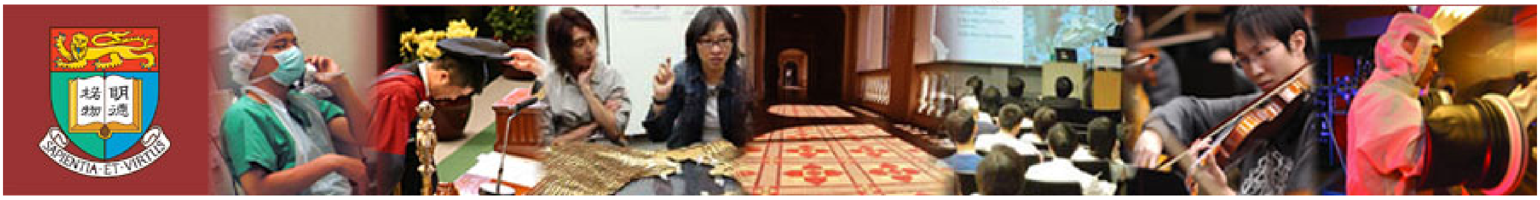

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Mechanical behaviour of sustainable concrete with waste ceramic aggregate replacement

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MECHANICAL BEHAVIOUR OF SUSTAINABLE CONCRETE WITH WASTE CERAMIC AGGREGATE REPLACEMENT

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ABSTRACT

Sustainability and material use have been becoming increasingly important in industry and academia in recent years, prompting investigations for ways to improve sustainability in construction materials. Past studies have investigated natural aggregate replacement in concrete with a variety of materials, including recycled concrete, glass, bricks, ceramics, and even automobile tires. These studies have produced varied results. Ceramic materials are a great prospective material for aggregate replacement due to their desirable mechanical properties and availability in waste streams worldwide. This study focusses on coarse aggregate replacement with ceramic tile materials of virgin and waste origins, reaching as high as 100% replacement. To limit the variability experienced in previous studies, great emphasis was placed on limiting parameters tested between series to the physical properties of the replacement ceramic materials alone. Test results thus far have shown that natural coarse aggregate can be replaced in ratios as high as 100%, with only minimal effects on the mechanical properties of the resulting concrete. Compressive, tensile, and flexural strengths have shown minor change, with only a slight increase in elastic modulus. This study shows that ceramic waste material has great potential for use in concrete when a suitable preparation method is used.

KEYWORDS

Sustainable materials, concrete, ceramic, aggregate replacement, recycling.

INTRODUCTION

There has been increased interest in concrete aggregate replacement schemes in recent years. Research has focussed on a variety of waste materials that could be used as sources, such as recycled concrete, post-consumer glass, recycled tires, recycled plastics, waste ceramics, waste bricks, cork, and more. These materials have, perhaps expectedly, exhibited wide variability in results due to the inherent variability in the replacement material selected. One material that is particularly promising is waste ceramics as the resulting recycled concretes have shown relatively steady strength with increased aggregate replacement. Some researchers have found modest strength decreases with increased ceramic aggregate replacements (e.g. Reddy 2010; Sekar et al. 2011; Senthamarai and Manoharan 2005). Furthermore, other studies have even shown improved strength with increased replacement ratios (e.g. Higashiyama et al. 2012; Guerra et al. 2009; Medina et al. 2012; Pacheco-Torgal and Jalali

2010; Torkittikul and Chiapanich 2010). The ceramic materials as well as the preparation methods used in different studies correspond to the varying results; therefore this study aims to establish a unifying relationship between ceramic material characteristics and recycled concrete material properties.

MATERIALS AND METHODS

Materials

The cement used in this study is standard Portland cement manufactured locally in Hong Kong. The coarse and fine aggregates used were composed of crushed granite, which was sourced and crushed locally in Hong Kong. The coarse aggregate had a maximum diameter of 20 mm, and the fine aggregate had a maximum diameter of 5 mm. Three different ceramic materials with varying physical properties were used to replace the coarse aggregate. The first was a standard ceramic floor tile that was store-bought in unused condition, in order to focus on the effect of the ceramic material itself and to limit the induced variables. The second was a standard ceramic wall tile that was also store-bought and undamaged, again to limit variables. The third ceramic source material was waste wall tile with mortar and grout attached, sourced from a local demolition site. The purpose of using actual waste material was to determine the effects of using ceramic material that would be more representative of waste material with additional materials included such as mortar, grout, and even dirt and grime. All the aggregate replacement materials used in this study were prepared by breaking manually with a 16 oz. ball-peen hammer to the desired size range (5-20 mm). The ceramic fragments produced using this method were visibly more angular and less cubical than the granite aggregates that the ceramic material was replacing. The angularity was determined by measuring the shape index, where a higher result indicates a higher angularity. After preparing the replacement material, the resulting crushed ceramic was sieved and separated into different size ranges which were then proportioned to match the gradation curve of the natural aggregate (Figure 1). This was done to eliminate varied gradation curves as a variable for comparison. The sieve sizes used to determine the grading curve for the coarse aggregate were 20, 14, 10, and 5 mm. The sieve sizes used for the fine aggregate grading curve were 5mm, 2.36mm, 1.18mm, 600μm, 300μm, 150μm, and 75μm. Any material retained on the 20mm sieve was crushed further until it was within the coarse aggregate range. In addition, any material passing the 5mm sieve was later used for fine aggregate replacement testing.

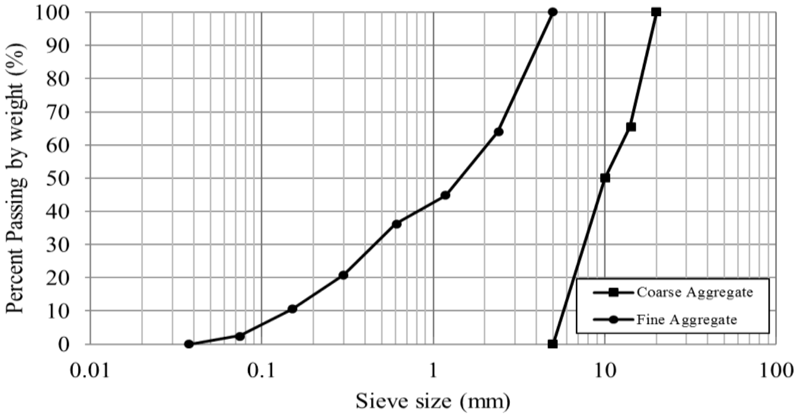

Figure 1. Gradation curves of course and fine aggregates used

A number of physical properties of the aggregate materials were determined for comparison. The density of the materials was measured according to BS EN 1097-6:2013. The angularity was determined by measuring the shape index according to BS EN 933-4:2008. The crushing value is used as an approximation of the strength of the aggregate materials, and it was measured according to BS 812-110:1990. The water absorption was tested according to BS EN 1097-6:2013. The results of the material physical properties testing are summarised below in Table 1.

Table 1. Material properties: test results

	Density (kg/m^3)	Shape Index	Crushing Value (%)	Water Absorption (%)
Granite	2,642	12	25.7	1.2
Floor tile	2,278	31	11.9	1.4
Wall tile	2,401	30	14.7	7.2
Waste ceramic	2,263	27	24.9	5.5

A standard concrete mix with a characteristic strength of 40 MPa was used in this study to represent a normal strength concrete. The mix design used to attain the desired characteristic strength utilised an aggregate-to-cement ratio of 4.17, and a cement/fine/coarse proportion ratio of 0/1.67/2.5. These ratios were held to the same values for all replacement series in order to maintain the same base design strength for comparison. Similarly, the water to cement ratio (w/c) was also held constant at 0.55 for all replacement series. A target slump of 80±15 mm for all series was used to maintain a desirable level of workability. No admixtures were used in this study, again in an effort to limit variables introduced in the testing scheme.

Test Methods

The aggregate replacement testing scheme was designed to test a variety of replacement ratios from 0-100% replacement, with the 0% replacement series representing the reference concrete. The floor tile replacement ratios tested were 0%, 20%, 35%, 50%, 65%, 80%, and 100%, and were named 0CD, 20CD, 35CD, 50CD, 65CD, 80CD, and 100CD, respectively. The numbers represent the replacement ratio, the C stands for ceramic, and the D specifies that the material was in a dry condition when incorporated into the concrete mix. It was determined after completing the floor tile series that the number of mixes per series could be reduced, therefore the wall tile and waste ceramic series used less test mixes. The reference concrete used in the floor tile series was repeated in each of the subsequent series, but retained the same name (0CD). Since both the wall tile and waste ceramic series had significantly higher water absorption than the natural aggregate and floor tile materials, the replacement wall tile and waste ceramic aggregates were pre-soaked to a saturated surface dry (SSD) condition before being incorporated into the concrete mix. The wall tile replacement ratios tested were 0%, 25%, 50%, 75%, and 100%, and were named 0CD, 25WS, 50WS, 75WS, and 100WS, respectively. In this series, the W refers to wall tile and the S indicates that the material was in a saturated surface dry condition when incorporated into the concrete mix. The waste ceramic replacement ratios tested were 0%, 25%, 50%, 75%, and 100%, and were named 0CD, 25RS, 50RS, 75RS, and 100RS, respectively, where the R refers to recycled ceramic. There were two additional mixes tested in this study using the floor tile, and both were designed with a 50% replacement ratio for comparison with the 50% floor tile replacement mix, 50CD. The first tested the effect of water absorption of the floor tile aggregates by pre-soaking to SSD condition. This was referred to as 50CS. The other additional mix tested the effect of replacing both coarse and fine aggregates as compared to just replacing the coarse aggregate, and was named 50CF where the F indicates fine aggregate.

In order to determine the effects of ceramic aggregate replacement on the mechanical properties of concrete, much effort were made to minimise the number of variables induced in the study. The mix proportions were maintained constant across all series, the w/c ratio was kept constant through all series, no admixture was used, and the floor and wall tile series investigated only one material replacement at a time. The gradation curve of the natural aggregate was matched with the replacement aggregate by measuring the proportions of each size range of the different sieves by weight. Since the replacement materials have lower densities than the natural aggregate in which they are replacing, matching the aggregate proportions strictly by weight would result in an increased volume and number of aggregate particles than the natural aggregate being replaced. For this reason, an adjustment was made to match the aggregate replacement by volume, simply by using a ratio of the densities. This was done to ensure the cement paste-to-aggregate ratio remained the same, while maintaining a similar cement paste coating on the aggregate particles. Since the wall tile and waste ceramic materials had relatively high water absorption, these aggregates were pre-soaked to a saturated surface dry condition before incorporating into the concrete mix in order to maintain a constant effective w/c ratio. This was done by soaking the replacement aggregates in water for a minimum of 24 hours, then draining the water and placing on plastic sheeting to air dry for one hour before being added to the concrete mix. Similar methods have been used by other to date (e.g. Cabral et al. 2010; Pacheco-Torgal and Jalali 2011; Poon et al. 2009).

The materials properties focussed upon in this study are the elastic modulus as well as the compressive, tensile splitting, and flexural strengths. Additionally, rebound hammer testing was performed to investigate if there were any noticeable changes to non-destructive test results. The rebound hammer testing was performed according to BS EN 12504-2:2012 using four 100 mm cube specimens, and then compressive strength testing was carried out according to BS EN 12390-3:2009 using the same four 100 mm cube specimens. Elastic modulus testing was performed according to BS 1881-121:1983 using four 150 x 300 mm cylindrical specimens, and then tensile strength was determined according to BS EN 12390-6:2009 using the same four 150 x 300 mm cylinders tested in split-tension. The flexural strength was established according to BS EN 12390-5:2009 using four 500 x 100 x 100 mm prism specimens tested in a four-point bending setup. In total, four 100 mm cubes, four 500 x 100 x 100 mm prisms, and four 150 x 300 mm cylindrical specimens were cast for each concrete mix.

The concrete mixes were produced by combining the coarse aggregate, ceramic aggregate, cement, fine aggregate, and water (in this order) to a 100 litre rotating pan mixer followed by mixing for two minutes. The workability of the mixed concrete was determined by means of slump testing according to BS EN 12350-2:2009. The concrete used for the sump test was returned to the mixer to combine for an additional 30 seconds. The mix was then transferred to steel molds and compacted using a vibrating compactor to form the individual specimens. The specimens were air-cured at room temperature (23±5 °C) for 24±1 hours before removal from the molds and then set to cure in water tanks kept at 20±2 °C for the remaining 27 days of curing before testing according to BS EN 12390-2:2009.

RESULTS AND DISCUSSIONS

The results of mechanical properties testing on all concrete mixes tested are shown below in Table 2.

Table 2. Mechanical properties test results

	Slump (mm)	Rebound Hammer (MPa)	Compressive Strength (MPa)	Tensile Strength (MPa)	Flexural Strength (MPa)	Elastic Modulus (GPa)
0CD	70	35.3	46.2	3.1	5.6	21.6
20CD	75	33.0	47.1	3.3	5.2	22.2
35CD	80	31.1	44.9	3.2	5.1	22.0
50CD	65	37.6	45.2	3.1	5.0	23.5
65CD	75	36.1	46.2	3.5	5.2	25.6
80CD	65	33.6	44.4	3.2	5.0	25.3
100CD	105	35.8	44.5	2.9	4.6	27.4
50CS	115	36.5	45.3	3.2	4.9	23.4
50CF	90	36.4	46.3	3.0	5.1	25.0
25WS	75	37.7	49.8	3.8	5.4	23.0
50WS	80	41.0	47.3	3.6	4.9	22.4
75WS	85	38.1	46.1	3.1	4.8	20.2
100WS	90	37.8	43.6	3.0	4.6	20.9
25RS	105	38.8	50.6	3.8	5.0	24.6
50RS	90	36.1	46.7	3.0	4.9	21.6
75RS	90	33.7	42.8	3.4	4.5	23.0
100RS	140	30.2	33.2	2.9	4.2	20.5

The compressive strength testing results are important when determining the suitability of any given aggregate replacement scheme. This was first gauged in a non-destructive manner by means of the rebound hammer tests, which exhibited wide variability in the results (Table 2). These numbers were generally significantly lower than the cube compression test results, and the trends between the series did not necessarily mirror the trends shown from the machine testing. The rebound hammer tests carried out immediately after the specimens were pulled from the curing tank, and the wet condition leads to the variability and underestimation experienced, as explained in BS EN 12504-2:2012. The machine test results show that the floor tile series exhibited the least variability in strength with increasing coarse aggregate replacement. Increasing the aggregate replacement ratio from 0% to 100% with the floor tile, wall tile, and waste ceramic resulted in strength decreases of 3.7%, 5.6%, and 28.2%, respectively, as shown numerically in Table 2 and graphically in Figure 2.

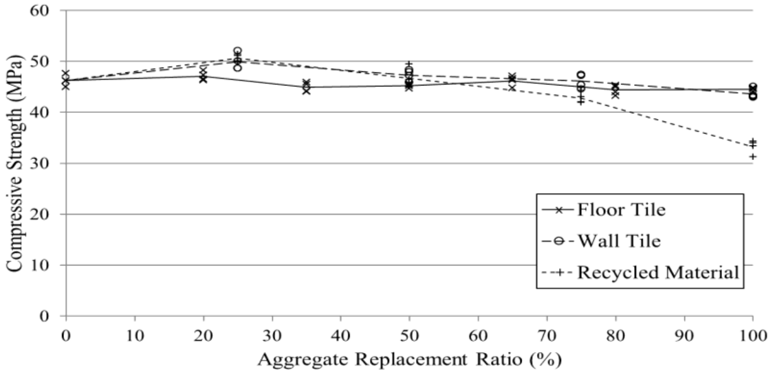

Figure 2. Compressive strength test results

The tensile splitting and flexural strengths are less commonly used when determining suitability of aggregate replacement schemes. Testing revealed notable responses to increasing aggregate replacement ratios from 0% to 100%. For tensile splitting strength, the floor tile, and waste ceramic showed strength decreases of 8.4% and 8.5%, respectively, whereas the wall tile strength improved by 2.2% (Table 2). For flexural strength, the floor tile, wall tile, and waste ceramic resulted in strength decreases of 17.6%, 25.9%, and 32.5%, respectively, as displayed in Table 2.

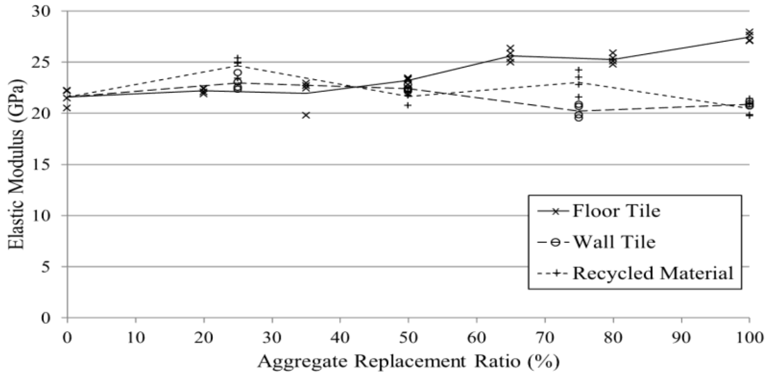

Figure 3. Elastic modulus test results

The elastic modulus is another important strength characteristic when determining the suitability of replacement schemes, as the elasticity of the material is important when considering the serviceability of constructed facilities. Ideally, aggregate replacement would result in limited change in the elasticity of the concrete, whereas an increase results in a more brittle and dangerous material. The wall tile and waste ceramic series exhibited decreases of 3.4% and 5.2%, respectively, with 100 % replacement, whereas the elasticity of the floor tile series increased by 27.0% with 100% replacement, as shown numerically in Table 2 and graphically in Figure 3.

CONCLUSIONS

This study shows that with certain ceramic materials, coarse aggregate replacement schemes up to 100% replacement may be suitable for varying structural concrete requirements. However, the effects on mechanical behaviour resulting from coarse aggregate replacement are variable, and rely on the mechanical properties of the ceramic waste material used in the replacement scheme. As an example, relatively dense ceramic materials that are strong in compression but have a high elastic modulus will increase the brittleness of the concrete they are incorporated into. Therefore, it is important to understand the effects of the different material properties on the mechanical behavior of the concrete produced. Additional testing of a wider variety of ceramic materials to build a larger database of ceramic material and concrete mechanical properties would allow for more precise correlations and models to be established.

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