- Technical Paper -

THE EFFECTS OF SEWAGE SLUDGE MOLTEN SLAG AGGREGATES IN CONCRETE

Carlos AQUINO[*1], Masumi INOUE[*2], Shogo YAGI[*3] and Takahisa OKAMOTO[*4]

ABSTRACT
The physical properties of sewage slag molten slag and its behavior in concrete mixtures are studied in this research. The molten slag was combined with common coarse aggregates in different proportions in concrete specimens. The tests conducted include; strength, modulus of elasticity, drying shrinkage (aggregates and concrete), freezing and thawing, tension softening and fracture energy. The results of these tests were compared with concrete specimens studied in previous years. It was found uniformity through the years and a higher performance of the specimens containing molten slag.
Keywords: sewage sludge molten slag, coarse aggregates, strength, fracture energy, shrinkage

1. INTRODUCTION

The concrete industry has always been in search of new raw materials which can give same or better performances at a competitive cost. In the other hand, the sustainable development has had a global impact that has made the industries became aware and minimize the environmental impacts caused by their production systems. Thus artificial aggregates in the concrete industry are a solution for both demands. However, these artificial aggregates from industrial and household wastes have to beat the natural aggregates to be a better option for construction. To make this possible, it is compulsory to improve their production systems and certify its behavior in concrete mixtures.

The molten slag used in these experiments comes from the sewage sludge of the northeastern region of Shiga prefecture. The water purification is one of the priorities to prevent pollution in Lake Biwa (the largest lake in Japan located in Shiga prefecture) and the extraction of natural aggregates has been prohibited in the areas near to Lake Biwa. Previously, the sewage sludge was landfill, but the difficulty to find new sites for it and the scarcity of aggregates for concrete created a better final disposal of this sludge.

In this paper, the molten slag properties are studied and compared to researches conducted in previous researches. The physical properties of concrete specimens produced of molten slag are improved, its strength and elasticity are higher, the shrinkage is lower and the bond adhesion between the aggregate and paste is slightly increased. Many studies have been done about the molten slag and its performance on concrete specimens (e.g.: [1][2][3]). This paper tries to promote the eco-friendly materials given the trust the constructors need to apply these materials in their own concrete structures, especially in the Kansai area in Japan. Furthermore, it gives the information tools for the constructors near Lake Biwa to use these types of materials. Possibly, this paper may seem very local, but like everywhere in the world, most of the cost of the natural aggregates is determined by the transport cost, the constructors may look for their nearest aggregates sources, natural or artificial. The information written in this paper could provide them a second thinking of the use of these materials, not only for concrete strength and other desired properties but also to protect the environment.

2. EXPERIMENTS

2.1 Experiments Outline

The cement type and fine aggregate (sand) were the same for all the specimens, in order to study the properties of the molten slag as coarse aggregate. Some specimens were produced with different replacement ratios (molten slag/gravel) to study the effect of the molten slag according its proportion in the concrete mixture. These specimens which include molten slag were compared with specimens produced of common aggregates (gravel and sand).

2.2 Materials

The Materials used for this research are as follow:

(1) Cement; Ordinary Portland cement (C), complying with the JIS R 5201 with density of 3.16g/cm^3 and Blaine of 3260cm^2/g.

(2) Fine aggregate; Crushed sand (S), from Osaka prefecture complying with JIS A 5005, dry density; 2.60g/cm^3, water absorption; 2.00%, F.M.; 2.75 and M.S.; 5mm.

*1 Graduate School of Engineering, Ritsumeikan University, JCI Member
*2 Assistant Prof., Dept. of Civil and Environmental Eng., Kitami Institute of Technology, Dr E., JCI Member
*3 School of Engineering, Ritsumeikan University
*4 Prof., Dept. of Environmental Systems Engineering, Ritsumeikan University, Dr E., JCI Member

Table 1 Physical properties of the coarse aggregates and its JIS standard values

Coarse aggregate	Specific gravity (g/cm^3)	Dry density (g/cm^3)	Water absorption (%)	Unit of mass per volume (kg/l)	Absolute volume (%)	Resistance to abrasion (%)	Crushing value (%)
Molten Slag(MG)	2.64	2.60	0.90	1.45	57.0	23.6	21.5
Molten Slag(MG2)	2.48	2.44	0.69	1.41	57.4	28.2	22.7
Molten Slag(MG3)	2.65	2.60	2.16	1.52	58.5	43.6	41.1
JIS A 5031	--	Above 2.50	Below 3.00	--	--	--	--
Crushed gravel(G)	2.65	2.64	1.32	1.59	59.1	9.8	8.96
JIS A 5005	--	Above 2.50	Below 3.00	--	Above 55.0	Below 40.0	--

Table 2 Mixtures and nomenclature of the concrete specimens

Name of the specimen	W/C ratio (%)	Molten slag replacement (%)	Unit content (kg/m^3)					Admixtures (cc/m^3)	
			Water	Cement	Sand	Gravel	Molten slag	Water reducer	Air reducer
55-0	55	0	175	318	807	986	0	636	1591
55-25		25	175	318	807	740	247	636	1591
55-50		50	175	318	807	493	493	795	1591
55-100		100	175	318	807	0	914	1273	318

(3) Coarse aggregates; Crushed gravel (G), from Osaka prefecture, complying with JIS A 5005, dry density; 2.65g/cm^3, water absorption; 1.32% and F.M.; 6.74. Molten slag (MG), complying with JIS A 5031, dry density; 2.60g/cm^3, water absorption; 0.90% and F.M.; 6.60. Both aggregates with sizes between 5mm and 20mm (see Fig. 1). The molten slag used in these experiments is produced in Shiga prefecture in the northeastern purification center with a temperature of calcination between 1400^{o}C and 1450^{o}C and cooled by air.

(4) Admixtures; High performance water reducer (Ad1) with a density of 1.10g/cm^3 and Air reducer, Polycarboxylic Acid Polymer, (Ad2) with density of 1.19g/cm^3, both admixtures complying with JIS A 6204.

Additionally, other 2 molten slag aggregates (MG2 and MG3) were compared with the molten slag (MG) used in these experiments. These MG2 and MG3 were used in previous researches by Inoue M. et al. [4] and Takeda, et al. [5] respectively. MG and MG2 were produced in the same facility in 2009 and 2008 respectively, while MG3 is from a different facility located in Shiga and it was produced in 2006.

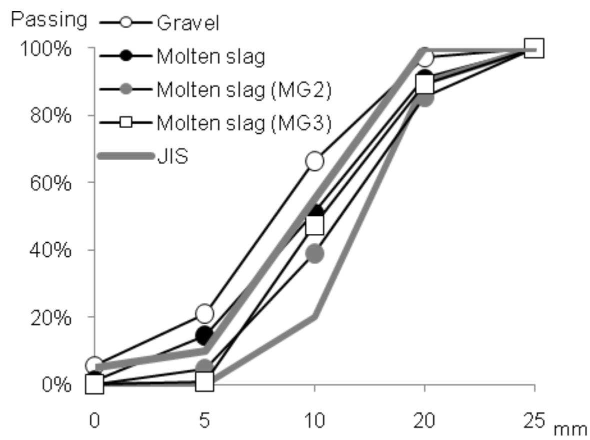


Fig. 1 Size distribution of the coarse aggregates

The main properties of the coarse aggregates and its standard values are listed on Table 1. The specific gravity of the MG is slightly lower than MG3 and G (only 0.01 g/cm^3). On the other hand, MG is harder than MG2 and MG3 (According to its abrasion and crushing tests).

The gravel (G) can absorb more water than the MG and MG2 aggregates and it may influence in the shrinkage of concrete, but this aggregate is harder than any molten slag according to its crushing and resistance to abrasion results.

(a)Molten slag (MG) (b)Molten slag (MG2)

(c)Molten slag (MG3) (d)Crushed gravel (G)

Photo 1 Example of various coarse aggregates

Photo 1 shows the coarse aggregates used in previous studies and in this research. Photo 1a shows the molten slag (MG) used in these experiments. Photo 1b shows the molten slag (MG2) used by Inoue M. et al. [4] in 2008. Photo 1c is molten slag (MG3) produced in the southern region of Shiga prefecture which was used by Takeda, et al. [5] in 2006 and Photo 1d shows the crushed gravel (common aggregate) used in these experiments. The molten slag used in these experiments has a slightly larger size compared with the molten slag used in 2008 (see Fig. 1). The shape, the presence of bubble and various layers of colors on the surface of the aggregates are still similar to the previous studies.

2.3 Mixtures and nomenclature of the specimens

The specimens consisted of 45 concrete beams of 10x10x40cm, 32 cylinders of Ø10x20cm and 24 cylinders of Ø15x15cm for a total of 101specimens. The specimens were casted and cured until their strength, modulus of elasticity, drying shrinkage, and fracture energy tests were conducted. Table 2 shows the nomenclature of the specimen and their materials. All the specimens produced for these experiments were made with a 55% of W/C, slump target of 7.5±1cm and entrapped air of 4.5±1% controlled by the admixtures.

2.4 Methods

For the common experiments, the Japanese Industrial Standards (JIS), Japanese Concrete Institute (JCI) and British Standard (BS) methods were applied as shown on Table 3. The drying shrinkage test of the aggregates was conducted without following a standard method.

Table 3 Tests and its standard method

	Test Name	Standard	Specimen size (cm)
Aggregates	Water absorption	JIS A 1110	--
	Density	JIS A 1109	--
	Resistance to abrasion	JIS A 1121	1.0-2.0
	Sieves analysis	JIS A 1102	--
	Crushing value	BS 812	1.0-1.5
Concrete	Slump	JIS A 1101	--
	Air volume	JIS A 1128	--
	Compressive strength	JIS A 1108	Ø10x20
	Flexural strength	JIS A 1106	10x10x40
	Tensile strength	JIS A 1113	Ø15x15
	Elasticity	JIS A 1149	10x10x40
	Drying shrinkage	JIS A 1129	10x10x40
	Fracture energy	JCI S 001	10x10x40
	Freezing and thawing	JIS A 1148	10x10x40
	Dyn. Mod. Elasticity	JIS A 1127	10x10x40

2.5 Special conditions of the experiments

The drying shrinkage test starts to be conducted after 7 days of curing the specimens under ordinary tap water in a temperature and humidity controlled room (20±1^{o}C, 60±5% RH). After being removed from water, the specimens were placed in a different temperature and humidity controlled room with the same characteristics as the previous but letting the specimens to dry. Its drying shrinkage was measured with a dial gauge complying with JIS B 7503 and it is accurate to 0.001mm. The specimens were rotated after every measurement.

The Fracture energy tests were conducted with an Autograph AG-X® system after 28 days of curing.

The dynamic modulus of elasticity and the rate of the mass loss were measured to the specimens 55-0, 55-50 and 55-100 (28 days) for the freezing and thawing test every 30 cycles.

For the shrinkage in aggregates, 5 rocks were sampled for every coarse aggregate (Including MG2 and MG3). The samples were cleaned and totally dried (1 day in an oven at 105^{o}C) after that, one of its surfaces was polished with regular sandpaper and then a double 2 mm gauge was attached to every sample and connected to data logger equipment (see Photo 2). The first 24 hours of measurement were under curing room conditions (20±1^{o}C, 60% RH) with no water. After that, the samples were totally immersing in ordinary tap water, for one week and one week more drying under the same room conditions.

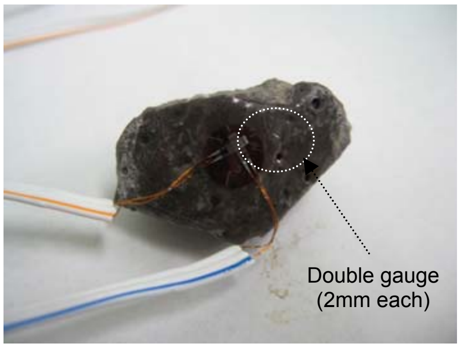


Photo 2 Measurement of shrinkage in aggregates

3. RESULTS AND DISCUSSIONS

3.1 Strength and modulus of elasticity

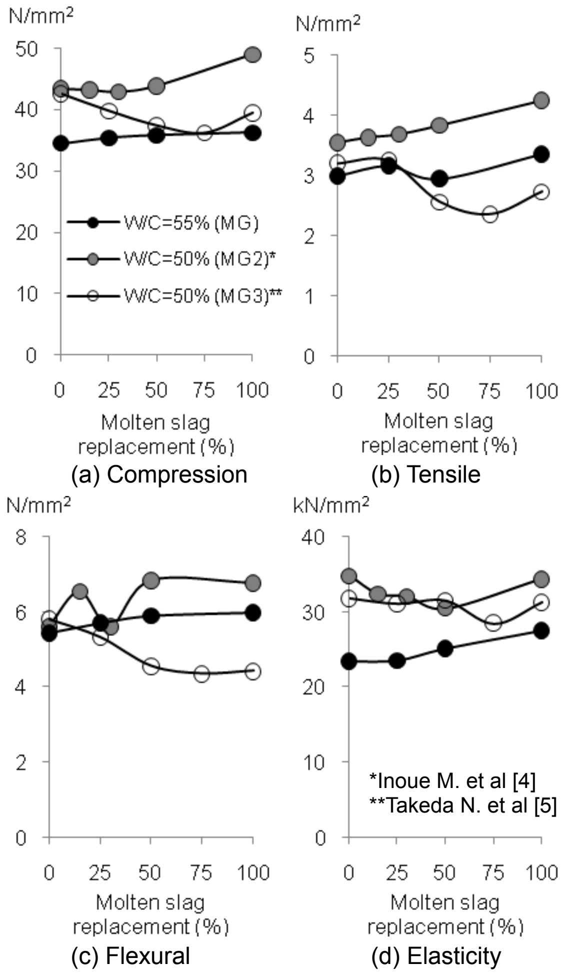


Fig. 2 Relation between the molten slag replacements. elasticity and strengths (28 days)

Fig. 2 shows the results of the strength and modulus of elasticity tests. The specimens produced in these experiments (W/C=55%) have very similar results in all their strength tests. However the specimen 55-100 had the best results in all the tests. The modulus of elasticity is increasing according the molten slag replacement is increasing. The specimen 55-100 has 15% more elasticity than the specimen 55-0. Thus, for these experiments the molten slag has a significance effect on the strength, and this aggregate provides more elasticity to the concrete.

From the previous studies, it is observed that the W/C ratio has a different effect in all the tests. The specimens produced by Inoue M. et al. [4] in 2008 have a W/C ratio of 50% and all of them have higher results compare with the specimens produced in this research. On the other hand, the specimens produced of MG3 (W/C 50%) decrease its strength and elasticity according its replacement of molten slag in all the tests.

Fig. 2a and 2d show larger results for MG3 than MG, however what is important of these figures is the tendency of the graph and not the value by itself. MG3 shows a tendency to decrease according its percentage of molten slag increases. On the other hand, MG shows a tendency to increase according its percentage of molten slag increases. Due to the specimens were not made in the same conditions (admixtures, sand, etc.) their strength and elasticity values cannot be compare directly.

3.2 Fracture energy and tension softening

The main goal of this test is to study the effect of adhesion of the molten slag and the paste. In these experiments the specimens 55-0, 55-50 and 55-100 were tested to be able to analyze the behavior of the molten slag according its replacement ratio.

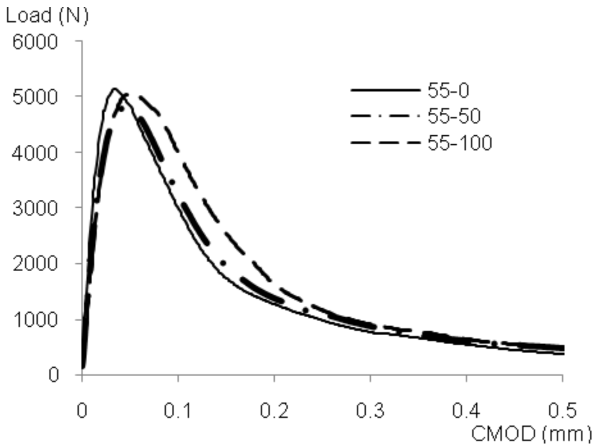
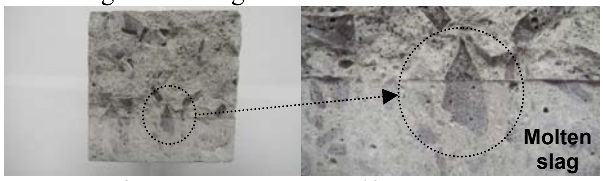


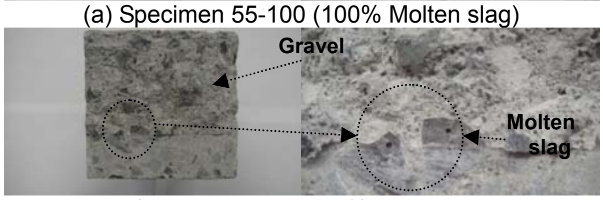
Fig. 3 Load and crack displacement curves

The strength properties of gravel and molten slag are different (see Table 1). However, the results of strength and modulus of elasticity show a similar tendency for the specimens 55-0 and 55-50 but higher for the specimen 55-100 (see Fig. 2). For this reason, more detail is needed and study the behavior of the crack according to the load applied.

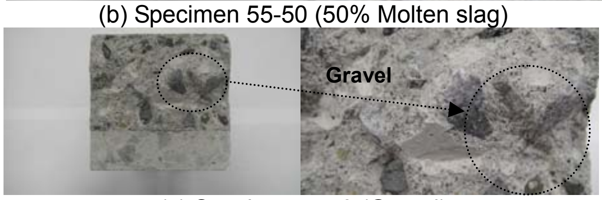
Fig. 3 shows the results of the load applied and the Crack Mouth Opening Displacement (CMOD). The specimen 55-100 has a larger area under the curve with 944 N/mm, followed by the specimen 55-50 with 838N/mm and lastly the specimen 55-0 with 818N/mm. These results are slightly higher for the specimens containing molten slag.



(a) Specimen 55-100 (100% Molten slag)



(b) Specimen 55-50 (50% Molten slag)



(c) Specimen 55-0 (Gravel)

Photo 3 Fracture surface

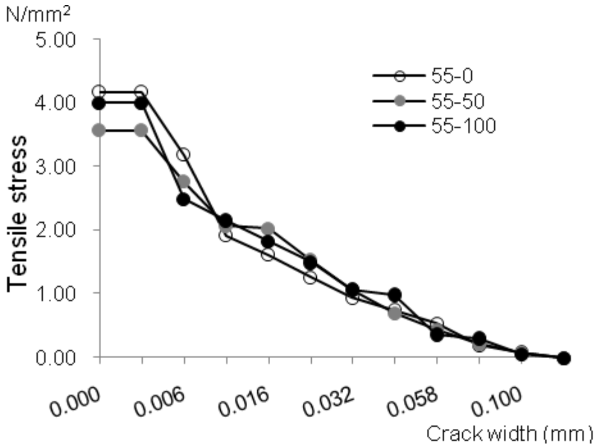
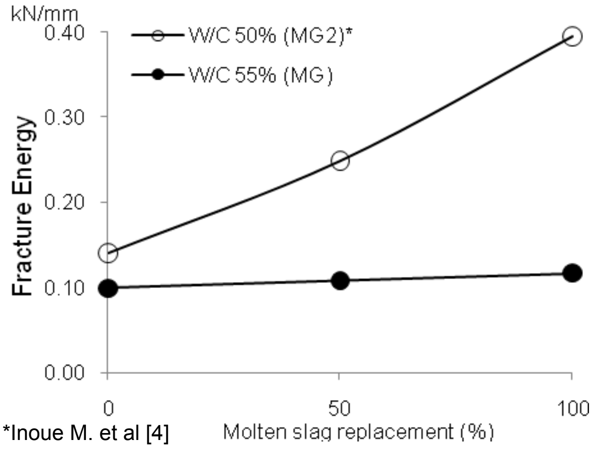


Fig. 4 Tension softening curves



*Inoue M. et al [4]

Fig. 5 Fracture energy

Photo 3 shows the surface of the specimens after the tension softening test. It is observed on Photo 3a that all the aggregates on the surface were broken, there is not complete aggregates separate from the paste as in the other 2 specimens (see Photo 3b and 3c). Some of the specimens produced with gravel have the complete rocks on the surface, and the fracture occurred between the paste and the gravel. Despite of this fact, both aggregates have similar values (Fig. 4) in this test.

The fracture energy applied is slightly higher for concretes produced of molten slag than those produced with common aggregates (see Fig. 5). In fact, according its molten slag replacement is increasing the strength is increasing. The difference are; about 20% for the specimens 55-0 and 55-100 and 10% for the specimens 55-0 and 55-50. However, from the results obtained by Inoue, et al [4] it is difficult to compare the molten slag properties by using the fracture energy test.

3.3 Freezing and thawing (F&T)

The specimens were tested by 300 cycles of temperature from 5°C to -18°C. After every 30 cycles their relative dynamic modulus of elasticity and their weight were measured. Figs. 6 and 7 show the results of this test. The specimens 55-0 and 55-50 presented more resistance to the temperature changes than the specimen 55-100 according to its durability factor.

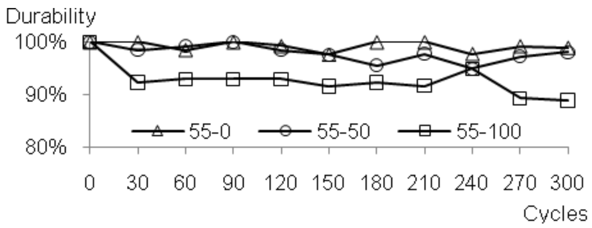


Fig. 6 Durability factor

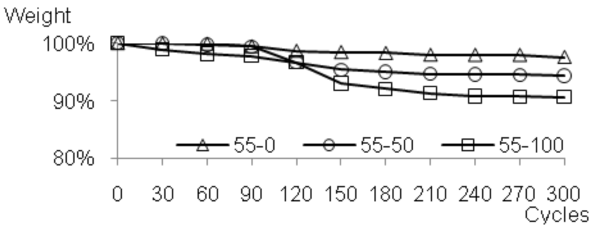
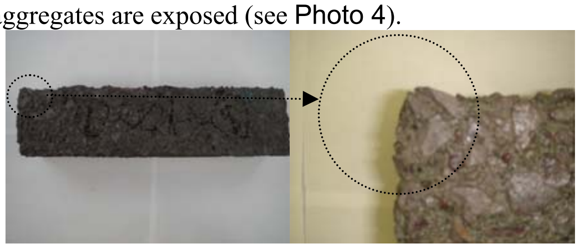
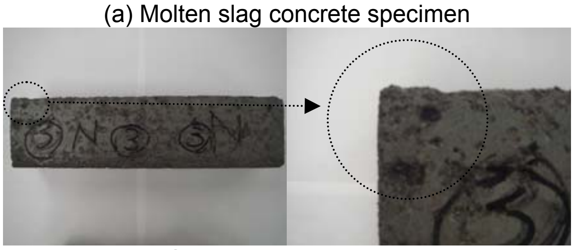


Fig. 7 Weight of the specimens after the F&T test

The loss of weight was minimum for all the specimens (see Fig. 7). However, those specimens produced of molten slag appear to have more damage. The surface of the specimen 55-0 seems smoother than the surface of the specimen 55-100 which its coarse aggregates are exposed (see Photo 4).



(a) Molten slag concrete specimen



(b) Gravel concrete specimen

Photo 4 Surface of the specimens after the F&T

3.4 Drying shrinkage

There is a considerable shrinkage reduction when using molten slag (see Fig. 8). The specimen 55-0 shrunk about 25% more than the specimens 55-50 and 55-100. Neville A. [6] and MacGregor J. mentioned [7] the relation between the elasticity of the aggregates with the shrinkage effect in concrete. In these experiments it seems to be a relation between the modulus of elasticity (see Fig. 2d) and the drying shrinkage. However this relation is not directly proportion, since the specimens 55-50 and 55-100 have similar shrinkage values but different modulus of elasticity results. Possibly, the effect to restrain the shrinkage could be similar for mixes from 50% to 100% of molten slag replacement.

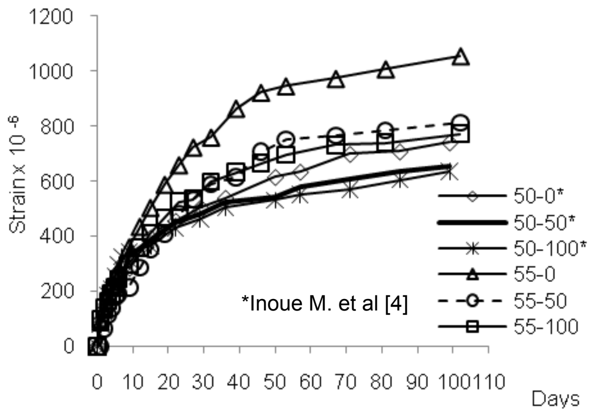


Fig. 8 Drying shrinkage in concrete specimens

According to Gambhir M. [8], the water amount influences the drying shrinkage in concrete. This was clearly evident when compare results with previous studies [4]. All the specimens produced with a W/C of 50% have lower shrinkage than the specimens produced in this research (W/C=55%). However the specimens produced with common aggregates are those with higher shrinkage in their respective researches. This proves the property of the molten slag to reduce the drying shrinkage, regardless of the W/C ratio. There is also a difference of 232μ between the 2 specimens containing 0% of molten slag, apart for the water/cement ratio is possibly that the moisture contain in sand were higher for the specimen 55-0 than the specimen 55-0. Since these 2 specimens were made on different experiments the most significant result from this figure is that in both cases (50 and 55) the specimens containing molten slag reduced the drying shrinkage in concrete.

3.5 Shrinkage in aggregates

Fig. 9 shows the shrinkage results in aggregates. The gravel shrinks more than any molten slag studied in this research. The hour 24th represents the time when the samples were immersed in water, from that time the gravel starts to swell faster than the other aggregates. In fact, the gravel has a small swell before it was under the water. It was slightly swelled only with the humidity of the room. The hour 192th was the time when the samples were removed from the water. The gravel tends to swell and shrink faster than the molten slag. The molten slags MG and MG2 have similar shrinkage results. On the other hand MG3 produced in a different facility shrinks more than the other 2.

The gravel has less water absorption and greater strength than the aggregate MG3 (see Table 2), but its shrinkage was higher, which makes us suppose that these properties are independent of each other. But these effects may change when are presented in concrete due to the paste characteristics. These results could represent the effect that the aggregates have in concrete. A similar effect may occur when the water is added into the materials when mixing the concrete. As long as the mix has some humidity the gravel will swell and eventually shrinks when the concrete is hardening (during drying).The total shrinkage of a concrete member could be the sum of its materials shrinkage.

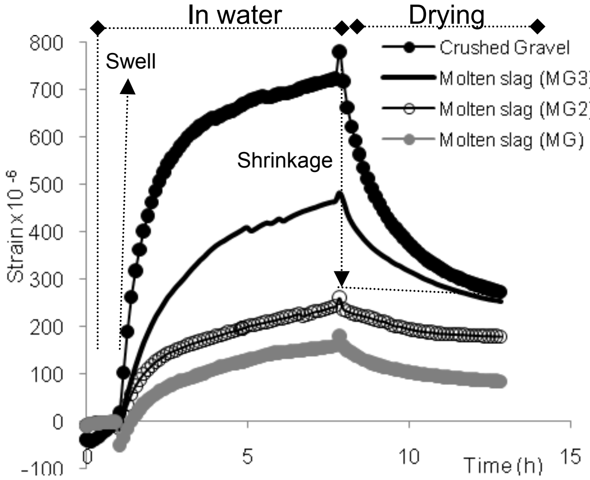


Fig. 9 Drying shrinkage of coarse aggregates

Another characteristic which may influence the concrete mix during the plastic stage and later on hardening is the bubbles on the surface of the MG and MG2 aggregates (as shown on Photos 1a and 1b). These bubbles may cause entrapped air if it is not well mixed during the fresh concrete. However during these experiments, the bubbles were not a factor to reduce the quality of the concrete.

4. CONCLUSIONS

4.1 General conclusions

The concrete industry need reduce the environmental impact caused by the exploitation of aggregates. Even more, it needs to increase its participation in the sustainable development as other industries are committing. This study proved the effectiveness of the sewage sludge molten slag aggregate in concrete mixtures. Its physical property can be equal and in many cases better than those offered by gravel. This research shows that;

(1) The specimens produced with 100% molten slag (55-100) have more compression, tensile and flexural strengths.
(2) The modulus of elasticity in concrete increases according the molten slag replacement increases.
(3) The bond between the aggregate and paste is slightly stronger in concretes produced with molten slag. The fracture energy required was higher for specimens containing molten slag.
(4) The drying shrinkage is less for concrete containing molten slag than those which are produced with gravel. However it could have a similar behavior for mixes containing 50% up to 100% of molten slag.
(5) The molten slag shrinks less than the crushed gravel, possibly this could be one of the consequence of low drying shrinkage in concrete.

The production of molten slag concretes contribute to the sustainable development, avoiding the exploitation of natural resources (such in Lake Biwa), and preserving sites previously occupied for sewage sludge landfills, minimizing pollution and possible sources of diseases.

4.2 Recommendation to JIS

At present, JIS A 5031 only provides standards for the dry density and water absorption, but JIS A 5005 also have standards for the absolute volume and resistance to abrasion. The authors suggest the implementation of other standards for JIS A 5031, which possibly could be the resistance to abrasion or the crushing value. The objective of this implementation is to increase the quality needed to compete with the natural aggregates.

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