Concrete curing and the effects of vibration

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#####Introduction

In this report, I use various descriptive and inferential statistical analysis methods to determine the effect of shock vibrations on curing concrete. Understanding how concrete reacts to shock vibrations is especially important for civil and environmental engineers and this report explains how concrete reacts to shock and what other facts may affect it. To do this, Kwan el al. collected data on the effects of shock on concrete and published the paper "Shock Vibration Test of Concrete" (Kwan et al. 2002). The study did this by using an accelerometer to measure the shock induced longitudinally on a specimen of concrete in the units mm/sec (peak particle velocity). The damage of the shock on the concrete was then determined by using the pulse transmission method to measure the ultrasonic pulse velocity before and after, and then using these measurements to create a ratio. This method to measure the damage is chosen because some of the damage may be hidden within the concrete and difficult to measure without access to inside the concrete, which ultrasonic waves can do. Additionally, the effects of water content in the concrete will be discussed to determine how it may affect the structural integrity of concrete.

#####Questions and Approach

1) Can the peak particle velocity (ppv) and the ratio of ultrasonic pulse velocity data be represented with a linear regression model?

Statistical Analysis Methods: linear regression model, scatterplot, normal Q-Q plot, residual plot

2) Find a 95% confidence interval of ratio for the average ppv of crack and another 95% confidence interval of ratio for the average ppv of no crack. Compare the confidence intervals for crack vs no crack and determince whether this is consistent with the results from question 1.

Statistical Analysis Methods: confidence interval calculation (standard deviation, mean, t critical)

3) Is the difference in means of the ultrasonic pulse velocity ratios in cracked concrete and non-cracked concrete equal to 0?

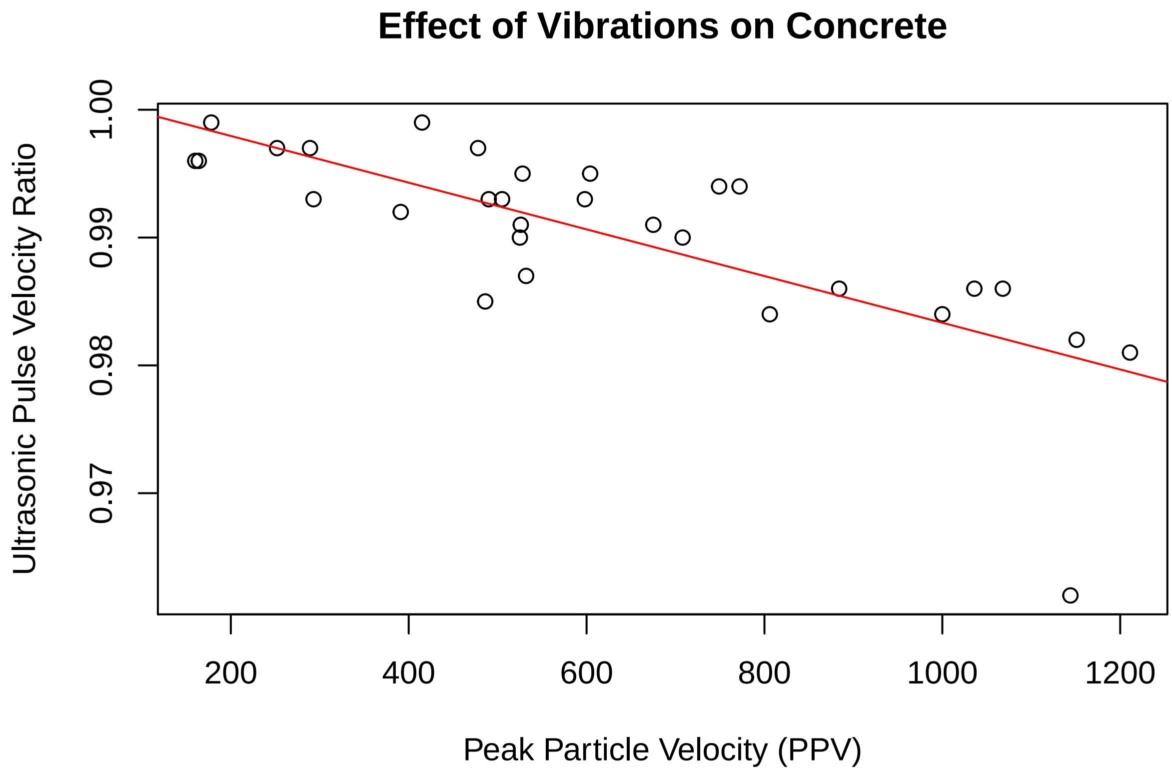
Statistical Analysis Methods: interquartile ranges, t-test, boxplots, hypothesis

#####Analysis & Results

1) What is the general algebraic relationship between peak particle velocity (ppv) and the ratio of ultrasonic pulse velocity?

   In order to determine the relationship between the peak particle velocity (ppv) and the ratio of ultrasonic pulse velocity I create a scatterplot comparing the two variables. The scatter plot appears to follow a linear trend so I create a linear regression model of the data, which appears to support my theory that the two variables are linearly related. I also created a summary of the linear regression model, which outputs important data such as data about the residuals. The residuals seem small relative to the ratio of ultrasonic pulse velocity, which suggests that the data is very close to the regression model. However, in order to confirm that the linear regression model accurately represents the data, I must create two more plots that relate the linear regression model to the peak particle velocity (ppv) and the ratio of ultrasonic pulse velocity.

```r
data <- read.csv("concrete data.csv") #imports concrete data
ppv <- data$ppv           #converts ppv column to a variable
ratio <- data$Ratio       #converts Ratio column to a variable

plot(ppv,ratio, ylab = "Ultrasonic Pulse Velocity Ratio", xlab = "Peak Particle Velocity (PPV)",
     main = "Effect of Vibrations on Concrete")    #generates scatterplot of ppv vs ratio
lreg <- lm(ratio~ppv)      #creates linear regression model for ratio vs ppv
abline(lreg,col="red")     #plots the linear regression line
```

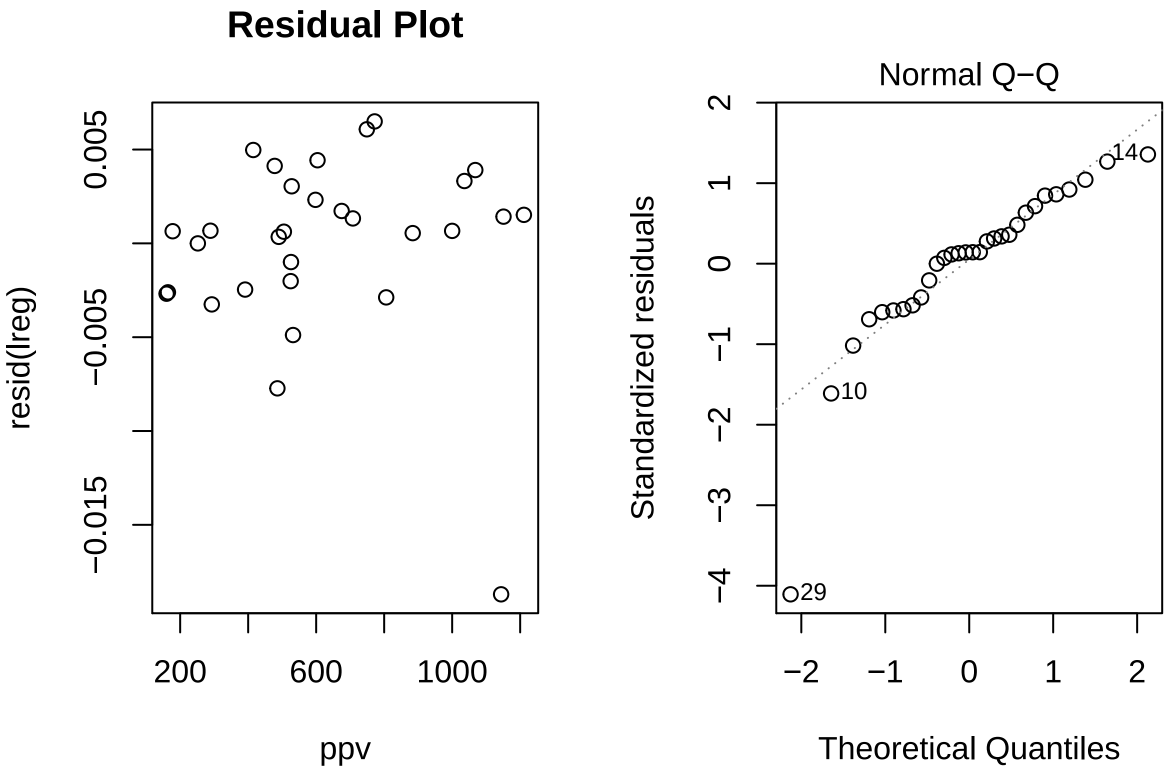



```r
summary(lreg)   #outputs summary of linear regression
```

```
##
## Call:
## lm(formula = ratio ~ ppv)
##
## Residuals:
##       Min        1Q    Median        3Q       Max
## -0.018704 -0.002350  0.000656  0.002861  0.006500
##
## Coefficients:
##               Estimate Std. Error t value Pr(>|t|)
## (Intercept)  1.002e+00  2.039e-03 491.180  < 2e-16 ***
## ppv         -1.827e-05  2.954e-06  -6.185 1.11e-06 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.004892 on 28 degrees of freedom
## Multiple R-squared:  0.5774, Adjusted R-squared:  0.5623
## F-statistic: 38.26 on 1 and 28 DF,  p-value: 1.113e-06
```

These two plots, a residual plot and normal Q-Q, measure whether the linear regression model is relevant to the data plotted above. A residual plot that shows a strong correlation between the regression model and the data is thoroughly scattered with no apparent patterns. Shown below, this is the case that the residual plot is scattered, but I must create one more plot to confirm the validity of the linear regression model. I create a normal Q-Q, which should follow a strong linear trend in order prove the linear regression model accurately represents the data. This is the case, so I conclude that ppv and the ratio of ultrasonic pulse velocity are linearly related and this relationship can be represented with the above linear regression model.

```
par(mfrow = c(1 ,2))    #creates 1 by 2 plotting area
plot(ppv, resid(lreg), main = "Residual Plot")    #creates residual plot
plot(lreg,which=2)      #creates Normal Q-Q plot
```



2) Find a 95% confidence interval of ratio for the average ppv of crack and another 95% confidence interval of ratio for the average ppv of no crack. Compare the confidence intervals for crack vs no crack and determince whether this is consistent with the results from question 1.

   Here I create two 95% confidence intervals to estimate the ratio of ultrasonic pulse velocity for ppv is the mean ppv of cracked concrete and for ppv is the mean ppv of non-cracked concrete. The 95% CI of the ultrasonic pulse velocity ratio when ppv is the average ppv of cracked concrete is [0.9928, 0.9973] and the 95% CI when ppv is the average ppv of non-cracked concrete is [0.9834, 0.9907]. By comparing these two CI's, we can check to see if these results are consistent with what I previously calculated with the linear regression model. According to that model the higher the ppv, we expect a lower ratio. The confidence intervals I calculated support this because the cracked concrete has a smaller mean ppv of 353 and the ultrasonic ratios in the confidence interval, [0.9928, 0.9973] is greater, and vice versa.

```
crack <-data[which(data$Obs<=12),]
#creates data frame of first 12 observations representing cracked concrete
nocrack <- data[which(data$Obs>=13),]
#creates data frame of last 18 observations representing non-cracked concrete
```

```r
mean(crack$ppv)        #calculates mean of ppv with crack
```

```
## [1] 353.1667
```

```r
mean(nocrack$ppv)      #calculates mean of ppv with no crack
```

```
## [1] 798.8889
```

```r
mean(crack$Ratio)      #calculates mean of ratio with no crack
```

```
## [1] 0.9950833
```

```r
mean(nocrack$Ratio)    #calculates mean of ratio with crack
```

```
## [1] 0.9870556
```

```r
sd(crack$Ratio)        #calculates standard deviation of ratio with crack
```

```
## [1] 0.003800917
```

```r
sd(nocrack$Ratio)      #calculates standard deviation of ratio with no crack
```

```
## [1] 0.007526207
```

```r
qt((1-0.95)/2,28)      #calculates t critical for two-sided, 95% confidence, 28 degrees of freedom
```

```
## [1] -2.048407
```

```r
mean(crack$Ratio)+qt((1-0.95)/2,28)*sd(crack$Ratio)/sqrt(12)
```

```
## [1] 0.9928358
```

```r
#calculates upper bound of confidence interval of ultrasonic ratio for ppv=mean ppv of cracked concrete
mean(crack$Ratio)-qt((1-0.95)/2,28)*sd(crack$Ratio)/sqrt(12)
```

```
## [1] 0.9973309
```

```r
#calculates lower bound of confidence interval of ultrasonic ratio for ppv=mean ppv of cracked concrete

mean(nocrack$Ratio)+qt((1-0.95)/2,28)*sd(nocrack$Ratio)/sqrt(18)
```

```
## [1] 0.9834218
```

```r
#calculates upper bound of confidence interval of ultrasonic ratio for ppv=mean ppv of non cracked
mean(nocrack$Ratio)-qt((1-0.95)/2,28)*sd(nocrack$Ratio)/sqrt(18)
```

```
## [1] 0.9906893
```

```r
#calculates lower bound of confidence interval of ultrasonic ratio for ppv=mean ppv of non cracked
```

3) Is the difference in means of the ultrasonic pulse velocity ratios in cracked concrete and non-cracked concrete equal to 0?

Null Hypothesis: the difference of ultrasonic pulse velocity ratio with crack and without crack is 0. Alternative Hypothesis: the difference of ultrasonic pulse velocity ratio with crack and without crack is not 0.

```r
t.test(crack$Ratio,nocrack$Ratio,0,alternative = "two.sided")
```

```
##
##  Welch Two Sample t-test
##
## data:  crack$Ratio and nocrack$Ratio
## t = 3.8487, df = 26.501, p-value = 0.0006757
```

```
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  0.003744184 0.012311371
## sample estimates:
## mean of x mean of y
## 0.9950833 0.9870556
```

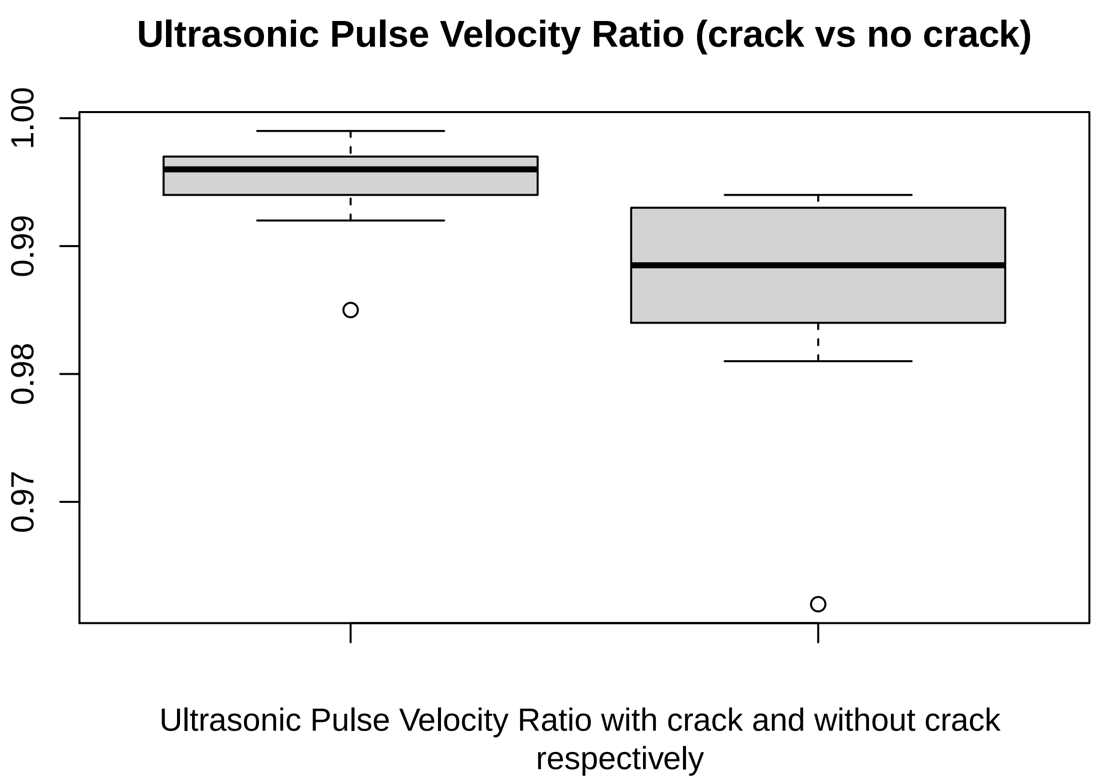
```r
#perform two-sided t test with 95% confidence, Ho=0

IQR(crack$Ratio)    #computes interquartile range of ratio with crack
```

```
## [1] 0.0025
```

```r
IQR(nocrack$Ratio)  #computes interquartile range of ratio with no crack
```

```
## [1] 0.008
```

```r
boxplot(crack$Ratio,nocrack$Ratio,xlab="Ultrasonic Pulse Velocity Ratio with crack and without crack
        respectively", main = "Ultrasonic Pulse Velocity Ratio (crack vs no crack)")
```



From the t-test, I conclude that the true difference of means is not equal to 0 because the outputted p-value, 0.0006757, is less than 0.05. Any p-value less than 5% the null hypothesis is rejected, and any p-value greater than 5% the null cannot be rejected. Thus, the null hypothesis that the difference of ultrasonic pulse velocity ratio with crack and without crack is 0 is rejected.

Another test of variance we can use to determine whether the data sets are the same is to use boxplots and calculate the IQRs. The interquartile range is very useful because it eliminates outliers, which will present a more accurate image of the bulk of the data. Similarly, a boxplot is another way to prevent outliers from affecting the rest of the data. Two boxplots are generated, one of the ultrasonic pulse velocity ratio with cracks and the other without cracks. The result is that pulse velocity ratio with cracks is visibly higher than the pulse velocity ratio without cracks, each with one outlier.

#####Discussion

Studying how concrete reacts to various conditions such as shock vibrations is vitally important for civil and environmental engineers to build effective and safe structures. Some applications of a study like this one could be determining how a concrete bridge foundation may react to the ever changing load and vibrations from the cars driving over the bridge, or how building foundations are affected by the shock vibrations from various magnitude earthquakes.

In this report, I interpret data to determine how concrete reacts to vibrations like these. From various descriptive and inferential statistical analysis methods, I can make three statements regarding the strength of concrete from shock vibrations with fair certainty. That is that concrete loses structural integrity as a linear relationship with the applied shock vibrations, the 95% confidence interval of the ultrasonic pulse velocity ratio when ppv is the average ppv of cracked concrete is [0.9928, 0.9973] and the 95% CI when ppv is the average ppv of non-cracked concrete is [0.9834, 0.9907], and with 95% confidence the true difference of means between the non-cracked ppv and the cracked ppv is not equal to 0. These conclusions were made using a variety of statistical methods and calculations, such as creating a linear regression model, normal Q-Q plot, residual plot, using standard deviation and t critical values to determine confidence intervals, finding interquartile ranges, creating boxplots, and performing a t-test.

My linear regression model shows that concrete loses strength as a linear relationship with the applied shock vibrations, however, there are some limitations to the results. Some variables may not have been accounted for that could affect results, such as the water content of the concrete. Despite this my conclusion that the ultrasonic pulse velocity ratio decreases linearly as ppv increases should still stand because ultrasonic pulse velocity and water content are linearly related according to Etsuzo Ohdaira and Nobuyoshi Masuzawa, who conducted a study questioning how water content of concrete affects ultrasonic propagation velocity. They concluded that "The propagation velocity of ultrasonic pulses and the transmission of frequency through concrete decreased approximately linearly in proportion to the decrease in water content" (Etsuzo Ohdaira and Nobuyoshi Masuzawa, 2000). This means that while water content does in fact affect the ultrasonic pulse velocity results, the relative relationship between the ultrasonic pulse velocity and ppv remain. Despite this linear relationship between shock vibrations and strength, an important distinction to note is that shock vibrations do not actually travel linearly throughout concrete according to S.A. Nield, M. S. Williams, and P.D. McFadden, who conducted a study on the "Nonlinear Vibration Characteristics of Damaged Concrete Beams" (S.A. Nield, M. S. Williams, and P.D. McFadden, 2003). That is that shock waves do not subside as a linear progression of distance from impact source. This is meaningful because despite the two different studies being closely related, the results are very different. Shock intensity may be linearly related to the damage it causes, but the shock waves themselves travel more exponentially through the concrete.

This report examines how concrete reacts to shock vibrations, but what about reinforced concrete? Concrete reinforced with steel is a much more applicable study to civil and environmental engineers that could be taken on in the next step. Reinforced concrete is more commonly used because of its significant added benefits of strength with small added cost. It would likely react differently to shock vibrations due to the unique characteristics of the steel. Reinforced concrete, with it added benefits and widespread applications, should be the next step for descriptive and inferential statistical analysis.

#####References

Kwan, A. K. H., Zheng, W., & Lee, P. K. K. (2002). Shock vibration test of concrete. Materials Journal, 99(4), 361-370.

Neild, S. A., et al. Nonlinear Vibration Characteristics of Damaged Concrete Beams. 15 Jan. 2003

Ohdaira, Etsuzo, and Nobuyoshi Masuzawa. "Water Content and Its Effect on Ultrasound Propagation in Concrete - the Possibility of NDE." Ultrasonics, Elsevier, 27 Mar. 2000