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An Investigation of the Effects of Aggregate Replacement with Pottery Cull in Concrete

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ABSTRACT

The Kohler Company manufactures a wide range of kitchen and bathroom fixtures worldwide. Their products are of the best possible quality. All products that do not meet their high standards are rejected. The rejected products are collected in a landfill at a rate of nearly 3,300 metric tons per month. This waste is known as pottery cull. The purpose of this paper is to determine if pottery cull can become a viable substitute for fine and coarse aggregate in concrete. For this research, pottery cull was used to replace natural fine and coarse aggregates at 15, 35, 50, and 100 percent levels. The concrete was then tested for compressive strength at 7, 14, 28 and 56 days. The results of the experiment showed that pottery cull is suitable for aggregate replacement in concrete. It is recommended that more research be done for alkali silica reactions, and freeze-thaw and abrasive durability.

Keywords. Pottery cull, aggregate, replacement, concrete, strength.

INTRODUCTION

The Kohler Company in Kohler, Wisconsin, is a world-known manufacturer of kitchen and bathroom fixture products. The Kohler Company strives for customer satisfaction and maintains high quality control. During several phases of the manufacturing process, Kohler inspects the products, and those that do not pass are removed from the production line. Roughly 30% of all pottery pieces produced for kitchen and bathroom products do not meet their quality control standards. (Lieffring, 2010). All rejected products are then sent to a Kohler landfill. This material is called pottery cull.

The Kohler-owned landfill ships out the majority of its pottery cull waste to assist as a sub-base layer for roadways, parking lots, concrete slabs, and backfill (Wisconsin, 1998). Kohler engineer, Craig Lieffring, explains that they have found other companies that will take pottery cull and crush it for use in their own production of concrete block (Lieffring, 2010). The Kohler Company owns multiple landfills throughout the world, and only a few recycle the pottery cull shipped there (Lieffring, 2010). This results in the use of more landfill space, and does not contribute towards bettering the environment. Pottery Cull's current usage as a sub-base layer reflects on the location of the landfills; it is cost prohibitive for Kohler to crush and ship cull to distant job sites.

As a result, new uses for manufactured aggregates must be discovered, tested, and implemented for concrete mix designs.

Concrete construction has been used for centuries and will certainly continue to be used in the future. In today's industry, the use of recycled materials in concrete has evolved and they have become common admixtures in concrete mixes. If pottery cull were to replace coarse and fine aggregate within concrete, there would be a new market for this Kohler byproduct.

The goal and hypothesis of this research is to show that pottery cull is an adequate fine and coarse aggregate replacement in concrete. Through multiple concrete mix designs, an attempt will be made to determine the point at which the maximum percentage of pottery cull replacement is acceptable without affecting the concrete compressive strength.

MATERIAL BACKGROUND

It has been found that pottery cull can be ground down to a powder to be used as a replacement for portland cement in mortar (Lieffring, 2010). However, because the cost of producing this fine material is more than the cost of portland cement itself, it is not economical to use it as a substitute. Cull has more potential to be used as coarse and fine aggregate replacement in concrete because it does not require as much grinding and preparation. Fine pottery cull aggregate consists of grains ranging between 0.0625 to 0.2 millimeters. Coarse pottery cull aggregate consists of particles having a size range between 4.75 to 19.10 millimeters.

Alkali silica reactions (ASR) are a common occurrence in many types of recycled concrete mixes. It has been found that recycled glass heavily contributes to ASR (Polley, Cramer and del la Cruz, 1998). Alkali Silica Reaction occurs when a reactive silica aggregate reacts with alkali, slowly expanding while reacting, creating internal stresses, which ultimately causes the concrete to break apart. The difference between ASR and a pozzolanic reaction is that ASR usually occurs in mature concrete because of its slow reaction period, while pozzolanic reaction occurs within the first few months after mixing (Dyer and Dhir, 2001).

EXPERIMENTAL SETUP

ASTM C39/C39M "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" was used as a guideline for this experiment (ASTM, 2009c). With the use of a concrete testing machine, a continual compressive force acted on the concrete cylinders until a point of fracture was apparent. During compression, this machine had the capability of recording the peak compressive force for each cylinder, making it easy to convert force into a compressive strength for the concrete cylinder. This is done by dividing the compressive force by the cross-sectional area of the concrete cylinder. Three cylinders from each concrete mix design were tested at 7, 14, 28, and 56 day intervals.

To ensure accurate and consistent data collection, ASTM C617 "Standard Practice for Capping Cylindrical Concrete Specimens" was used (ASTM, 2009a). Compliance with this ASTM standard in the testing of all concrete cylinders ensured that force acting upon the cylinder is uniform, and all stresses in the cylinder act parallel to the direction of the force. This resulted in receiving more accurate fracture path characteristics for all concrete cylinders.

Seventy-two cylinders were mixed on February 10th, 2011 and eighty-four cylinders were mixed on February 14th, 2011 in Milwaukee School of Engineering's (MSOE's) Construction Science and Engineering Center Lab. Including control batches, which used no cull replacement, a total of 156 cylinders were made. Standard 76 mm [3 inch] diameter plastic cylinder molds were used to mold all concrete specimens.

On the 28th day test, all concrete samples were further analyzed using a compressometer to determine the concrete's Modulus of Elasticity and Poisson's Ratio. A compressometer uses two displacement-measuring instruments (LVDT) that take displacement readings in the axial and lateral directions. ASTM C469 "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression" recommends the use of a compressometer when determining these two values (ASTM, 2010). The compressometer was then placed in the concrete testing machine to be tested for maximum compression. Measuring all displacements and forces electronically, made it possible to plot a stress-strain curve using Microsoft Excel. From these data, the Modulus of Elasticity and Poisson's Ratio were calculated using equations presented in ASTM C469. By performing this test, one can further determine if pottery cull aggregate substitution affects the physical properties of concrete.

All material and liquid measurements were made using an electronic scale. A small electric concrete mixer was used to mix each concrete batch. All twelve concrete cylinders per mix design were molded from one batch of concrete. Two control groups were added to the project to further examine the compressive strength effects of adding pottery cull to a concrete mix. Control A consists of a normal concrete mix design consisting of no admixtures. Control B is identical to Control A, except class F fly ash was used to replace 30% of cement. Since fly ash is a common admixture in today's concrete and will be used in all concrete mix designs, Control B group was used to compare all pottery cull replacement levels.

All mix designs presented in this paper were designed using ACI 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete" (ACI Committee 211, 1991). The design is set to yield a concrete compressive strength of 41.4 MPa [6000 psi]. A volume replacement method was used to replace specific quantities of pottery cull in each mix design.

All molds were filled in two layers, and were tamped twenty-five times with a 15.875 mm [5/8 inch] diameter cylindrical rod. Upon filling and tamping the concrete molds, they were capped with a plastic cap and stored in a large plastic container. To ensure compliance with ASTM C192, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory", plastic molds were stored for twenty-four hours, and then removed from the concrete cylinders (ASTM, 2009b). They were then immediately stored in a water tank until they were tested.

Two control batches were made that included no replacement of fine or coarse pottery cull. Control A consisted of no admixtures, while Control B consisted of 30% replacement of cement with Class F Fly Ash. A total of 12 cylinders were made for each batch, where three cylinders per break period were tested.

Four batches of fine cull replacement were made. Each batch contained fine cull replacement of 15%, 35%, 50%, and 100%, respectively. A total of 48 cylinders were made for all four batches. Twelve cylinders were dedicated for each percentage of cull replacement. Three of the twelve cylinders were tested per each break period.

Four batches of coarse cull replacement were made. Each batch contained coarse cull replacement of 15%, 35%, 50%, and 100%, respectively. A total of 48 cylinders were made for all four batches. Twelve cylinders were dedicated for each percentage of cull replacement. Three of the twelve cylinders were tested per each break period.

The last three batches contained a mix of both fine and coarse cull replacement. Each batch contained fine and coarse cull replacement of 15%, 35%, and 50%, respectively. A total of 36 cylinders were made for all three batches. Twelve cylinders were dedicated for each percentage of cull replacement. Three of the twelve cylinders were tested per each break period. As a result, a total of 156 cylinders with varying fine and coarse pottery cull replacements were made for this experiment.

Prior to mixing the concrete, it was observed that both fine and coarse pottery cull particles were more angular in shape than natural coarse and fine aggregate particles. This was viewed positively as angular aggregates might have a better interlocking effect in the concrete mix. A drawback to having angular aggregate is that it will absorb more water, which will affect water-to-cement ratios in concrete. In order to prevent extra absorption by these aggregates, all pottery cull aggregate was fully immersed in water for 24 hours and left to surface dry prior to mixing the concrete batches. Even though the pottery cull was soaked, it still absorbed extra water during the mix, resulting in a dry and unworkable mix. Since this was a unexpected characteristic of pottery cull and there were no water reducing admixtures available, extra water was added to achieve a workable concrete mix. Performing this task has shown that pottery cull has the ability to absorb an abundant amount of water. When it comes to achieving a good water to cement ratio, this may be a compromising characteristic that needs to be remediated with the use of a water reducing admixture rather than adding extra water. Table 1 reflects the actual mix design including any extra water added to the concrete.

Table 1. Fine, Coarse, and Fine/Coarse Cull Replacement Actual Mix Designs

Mix Design	Water (kg) [lb]	Cement (kg) [lb]	Fly Ash (kg) [lb]	FA (kg) [lb]	Fine Cull (kg) [lb]	CA (kg) [lb]	Coarse Cull (kg) [lb]
CA	3.0 [6.7]	7.0 [15.4]	0.0 [0.0]	10.7 [23.6]	0.0 [0.0]	14.0 [30.8]	0.0 [0.0]
CB	3.2 [7.0]	4.9 [10.7]	2.6 [5.8]	10.7 [23.6]	0.0 [0.0]	14.0 [30.8]	0.0 [0.0]
F15	3.0 [6.7]	4.9 [10.7]	2.6 [5.8]	9.1 [20.0]	1.5 [3.3]	14.0 [30.8]	0.0 [0.0]
F35	3.0 [6.7]	4.9 [10.7]	2.6 [5.8]	6.9 [15.3]	3.5 [7.7]	14.0 [30.8]	0.0 [0.0]
F50	2.9 [6.4]	4.9 [10.7]	2.6 [5.8]	5.3 [11.8]	5.0 [10.9]	14.0 [30.8]	0.0 [0.0]
F100	2.8 [6.2]	4.9 [10.7]	2.6 [5.8]	0.0 [0.0]	9.9 [21.9]	14.0 [30.8]	0.0 [0.0]
C15	3.0 [6.7]	4.9 [10.7]	2.6 [5.8]	10.7 [23.6]	0.0 [0.0]	11.9 [26.2]	1.9 [4.2]

C35	2.9 [6.4]	4.9 [10.7]	2.6 [5.8]	10.7 [23.6]	0.0 [0.0]	9.1 [20.0]	4.5 [9.9]
C50	2.9 [6.4]	4.9 [10.7]	2.6 [5.8]	10.7 [23.6]	0.0 [0.0]	7.0 [15.4]	6.4 [14.1]
C100	2.8 [6.3]	4.9 [10.7]	2.6 [5.8]	10.7 [23.6]	0.0 [0.0]	0.0 [0.0]	12.8 [28.2]
FC15	2.8 [6.3]	4.9 [10.7]	2.6 [5.8]	9.1 [20.0]	1.5 [3.3]	11.9 [26.2]	1.9 [4.2]
FC35	2.8 [6.3]	4.9 [10.7]	2.6 [5.8]	6.9 [15.3]	3.5 [7.7]	9.1 [20.0]	4.5 [9.9]
FC50	2.8 [6.3]	4.9 [10.7]	2.6 [5.8]	5.3 [11.8]	5.0 [10.9]	7.0 [15.4]	6.4 [14.1]

An average of 0.35 water-to-cement ratio was achieved for each mix design, yielding a slump range between 25.4 [1 inch] to 76.2 [3 inches] millimeters.

Peak force for all concrete cylinders was measured and recorded using the compression tester. Compressive stresses were then determined by dividing the peak force by the cross-sectional area of the concrete specimen. In all compressive strength figures, the data points represent an average of three compressive strength results from the three specimens.

RESULTS

As described earlier, fine pottery cull contains angular aggregate, and extra finer particles in the form of powder. It can be seen that increasing fine aggregate replacement up to the 100% level has little effect on the concrete's compressive strength. All mix designs reached the necessary 41.4 MPa [6000 psi] concrete compressive strength at the 28-day test. Towards the 56-day test, all concrete mix designs seem to converge together, adding an extra 6.9 MPa [1000 psi] to its compressive strength. Compared to Control B, fine aggregate replacement with fine pottery cull yielded a compressive strength increase of 7.5%. Overall, there is little variation when replacing fine aggregate with pottery cull at any percentage level. It can be concluded that fine pottery cull powder particles may have acted as extra supplementary cementitious material (SCM). As a result, this extra cementitious material may have contributed to giving the mix design extra strength in the concrete. These results are shown in Figure 1.

Similar to fine pottery cull, coarse pottery cull contains angular aggregates that create an interlocking affect in the concrete mix. Many natural coarse aggregates are rounded which may prevent aggregates from interlocking with each other. This interlocking affect may give the concrete mixed with cull a higher compressive strength than with natural aggregates. However, the coarse cull also often has faces that have a very smooth glass-like finish. This could decrease the strength. These two features seem to balance each other out. It can be seen that increasing coarse aggregate replacement up to the 100% level has little effect on the concrete's compressive strength. All mix designs, except for C15 and C100, reached the necessary 41.4 MPA [6000 psi] concrete compressive strength at the 28-day test. C15 and C100 did not reach 41.4 MPa [6000 psi] until the 56-day test. Overall, all mix designs presented in Figure 2 have little variation, and exhibit the same compressive strength characteristics. Compared to Control B, coarse aggregate replacement with coarse pottery cull increased the concrete's compressive strength by 4%. This is roughly half the compressive strength increase seen when replacing fine aggregate with fine pottery cull.

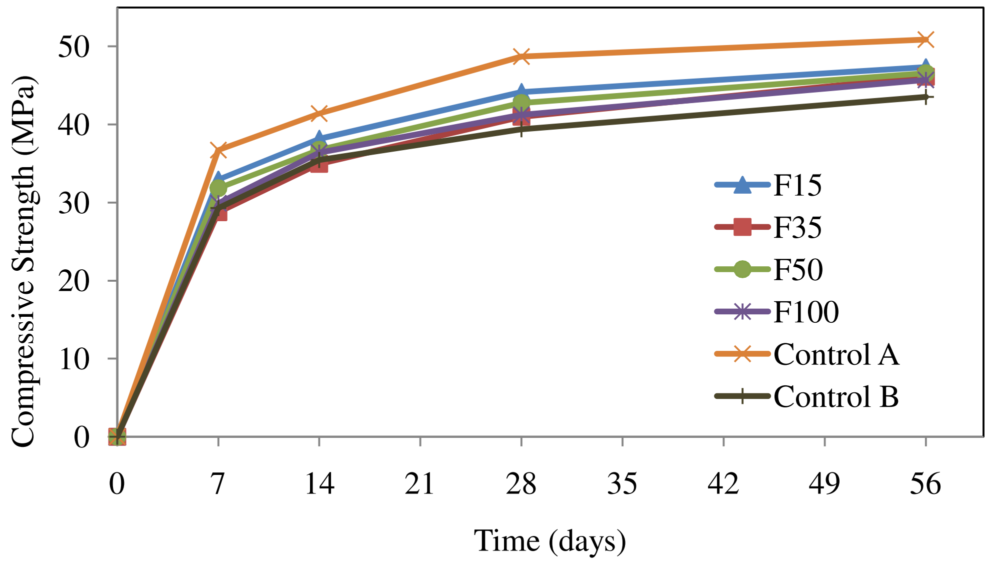

Figure 1. Fine Aggregate Replacement Compressive Strengths

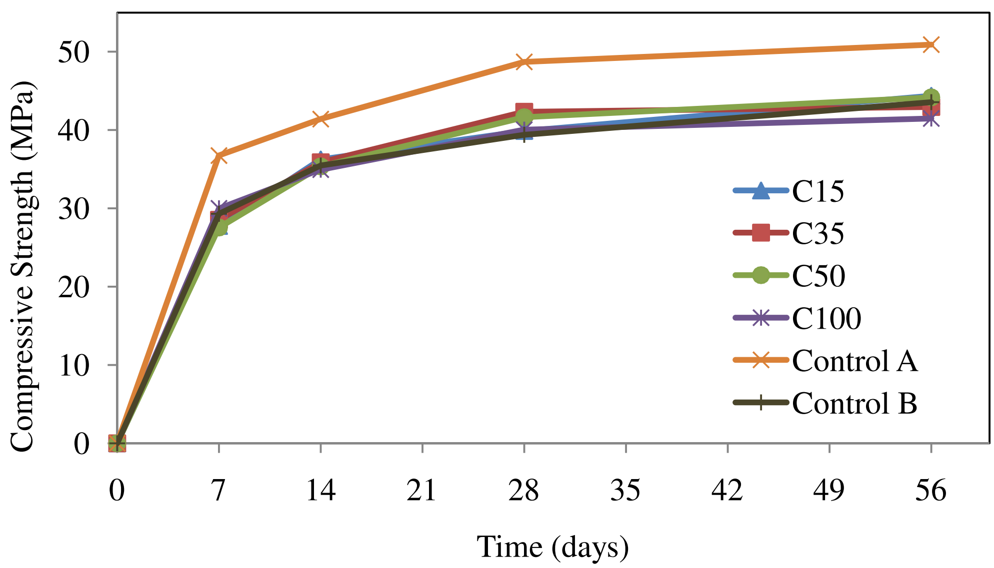

Figure 2. Coarse Aggregate Replacement Compressive Strengths

To further quantify that fine pottery cull increases the compressive strength of concrete, compression tests were run for mixtures of both fine and coarse pottery cull replacement. These showed that increasing both fine and coarse aggregate replacement up to the 50% level had little effect on the compressive strength. All mix designs reached the necessary 41.4 MPa [6000 psi] concrete compressive strength at the 28-day test. As predicted earlier, adding fine pottery cull replacement in these mix designs added extra strength to the concrete. This same relationship was shown when replacing only fine aggregate in the concrete mixes in Figure 1. Compared to Control B, fine and coarse aggregate replacement with pottery cull increased the concrete's compressive strength by 9%. These comparisons are seen in Figure 3.

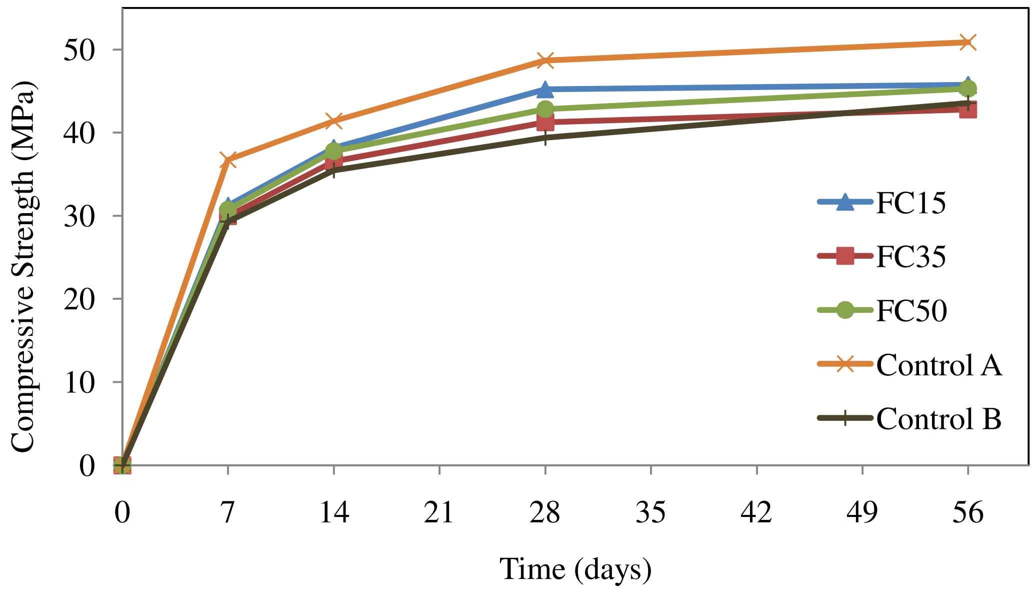

Figure 3. Fine & Coarse Aggregate Replacement Compressive Strengths

In this experiment, it was shown that pottery cull could replace both fine aggregate and coarse aggregate in concrete without having any negative effects to the compressive strength. As reported earlier, replacing fine aggregate increased the compressive strength of the concrete by 7.5%. Finer particles were found in fine pottery cull, resulting in an increase in SCM's and compressive strengths in the concrete mix. Coarse aggregate replacement resulted in similar compressive strengths of Control B mix design, but still increased the concrete's compressive strength by 4%. Lastly, combined fine and coarse aggregate replacement resulted in similar compressive strength results as fine aggregate replacement, increasing the compressive strength by 9% compared to Control B. Overall, it can be concluded that replacing natural limestone aggregate and sand with pottery cull has no negative effects on the concrete's compressive strength.

Stress-strain curves can also describe what is happening to the concrete cylinder during compression. During the loading process, one can accurately predict when the specimen is about to fail or reach its full capacity. For each mix design and sample for the 28-day test break, stress-strain curves were created to find similarities or differences between samples. This further shows that all samples are consistent, and that there are very few differences between them. A theoretical stress-strain curve known as the Modified Hognestad analytical model was also plotted to compare to the stress-strain curves.

It has been identified that the Modified Hognestad stress-strain curve has a maximum strain at 0.0022 when a 41.4 MPa [6000 psi] strength concrete theoretically fails. The majority of all stress-strain curves created for fine pottery cull replacements closely resemble that of the Modified Hognestad stress-strain curve. For each mix design for fine pottery cull replacement, there is only one mix design (F50) that yielded a lower strain value; otherwise, they all failed at a strain of 0.0022. Even though mix design F50 only achieved a strain of 0.0020, this value is essentially the same as the Modified Hognestad value.

Coarse pottery cull replacement stress-strain curves were also created to determine any similarities to the Modified Hognestad curve. This time only one out of the four mix designs resembled the Modified Hognestad strain value. The only mix design that was closely related to the Modified Hognestad Curve is mix design C15. As more coarse pottery cull aggregate was added to the mix design, the more brittle the concrete became.

Lastly, stress-strain curves were created for each mix design associated with replacing both fine and coarse aggregate with fine & coarse pottery cull. The majority of all stress-strain curves, except for FC15, closely resemble that of the Modified Hognestad stress-strain curve. Mix design FC15 yielded a higher strain value of 0.0023. This can still be said to be comparable to the Modified Hognestad curve; otherwise, the other two mix designs yielded a strain value of 0.0022.

These tests indicate that either fine replacement alone, or a combination of fine and coarse aggregate replacement with pottery cull in concrete will produce the best correlations with the Modified Hognestad Curve.

CONCLUSIONS

Based on the results of this research, pottery cull can be considered a viable substitute for both fine and coarse aggregates in up to 100% replacement ratios. The concrete produced was equal to the control group from both a strength and elasticity point of view. Additional research should be done to determine the aggregate's effect on alkali silica reactions and freeze-thaw resistance. In addition, its abrasive wear ability should also be assessed although there is no reason to assume the cull will not perform as well as natural aggregate. Once these tests are done, cost comparisons can be completed to determine the marketability of these products.

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