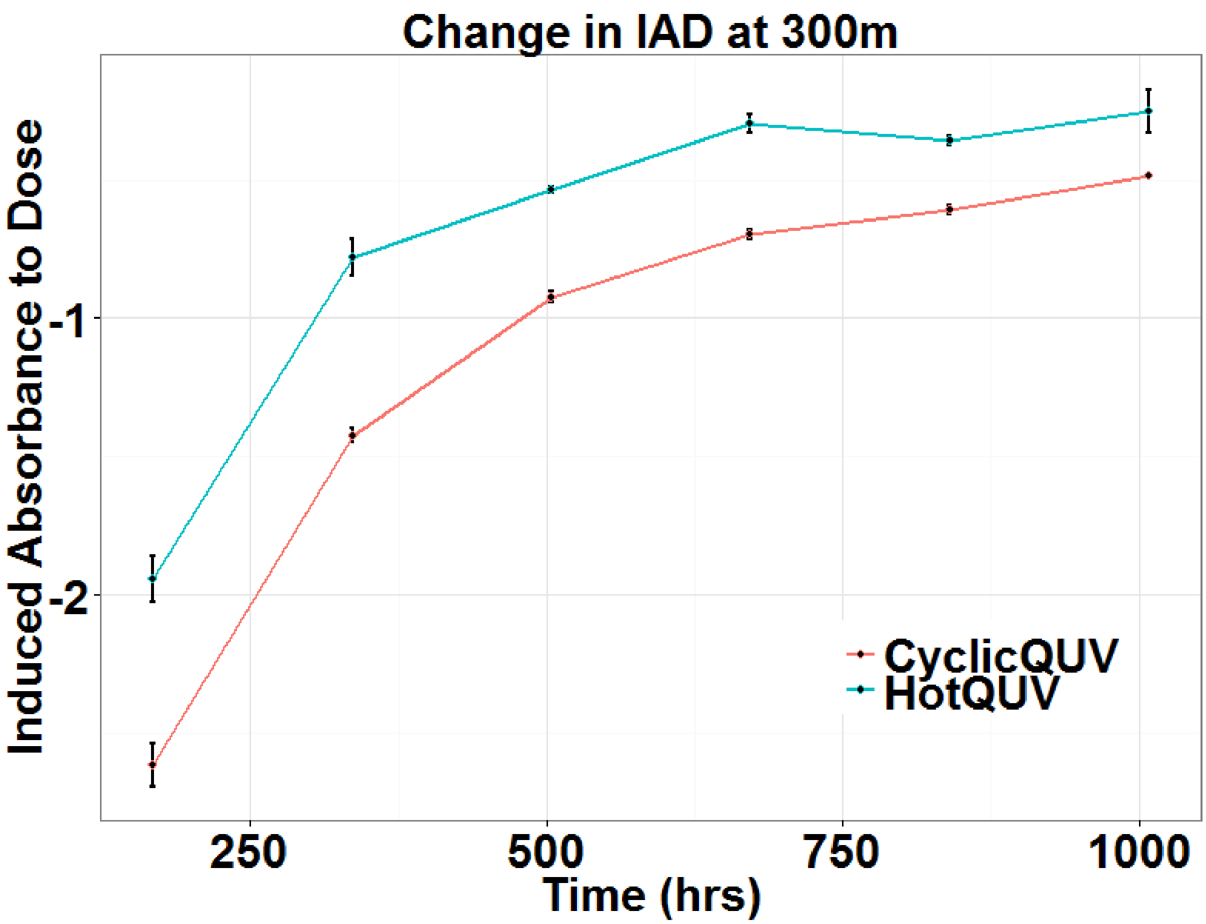


Figure 9: Figure



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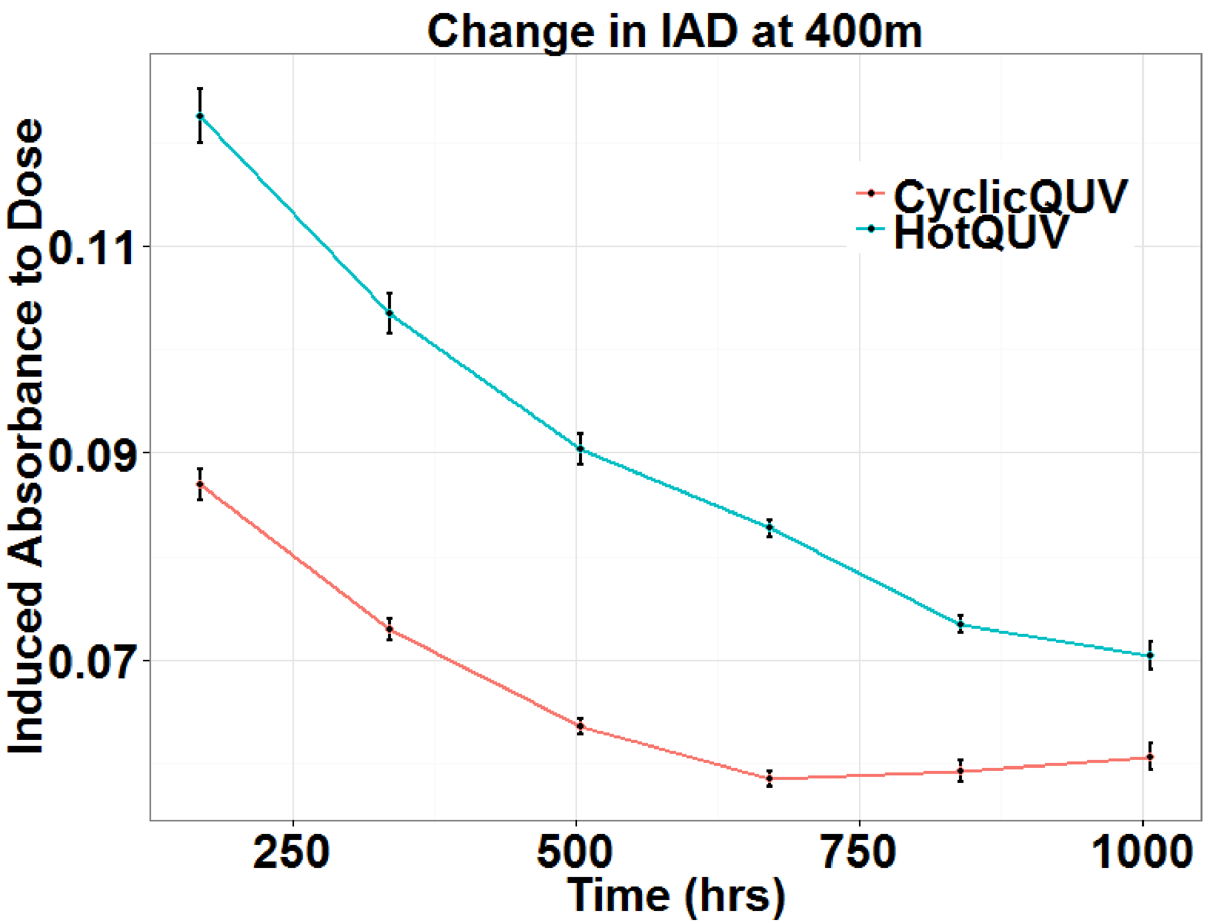

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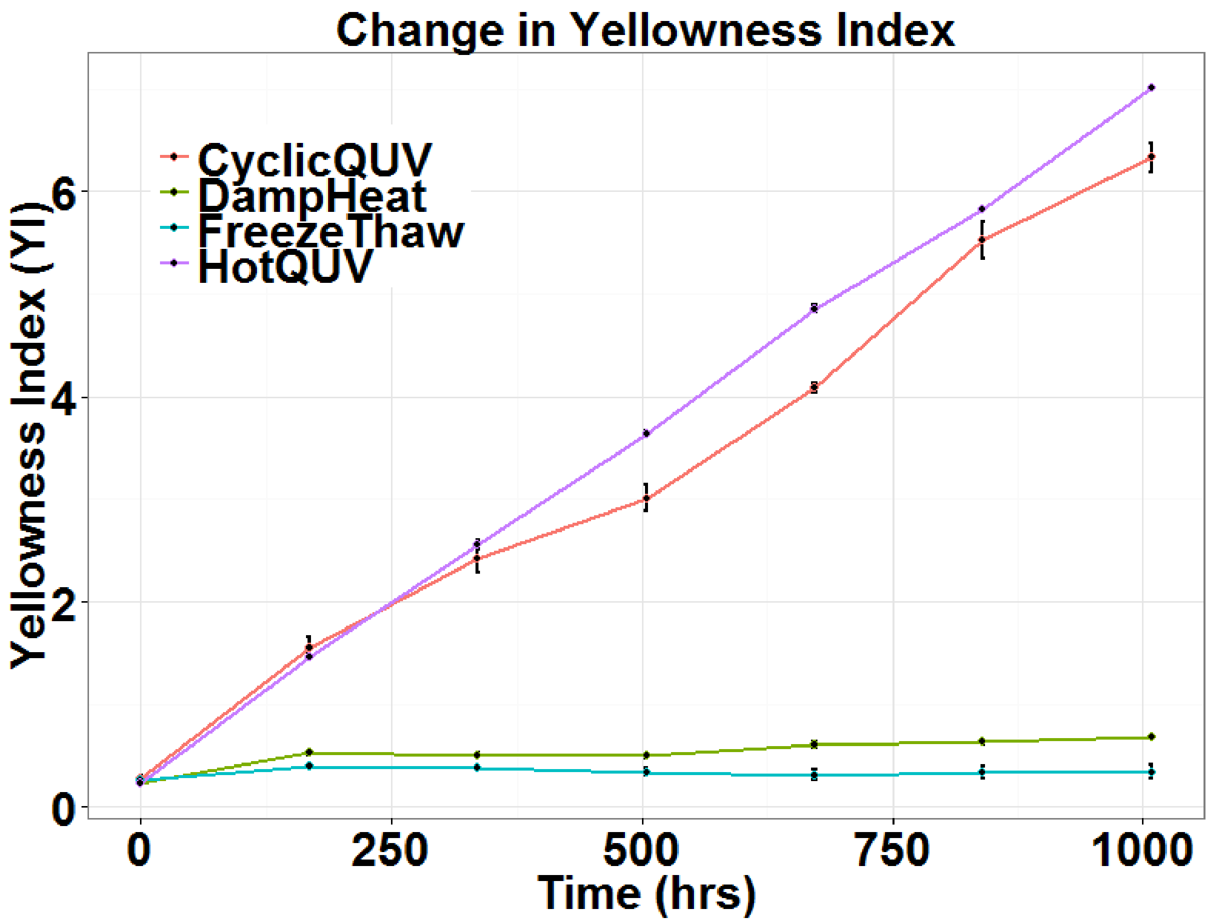


Figure 12: Figure

4.1.2.15.2 Exploratory Data Analysis

Yellowness Index and Haze(%) for Unstabilized PET

4.1.2.15.3 Exploratory Data Analysis

Absorbance at 300 nm and 400 nm for UV stabilized PET

4.1.2.15.4 Exploratory Data Analysis

IAD at 300 nm and 400 nm for UV stabilized PET

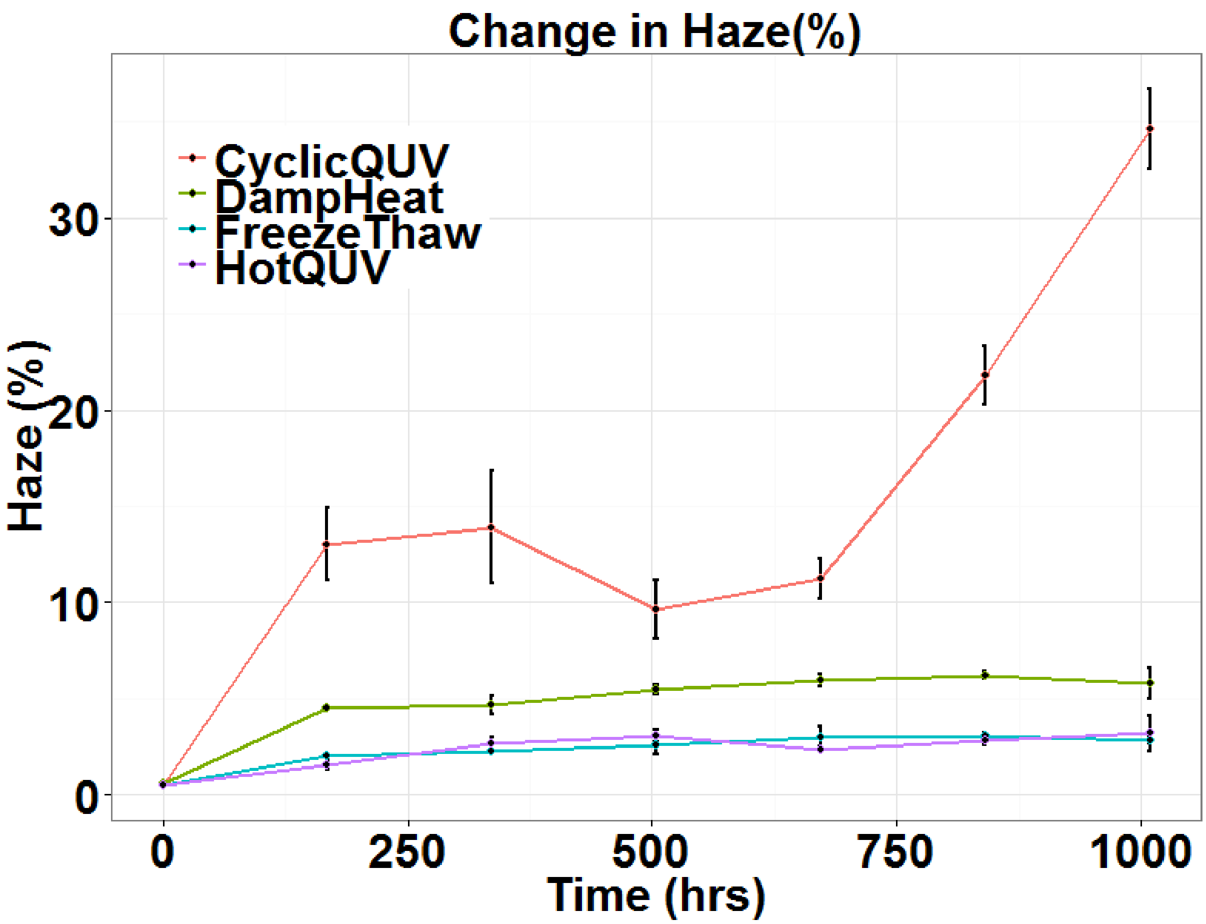
4.1.2.15.5 Exploratory Data Analysis

Yellowness Index and Haze(%) for UV stabilized PET

[Figure](../2-class/figs/UVStab-Haze.png

4.1.2.15.6 Exploratory Data Analysis

Absorbance at 300 nm and 400 nm for Hyd. stabilized PET



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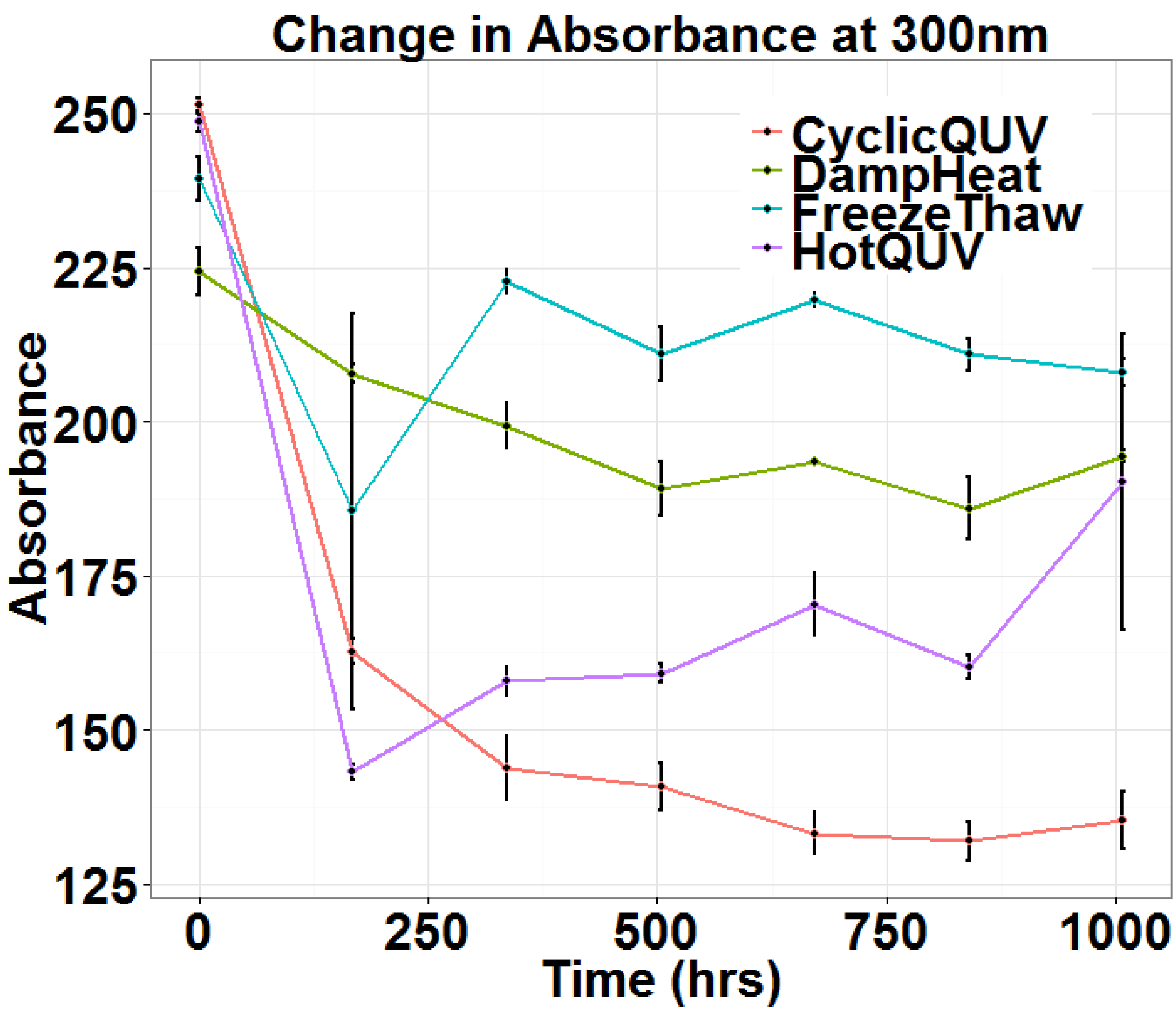

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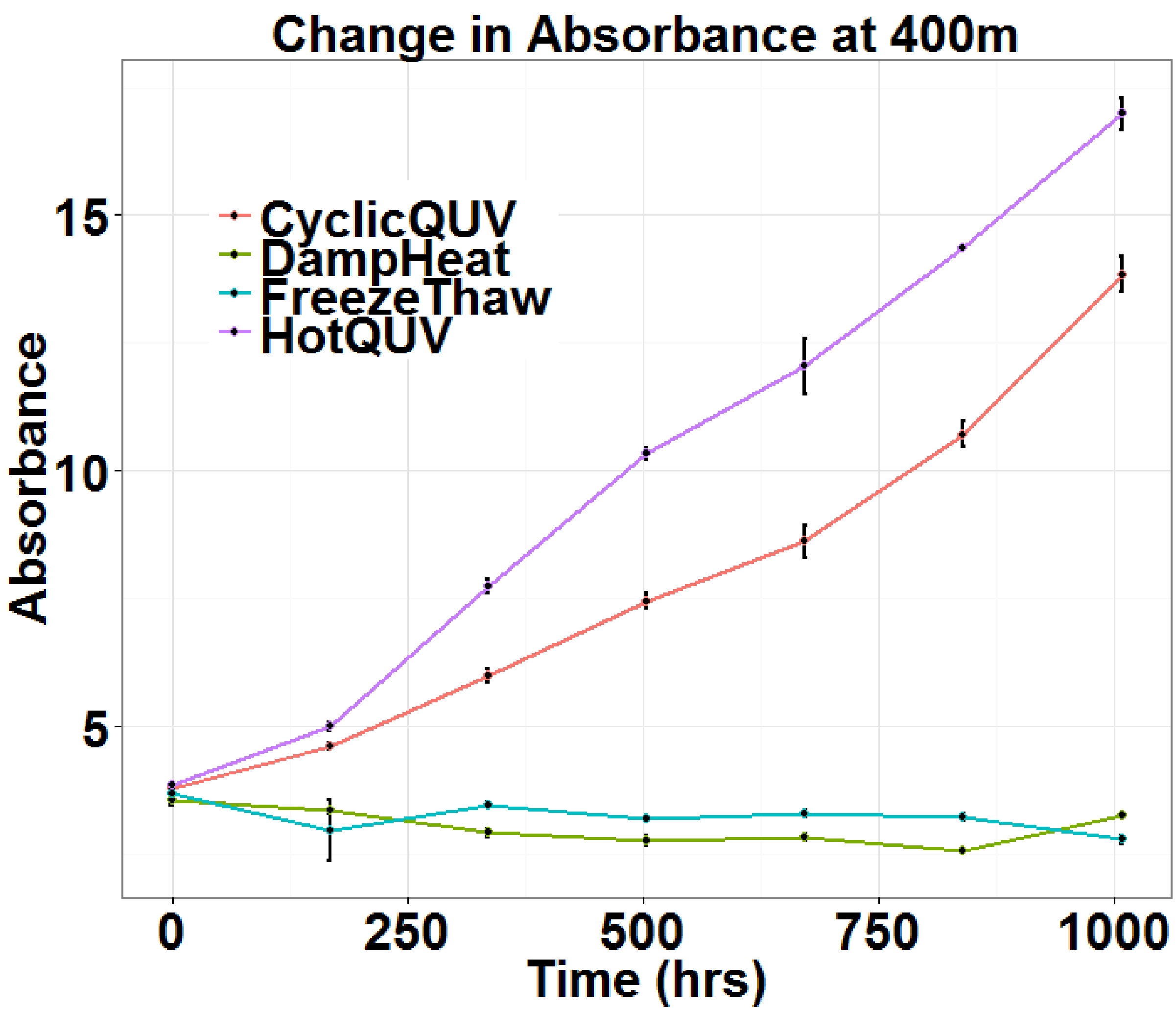

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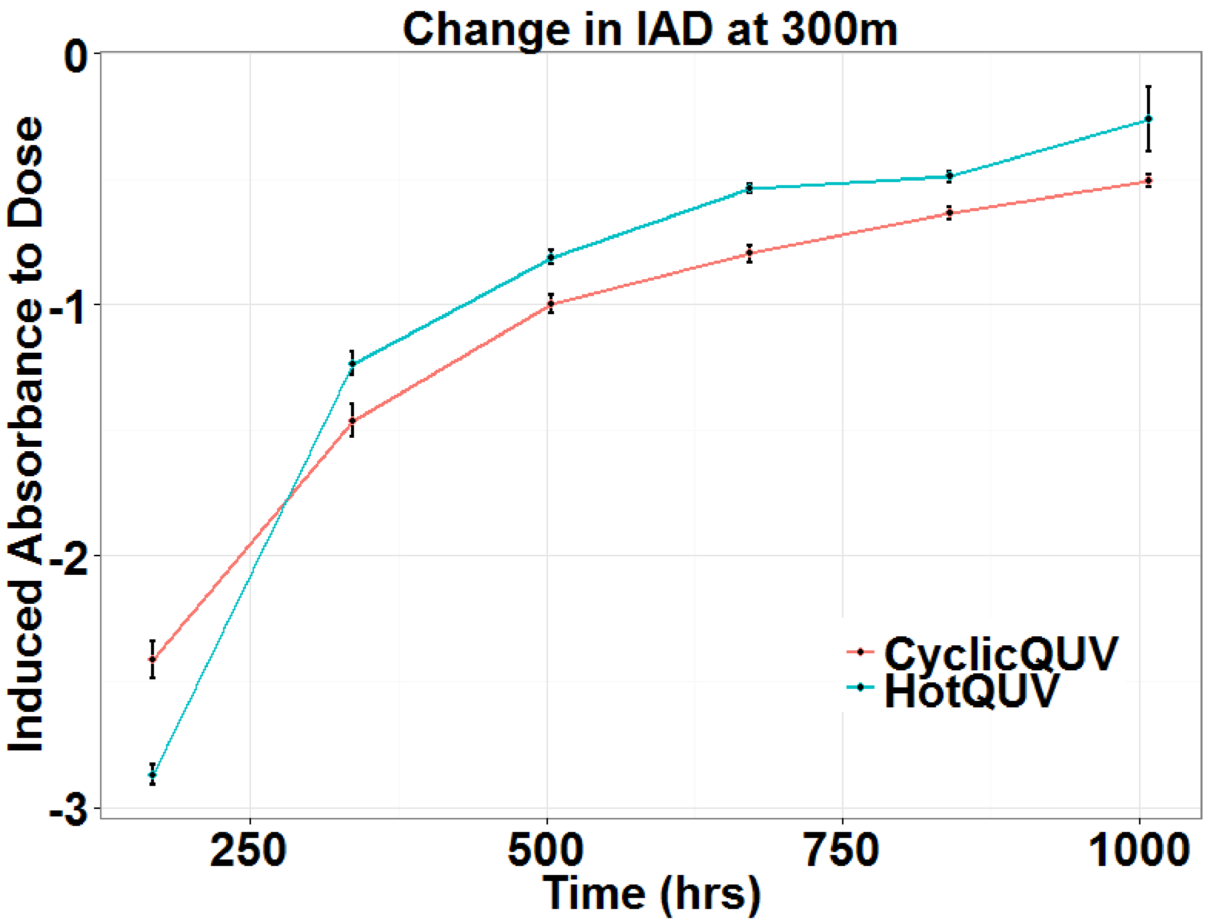
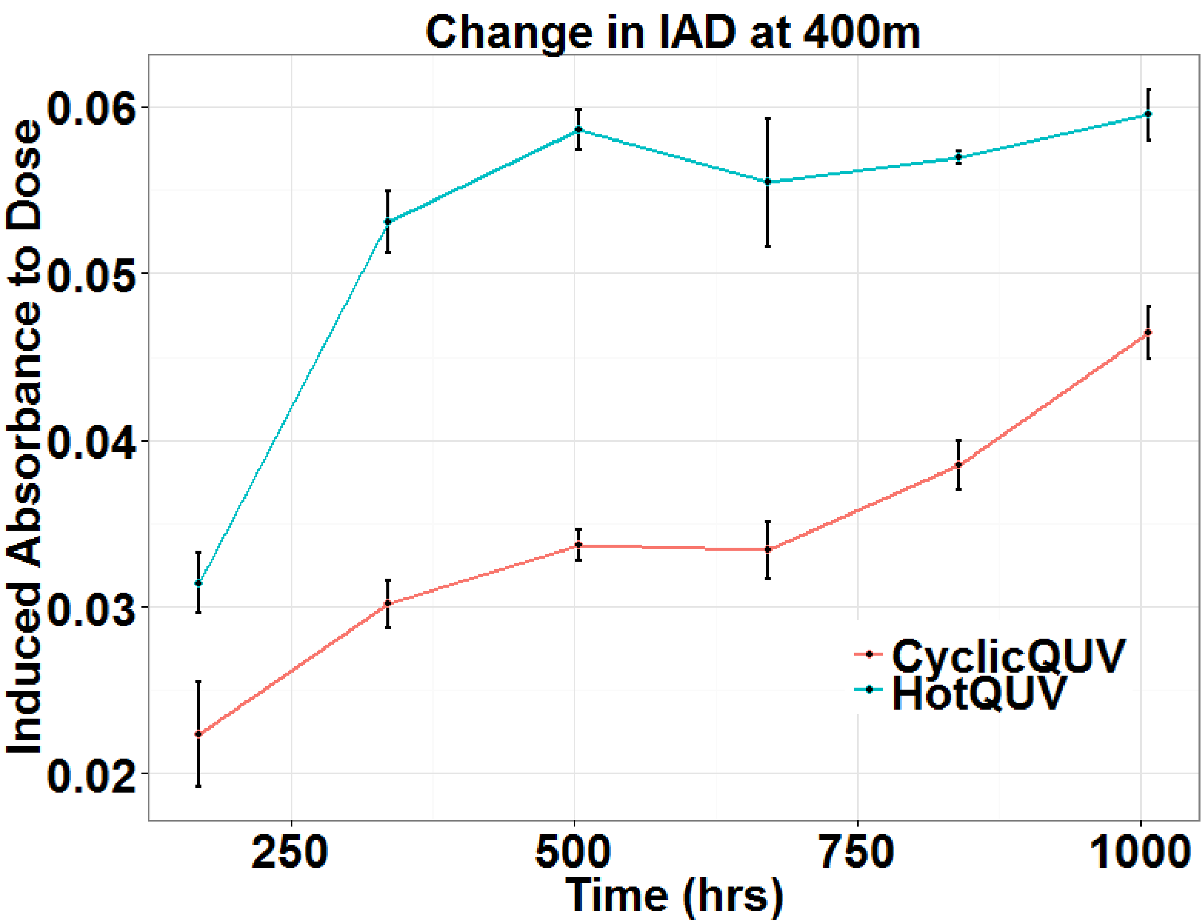


Figure 16: Figure



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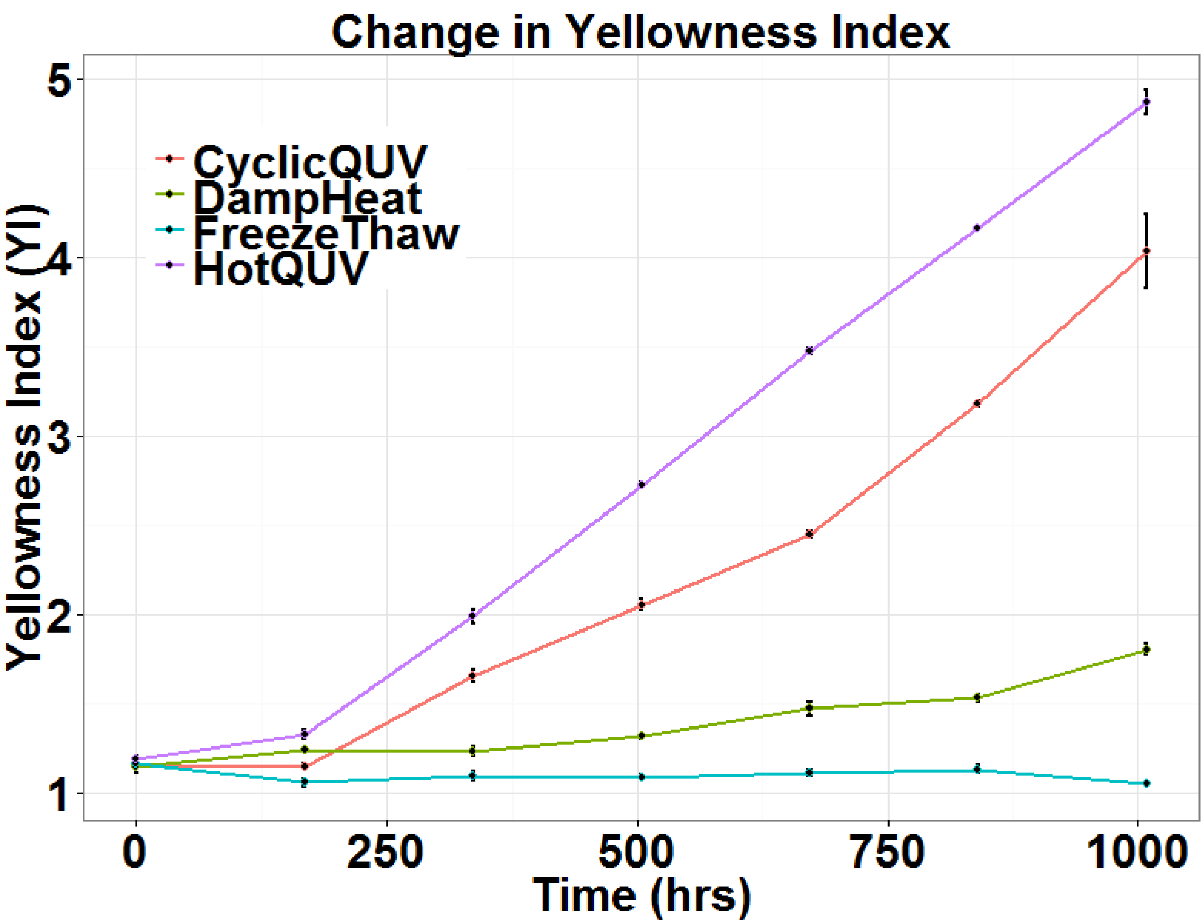

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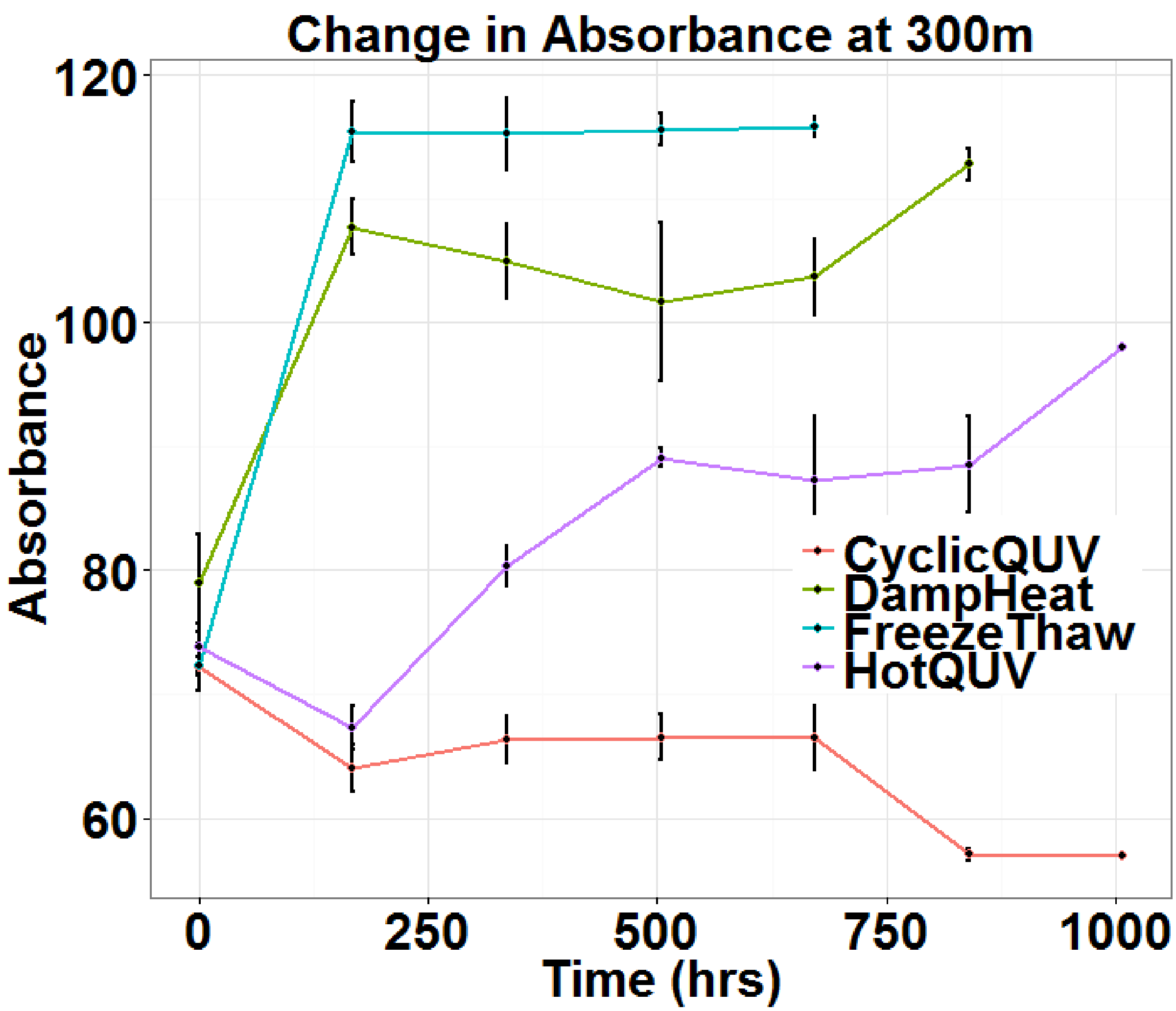

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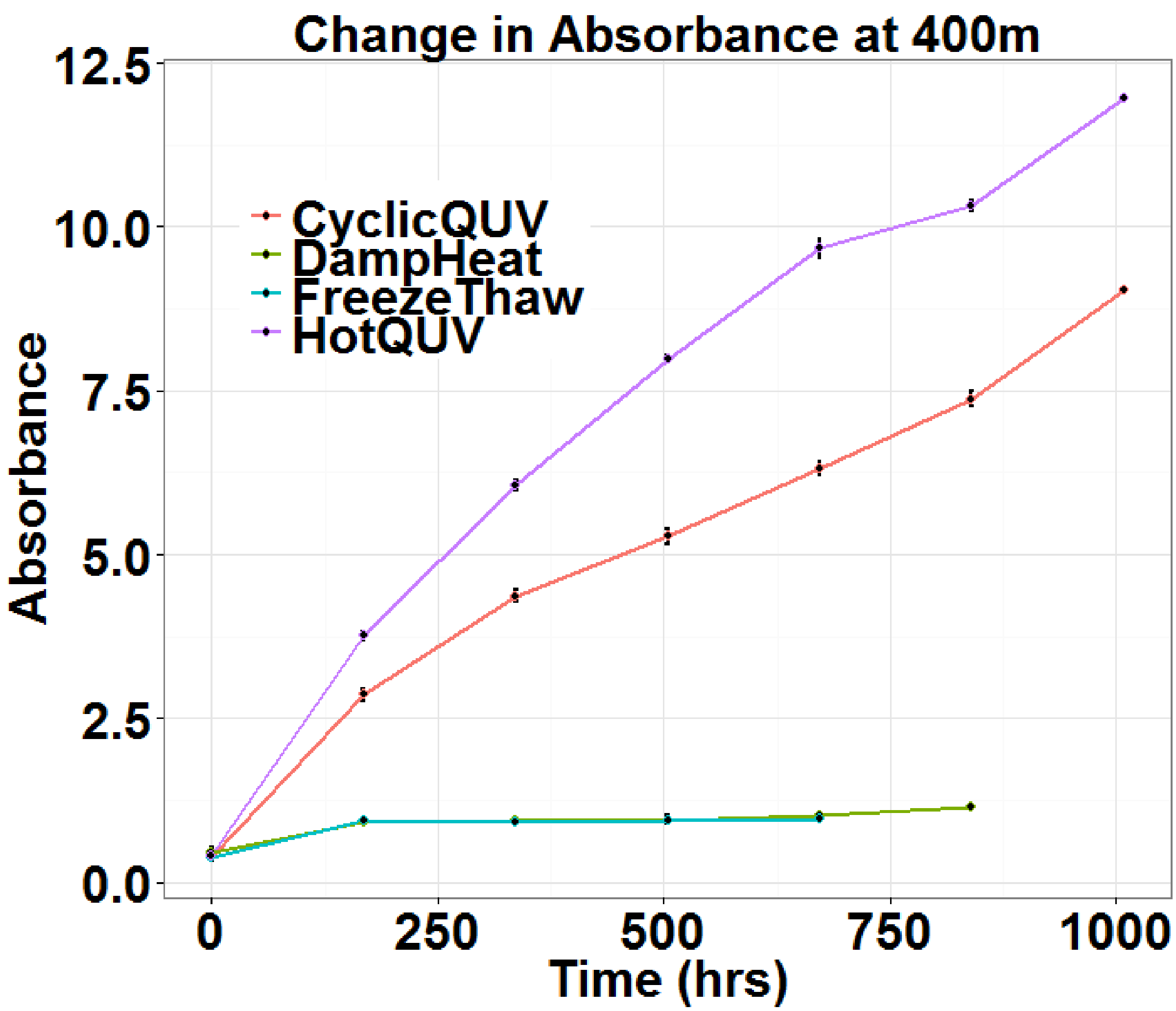

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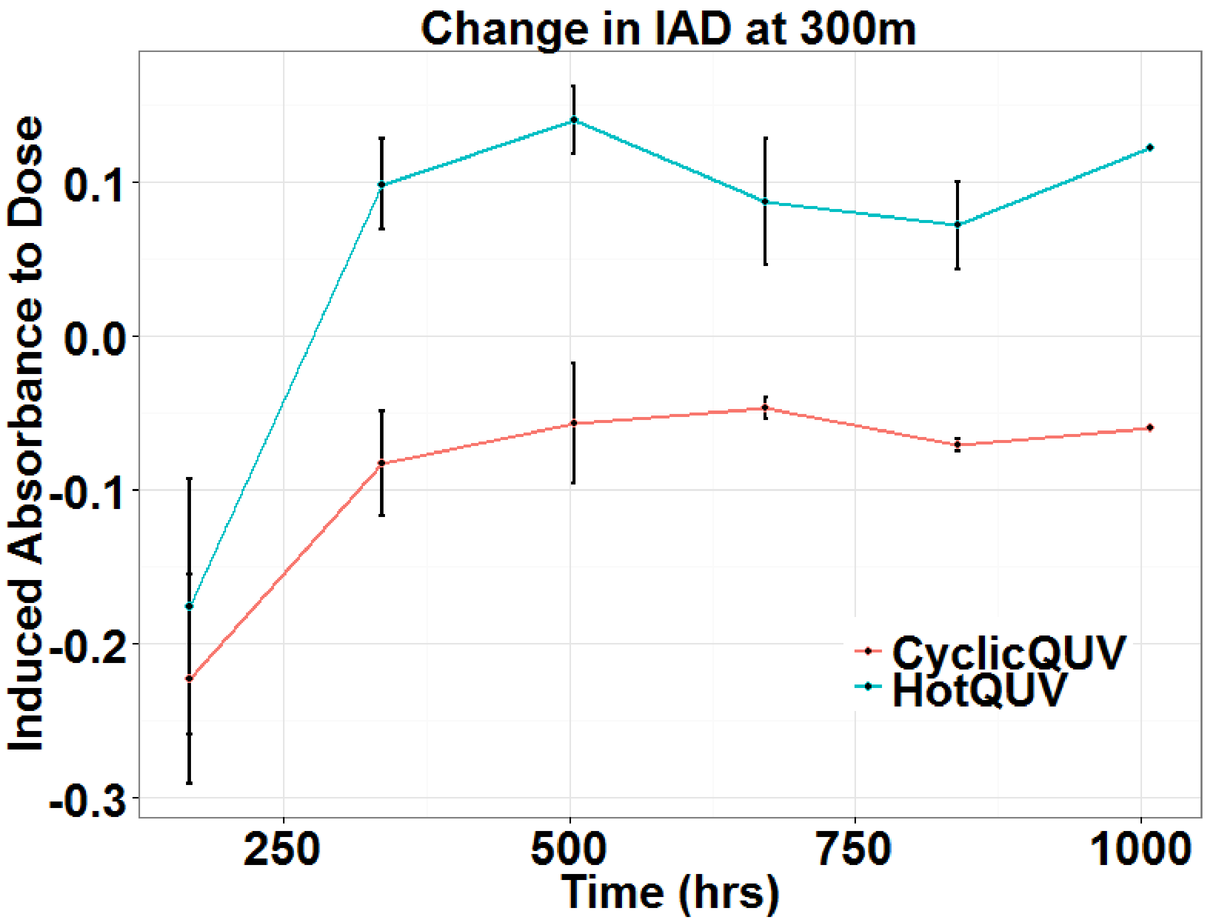


Figure 21: Figure

4.1.2.15.7 Exploratory Data Analysis

IAD at 300 nm and 400 nm for Hyd. stabilized PET

4.1.2.15.8 Exploratory Data Analysis

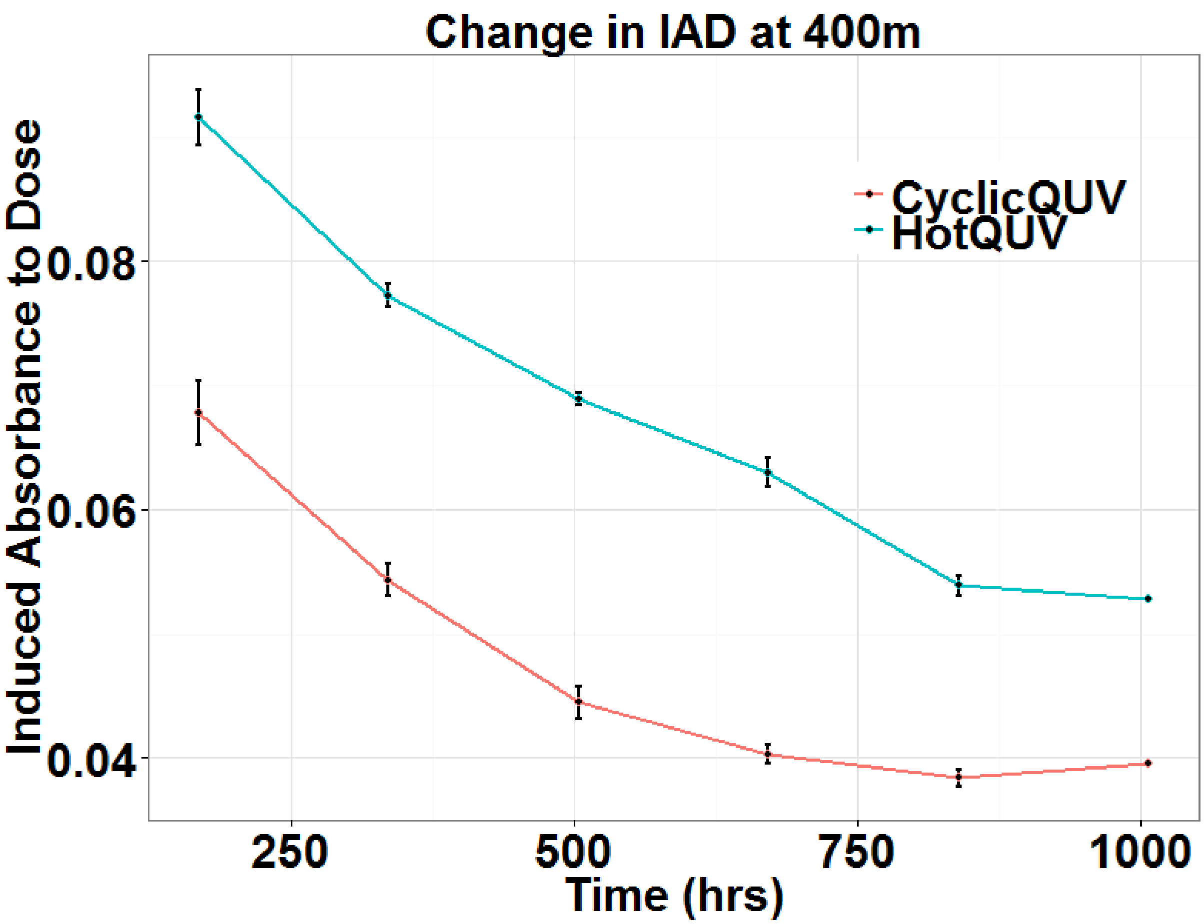
Yellowness Index and Haze(%) for Hyd. stabilized PET

4.1.2.16 Comments

- Light induced yellowing in light exposures (con't UVA and cyclic UVA)
- Moisture induced hazing (cyclic UVA and damp Heat)
- It's more detrimental when light and moisture are coupled
- Freeze thaw is the less damaging
- Change point observed in the UV stabilized PET due to stabilizer consumption in light exposures.

4.1.2.17 Concluding Remarks

- R is a powerful tool!!!



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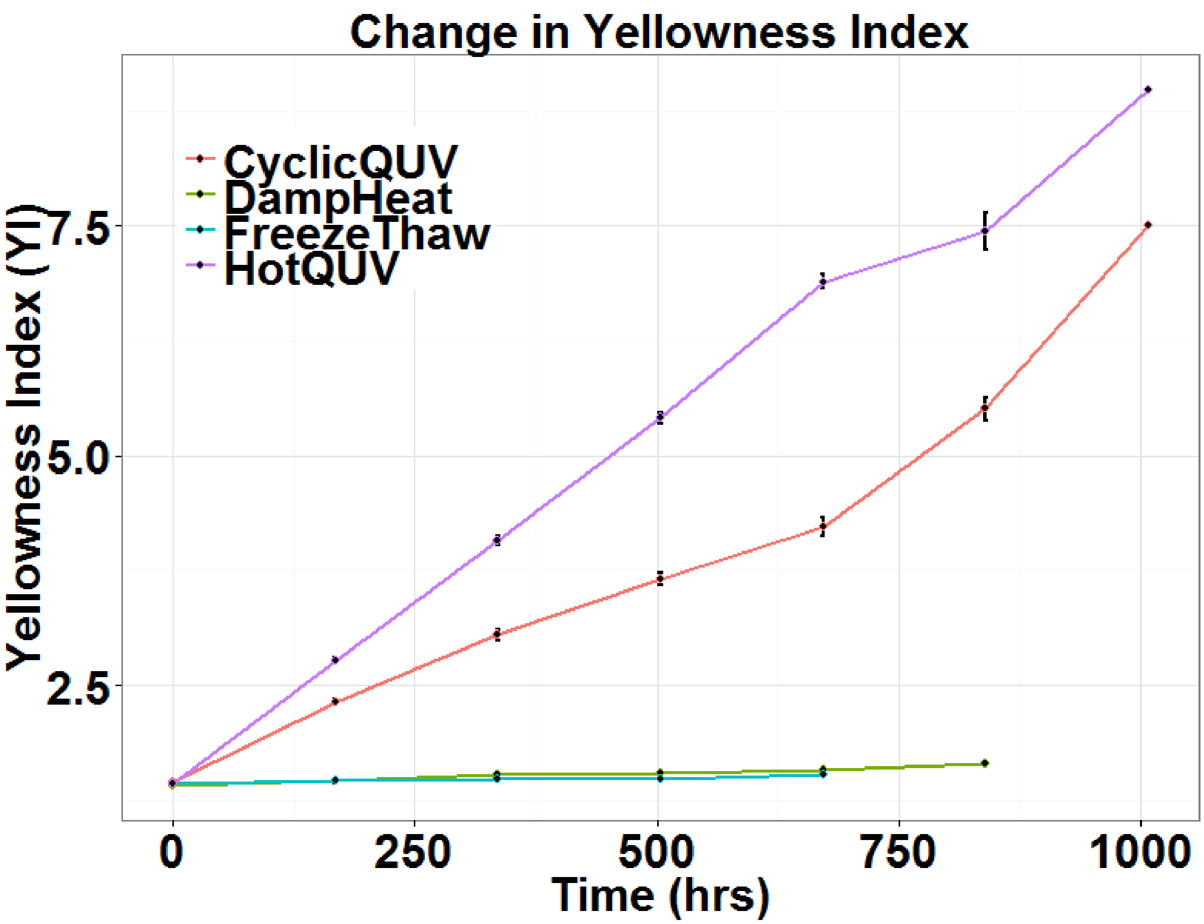

Figure 23: Figure

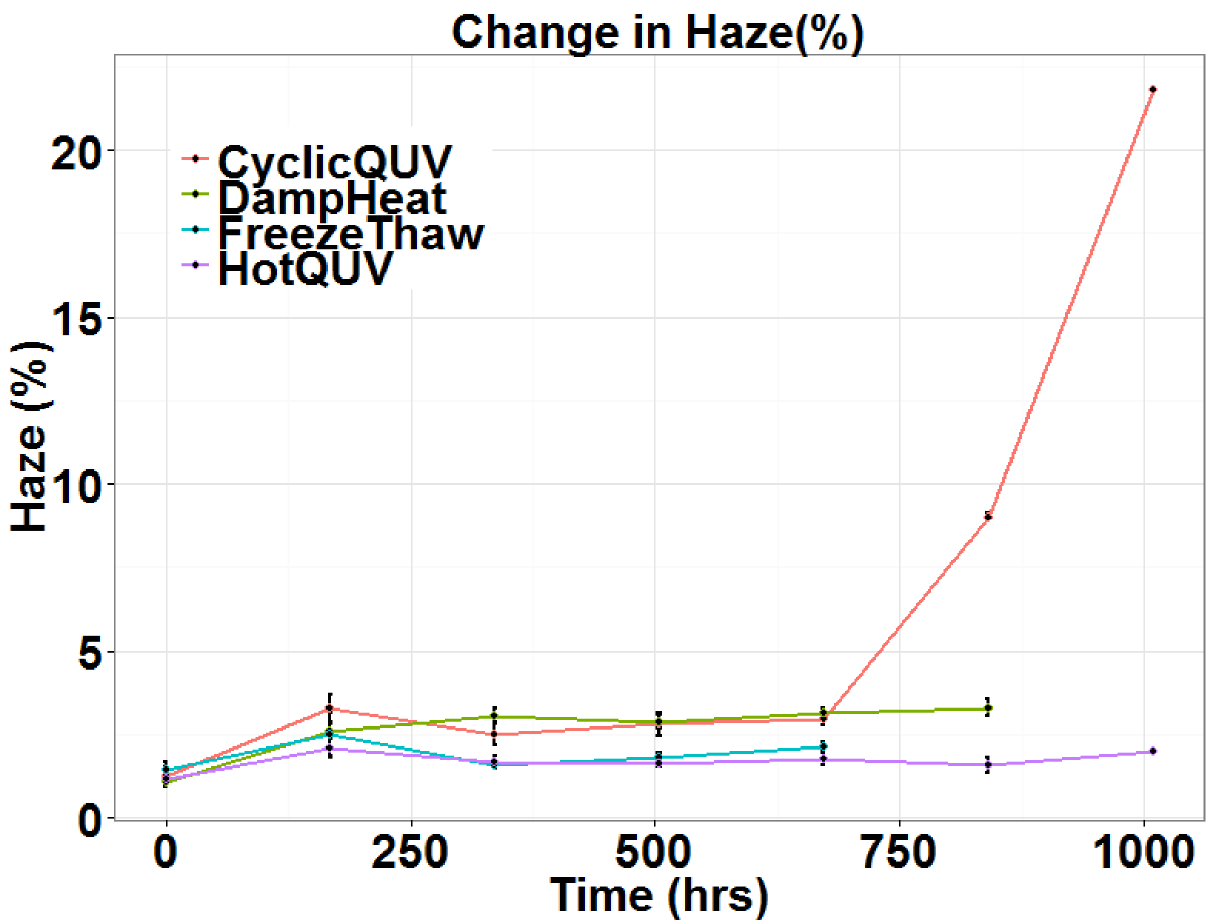

Figure 24: Figure

4.1.2.18 Update on PetDegr Materials

Six candidate materials and seven exposures

Exposure	Condition	Status
Outdoor 1X	1X conc. on dual axis trackers	Ready
Outdoor 4X	4X conc. on dual axis trackers	Ready
Continuous UVA	Constant exposure of UVA light at 1.55 W/m^2 at 340nm at 70°C	Ready
ASTM G154-4	Cyclic exposure of UVA light at 1.55 W/m^2 at 340nm at 70°C for 8 hours and condensing humidity at 50°C in the dark for 4 hours	Ready
Modified Damp Heat - IEC 61215	Constant exposure x°C / 85% RH exposure	Temperature TBD
Modified Humidity Freeze - IEC 61215	Cyclic exposure of y°C / 85% RH and -c°C / 0%RH	Temperature TBD
Multi-Factor	Full spec. light, heat, and humidity	Temperature and humidity TBD

4.1.2.18.1 Update on PetDegr Materials

Baselining is ongoing

Evaluation	Instrument	Technique	Progress
UV-Vis-NIR Optical spec.	Cary 6000i with DRA (200-1800nm)	Center mount absorbance	DOne
UV-Vis-NIR Optical spec.	Filmetrics PartsUV (200-1100nm)	Direct T% and specular R%	Done

Evaluation	Instrument	Technique	Progress
Color Measurement	Hunterlabs UltraScanPro (350-1050nm)	CIE $L^{*}a^{*}b^{*}$ Color - YI and Haze	Done
Gloss Measurement	BKY Gardner Micro-TRI-Gloss	20-60-85^{o} Gloss	Done
Scattering BRDF and BSDF	ScatterMaster	Transmissive and Reflective Scattering	Done
Fluorescence Spec.	Cary Eclipse Fluorimeter	Fluorescence Spectra	Developing method
Nanoindentation	Agilent Nanoindenter G200	Elastic modulus and hardness	Developing method
Infrared Spec.	Agilent Cary 630 FTIR	Diamond ATR-IR Spectra	Developing method