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MATERIAL PROPERTIES OF CONCRETE WITH DIFFERENT TYPES OF AGGREGATES

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ABSTRACT

A series of tests were carried out recently, where two types of waste materials, including steel slag (by-product of the steel-making process) and crushed waste glass, were adopted as the coarse or fine aggregates of the concretes. To compare with the new concretes using waste materials, two batches of concretes using normal limestone and lightweight aggregates were also prepared and tested. The material properties of concretes, such as the slump value, density, modulus of elasticity, compressive strength and flexural strength were measured and the results are reported and discussed in this paper. Furthermore, fire tests were conducted on concrete columns with different aggregates. The fire performance of concretes made with those selected aggregates is compared with that of normal concrete.

KEYWORDS

Concrete, steel slag, waste glass, lightweight aggregate, mechanical properties, fire resistance.

INTRODUCTION

Concrete is one of the most widely used construction materials in the world. In recent few decades, many new types of concrete materials in contrast to ordinary concrete have been developed. Especially in recent years, there has been a growing emphasis on the utilisation of waste materials and by-products in construction materials, which is a partial solution to environmental and ecological problems. If these materials are used in producing cement, concrete, and other construction materials, it not only helps in reducing the cost of cement and concrete manufacturing, but also has numerous indirect benefits such as reduction in landfill cost, saving in energy, and protecting the environment from possible pollution effects.

Steel slag is a by-product of the steel-making process and the use of slag in its many contemporary applications is a fairly recent development. Research in recent years found that the steel slag could be used as aggregate in concrete which had similar compressive and flexural strengths compared with normal concrete, whilst the splitting tensile strength and modulus of elasticity for the steel slag concrete were higher than those of normal concrete (Maslehuddin et al. 2003). Besides, waste glass was found to have potential use in the mix of concrete and it did not have a significant effect on the
workability of concrete (Topçu and Canbaz 2004). Normally the compressive, tensile and flexural strengths of concrete decrease with the increasing of waste glass content due to that the waste glass has relatively poor shape, poor surface characteristics and high friability. Moreover, concrete with waste glass as fine aggregate has better compressive and flexural strengths than concrete using waste glass as coarse aggregate (Polley et al. 1998). Furthermore, it was found that steel slag, waste glass as well as lightweight aggregate (LA) have the potential to be used in concrete to improve the fire performance of concrete (Aydin and Baradan 2012; Ling et al. 2012; Hossain and Lachemi 2007).

Therefore, steel slag, waste glass and lightweight aggregate were selected in this research to replace coarse and/or fine aggregates in normal concrete. A series of tests were carried out to investigate the mechanical properties of concretes with those special aggregates, and fire tests on those concretes were also carried out to investigate their fire resistance.

**EXPERIMENTAL INVESTIGATION**

**Tests on Mechanical Properties**

There were two batches of concrete cast for measuring the mechanical properties. For the control normal concrete, limestone with a nominal size of 20 mm was selected as coarse aggregate and natural yellow sand was used as fine aggregate. Then other types of concretes were mixed by replacing the coarse or fine aggregates with lightweight aggregate, steel slag and waste glass. The raw steel slag was sieved by using 20 mm and 4.9 mm standard meshes in the laboratory. Steel slag with the size between 4.9 and 20 mm was used as replaced coarse aggregate, whilst steel slag with the size below 4.9 mm was adopt as replaced fine aggregate. Lightweight aggregate with nominal sizes of 14 mm and 20 mm were purchased. Necessary cleaning procedure was applied to the waste glass in order to remove dust and crushed labels among them before using as aggregate in concrete. Waste glass with a size between 4.75 mm and 19 mm was used for the first batch of concrete and waste glass with a smaller size between 4.75 mm and 13.2 mm was selected for the second batch of concrete by reducing the smooth surface effects of large glass. All used aggregates in this paper were shown in Figure 1.

![Typical aggregates used in the test program](image)

To determine the mix design of concretes with different types of aggregates, the specific gravity, density and water absorption of each type of aggregate were measured before concrete mixing. Considering the high water absorption of lightweight aggregate and steel slag, the water to cement (W/C) ratio in the first batch was selected as 0.55. Based on the mix design of the control concrete, other types of concretes was designed by replacing the limestone with lightweight aggregate, 100% coarse steel slag and 85% coarse steel slag and 15% waste glass, respectively. For the second batch of
concrete, the W/C ratio was reduced to 0.42 and the cement content was increased by 20 kg to improve the compressive and flexural strengths. Different from the first batch, only 14 mm lightweight aggregate was adopted for the mix M2-2 and a new type of concrete M2-5 was designed by replacing yellow sands in normal concrete with 100% fine steel slag. The details of the mix design for different concretes were presented in Table 1, where SP in the table represents the superplasticizer. Polyheed 850 was selected as a ready-to-use liquid superplasticizer to provide water reduction and acceleration to the setting time of concrete.

<table>
<thead>
<tr>
<th>Batch Label</th>
<th>Cement (kg)</th>
<th>Water (kg)</th>
<th>Coarse Aggregates (kg)</th>
<th>Fine Aggregates (kg)</th>
<th>SP (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td></td>
<td></td>
<td>Limestone</td>
<td>Lightweight</td>
<td>Steel slag</td>
</tr>
<tr>
<td>M1-1</td>
<td>400</td>
<td>220</td>
<td>–</td>
<td>1115</td>
<td>–</td>
</tr>
<tr>
<td>M1-2</td>
<td>400</td>
<td>220</td>
<td>–</td>
<td>348</td>
<td>348</td>
</tr>
<tr>
<td>M1-3</td>
<td>400</td>
<td>220</td>
<td>–</td>
<td>220</td>
<td>–</td>
</tr>
<tr>
<td>M1-4</td>
<td>400</td>
<td>220</td>
<td>–</td>
<td>220</td>
<td>–</td>
</tr>
<tr>
<td>2nd</td>
<td></td>
<td></td>
<td>Limestone</td>
<td>Lightweight</td>
<td>Steel slag</td>
</tr>
<tr>
<td>M2-1</td>
<td>420</td>
<td>176.4</td>
<td>1116</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>M2-2</td>
<td>420</td>
<td>176.4</td>
<td>–</td>
<td>–</td>
<td>450</td>
</tr>
<tr>
<td>M2-3</td>
<td>420</td>
<td>176.4</td>
<td>–</td>
<td>–</td>
<td>1479</td>
</tr>
<tr>
<td>M2-4</td>
<td>420</td>
<td>176.4</td>
<td>–</td>
<td>–</td>
<td>945</td>
</tr>
<tr>
<td>M2-5</td>
<td>420</td>
<td>176.4</td>
<td>1116</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

To measure the mechanical properties, nine 100 mm diameter cylinder specimens with a height of 200 mm were prepared for each type of concrete. The corresponding density, compressive strength and modulus of elasticity were measured at 3 days, 7 days and 28 days by using these cylinder specimens. Besides, six beam specimens with a dimension of 100×100×400 mm were also prepared to measure the flexural strength of different concretes at 3 days, 7 days and 28 days. All tests were conducted according to the relevant Australian Standards.

**Fire Tests on Concrete Columns**

Five circular concrete columns with a diameter of 250 mm and height of 800 mm were prepared for fire testing. The mix design for each type of concrete in the fire tests was the same as that in the second batch of mechanical properties tests. The only difference was that 50% fine steel slag plus 50% yellow sands were used for M2-5 rather than using steel slag to replace all fine aggregate earlier. This aimed to improve the cohesion between the cement paste and aggregate for this type of concrete.

![Figure 2. Positions of thermocouples and the test setup](image)
Fire tests of the concrete columns were carried out in a furnace which was 640 mm in width and 630 mm in depth with a height of 880 mm. Each concrete column was subjected to an axial load, which was determined based on the defined load level and the compressive strength of the concrete cylinder on the test day. The load ratio was initially selected as 0.45 for all specimens. However, due to the serious concrete spalling and low fire resistance time observed in the first test on the normal concrete column, the load ratio for the rest of columns was reduced to 0.3. The predetermined load was applied and kept constant and then the furnace was switched on to increase the temperature gradually to 800°C. Then the furnace temperature was kept at 800°C until the concrete column failed. The test terminated when the axial shortening of the concrete column exceeded 0.01\( \text{mm/m}$\) or the axial deformation rate exceeded 0.003\( \text{mm/min}$ (2.4 mm/min), where \( H \) is the length of the concrete column. Three thermocouples were installed inside the concrete column to measure the temperature development. Figure 2 shows the positions of the thermocouples and the test setup.

**RESULTS AND DISCUSSION**

All the density values for the concretes at 3 days, 7 days and 28 days were measured and given in Table 2. The density remained almost the same and fluctuated within a small range with increasing concrete age. Obviously, lightweight concrete reduced nearly 20% of density when compared with normal concrete due to the lower specific gravity of aggregate. Lightweight concrete in the first batch was lighter than that of the second batch. This might be due to that only 14 mm size lightweight aggregate was adopted in the second batch. Large size lightweight aggregate contains more internal pores to achieve lower gravity. Using steel slag in concrete caused around 10% growth in density, and replacing with fine steel slag led to more increment than replacing of coarse steel slag. However, adding 15% waste glass in coarse steel slag concrete could reduce the density growth to almost half. This proved that adding glass was a reasonable way to reduce the heavy density of steel slag concrete.

<table>
<thead>
<tr>
<th>Batch</th>
<th>Concrete</th>
<th>Density (kg/m$^3$)</th>
<th>At 3 days</th>
<th>At 7 days</th>
<th>At 28 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1$^{st}$</td>
<td>Normal</td>
<td>2323</td>
<td>2388</td>
<td>2335</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lightweight</td>
<td>1824 (-21.5%)</td>
<td>1872 (-21.6%)</td>
<td>1818 (-22.1%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coarse Steel Slag</td>
<td>2545 (+9.6%)</td>
<td>2611 (+9.3%)</td>
<td>2574 (+10.2%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coarse Steel Slag + Glass</td>
<td>2468 (+6.2%)</td>
<td>2481 (+3.9%)</td>
<td>2444 (+4.7%)</td>
<td></td>
</tr>
<tr>
<td>2$^{nd}$</td>
<td>Normal</td>
<td>2384</td>
<td>2357</td>
<td>2364</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lightweight</td>
<td>1988 (-16.6%)</td>
<td>1956 (-17.0%)</td>
<td>1947 (-17.6%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coarse Steel Slag</td>
<td>2652 (+11.2%)</td>
<td>2625 (+11.4%)</td>
<td>2596 (+9.8%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coarse Steel Slag + Glass</td>
<td>2508 (+5.2%)</td>
<td>2514 (+6.7%)</td>
<td>2494 (+5.5%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fine Steel Slag</td>
<td>2677 (+12.3%)</td>
<td>2673 (+13.4%)</td>
<td>2673 (+13.1%)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3 shows the compressive strength \( (f'_c) \) of different types of concrete at 3 days, 7 days and 28 days. Obviously the compressive strengths increased with increasing concrete age. Higher compressive strength was achieved when the W/C ratio was reduced. Adding waste glass reduced compressive strength in the first batch. On the contrary, the glass concrete showed higher compressive strength when a smaller size of waste glass was used in the second batch. Replacing normal sand with fine steel slag led to higher compressive strengths, but other types of concrete with replaced aggregate had lower mechanical properties. Overall, concrete made from those special aggregates worked well and demonstrated reasonable behaviour. Similarly, flexural strengths \( (f'_{c,f}) \) also increased with increasing concrete age as shown in Figure 4. Reducing the partial size of waste glass in steel slag concrete could also improve the flexural strength. Similar to the results of compressive strength, fine steel slag in concrete led to higher flexural strengths as well. It is worth to note that the lightweight concrete in the first batch had much lower compressive and flexural strengths than other concretes, but the lightweight concrete in the second batch has comparable strengths as others.
The modulus of elasticity \( (E_c) \) for different concretes was also tested accordingly, and the results are shown in Figure 5. Once again, the modulus of elasticity grew steadily with the increasing of concrete age. Lightweight aggregate concrete obtained much lower modulus of elasticity, which was only about half of the value of other types of concrete in the same batch. Similar finding was reported by others (Hossain and Lachemi 2007) and it is explained by the high volume of pores in the lightweight aggregate. Although steel slag also has internal pores, the modulus of elasticity of coarse steel slag concrete was close to that of normal concrete. Moreover, the concrete with fine steel slag achieved higher modulus of elasticity than that of normal concrete. Furthermore, it was worth to note that adding large size of waste glass in steel slag concrete reduced the modulus of elasticity. However, the glass concrete in the second batch had similar or higher modulus of elasticity when a smaller size of waste glass was used.

Figure 3. Compressive strength \( (f'_c) \) for different types of concrete

Figure 4. Flexural strength \( (f_{ct}) \) for different types of concrete

Figure 5. Modulus of elasticity \( (E_c) \) for different types of concrete

Figure 6 shows the axial deformation \( (\Delta) \) versus time \( (t) \) curves for different types of concrete. The fire resistance of all the steel slag concretes exceeded 90 minutes. Among the three types of concrete with
steel slag, the concrete with the addition of glass obtained the best fire performance. However, lightweight and normal concrete had much lower fire resistance, due to the serious concrete spalling during fire exposure. Therefore, in the forthcoming tests, concrete made with steel slag and glass, as well as lightweight aggregate will be used to fill in hollow tubes to investigate the fire performance of composite members using these concretes. The concrete spalling of lightweight concrete may be avoided by the protection of the steel tube.

![Graph](image.png)

Figure 6. Axial deformation ($\Delta$) versus time ($t$) curves for different concrete columns

**CONCLUSIONS**

Preliminary experimental research results on concretes made from waste materials and by-products were reported in this paper. According to the test results, concretes made from those special aggregates performed very well and demonstrated reasonable behaviour when compared with normal concrete, and sometimes even better compressive and flexural strengths can be obtained. Moreover, fire tests indicate that concretes made with those selected aggregates showed better fire performance than normal concrete, especially for the concrete made with steel slag and waste glass.

The research findings highlight the potential application of the innovate concretes in engineering practice. Further work will be conducted on composite members with these special concretes.

**ACKNOWLEDGMENTS**

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**REFERENCES**


