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Master's Thesis
Academic Year 2020

Testing Feasibility of Making Products with Recycled Ceramics

Keio University
Graduate School of Media Design

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A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Xiang Yu

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Abstract of Master's Thesis of Academic Year 2020

Testing Feasibility of Making Products with Recycled Ceramics

Category: Science / Engineering

Summary

With the incredible increasing number of plastic products produced over the years, plastic waste has made serious impact on the environment and other living species. Meanwhile, large amount of broken ceramics are wasted and dumped into landfills, disregarding their recycle potentials. This research paper explores the possibilities of replacing part of those plastic products with materials composed of recycled potteries. The research started with combining Portland cement and crushed potteries recycled from a local ceramic workshop.Later along with more literature reviewed, wood ash was added to test if it could be suitable for replacing cement as it is another wasted product with great recycling potential. The research contains two phases of experiments: making of materials and testing of their properties. The materials were divided into three groups with different levels of wood ash and crushed potteries content. Group 0 was control group and the subject was made by cement and dry sand. Group 1 subjects include 15, 30, 50, and 75 percentage of cement with wood ash, plus dry sand. Group 2 subjects contain 50, 75 and 100 percent replacement of dry sand with crushed potteries. After the materials were made, they were put through 3 individual property tests including water resistance, fire resistance and dropping tests. The result showed that although different level of wood ash or recycled potteries content had little effect on water and fire resistant ability in comparison to control subject, strength level varied drastically(50 and 75 percent wood ash were excluded from all tests since they broke during demolding process). In dropping test, as control group subjects managed to withstand at least 20 times of falling from 100cm height, wood ash subjects failed to demonstrate the same trait and the more wood ash content the more easily it broke(15 percent subject took 6 times to break and 30 percent broke right away at the first test). Yet crushed burnt clay maintain the same level of strength as 100 percent replacement with clay subject was also able to withstand at least 20 times of tests. It showed that cement-clay combination was able to create decent quality materials. To further prove the workability of creating products with such material, three rough prototypes were made put into real life use for a week. They were spatula, toothbrush and flash drive. After a week of actually using, no sign of breaking or severe disadvantage of occurred from prototypes made with such material. It preliminary concluded that it is possible to create sustainable materials using ordinary Portland cement with recycle ceramics and make products with it.

Keywords:

Sustainable Material, Experiments, Recycling, Ceramics, Cement, Wood Ash

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Chapter 1
Introduction

1.1. Background

1.1.1 Plastic Waste Crisis

As of 2015, about 7.8 billion tonnes of plastic was produced cumulatively, and only 19.50 percent of them were recycled and 25.50 percent of them were incinerated, leaving a good chunk of 55 percent to waste(Figure 1.1). All those plastic wastes will take decades or even hundreds of years to decompose. Fishing line and plastic bottles can take up to 600 and 450 years to break down(Figure 1.2). Therefore, with current rate of plastic production and no further actions taken, the number of plastic wastes accumulated can go up to 12 billion tonnes by 2050 [2], as the number increases exponentially.

These wastes are negatively affecting the earth and wildlife, and even can have potential impact on humans. Marine debris has been harmful to over 800 species of marine life [3], including sea animals and coral reefs [4]. Since these plastic debris eaten by various wildlife such as fish and shellfish that end up being seafood consumed by human, potentially with poison brought to our body as well. [5]

1.1.2 Japan's Struggle with Recycling

Back in 2004's G8 summit, Japan proposed "3R initiatives", which stands for reduce, reuse, and recycle to achieve a more material sustainable society [6]. Since then, Japan has been putting in efforts promoting and executing the initiatives, yet the results are mixed. Although Japan is know to have one of the strictest

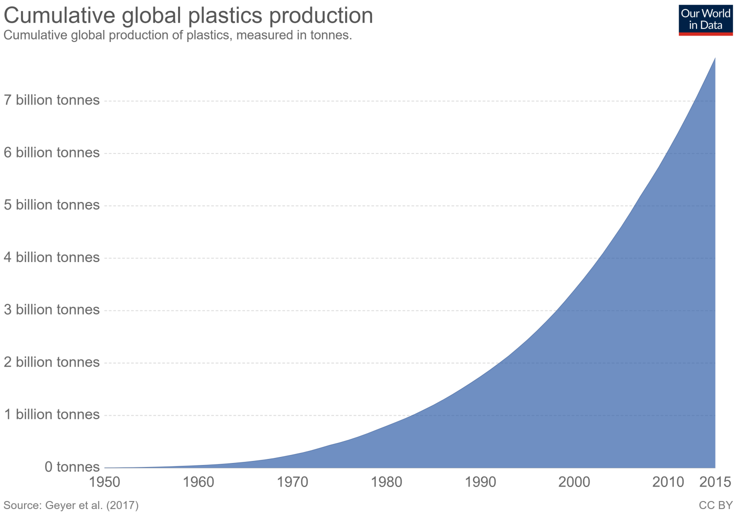

Figure 1.1 Cumulative Global Plastic Production

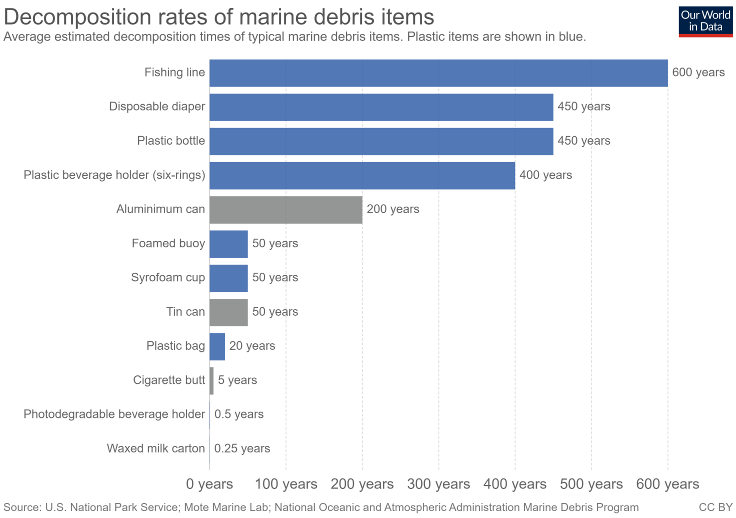

Figure 1.2 Decomposition Rates of Marine Debris Items

garbage sorting rules in the world, the domestic recycling rate is surprisingly low, as in 2017 only 20 percent of municipal waste was recycled, one of the lowest rate among OECD(Organisation for Economic Co-operation and Development) members [7].

As for plastic waste, the situation in Japan is not optimistic either. According to data provided by Plastic Waste Management Institute(PWMI), some progress to reduce plastic productions was made after 2005, but the results were marginal in recent years. From 2005 to 2009, the total plastic production in Japan went from 10060 kt to 9120 kt, dropped by around 10 percent, yet at 2018 the number still stand at 8910 kt, only about 2 percent less than the number in 2009 [1].

And although it was claimed that at 2018, 84 percent of plastic waste was recycled [1], it seems problematic when breaking down the statistics in details. In Japan, plastic recycling is classified into three categories: Mechanical recycling, feedstock recycling, and thermal recycling. Mechanical recycling is to create new plastic products through mechanically processing wasted plastics. Feedstock recycling is to process wasted plastics chemically and break them down into basic chemical components and create new raw materials. The third option is thermal recycling, which is basically burning plastics in exchange to energy. Only mechanical recycling and feedstock recycling are able to create reusable plastics from the wastes, and unfortunately the rate is low. Out of the "84 percent" recycled plastics, most of the number are contributed by thermal recycling, aka incineration for energy recovery. In 2018, 5020kt of plastics were incinerated for energy fuel, and only 2080 and 390 kt were recycled mechanically or chemically [1]. It means only about 27 percent of plastic wastes were recycled for reusing directly or indirectly. The rest of the recycled number came from incineration(56 percent), which is often not considered as "recycling" in many other countries. In comparison, EU identifies their incineration(with or without energy recovery) as a separate plastic waste treatment aside from recycling, which accounted for 39 and 30 percent of plastic waste in 2015 [8]. Whether incineration for energy is sustainable is questionable since even with gas collecting and filtering technology, nonetheless toxic pollutants, such as Dioxins, Furans and Mercury [9] from burning plastic are being released nonetheless, not to mention the CO2 gas emitted during the process.

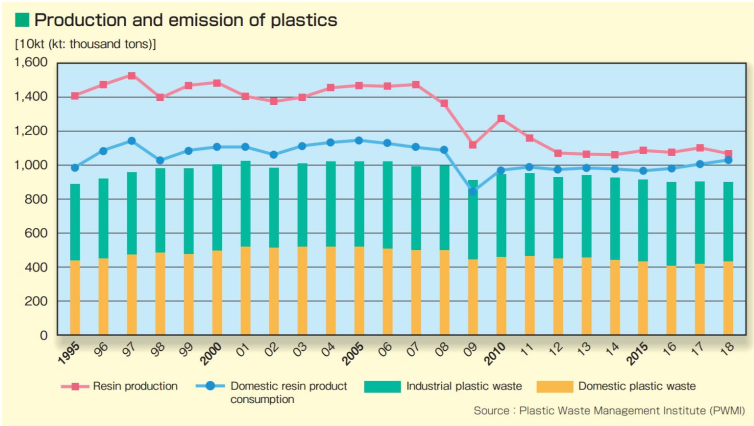

Figure 1.3 Plastic Production in Japan in Recent Years [1]

Trends in quantity and rate of effective utilization of plastic waste

(10 kt)

	Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total waste plastic emissions		1,006	1,005	994	998	912	945	952	929	940	926	915	899	903	891
Effective utilization	Mechanical recycling	185	204	213	214	200	217	212	204	203	199	205	206	211	208
	Feedstock recycling	29	28	29	25	32	42	36	38	30	34	36	36	40	39
	Thermal recycling	368	457	449	494	456	465	496	502	535	534	521	517	524	502
	Total	582	688	692	733	689	723	744	744	767	768	763	759	775	750
Effective utilization (%)		58	69	69	73	75	77	78	80	82	83	83	84	86	84

Source : Plastic Waste Management Institute (PWMI)

Figure 1.4 Utilization of Plastic Waste [1]

Moreover, a bigger challenge has yet to arrived for Japan dealing with plastic wastes. In addition to the plastics treated domestically, about 1500kt of more are exported overseas annually, mostly to China, to relieve the domestic waste problem [1]. However as of the end of 2017, China decided to ban imports of several waste including plastics [10]. Such act forces Japan to manage even more waste each year, and can potentially do more impact on its environment, air quality and landfill capacity. New actions need to be considered by Japan to face the upcoming challenge, and it should involve reducing plastic uses by replacing with more ECO-friendly materials, such as ceramics.

1.1.3 Ceramic as Substitution and Its own Problems

Ceramic is one of the decent candidates as a plastic substitution for its several good attributes as well as its ECO-friendliness. Ceramic products are generally very durable since they present good resistance to water, high heat and many hazard chemicals, as well as their hardness, making them perfect for kitchen and table ware. Ceramics usually have extremely long lifespan as the can possibly last centuries without corrosion. The oldest known ceramic artifact, Venus of Dolní Věstonice, can be dated back to 29,000 BCE [11]. Moreover, ceramics are made from various clays found in nature with little chemical processing, meaning such products is mostly harmless to the environment. Its longevity and pure natural components make ceramics a sustainable option as potential plastic replacement.

However two major setbacks of ceramics cannot be overseen. Production of ceramics requiring firing raw clay at extremely high temperature, during which create greenhouse gases(GHG), responsible for global climate change. It is estimated that yearly the emissions of GHG from ceramic production is over 400 million tons CO2 globally [12]. The addition GHG released from ceramic production has made it less credible as an ECO-friendly material. Meanwhile, although ceramics can endure extreme environments such as heat and acid, it is also known to be brittle and bad at taking impact. Once a ceramic is broken, it is very difficult to repair since it often breaks into pieces. Broken ceramics will be dumped and lead to another issue, landfill capacity stress.

Wasted ceramics are most likely disposed at landfills since they don't either burn or dissolve with chemicals. Ceramics make up 54 percent of the construction and demolition wastes, highest among all materials [13]. In Japan, broken glasses and ceramics are classified as incombustible waste and eventually go into landfills without recycling [14]. Since they are made from natural materials(clay and sand),they do not present harmful characteristics to the environment, yet they still take up a lot of spaces in landfills and further decrease Japan's landfill capacity that's already under pressure(around 20 years remaining) [15]. These ceramic wastes do not decompose and will stay at landfill for hundreds and thousands of years. And as more ceramic wastes are generated each year and disposed, more and more landfill spaces will be deprived, leading to landfill shortage eventually.

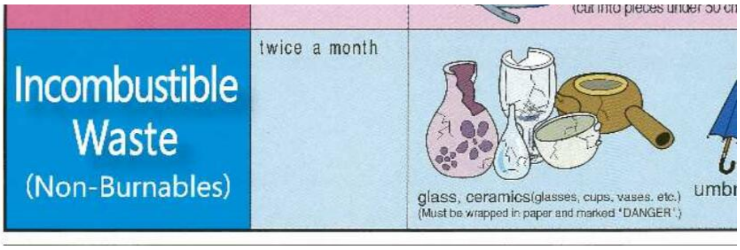

Figure 1.5 Broken Ceramics as Incombustible Waste in Arakawa City, Tokyo

1.2. Research Goals

1.2.1 Inspirations from Current Problems

- As Japan's "reuse" and "recycle" policies for plastics has hit a plateau in recent years, actions need to be taken to reduce plastic wastes. Ceramics can be selected as a replacement to reduce plastic products emissions.
- Although ceramics come from ECO-friendly materials, the production process releases sufficient amount of greenhouse gases, which might contribute to climate change.
- Large amount of ceramic wastes are also generated and dumped into landfills, pressuring Japan's landfill capacity. Yet in the meantime it is also an indication that large quantity of broken ceramics are available for recycle.
- These wasted ceramics could be a better option as plastic substitution, since these products do not need further burning in high temperature for hardening(no extra GHG emission).

1.2.2 Objectives

The objectives of this research were inspired by current situations of plastic and ceramic wastes in Japan, and to try to relieve both problems at the same time:

- To examine the possibility of creating materials with acceptable quality using recycled broken ceramics, in order to reduce ceramic wastes.
- To examine the possibility of making everyday products with such material which are generally produced with plastics, in order reduce plastic wastes.

1.2.3 Hypothesis

Typically a ceramic product fired at its raw clay stage with adequate amount of heat(800 degrees or above), and process gradually burns out any water content and make other components stick to each other tightly. For broken ceramics, firing is no longer effective thus additional glue, or binder is necessary to re-combine the pieces.

Therefore it is hypothesized that:

- Paired with a proper binding material, it is achievable to recycle broken ceramics and create a material, and such material can be used for creating products.

Chapter 2
Literature Review

2.1. Introduction

Similar approach can be found in production of concrete. Concrete, as a ceramic composite, is the most widely used material in construction industry, as the consumption number goes about 11 billion tonnes each year, and various reasons are demonstrated in Mehta and Monteiro's book, including its great water resistance, workability and economy aspect [16]. In comparison to wood and steel, concrete can withstand water for long without corrosion, thus little maintenance is needed. During making of concrete, material blend can be molded into different shapes and size, allowing them to be used for difference locations and purposes(such as a pillar vs a concrete block). Moreover, the cost of concrete is very low, as per cubic metre price ranges from 60-100 US dollars depending on transportation cost [16]. These excellent attributes not only allow concrete to play a vital role in construction industry, but also display possibility to be a part of everyday products.

Figure 2.1 Concrete in Different Shapes

Binder and aggregates are the key components of concrete. Ordinary Portland cement is commonly applied as the binding material for its inexpensiveness and accessibility across the world. Aggregates contain two different types: fine aggregate and coarse aggregate. Fine aggregates are materials whose particle size is below 4.75mm while coarse aggregate has the particles larger than 4.75mm. Nature sand is the most common fine aggregate and gravel/crushed stone is most common for coarse aggregate. Although these resources are generally available across the world and can be accessed at a low price, they are not unlimited. The demand for sand and gravels is very high, even exceeding fossil fuels [17]. The amount of river sand and gravel evacuated each year is beyond the renewal rate from nature [18].

2.2. Clay as Aggregate Replacement

Even though concrete has decent attributes to be use for everyday products at home to replace some of the plastics, due to the current conditions of natural resources, a more sustainable approach needs to be applied, such as using recycled materials to play the roles for sand and gravels. A number of researches from construction industry across the world have been conducted to explore the possibility to replace part of concrete's components with wasted clay. Dahiru, Usman and Yusuf studied the properties of concrete using burnt clay compared to traditional concrete(using crushed stone) [19]. They used burnt clay fired at 600 degrees to 1200 degrees as coarse aggregate and conducted several tests including bulk density, absorption capacity, specific gravity, compressive strength and more. As a result, burnt clay exposed to 1200 degrees have the highest compressive strength value(11.20N/mm2) after 28 days of curing, yet still much lower than control group(24N/mm2). Meanwhile since burnt clay has higher water absorption ability, authors recommend use more water to the mix.

Siva, Thamilselvi, Nisha Devi and Ashvini [20] experimented on how different percentage of replacement of river sand as fine aggregates with recycled burnt clay could have effects on concrete's performance. The research tests split tensile strength for concrete made with 0, 10, 15, 20 and 25 percent replacement with burnt clay powder after curing after 28 days. The result shows that although control sample group(normal concrete setup) still preserves the best tensile strength number 2.9 N/mm2, replacement of 20 percent burnt clay powder is comparable at 2.89 N/mm2. Beyond 20 percent the strength shows a visible decrease. The paper also concludes that as more burnt clay is used, workability of the mix decreases.

Kumar, Chandramauli and Ashutosh [21] made similar research on partially replacing river sand with fire bricks as fine aggregates. They replaced sand with wasted fire brick powder at percentage of 0,22, 25, 28, and 31 and conducted spilt tensile strength test after 7 days of concrete curing. Results show that 28 percent replacement of fire bricks has the most optimal result(12.31KN/mm2, 8.17 percent increase), compared to control group(11.38KN/mm2) , while both 25 and 31 percent replacement still have positive impact on strength level(11.45KN/mm2 and 11.65KN/mm2). Since 31 percent replacement displays a decline in strength in comparison to 28 percent, it is reasonable to suspect that more percentage of replacement with fire bricks will cause further drop in strength of concrete made with such material mix.

Bolouri Bazaz, Khayati and Akrami [22] experimented on performance of concrete made with crushed bricks as fine and coarse aggregates. The result of compressive strength is unappealing as both fine and coarse aggregate replacement with fired bricks shows significant strength decline compared to control subject. Concrete with both fine and coarse aggregates replaced with bricks has 170kg/cm2 in compressive strength test after 28 days, less than half the number of control using crushed granite, which is at 450kg/cm2. Concrete made with granite for fine aggregate and crushed bricks with coarse aggregate shows better result at 255kg/cm2, yet the number is still way behind the strength of ordinary concrete. It is likely due to the lack of qualitied bricks used in the experiment. The study also presents compressive strength(in kg/cm2) from a number of sources including bricks, granite and other stones. Brick material has the lowest strength at only 30-70, far lower than the second lowest, sandstone, which is at 280-1400.

2.3. Wood Ash as Cement Replacement

Production of ordinary Portland cement includes firing limestone, shells and/or other minerals at a very high temperature(2700 degrees Fahrenheit or 1482 degrees Celsius) in a kiln, then grounded into fine powders [23]. Similar to aggregates, its materials are also easily accessed across the globe and low on cost. However, the manufacture of cement also create some environmental problems. The process requires burning of limestone, which contains CaCO3, to produce the main component of cement, calcium oxide(CaO), and carbon dioxide(CO2), known to be responsible for global warming, is emitted as a byproduct. Burning also consumes lots of energy as well as creates flying ashes that pollutes the air.

In order to reduce large amount of cement consumption, Many researchers have been looking at other more sustainable materials as substitution, such as wood ash. Wood ash is byproduct created through combustion of wood and wood related materials. Many countries use wood as a fueling tool, especially developing countries, accounting for 50-90 percent of total energy consumption [24].

Researchers have been looking for methods to reusing these wood wastes in construction industry. Udoeyo, Inyang, Young and Oparadu tested properties of concretes produced with replacing 0, 5, 10, 15, 20, 25, and 30 percent of cement with wood ash by weight [25]. Experiment result shows that addition of wood ash decreases compressive and flexural strength, as 30 percent replacement exhibits greatest strength loss, granting only 62 and 65 percent of the control group(normal concrete), while water absorption ability increases as more wood ash is use in the mix.

Rajamma et al. used two different types biomass fly ash from wood combustion to examine strength levels of cement mortar [26].Group One fly ash contains less CaO(11.4 percent) than the group two(25.4 percent). 0(control), 10, 20 and 30 percent substitution by weight were executed for both fly ashes. After 28 days of curing, compressive strength and flexural strength were tested. Group 1 mortar mixes obtain 4.96MPa and 43.31Mpa, 4.16MPa and 32.53MPa, and 3.39MPa and 22.59MPa on flexural and compression tests at 10, 20, and 30 percent, while group 2 shows 4.23MPa and 35.76MPa, 4.31MPa and 30.13MPa and, 3.14MPa and 26.72MPa under the same circumstances. Control mortar mix presents 6.98MPa and 41.48MPa on the matching tests. Both groups of wood ash maintain comparable result at 10 percent, as the mix in group one surpasses control in compressive strength(43.31 vs 41.48). In the meantime, strength level declines significantly once additive of wood ash exceeds 10 percent, indicating utilization of wood ash in large quantity may not be applicable in normal concrete set-up. This research also shows that different types of wood ash can cause remarkable differences in mortar characteristics.

Chowdhury, Mishra and Suganya [27] collected data from a number of works and studies on characteristics of concrete made with wood ash as cement replacement from 1991 to 2012, including chemical components. Main useful chemicals in wood ash for substituting cement includes silica (SiO2), alumina (Al2O3), iron oxide (Fe2O3) and quicklime (CaO), yet percentage of these components can be very distinct depending on the source wood types. Chowdhury et al. summarized chemical components of wood ash used in four independent yet related studies. In those experiments, silica(SiO2) content ranges from 31.8 percent to 78.92 percent and calcium oxide(CaO) ranges from 0.58 to 10.53 percent in four different wood ashes. Vassilev et al. [28] also provide extensive information about chemical composition of 86 different biomass ash, 28 of which are from wood and wood related products(bark, sawdust and chips, etc.,). It appears a even more significant differences across all wood species, as silica, calcium oxide and alumina contents range from 1.86 to 68.18, 5.79 to 83.46, and 0.12 to 15.12 in percentage. This data sheet indicates that not all wood ash types are suitable for cement replacement, since normal Portland cement contains 60 percent CaO, 20 percent SiO2 and 5 percent Al2O3 [29].

2.4. Information Attained from Researches

After researching and reviewing a few works and studies on related topic, several pieces of information are gathered that can possibly be carried over into next steps of this research

- Concrete material have potentials to be made in to more varieties of products other than construction industry giving its decent properties in strength, fire/water resistance and cost.
- Cement(ordinary Portland cement) is an excellent binding material as it's not only accessible and economical, it also cures and hardens with only added water.
- A number of studies have suggested that although it is probable to produce concrete with crushed clay and wood ash as sand, rock and cement replacement, large amount of substitution will result in significant strength loss and they are unlikely to be accepted for construction purposes. However the possibility of using such material mixes in a less strength required situation, such as for smaller everyday products, still exists and is worth exploring.
- Concrete and cement generally cure in 24-48 hours, yet their strength continues to grow overtime. Many researchers conducted their experiments at 7, 14 or 28 days.
- Not all wood ashes are created equally. Depending on their sources, chemical compositions vary drastically, most likely causing significantly different results in concrete making.

Chapter 3
Experiments

Based on information gathered from literature reviews, procedure to conduct experiments are designed and ready to proceed. This includes gathering materials, designing mixes into groups, and testing properties of water resistance, heat resistance and strength.

3.1. Materials

BINDER

Ordinary Portland cement is used as binder, while one type of wood ash(contains 10.9 percent of CaO) is used to test feasibility as cement replacement.

AGGREGATES

Normal dry sand at 0.2mm to 0.3mm particle size is used as fine aggregate for control. Broken potteries are recycled from local pottery workshop, then crushed into finer particles under 4.75mm, as fine aggregate.These recycled potteries were fired in a kiln at 800 to 900 degrees Celsius. This experiment does not utilize coarse aggregate because the particles are too large in size for making small scale products as they surpass 4.75mm.

WATER

Fresh water at room temperature is used for both activating cement and for water resistance test. Water and cement ratio is set to 0.5(1 part water:2 part cement by volume).

Figure 3.1 Recycled Broken Potteries

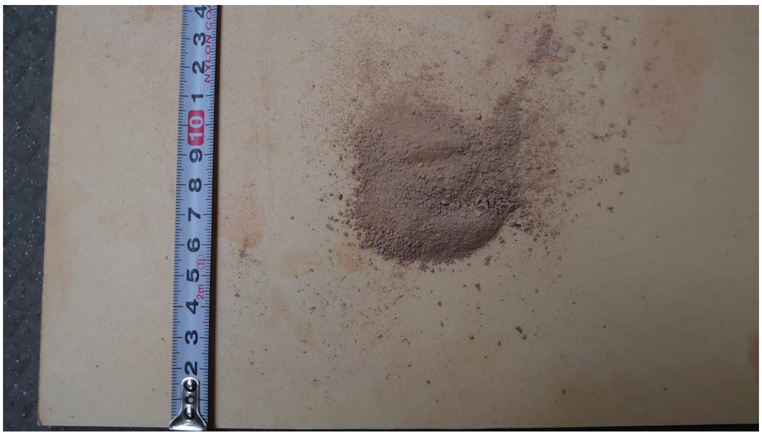

Figure 3.2 Crushed Pottery Powder

3.2. Methods

DESIGNING MATERIAL MIXES

This experiment utilized a far more aggressive mix design in terms of ratio of replacement materials compared to other researches and studies which usually use no more than 30 percent of substitution. This is due to the main purpose for them was to determine whether the materials were proper for general concrete uses, thus requires sufficient level of strength. For this research, main goal was to design material blends suitable for home products, therefore it is unnecessary to have same level of strength.

The base material mixtures were made with 1 part water, 2 part binder, and 3 part aggregate. Three groups were designed with different purposes. Group 0 was to test if the methods of this experiment worked fine, such as ratio of mixtures, mixing and moulding methods. It includes only test subject made with Portland cement and dry sand mixed with water, serves as control group as well. Group 1 was to test how wood ash contents affect properties of the mixtures. It was designed to have 15, 30, 50, 75 percent of wood ash as replacement of Portland cement. Meanwhile 100 percent normal dry sand was still used as aggregate. Group 2 was to examine the effect of level of crushed clay percentage on test subjects, therefore 50, 75 and 100 percent replacement were used as full Portland cement was used as binder.

	Water	Binder	Aggregate
Volume	0.5	1	1.5

Table 3.1 Ratio of Basic Mixture Design

Group 1	Water	Wood Ash	Cement	Sand
1A	0.5	0.15	0.85	1.5
1B	0.5	0.3	0.7	1.5
1C	0.5	0.5	0.5	1.5
1D	0.5	0.75	0.25	1.5

Table 3.2 Ratio of Group 1 Mixture Design

Group 2	Water	Cement	Crushed Clay	Sand
2A	0.5	1	0.75	0.75
2B	0.5	1	1.125	0.375
2C	0.5	1	1.5	0

Table 3.3 Ratio of Group 2 Mixture Design

MOLDING

First set of molds are transparent plastic cups, 35 ml in volume, 4 cm on upper diameter and 3 cm on lower diameter. The set was used for group 0 and group 1 subjects. Later on for group 2 subjects, molds were switched to 3 cm by 3 cm by 4 cm boxes made with LEGO bricks. It is solely because that demolding process was much easier with LEGO bricks as it could be achieved by simply popping out individual brick.

3.3. Execution

Group 0 was produced first to test legitimacy of this process. Different components were mixed at their dry status first in different ratios based on the design above, and added in adequate amount of water and mixed thoroughly. Then the mixtures were poured into molds, firmly pressed and shaked to eliminate any bubbles inside. Once they filled the molds, they were let sit for 48 hours at room temperature to cure, and then demolded.

Once group 0 product was made and showed decent soundness, the method was approved and all other groups were to proceed the same process. During demolding of group 1, 50 and 75 percent replacement materials broke, indicating that after 48 hours, these material mixtures could not cure when binder contained too much wood ash. It automatically negated the possibility of 50 and higher contents of wood ash as suitable substitution for Portland cement.

All other subjects presented workable soundness, therefore they were let sit for additional 14 days, and ready to proceed property tests.

Figure 3.3 Mixing of Materials(Group 1)

Figure 3.4 Molding of Materials(Group 1)

Figure 3.5 Group 1 Subjects

Figure 3.6 Group 2 Subjects

Chapter 4
Results and Discussions

4.1. Properties Tests

Since the materials were created for home and daily uses, tests of properties are different from ordinary tests for concretes.Three properties were tested and ranked to determine their usability, including water resistance ability, heat resistance ability and strength level which is determined through dropping tests. It should be noted that, these tests were conducted independently, and 2B and 2C subjects from group 2, which were previous broken during demolding, were excluded from all tests.

4.1.1 Water Resistance

Water resistance tests were conducted to assess how likely the materials could be use with water and/or in damp environments, such as kitchen and bathroom. Tests were conducted simply pull all subject blocks in normal fresh water at room temperature for 48 hours. After 48 hours, check the status of these materials. A indication of good water resistance would be no sign of dissolution of materials.

As an outcome, all subjects in both groups(excluding two broken ones in group 1) appeared no sign of change or damaging in physical form. No dissolution or deformation happened to any test subjects after 48 hours being inside water. The result shows that such material combination(cement + aggregate) has high endurance(at least 48 hours) to water. Different levels of clay contents(50, 75 and 100 percent) as aggregate replacement have no impact on the material's water resistance ability. Meanwhile 30 and less percentage of wood ash also shows no negative effect on such attribute.

Figure 4.1 Water Resistance Test

4.1.2 Heat Resistance

Heat resistance is another important attribute of a material. It determines how much heat such material can tolerate therefore it determines whether it can be used under more extreme conditions. It was tested by giving each material block at different temperature for a certain period of time. Each subject was fired at with a heat gun at 100, 200, 300, 400, 500 and 600 degrees Celsius or until breaking down, for 3 straight minutes, or until breaking down.

Figure 4.2 Color of Surface Turned Brown at 600 degrees

Result has showed that all test subjects were able to withhold 600 degrees direct heating for at least 3 total minutes. No visible breakdown of materials occur, yet temperature of surface did rise after 1 and a half minute and after 3 minutes browning appeared as well on surface. Overall such material mix presents satisfying heat tolerance, with only color change happened to the surface. Wood ash contents below 30 percent as well as all quantity of burnt clay content did not show nullification to the heat resistant ability. The result is not surprising, since majority of components(cement, wood ash and recycled potteries) in the material mix were manufactured by firing at high heat before hand. In comparison, most common plastics don't have the resistance ability to temperature over 150 degrees, as PE 70-90℃ , PP 100-140℃ , PVC 60-80° C, ABS 70-100° C, and PET 70-200 ° C [1].

4.1.3 Free Falling Tests

Strength level is a very important factor to make a reliable and durable concrete block, and it is commonly evaluated through compressive and split tensile strength tests in construction industry as concretes are expected to handle a lot of forces for a very long duration. For the purpose of this research, the ability to survive a sudden impact is more essential for general home uses. A free falling test was design as a method to evaluate sudden impact endurance level for each subject. Each material mix was let fall without applying additional force non-stop repeatedly until break, or until reach 20 times. If the material could survive falling from a height for 20 times, that would mean it has good resistance to breaking under normal circumstances at home. The height was set to 100 cm and it was decided by measuring the heights from various desks, tables and counters at home.
Results of the test are showed at following tables.

Group 1	Falling Numbers	+/- Compared to CG
Control Group(CP)	20	N/A
1A	6	-14(30 Percent of CG)
1B	1	-19(5 Percent of CG)

Table 4.1 Result of Group 1 Dropping Test

Group 2	Falling Numbers	+/- Compared to CG
Control Group(CP)	20	N/A
2A	3	-17(15 Percent of CG)
2B	7	-13(35 Percent of CG)
2C	20	0(100 Percent of CG)

Table 4.2 Result of Group 2 Dropping Test

The result shows that control group subjects from both groups were able to maintain completeness from dropping for 20 times over and over again. However, unlike previous two characteristics, different percentage of wood ash and burnt clay contents had significant impact on strength level of such material. Group 1 data presents a decline in strength as more cement was replaced with wood ash, where 30 percent wood ash substation could not get through more than one drop from 100 cm height. It is predictable since the other 2 subjects(1C and 1D) already displayed a lack of strength previously.

Reaction of group 2 materials suggests else wise. With the increase in amount of crushed potteries as aggregate replacement, impact resistance of the materials also rose. 2A subject(50 percent) were only to take three hits until broken, yet 2B(75 percent) managed to double the amount with 7 droppings. And 2C(full replacement) showed the same strength level of control group, which withstood full 20 falling tests without breaking.

Figure 4.3 Failure of Test Subjects

It is also worth noting that the breaking of such material appeared differently to normal ceramic products. When broken from falling, subjects not only divided

Figure 4.4 Failure of A Ceramic Cup

into different sizes of pieces, they also generated some small powders, whereas generic ceramics would break into complete pieces without dust or particles.

4.1.4 Discussions

Based on the results from three individual tests fro three properties, it can conclude that ordinary cement and normal sand can create materials resistant to water and heat, while maintaining decent strength level which can survive a few fallings at a certain height. Although wood ash contents showed no notable effect on both water and heat resistance level, it severely decreased strength from impact by as much as 95 percent, compared to control group.

On the other hand, addition of crushed burnt clay not only had not negative impact on its ability to withstand water and heat, but also preserve the strength level when at full replacement of sand. Partial substitution of sand with clay actually caused a remarkable strength loss at low level of percentage, opposite to wood ash as cement replacement.

To sum up, using 15 percent of wood ash as partial cement replacement is viable, though not suitable, as it not only causes strength drop but also extra cost as an extra material. The level of replacement is too little to make significant changes on environment and not worthy of the additional expenses. A full use of crashed clay should be encouraged, since it shows not difference in all properties tested above and it can help reduce ceramic wastes.

4.2. Prototypes

To further examine the practicality using recycled ceramics for making new products, four rough yet usable prototypes were made and tested for duration of 7 days. These products come from three different categories of commonly used daily necessities which are often made with plastics. These prototypes were to test if they could replace some of the plastic products in everyday life to lessen plastic wastes. Based on previous experiment results, Portland cement + crashed potteries mix was used to create these products. Similar to material experiments before, they were all let sit for 14 days to further harden before putting into use.

Four products selected were spatula, tooth brush, flash drive and cup, and they each represent one area of everyday product: kitchen, bathroom and portable electronics. During a week, number of times of uses of each product was recorded as well as their condition. If they were damaged or broken, causes were also written down, along with any difficulties when using.

	Spatula	Tooth Brush	Flash Drive	Cup
Original	PVC	PP	PVC	PE

Table 4.3 Plastic Products Material

4.2.1 Spatula

A spatula is an indispensable tool for cooking and typically its head and handle are made with plastics. It has some advantages such as low price and light weight, however its plastic body can sometimes be troublesome. While cooking, a spatula can easily be placed on a pan or near a stovetop for convenience. In such circumstance, the heat can be quite damaging to the plastic body and cause a reduce of its longevity.

The cement-clay material blend was used to prototype the handle of a spatula to test since it had shown success in resistant heat up to 600 degrees in previous experiment. It was tested under real life using including cooking and cleaning for a week to evaluate the feasibility to become a eligible replacement.

During a week, the prototype was used in a total of six times. There was no heat damage in the handle like what occurs to a normal plastic part and it could be washed with normal dish soap just like other cooking ware. A downside of this prototype is its weight. Although the rough prototype is much larger than it should be, it still appears to be much heavier than a normal plastic one, as the prototype weighed 149.8g, almost 3 times heavier than normal one at 52.8g. A much longer duration of test is obviously necessary, but preliminary conclusion can be drawn that it is doable to replace plastic handle of a spatula with cement-clay mix. Ideally, the handle should have a long lifespan and only the head needs replacing,therefore plastic usage could be reduced. The table below shows materials from original items designated to be replaced by the prototypes.

4.2.2 Tooth Brush

Similarly, tooth brushes are another essential items in our daily life and often appear in the form of plastic. They are also replaced often as American Dental Association(ADA) suggested to replace toothbrush every three or four months or even more frequently [30]. A lot of plastic wastes can be generated as used toothbrushes are thrown away. The cement-clay material could play a part here and The body part of a toothbrush was made into cement-clay material as the head was kept in plastic. The prototype was used 14 times during a week, once in the morning and once at night. No damage or breaking appeared during using and water had not effect to the material. In an ideal situation the hand of toothbrush should be made replaceable and the body could be kept for a long period of time.

Figure 4.5 Heat Damage in A Spatula

The prototype suffered from the same issue of being too heavy compared to normal toothbrush(68.9g vs 14.4g).

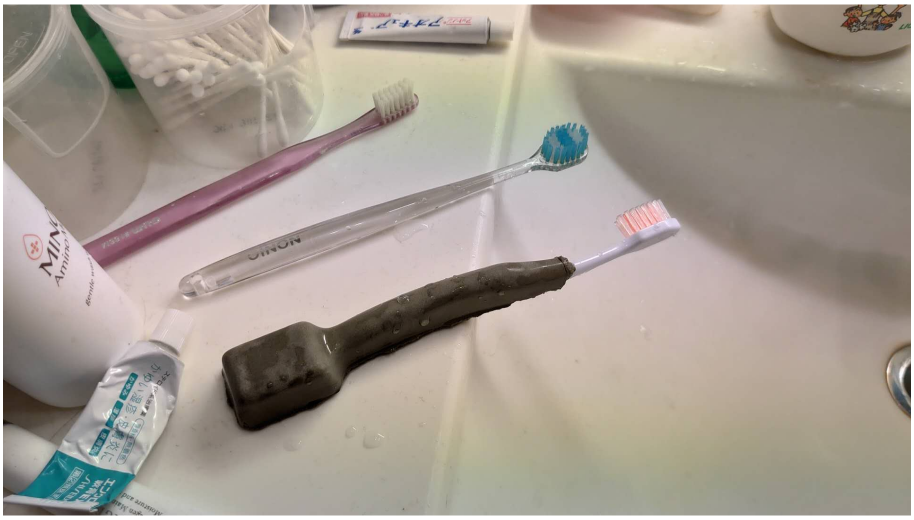

Figure 4.6 Prototype Toothbrush

4.2.3 Flash Drive

Flash drives have been an impactful object nowadays for its reliable role in file transferring. It has the advantage of small and light, so it can be taken away conveniently. Using cement-clay material might have negative effect on its portability since the material is weighty in nature. The prototype flash drive was only used twice during test period. Once it was used to transfer files between two computers at home and the other use was to carry out to a near convenience store for printing. And most other time it simply sat on the desk thus no damage was applied. When it was carried out, the presence of its weight could be obviously sensed as it was much heavier than regular flash drives. The prototype weighed 40.1g, 5 times heavier than a generic flash drive, 8g. However even with the significant increase in weight, it was still much lighter than other portable items such as smartphones and wallets, therefore the sacrifice in portability in exchange of sustainability was not obvious.

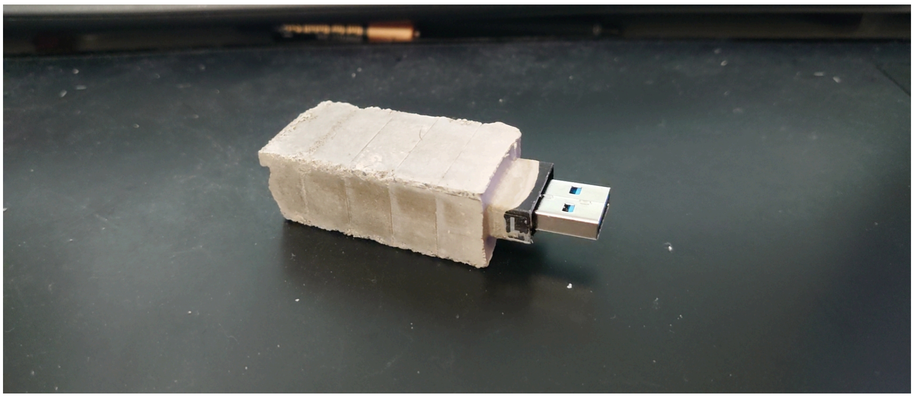

Figure 4.7 Prototype Flash Drive

4.2.4 Cup

Cups are one of the most common items in people's everyday life and they come with different materials, from plastic, ceramics to steels. The prototype was used daily for drinking hot(boiled) and cold water, average 3 times a day. The material was able to handle different temperature of water pretty well and showed no sign of damaging during a week of trial. A similar issue did occur as the weight is much heavier compared to cup made with PE plastic with similar volume(150ml). The prototype presented 288g in weight, almost 10 times heavier than a PE cup in the same size. A sense of weight is much more obvious than previous prototypes, which might be an indication that such material is not suitable for containers with large volume.

4.2.5 Discussion

Overall, the prototypes showed great durability as no damage and breaking happened, and they displayed great heat and water resistant capacity in different situations throughout a week. Obviously the test period was not long enough, but it makes good start to prove the potentials of using such material mix for making products and is able to achieve the same role that plastics do, if not better.

One major issue is the weight. The prototypes are much more heavier than the

Figure 4.8 Prototype Cup

original products. Although the prototypes are relatively small, and even with the added weight it is totally manageable in most case, it can be foreseen that larger products are likely to preserve even heavier weight, making it hard for users to utilize the items.

Weight(gram)	Spatula	Tooth Brush	Flash Drive	Cup
Original	52.8	14.4	8	32.3
Prototype	149.8	68.9	40.1	288
Difference	+283 percent	+478.4 percent	+501 percent	+891.6 percent

Table 4.4 Weight of Prototypes

Chapter 5
Conclusion

5.1. Overall Conclusions

Based on the experiments of material making and property tests, it can be concluded that with the help of Portland cement as binder, it is plausible to create materials with recycled ceramic products. A 1 to 1.5 ratio of cement and aggregate setup was used in the research and the most optimal performance in water, heat resistance and free falling tests was obtained by 100 percent usage of crushed potteries as aggregates.
Meanwhile, a dissatisfying result was demonstrated by the experimental attempt to replace cement with wood ash. Replacement percentage over 30 showed severe strength loss compared to control group and 15 percent wood ash also failed to preserve the same quality of strength. It is concluded that although feasible, it is not optimal to use wood ash as cement replacement in large quantity.

Three usable prototypes including a spatula, a toothbrush and a flash drive were created with cement-crushed potteries material combination, and underwent using test in real life situation in a period of 7 days. All items were able to maintain decent conditions after 7 days and showed no significant differences during using compared to the original products. In conclusion, it is possible to create more sustainable everyday products with recycled ceramics to replace and reduce the usage of plastics.

5.2. Advantages and Disadvantages

Certain advantages and disadvantages of creating products with such material are discovered through out the process of research.

ADVANTAGES

- The material utilizes Portland Cement and wasted ceramics, which can be easily accessed globally as well as economically.
- Compared to normal plastic products, it can resist much higher level of heat.
- The making of such material does not consume extra energy as cement naturally react with fresh water.
- The material is eco-friendly and sustainable as it is made from recycled materials and natural materials.

DISADVANTAGES

- The material appears to be much heavier than plastic.(average 4.5 times heavier comparing three prototypes to their real life counterparts)
- The making process of this material could limit its applications. When mixing with water, the consistency of this material is not fluid enough to simply be poured into molds. Small fine products might not be workable due to difficulty in molding.
- The material takes at least 2 days to cure and subjectively extra 7 to 28 days to fully harden(all subjects were tested at 14 days in this research), which can cause too long of production cycle.
- Production of Portland cement can create large CO2 emission and air pollution, as well as energy consumption, thus decreases the sustainability of this material.
- The material breaks not only into different sizes of pieces, but creates small particles, which can increase the labour of cleaning up.

5.3. Limitation

There are a few limitations of this research:

- Experiments in the research were mostly conducted by hand and could cause errors.
- Microstructure of each subjects were not tested for more detailed analysis.
- The property tests were proceeded independently, meaning that how one property test result could affect the other results were nullified in order to get more accurate results. However testing how one property test could impact another can be equally important to get a more precise evaluation. For example, a free falling test right after heat resistance test is worth exploring to further examine the effect of heat on material's strength.
- Only one type of wood ash was used. Other types of wood ash might present different results due to differences in chemical components [28].
- Each property was only tested once, which might contain inaccurate results due to fortuity.
- Heat resistance test only went up to 600 degrees.
- Duration of prototype tests was no long enough to produce a concrete statement.
- Recycle ability of this material was not tested.

5.4. Future Directions

Here are future directions for further proof of concept:

- How different types of recycled ceramics(e.g. ceramics burnt at 800 degrees vs burnt at 1400 degrees) could effect on materials properties should be tested.
- Prototypes should be tested by more users as a greater duration(more than 3 months).
- Other items from different categories should be made as new prototypes to expend applications of this materials.

- The true cost of cement-recycled clay material in comparison to plastic needs to be calculated to determine its commercial value.
- The emissions of GHG from producing such material and products need to be calculated and compared to ceramic production and plastic production to determine the level of ECO-friendliness.

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Appendices

A. Example Clip of Heat Resistance Test

Here is a sample clip of how free falling test was conducted in the research. https://youtu.be/GkBJbyomnOo

Figure A.1 Heat Resistance Test Clip

B. Example Clip of Free Falling Test

Here is a sample clip of how free falling test was conducted in the research. https://youtu.be/vKtSGt9sGhE

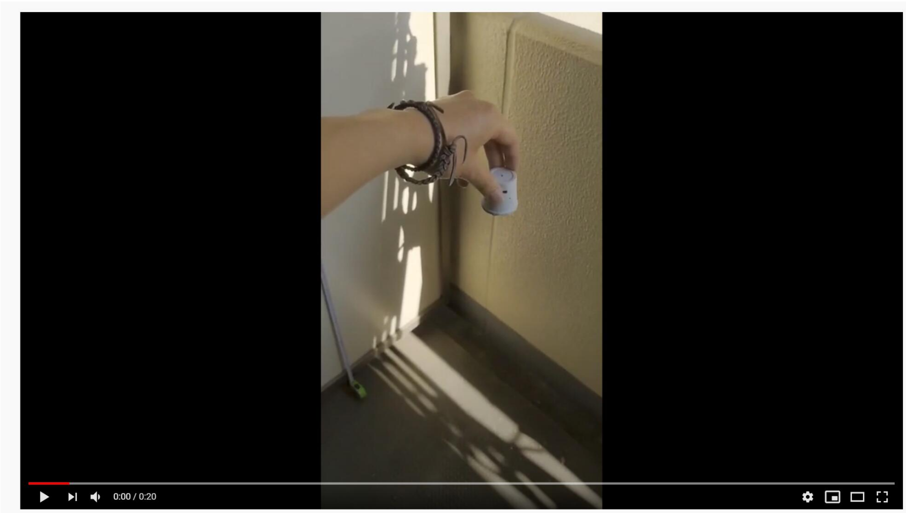

Figure B.1 Free Falling Test Clip

C. Info of Materials Used in the Research

The Portland cement, sand and wood ash used in the research were purchased and their detail components can differ greatly from brand to brand. here are detail info of the materials provided by their manufacturer.

Portland Cement: `https://www.kateikagaku.co.jp/products/items_page/p_4905488043067.html`

Dry Sand:`http://www.matelan.co.jp/product-detail/13/`

Wood Ash:`http://www.joy-agris.com/dojyou/`

生セメント 4kg

カラー グレー

※パッケージが変わる場合があります

特徴

保水剤、接着剤等を配合しているので、砂、砂利等を加えるだけで、使いやすく優れたモルタルができ上がります。
【注意】･･･ 海砂や粘土質のものを使用するとクラック(亀裂)や硬化不良の原因になります。

用途／使用場所

モルタル作り、モルタル塗り。

JANコード	4905488043067
NET	4kg
サイズ	220 x 280 x (厚) 45mm

荷姿(mm)	440 x 260 x (高)195
入数	6

シリーズ製品

製品名	JANコード	NET		サイズ	荷姿(mm)	入数
生セメント 10kg	4905488103020	10kg		360 x 320 x (厚) 80mm	365 x 300 x (高)160	2
生セメント 4kg	4905488043067	4kg		220 x 280 x (厚) 45mm	440 x 260 x (高)195	6

Figure C.1 Cement Used in the Research

トップページ > マテリアル事業 > 製品一覧 > 珪砂(トーヨーシリカサンド) > 乾燥砂６号　ポリ袋　2kg

乾燥砂６号　ポリ袋　2kg

粒度ピーク（重量比）が、約０．２～０．3mmの珪砂

JANコード	色	容量
4975160100999	白灰色	２Ｋｇ
袋素材	荷姿	水量
ポリ袋	２Ｋｇ×１０袋	----
硬化時間	練り上がり量・㎡数	製品サイズ 縦×横(mm)
----	----	265×160
段ボールサイズ 縦×横(mm)		
315×255		

Figure C.2 Sand Used in the Research