

# Designing Glaze Colours

*Timothy Ebert explains his project researching different glaze colours*

There are two goals in this project. First, I looked at books of glazes with pictures of a series of test tiles showing a gradual change in colour as the quantity of iron or other metal oxide increases or decreases. I thought that it would be possible to develop a predictive model for estimating the entire range in colour with far fewer test tiles. I would like to offer my results to other potters. Second, it is difficult to devise projects that require integrating several sciences. This project uses skills that should be familiar to people with a high school level algebra and chemistry class. On the other hand, the entire project could also be expanded to explore issues in statistics and chemistry at the college level. This is the first step, made possible with the help of Sam Sheller and his students in the 2003 ceramics class at Smithville High School (USA, Ohio).

Science is about observing, experimenting, and predicting new outcomes. Many experiments begin with an "observation" that results in the design of an experiment using a group of unrelated variables to understand differences. An alternative approach deals with experiments where there are a group of related variables -- where it is called a mixture design. With only 3 variables, potters would call this a triaxial blend.

A triaxial blend is a way to mix 3 colourants so the potter can visualize the glaze colour by looking at the resulting test tiles. The more mixes used by the potter the more complete is the visualization of the potential range in colours. In some cases a potter has used over 100 test tiles. The alternative is to model the colour and use mathematics to predict the colour of all possible blends. To this end, this project uses knowledge in chemistry, math, statistics, experimental design, prediction, and replication. While developing these skills, students will learn how potters can choose a colour and make a glaze to match that colour. To this end, this project uses knowledge in chemistry, mathematics, statistics, experimental design, prediction and replication. While developing these skills, students will learn how potters can choose a colour and make a glaze to match that colour. This might be useful if the potter is working on a design where he wants a specific colour -- like a painter mixing colours on his palette.

The tools required for this project are kept to a minimum, and should be affordable by most schools (see list at end of article). Expensive tools (electronic balances, microscopes, 15 megapixel cameras, etc.) might improve the accuracy of the results, but they are not necessary to demonstrate the process. There are trial versions available for the specialized software packages used in the project, so instructors can try the project before buying specialized software. The requirements for this project are a computer, some way to get colour digital images, a spreadsheet program like Microsoft Excel<sup>®</sup>, access to the internet, and a pottery studio.



Cobalt spectrum showing the increase of pigment

## CHEMISTRY

A glaze is a mixture of molecules. This mixture has both crystalline and fluid properties. In any crystal structure molecules are arranged to fit into a space, sort of like a bunch of very small marbles of different sizes. The dominant components of the glaze are silicon dioxide ( $\text{SiO}_2$ ) and aluminum oxide ( $\text{Al}_2\text{O}_3$ ). The packing of these compounds in the glaze leaves spaces where other molecules can fit in. The number of occupied spaces and the nature of the molecule or compound occupying the space determines how well the molecules pack which, in turn, will affect glaze durability, fluidity, and appearance. A web site for looking at the periodic table of elements and the crystal structure of some common glaze components visit <http://www.webelements.com>. To find the crystal structure of silicon dioxide, use the periodic table to find silicon (Si), on the right side of the page is a table of compounds including oxides.

Because each molecule fills a space, keeping track of the number of molecules is important - a glaze is a mixture of different molecules and adding a new molecule will displace other molecules, or change glaze density. An easy way to keep track of the number of molecules is the mole, one of the seven basic SI units. A mole is defined as 12 grams of carbon 12, and has Avogadro's number of atoms. Avogadro's number is abbreviated  $N_A$ , and it equals about  $6.022214 \times 10^{23}$ . The weight of this many particles equals the atomic mass in grams. Avogadro's number of atoms of Carbon 12 ( $^{12}\text{C}$ ) weighs 12 grams, but in the natural world, most elements occur as several isotopes that differ in the number of neutrons in the nucleus. The proportion of these isotopes has been measured and the average result is the mass usually printed as part of the Periodic Table of Elements (see [www.webelements.com](http://www.webelements.com) and look at atomic weights). The mass listed for carbon is 12.011, so Avogadro's number of atoms of naturally occurring carbon weighs 12.011 grams. The use of moles applies equally to compounds as it does atoms. A mole of silicon dioxide ( $\text{SiO}_2$ ) weighs  $28.086 + 2 \times (15.9994) = 60.0848$  grams and contains 1 mole of silicon and 2 moles of oxygen per mole of silica.

Weights alone are easy to use, but the problem is that 10 grams of black iron oxide and 10 grams of black copper oxide have a different number of particles (0.139 moles of iron versus 0.126 moles of copper respectively). Despite the usefulness of converting everything to moles, this is not always possible. Stains contain a proprietary blend of different metals, so tests with stains must be based on weight. We decided to try mixing colourants in two ways: 1) use metal oxides and moles; 2) use stains and weight.

### STATISTICS: SIMPLE LINEAR REGRESSION

Students making triaxial blends of stains added 10 grams of stain to 100 grams of a base clear glaze (Table 1). The proportion of stain to glaze was based on Sam's experience with using these stains in glazes. The five students testing stains selected three stains, and weighed out the 13 blends (Figure 1). The two students testing metal oxides chose cobalt carbonate, copper carbonate, and manganese carbonate. The problem is how much oxide should be added to the glaze? From personal experience, cobalt is the strongest colourant molecule for molecule. Therefore, I ran an initial test to look for the point where further additions of cobalt had little affect on glaze colour. This initial step also allowed me to work out some of the problems with the digital representation of colour. I used cobalt because molecule for molecule it has the greatest affect on glaze colour.

I mixed 5 kg of base glaze 3 (Table 1) plus 2 liters of water. This made 4 liters of a thick glaze paste, where about 80 milliliters (ml) equaled 100 grams (g) of dry glaze. Because it is soluble, I used cobalt chloride hexahydrate in this test. I made solution of 3.5 moles/liter cobalt, and added 20ml of this solution to 100 g base glaze. I then diluted the cobalt solution in half. In another container, added 20ml of this diluted solution to 100 g base glaze.

While I focus on triaxial blends, I also show a quadaxial blend. Companies making stains often blend over four components. A black Ferro stain is a blend of five components (Fe, Cr, Mn, Ni, and Co), while the soft green gray Mason stain is a blend of eight. Using math reduces the number of tests necessary to blend a specific colour by allowing one to predict the results of untested blends based on the results of a few tests. In making triaxial blends, 21 test tiles are often recommended. The mathematical model for a triaxial blend requires only 13 test tiles. In working through this project, we need to look carefully at how a triaxial blend (the potter's term) relates to a mixture model (the statistician's term). Forging this bridge will take us from chemistry through statistics, and include a small detour through photography and the numerical description of colour.

Table 1: The glaze formulae for 3 clear gloss cone 6 glazes, and the clay body used in this project.

	Glaze 1 <sup>a</sup>	Glaze 2 <sup>b</sup>	Glaze 3 <sup>c</sup>
China Clay	6.00	7.04	Silica 20
Whiting	17.00	17.05	EPK Kaolin 20
Zinc Oxide	5.00	5.00	Wollastonite 20
Silica	25.00	25.84	Frit 3134 20
F-4 Feldspar	45.00	45.08	Custer Feldspar 20
Bentonite	2.00		
Clay Body	Standard #153		Standard #182

<sup>a</sup>Glaze 1 BG1 in Bailey 2001.  
<sup>b</sup>Glaze 2 is nearly identical to BG1 with minor changes in proportions of Ca, Mg, and K.  
<sup>c</sup>Glaze 3 is the 20X5 glaze from Digitalfire.com, I used EPK kaolin rather than Pioneer kaolin because I already had EPK kaolin.

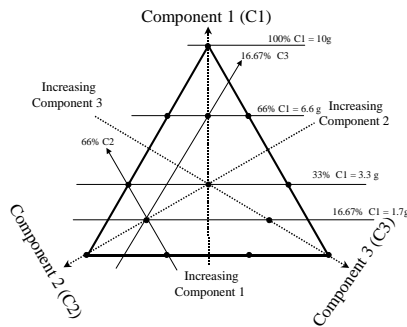


Figure 1: A triaxial blend with dots showing the locations of treatments, and associated weights for component 1 (assuming 100% of the total is 10 grams).

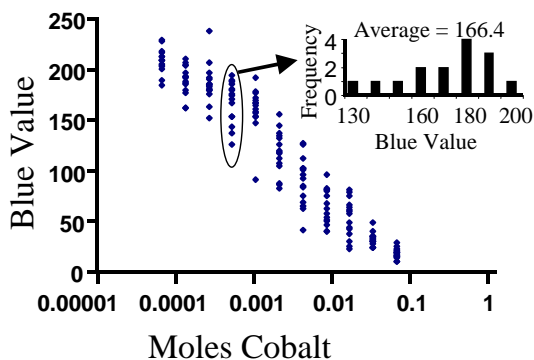


Figure 2. It would be difficult to take a ruler and draw a straight line through these data points. In this particular case, taking Figure 2: Predicting blue value based on cobalt concentration, and showing the variability in measurements about each concentration.

I continued this dilution process to get a range of concentrations from about 0.7 mole/kg down to 0.0007 moles/kg (11 test tiles): equivalent to a range of about 5.25 g down to 0.005 g cobalt oxide per 100 g glaze. The glaze was applied to test tiles made of Standard 182 clay body. The tiles were then fired in an electric kiln to cone 6. Each tile was then photographed using a digital camera, and viewed in Adobe Photoshop®.

Using the eyedropper tool, I selected individual pixels within a tile, and with the colour picker I found the red-green-blue (RGB) values for the pixel. I noticed differences in colour from pixel to pixel, even over short distances (a few pixels). This may be due to uneven mixing (only once through a 100 mesh screen), differences in glaze thickness, or possibly differences in how light reflected off the glossy but uneven surface (uneven under a microscope). Because of this variability in colour, there is no single number that will describe the glaze. The best we can do is to use the average colour of several pixels.

To predict the colour of these tiles we will need to have several observations of each test. In an ideal world, we would mix fresh batches of glaze for each observation, and fire them separately. These would then be replicates by the principles of statistics. However, this is too much work - at least for this project. I used one test tile per glaze mixture, took a digital picture, and measured the colour at several different places on the tile. Technically these are subsamples, or pseudoreplicates. However, using subsamples will not matter if I assume that I mixed the glaze perfectly, the kiln is of uniform temperature, and the kiln makes each firing exactly like all previous firings. The blue values for tile eight were taken at 100 points (Figure 2), that average to 166.4. The expected value for blue of 0.0005 moles of cobalt per 100 g glaze is 166.4. The other tiles were measured in the same way, but I used only 15 sample points.

The goal is to predict new outcomes, so we need to be able to find the expected value for a test tile that we have not made. A method of least squares linear regression does this. This is a fancy name for a simple process for calculating a line that best describes the data. This line is found by minimizing the squared distance from each data point to the line. A program like Excel will do linear regression (use the help function and search for linear regression or regression analysis). The data for all 11 tiles are shown in the  $\log_{10}$ (blue value) and plotting it on the  $\log_{10}$ (moles used per 100 grams) provides a straight line. In Excel, typing in  $=\log(\text{number})$  gives the  $\log_{10}$  of that number. Using the regression analysis feature in Excel, provides us with three important numbers. First, the “Adjusted R Square” is a measure of how much of the variability in our data is explained by our equation. The value is 0.91 which indicates that we have explained 91% of the variability in our data.

Second, there is a heading “Significance F”. This is a test of the hypothesis that there is no relationship between the blue value and the quantity of cobalt. This is called the null hypothesis, and the significance F is an estimate of the probability that we would find a set of data points by chance alone that would result in our model. The value is  $3.2 \times 10^{-89}$ . Scientists often decide their model is “significant” if the “Significance F” value is 0.05 or smaller and are usually content to report very small values as  $<0.001$ .

Significance in a statistical sense is nothing more than a point where someone decides that a mathematical model helps explain some observed trend. Third, we need the equation (Table 2). In this case the equation is  $\log_{10}(\text{blue value}) = 1.009 + (-0.35 \times \log_{10}(\text{moles cobalt}/100\text{g}))$ , or in Excel use  $=\text{power}(10, 1.009 + (-0.35 \times \log_{10}(\text{moles cobalt}/100\text{g})))$  to get the blue value. In Excel,  $=\text{power}(10, \text{number})$  is the opposite of  $=\log(\text{number})$ . The “moles cobalt/100 g” is often called the dependent variable because it is dependent on other variables. The “blue value” is the independent variable in this equation. Dependent variables always are on the left side of the equal sign. The equations for red and green were obtained by following the same process, with results shown in Table 2. The results for all three colours were then estimated for specific concentrations of cobalt from 0.00005 to 0.01 moles per 100 grams. Figure 3A is a picture of the test tiles and Figure 3B shows the predicted colour based on the equations in Table 2.

#### STATISTICS: MIXTURE DESIGNS

Simple linear regression uses one explanatory variable. Multiple linear regression is based on the same principles but uses more than one explanatory variable (often called independent variables by statisticians). Mixture designs are a special case of multiple regression. It is important for this project to understand the difference between a mixture design and multiple regression because we need a program that will analyze mixture designs. Some statistics programs have trouble dealing with mixture designs, or can analyze the data only with the purchase of a special enhanced version. If someone wanted to see how mixture designs work without having to generate a triaxial blend, go to

“<http://www.duncanceramics.com/ceramics/projects/project.asp?ID=5365&SID=9>” where a very nice picture of a triaxial blend can be downloaded as a JPG file and picked up in Photoshop. Or, search the world wide web for web pages on triaxial blends and find another image.

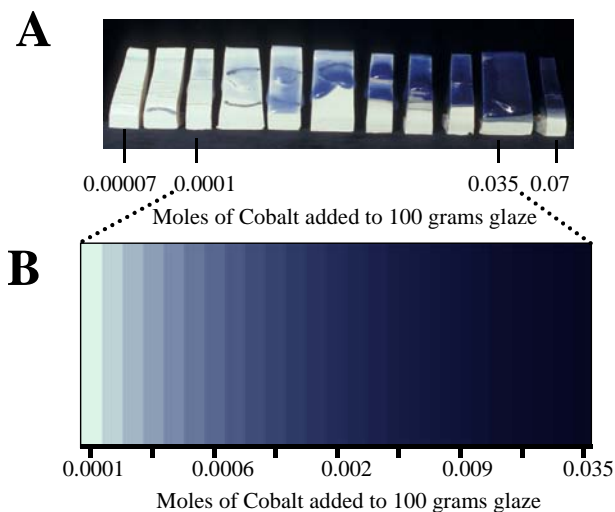


Figure 3: The test tiles (A) and the predicted RGB color (B). Note the scale in each figure is not linear so that the difference between two consecutive observations is smaller on the left side relative to the right side.

We now know that the digital description of colour is related to the quantity of cobalt. We also have a basic understanding of linear regression. Finally, a visual inspection of the tiles showed that the glaze was nearly saturated at between 0.01 and 0.03 moles/100 grams. We chose 0.02 moles as our total to look at the effects of blends of colourants on glaze colour.

Simple linear regression is the name for models with one variable that we want to predict (colour) and one variable that we want to use to explain differences in colour (cobalt concentration). In this case we have done three simple linear regressions, one for each colour.

Table 2: Equations relating RGB values to cobalt concentration.

Note: in the equation $y=mx+b$ where x and y are variables, the line crosses the y axis of the graph at the intercept b, and m is the change in y as x changes which is the slope.			Coefficients	R <sup>2</sup>	Significance F
	Red	Intercept	-0.24518	0.89	<0.001
	Slope	-0.67095			
Green	Intercept	-0.032	0.87	<0.001	
	Slope	-0.62744			
Blue	Intercept	1.009202	0.84	<0.001	
	Slope	-0.35167			

#### DIGITIZING COLOUR

In digitizing colour everything makes a difference. The quality and intensity and uniformity of light alters the perceived colour. A flatbed scanner will keep these variables fairly constant, but the quality of light changes a bit as the bulb ages or the scanner gets dirty.

For best results, the scanner will need to be calibrated for colour. Slide or Print film can be used, and filters are available to correct the slide colour for incandescent or fluorescent lights. However, film will need to be scanned. So the colour will be a function of the film, any filters, the light source, scanner quality, and scanner calibration.

Digital cameras are good, but sometimes it is difficult to get good colour reproduction either because of the way the camera digitizes colour or because of lighting problems. All of these issues can be overcome by buying better equipment, proper calibration, digital colour adjustment, or just more experience in dealing with a particular piece of equipment. The bottom line is that the numerical representation of colour will be different depending on the person and equipment used to photograph the colour. Among other things, this means that if you scan in one of the pictures from this article and redo the analysis you will not get the same numbers. Studying these effects could occupy a lifetime, but this is not necessary to get the process to work.

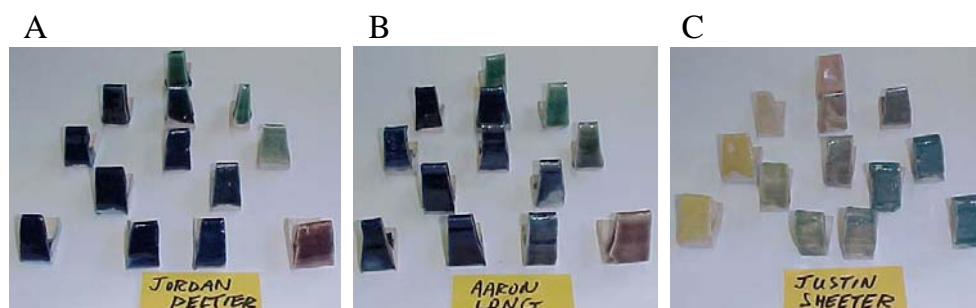
Multiple regression is where there is more than one independent variable. It is necessary that the independent variables are independent from one another. For example: "plant growth" = "fertilizer applied" + "rainfall" is an experiment in multiple regression because the quantity of fertilizer applied to a field will not affect rainfall - they are independent. In our case this assumption is false. If we add 0.02 moles of colourant to the glaze, we might have 0.02 moles of cobalt but no other colourant (100% cobalt). However we could have 0.01 moles cobalt and 0.01 moles iron (50-50% cobalt-iron), or 0.01 moles iron and 0.005 moles cobalt and 0.005 moles copper (50-25-25% iron-cobalt-copper). Adding a bit more of one colourant results in a decline of some other colourant to keep the total addition to 0.02 moles. This is a mixture design problem. A mixture design is only useful when the sum of the independent variables equals a fixed total. The independent variables in this case are referred to as mixture variables, and the contribution of each mixture variable is expressed as a percentage of the total. In mixture models, the analysis is done using polynomial regression. In mixture problems, the polynomial equation may have a linear component, a quadratic component, and a cubic component. A linear equation (or the linear component of a cubic equation) means that one could take a ruler and draw a line through the data points. If the best fit requires an inflexion point (a place where the straight line bends), a quadratic equation will provide the best fit. If the best fit requires two additional inflexion points, a cubic model will work best. I selected data points for the analysis of a cubic model (Figure 1). This will always work, but if the best model is not cubic you will have made more tests than necessary.

The class made a large batch of each base glaze and measured by volume the right quantity of glaze to use in each of their 13 batches. The key step in this procedure is to measure the quantity of water added to the dry glaze. For Glaze 1 they used 3 liters of water with 4.2 kg of dry glaze, so the mix is 58.3% glaze by weight. Using a syringe, they sucked up 20 ml of glaze and weighed it on a balance at 30.7 grams. So there was 0.895 grams dry glaze per ml of wet glaze, and it will take 112 ml to get the equivalent of 100 grams dry glaze per test batch. A similar approach was used to get 100 grams equivalent dry glaze per test with the other glazes. To this 100 grams was added either 10 grams of stain, or 0.02 moles of metal as shown in Table 3 (note: I made a mistake here because I used the molecular weight for manganese dioxide rather than manganese carbonate, so they used 1.16 grams as 100% rather than 1.53 grams). 100% copper carbonate was 1.87 grams, while 100% of cobalt carbonate was 2.38 grams. Treatments are calculated by taking the percentages of each to make 100% of the total as shown in Figure 1.

Sam Sheller had 7 advanced ceramics students in his spring 2004 pottery class. The class made bisqued test tiles before mixing glazes. The students started the project by selecting three colourants (Table 3). The class then mixed up 2 different clear glazes (Table 1).

Table 3: The students and their colourants.

Student	Clear Glaze	The Total	Colourants
Eric Beichler	2	10 g	Orange, Black, Green
Eric Horst	2	10 g	Dark Green, Crimson, Light Green
Aaron Long	1	0.02 moles	Copper Carbonate, Cobalt Carbonate, Manganese Carbonate
Benjamin Marty	1	10 g	Crimson, Pink, Blue Green
Jordan Peltier	2	0.02 moles	Copper Carbonate, Cobalt Carbonate, Manganese Carbonate
Kathrine Sheehan	1	10 g	Blue, Yellow, Green
Justin Sheeter	2	10 g	Orange, Yellow, Green



## RESULTS

Students used a one megapixel digital camera with a blend of natural light and overhead fluorescent lights to take pictures of the test tiles. Figure 4 shows the results from 3 of the student projects. Three pixels per tile were selected, and their RGB values written down. These values were then entered by hand into Excel®, and the Excel worksheet was pasted into Design-Expert®. Design-Expert® is the program we used for data analysis (see end of article for more detail).

The output to focus on is the same with mixture models as it was with simple linear regression: “Significance F”, “Adjusted R<sup>2</sup>”, and the regression coefficients. “Significance F” is not the usual heading in most statistics programs. Usually it is a shortened version of probability of greater F, which in Design-Expert is “Prob>F.” We also looked at two additional statistics: “Lack of Fit”, and “Signal to Noise ratio.” The “Lack of Fit” tests the null hypothesis that the model fits the data. Ideally it should, but having a significant “Lack of fit” test does not instantly make the model bad. Another way to look at the quality of the model is the signal to noise ratio. The output from Design-Expert states that anything greater than 4 indicates that the model is a good predictor of new outcomes.

Table 4: Model performance predicting colour based on colourant blend<sup>a</sup>.

Student	Eric Beichler			Eric Horst		
Colour	Red	Green	Blue	Red	Green	Blue
Model	Cubic	Cubic	Quadratic	Cubic	Cubic	Quadratic
Prob>F	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
R2	0.90	0.89	0.86	0.90	0.48	0.42
Lack of Fit	0.08	0.28	0.28	0.26	0.15	0.13
Signal:Noise	26	20	22	20	11	10
Student	Aaron Long			Ben Marty		
Colour	Red	Green	Red	Red	Green	Blue
Model	Quadratic	Quadratic	Cubic	Cubic	Quadratic	Cubic
Prob>F	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
R2	0.68	0.69	0.96	0.96	0.95	0.89
Lack of Fit	0.03	0.01	0.34	0.34	0.75	0.14
Signal:Noise	17	15	37	37	39	24
Student	Jordan Peltier			Kate Sheehan		
Colour	Red	Green	Blue	Red	Green	Blue
Model	Cubic	Cubic	Cubic	Cubic	Cubic	Cubic
Prob>F	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
R2	0.82	0.87	0.82	0.96	0.97	0.92
Lack of Fit	0.00	0.00	0.04	<0.001	<0.001	0.07
Signal:Noise	14	17	15	30	32	21
Student	Justin Sheeter					
Colour	Red	Green	Blue			
Model	Cubic	Cubic	Cubic			
Prob>F	<0.001	<0.001	<0.001			
R2	0.95	0.88	0.44			
Lack of Fit	0.68	0.75	0.62			
Signal:Noise	33	20	8			

**PROJECT TIME COMMITMENT**

This activity took eight 90 minute periods. This included one period to describe the project and weigh out the base glaze. Four periods to select the colourants, weigh them, and mix them. Three periods to gather the data and analyze the results. This time could have been reduced but seven students had to share three balances, two sieves, and one computer.

All models have a very high signal to noise ratio and a high adjusted  $R^2$  (Table 4). For these reasons I did not transform any of the variables, and so far have not found a transformation necessary. However, Design-Expert<sup>®</sup> provides a list of transformations. The log transformation may be useful with some data sets. It may also makes some sense to try the Logit transformation because all RGB values are bounded between 0 and 255. The list of specific reasons for choosing a transformation exceed the scope of this article.

In table four the regression coefficients have been omitted because the specific values are unique to the set-up in Sam Sheller's studio. The method in this project is universal, but the specific results are unique to an individual because the results depend on equipment and lighting differences.

All of the students did a good job with this project. The set of 13 test tiles requires weighing out each of the colourants nine times, weighing them correctly, and putting the sample into the correct container. If someone makes a mistake, it can be detected using the statistics program. In Design-Expert<sup>®</sup>, there is a section called diagnostics. This module will produce two useful plots: a normal probability plot, and a plot of the observed value versus the expected value based on the regression. A mistake will show up in these plots

Table 5: Model performance for predicting colour based on the quantity of cobalt, copper, iron, and titanium in the glaze.

Colour	Red	Green	Blue
Model	Cubic	Cubic	Quadratic
P > F	<0.001	<0.001	<0.001
R2	0.96	0.95	0.68
Lack of Fit	<0.001	0.003	0.143
Signal:Noise	34	29	20

as a small group of data points that are far from the other data points. For example, Figure 5 is a plot of the predicted versus observed values. If a set of data points were to be seen near the letter A, one might question their validity. No such points exist, in any of the data sets.

#### A QUADRAXIAL BLEND

The project worked well for triaxial blends, but often there are more than three colourants required to get a specific colour. I decided to try a quadraxial blend. A quadraxial blend is still a mixture design problem. Each of the four mixture variables goes from 0% to 100%. As such it is best viewed as a tetrahedron. I decided to use cobalt carbonate ( $\text{CoCO}_3$ ), black copper oxide ( $\text{CuO}$ ), black iron oxide ( $\text{FeO}$ ), and rutile (mostly  $\text{TiO}_2$ ) mixed with Glaze 3 (Table 1). Like with the triaxial blend (Figure 1), treatments consist of vertices, thirds of edges, a central point, and point 1/3 the way to the opposite face along a line that passes through the center - for a total of 20 blends. Table 5 shows the model output for the quadraxial blend.

#### CONCLUSION

While this project worked very well, there is a great deal that I have left out. Linear regression models make some assumptions about the data. These assumptions were not discussed, nor were the statistical tests for these assumptions performed by the class. However, most programs for statistical analysis provide options for making these tests. Exploring the output and options in these programs would be a good way to introduce additional topics like “what is the validity of the sampling approach used in the tests,” and “are three samples too many or too few?” With the right program, one could also explore the affect of changing the number of moles using models that combine process variables and mixture variables.

#### LITERATURE

Bailey, M. 2001. *Glazes cone 6 1240 C/2264 F*. A&C Black. London. 128 pp.  
 Cornel, J. 1990. *Experiments with mixtures: designs, models, and the analysis of mixture data*. Wiley-Interscience. New York. 632 pp.

Note: Sam Sheller had instructed his students in glaze safety before the class worked on this project. Glaze materials are breathing hazards and heavy metals can be absorbed through the skin. Everyone wore protective clothing.

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Dr. Timothy Ebert is an entomologist and a practicing potter. He has a particular interest in how science can enhance art. He thanks Sam Sheller for his participation in this project. He also thanks the students: Eric Beichler, Eric Horst, Aaron Long, Ben Marty, Jordan Peltier, Kate Sheehan, and Justin Sheeter. Without their enthusiastic help, this project would not have been possible.

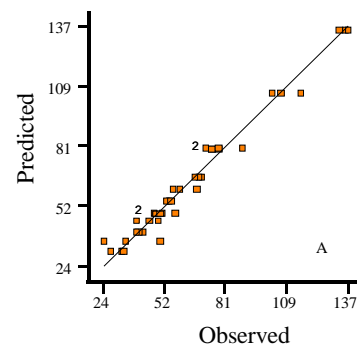


Figure 5: A plot of predicted versus observed for the colour red from Benjamin Marty's data. Point A is an example of an outlier and could indicate bad data if it exists.

#### SPECIAL EQUIPMENT LIST:

- 1) Adobe Photoshop® (Adobe Inc. at [www.adobe.com](http://www.adobe.com)), or equivalent program that will let you describe colour in some way. Common methods are RGB, CYMK, HSB, and Lab. RGB is how a CRT television screen represents colour. CYMK is how printers represent colour.
- 2) Design-Expert® (Stat-Ease Inc. at [www.statease.com](http://www.statease.com)), or equivalent software that will analyze mixture designs. Statistica, and some other packages will work. Statsoft, and possibly other companies provide free trial versions of their program. If the program works for you, please buy it and thereby encourage companies to keep free trials available for others.
- 3) Digital camera, or film camera and slide scanner, or flatbed scanner.
- 4) It is useful to have a program like Excel® (Microsoft Inc. at [www.microsoft.com](http://www.microsoft.com)). A spreadsheet can help with calculations, and keeping track of data. Excel® can also be used to do some data analysis.