Comparison of Mechanical Characteristics of Slag Base-course Materials Produced by Various Iron and Steel Manufacturers in Japan

N. Yoshida & H. Kimura
Research Center for Urban Safety and Security, Kobe University, Kobe, Hyogo, Japan

T. Miyahara
Engineering Headquarters, Kansai International Airport Co., Ltd, Izumisano, Osaka, Japan

ABSTRACT: In Japan, hydraulic graded iron and steel slag, which is commonly known as HMS, is a popular base-course material mainly because of its hydraulic nature. In this paper, the national industrial standard is first briefly described with a focus on the specifications for HMS. Then, compaction, uniaxial strength and resilient deformation characteristics are presented for HMS produced by five different iron and steel manufacturers in Japan, and difference in their characteristics is discussed. It is shown that all HMS exhibit a solid density in a narrow range but that for the maximum dry density and optimum water content only four HMS exhibit similar values. Moreover, for these four HMS, the magnitude of uniaxial compressive strength and resilient modulus and their increase with curing time are similar to each other and the other HMS exhibits much higher strength and resilient modulus. The differences between these four and the other HMS seem to increase with curing time. This observation may suggest that an appropriate modification should be made in the authorized specifications for a more effective use of HMS.

KEY WORDS: Slag, compaction, strength, resilient characteristics, standard specifications.

1 INTRODUCTION

Iron and steel slag is a by-product in the process of making iron and steel and considered as one of alternatives to natural aggregates. For instance, in UK, about two million tons of blast-furnace slag were produced in 2005, out of which 0.5 million tons were used as aggregates. At the same time, 0.51 million tons out of total 0.76 million tons of steel slag were used as aggregates (Communities and Local Government, 2007). In USA, total 18.8 million tons of iron and steel slag were sold in 2008, out of which about 10.1 million tons were blast-furnace slag and the rest was steel slag. About 40% of 6.9 million tons of air-cooled blast-furnace slag and about 60% of steel slag were used in road bases and surfaces (USGS, 2010).

In Japan, iron and steel slag aggregate has been used in road construction since about 1978 when the material was included in the manual for asphalt pavements, and its national industrial standard was established in 1979 (Japanese Standards Association, 1992). Since then, iron and steel slag aggregate has been used mainly in base-course and hot asphalt mix, mainly where it is available and economically transportable. Hydraulic graded iron and steel slag (commonly known as HMS) among others, is a popular base-course material mainly because of its hydraulic nature, and more importantly because of difficulty in getting good-quality natural aggregates due to social attention to natural environment protection.

Iron and steel slag are produced by iron and steel works belonging to three major design and the other smaller steel mills. According to Japan Slag Association (2009), as of 2008, 22.877 million tons of blast-furnace slag were produced while 13.208 million tons of steel slag were produced in Japan. 3.185 million tons of blast-furnace slag were used in road construction, of which 3.044 million tons were slowly air-cooled slag and the remaining 0.141 million tons were water-granulated slag. On the other hand, steel slag used in road construction was 2.876 million tons, of which 1.875 million tons were converter slag and the remaining was electric arc furnace slag. Furthermore, the amount of iron and steel slag used as base-course material was 5.761 million tons and 0.187 million tons were used in asphalt mix.

In Japan, the design method of pavement structure is moving toward a semi-empirical mechanistic approach adopting a structural analysis based on a multi-layered linear elasticity (Japan Road Association, 2006); however, an empirical design method using layer equivalency conversion coefficients, a so-called T_A method, still predominates in practice. Although there is still much room for research and development, establishing the mechanistic approach is urgent even for using natural aggregates more effectively. Considering the fact that obtaining good quality natural aggregates is becoming difficult in Japan, effective use of iron and steel slag and other alternative aggregates will be more important than ever.

In this paper, the national industrial standard is first briefly described with a focus on the specifications for HMS. Then, compaction, uniaxial strength and resilient deformation characteristics are presented for five HMS produced by different iron and steel manufacturers in Japan, and difference in their characteristics is discussed.

2 SLAG BASE-COURSE MATERIALS IN JAPAN

In Japan, the national industrial standard of iron and steel slag for use in road construction was established in 1979 mainly for blast-furnace slag, and steel slag was included in the standard in 1992 (Japan Standards Association, 1992).

Iron and steel slag possesses hydraulic nature to a greater or lesser extent. In case of granulated blast-furnace slag, for instance, hydraulic nature results from hydrates formed with calcium oxide, silica dioxide and alumina oxide seeped out from vitrified portion in the slag upon contact with water and in an alkaline environment. Air-cooled blast-furnace slag and steel slag also possess vitrified portions but only a little; thus hydraulic nature is much smaller than the granulated blast-furnace slag. Average chemical components of each slag in Japan

Table 1: Average chemical compositions of iron and steel slag used in Japan (modified after Japan Slag Association, 2004)

		SiO_2	CaO	Al_2O_3	T Fe*	MgO	S	MnO	TiO_2
Blast-furnace slag		33.8	42.0	14.4	0.3	6.7	0.84	0.3	1.0
Steel slag	Converter slag	13.8	44.3	1.5	17.5	6.4	0.07	5.3	1.5
	Electric arc furnace oxidizing slag	19.0	38.0	7.0	15.2	6.0	0.38	6.0	0.7
	Electric arc furnace reducing slag	27.0	51.0	9.0	1.5	7.0	0.50	1.0	0.7

* ferric oxide, *etc*. (in percent by mass)

are given on Table 1 (Japan Slag Association, 2004).

Presently, five types of iron and steel slag are used for road construction in Japan and Table 2 summarizes the characteristics of these five slag materials required in the Japanese industrial standard. The term "coloration" is to check if or not sulfur in blast-furnace slag is sufficiently stabilized. The blast-furnace slag contains a small amount of sulfur in a form of calcium sulfide: upon contact with water, calcium sulfide is hydrolyzed and in the progress of successive reaction, polysulfide iron is produced of which solution exhibits a yellow color, often emitting a bad smell (commonly known as a "yellow water" problem). The item "aging" is a treatment required for free lime in steel slag to be hydrated to stabilize its expansion problem. A basic aging treatment is simply to store slag in open yard for the specified period of time but in present practice, warm water or vapour are applied for accelerating the both reactions (Japan Slag Association, 2004). The items "coloration" and "immersion expansion ratio" are for confirming that sulfur and free lime contained in slag are sufficiently stabilized, respectively. Hydraulic, graded iron and steel slag (designated as HMS) and graded iron and steel slag are used mainly in base-course and crusher-run iron and steel slag is in subbase-course while single-graded steel slag and crusher-run steel slag are used in hot asphalt mixtures or in asphalt stabilization.

HMS is composed of solely blast-furnace slag, a mixture of blast-furnace slag and steel slag, or a mixture of other combinations of slag with or without additives. For instance, one type of HMS used in this study is a mixture of air-cooled blast-furnace slag, granulated slag and converter slag without any additives. As can be seen in the table, hydraulic nature is defined in terms of uniaxial compressive strength in such a way that it should be 1.2 MPa or greater after 13-day curing. Since only the lower-bound value is specified in the table, the base-course material may exhibit much higher strength depending on the ingredients in HMS.

Table 2: Iron and steel slag used for road construction in Japan (modified after Japanese Standards Association, 1992)

Slag type / Items	Hydraulic graded iron and steel slag	Graded iron and steel slag	Crusher-run iron and steel slag	Single-graded steel slag	Crusher-run steel slag	Notes
Designations	HMS-25	MS-25	CS-40, CS-30, CS-20	SS-20, SS-5	CSS-30, CSS-20	
Usage	Base-course	Base-course	Subbase-course	Hot asphalt mix	Hot asphalt-stabilization	
Coloration	No coloration	No coloration	No coloration	-	-	only for blast-furnace slag
Immersion expansion ratio (%)	1.5 or smaller	1.5 or smaller	1.5 or smaller	2.0 or smaller	2.0 or smaller	only for steel slag
Unit weight (kg/liter)	1.5 or larger	1.5 or larger	-	-	-	
Uniaxial compressive strength (MPa)	1.2 or larger (13-day cured)	-	-	-	-	
Modified CBR (%)	80 or larger	80 or larger	30 or larger	-	-	
Specific gravity in saturated surface-dry condition	-	-	-	2.45 or greater	-	
Water absorption percentage (%)	-	-	-	3.0 or smaller	-	
Abrasion (%)	-	-	-	30 or smaller	50 or smaller	
Aging	6 months or more	6 months or more	6 months or more	3 months or more	3 months or more	for steel slag
Plasticity index (%)	-	-	-	-	-	

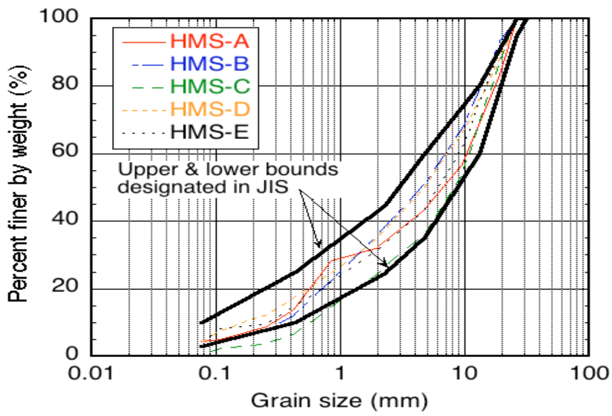


Figure 1: Grain size distributions of five types of hydraulic, graded iron and steel slag

As mentioned earlier, in Japan, the predominant design method for pavement structure is an empirical one called "TA method" but a semi-empirical, mechanistic design approach is also being promoted presently in which key element is a response analysis based on a multi-layered linear elasticity (Japan Road Association, 2006). For practical use, however, it is imperative at least that some kind of a database of resilient properties for various pavement materials, not only traditional, natural but also new, recycled ones, be established.

3 TESTING OF 5 TYPES OF HMS

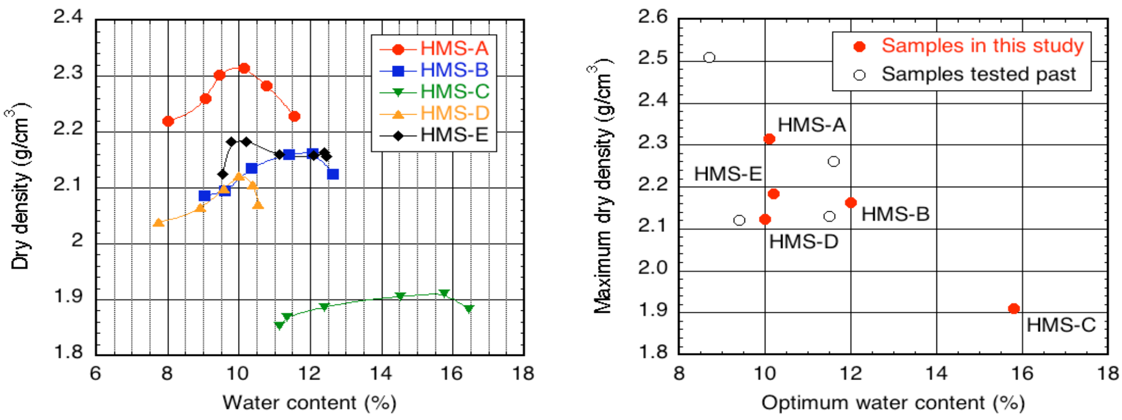
3.1 Test material and compaction characteristics

Five types of HMS were tested which were brought in from five different manufacturers in Japan for this study. As stated in the previous section, HMS may consist of air-cooled blast-furnace slag alone, a mixture of air-cooled blast-furnace slag and steel slag, or a mixture of other combinations of slag with or without additives. The ingredients and mixing proportions for the HMS tested in this study are not informed to the authors due to the company secret. In Table 3, the density of solids for each HMS is given. HMS-C shows the largest density of solids while HMS-D the smallest. The density of solids obtained previously for other HMS, although not shown here, ranges from 2.37 to 3.09 g/cm^3; thus these five HMS can be said to be ordinary ones. From difference in the density of solids, it may be speculated that HMS-A and C contain more a heavier component such as steel slag.

All these base-course materials satisfy the requirements imposed by the Japanese industrial standard such as those in Table 2. Their grain size distributions are shown in Figure 1. The range designated in the national standard is also indicated in the figure. It is seen that all the materials are roughly within the range. HMS-C exhibits a grain size distribution lying along the lower-bound distribution and lacks finer portions a bit while the grain size distributions of

Table 3: Density of solids and compaction characteristics for five HMS

Sample type	Max dry density (g/cm3)	Optimum water content (%)	Solid density (g/cm3)
HMS-A	2.314	10.1	3.122
HMS-B	2.162	12.0	3.050
HMS-C	1.910	15.8	3.148
HMS-D	2.122	10.0	2.937
HMS-E	2.183	10.2	3.008



(a) Compaction curves

(b) Relationships of maximum dry density with optimum water content

Figure 2: Compaction characteristics

other four HMS lie in the middle of the range.

Compaction characteristics are essential to preparation of samples for uniaxial compression tests and repeated loading triaxial compression tests. Compaction tests and sample preparation were all carried out within a week after the receipt of each base-course material. Compaction tests were carried out with a compaction effort of about 2480 kJ/m^3, following the Japanese industrial standard termed "JIS A 1210: Test method for soil compaction using a rammer".

Table 3 summarizes the compaction characteristics of these five materials, and their compaction curves and relationships of maximum dry density with optimum water content are shown in Figure 2. It seems that the shape of compaction curve for HMS- C is flatter than the others and that there is a tendency that the maximum dry density increases as optimum water content decreases with some exceptions. It is also noticed that HMS-C exhibits smaller maximum dry density and larger optimum water content than the other HMS including the past HMS.

3.2 Sample preparation for uniaxial and repeated loading triaxial compression tests

Samples were prepared in the following manner. The water content of material was first adjusted to its optimum water content with distilled water. Then, a prescribed amount of the material was placed into a mould in 5 stages, in each stage compaction being performed using a rammer with a mass of 4.5 kg, in such a way that the resulting dry density becomes 95% of its maximum dry density. Note that grains not passing a 19.1mm sieve were excluded for the sample preparation considering the sample size with a diameter of 100 mm and a height of 200 mm. Each sample with its mould was double-wrapped up with polyethylene bags and a weight of 49N was placed on its top; then they were cured in a dark room with a moisture of about 60% and a temperature of about 20˚C for a prescribed period of time.

4 UNIAXIAL STRENGTH AND RESILIENT DEFORMATION CHARACTERISTICS

4.1 Uniaxial strength characteristics

Uniaxial compression test was carried out with a loading rate of 1% strain per minute,

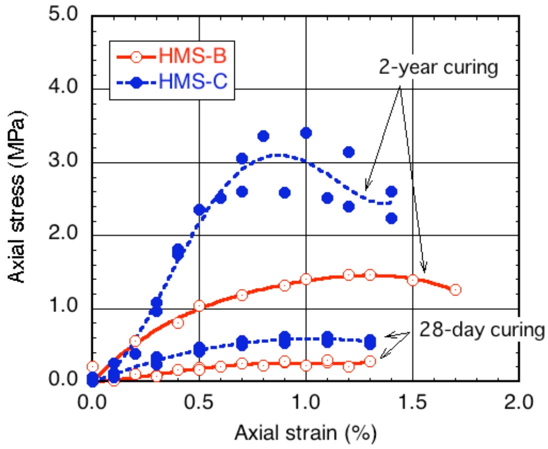


Figure 3: Relationships of axial stress with axial strain for HMS-B and -C at 28-day and 2-year curing

following the Japanese industrial standard termed "JIS A 1216: Method for unconfined compression test of soils".

Figure 3 compares the axial stress - strain relationships between HMS-B and HMS-C at curing time of 28 days and two years. At 28-day curing, both the HMS show a similar axial stress-strain relationship having a gradual increase in axial stress with axial strain, although HMS-C sustains slightly larger axial stress. Two years later, however, HMS-C sustains much larger axial stress than HMS-B, exhibiting kind of a brittle stress-strain relationship having a distinct peak.

Increase of uniaxial compressive strength with curing time is given in Figure 4 for all five HMS. It is seen that all five HMS exhibit an increase in strength with curing time. Without curing (0 day), unaxial compressive strengths, although difficult to read out from the figure, are on average 0.202 MPa for HMS-A, 0.109 MPa for HMS-B, 0.363 MPa for HMS-C, 0.180 MPa for HMS-D and 0.248 MPa for HMS-E. There is only a little difference in strength at the early stage of curing; but as curing continues for a longer period of time, the difference in strength becomes pronounced, at least between HMS-B and HMS-C. HMS-C exhibits the largest strength and HMS-B the smallest after one year curing, and even after two years curing, the tendency is the same. At curing of two years, the strength of HMS-C doubles that of HMS-B. Moreover, in HMS-B, -C, -D and -E, the strength increase tends to

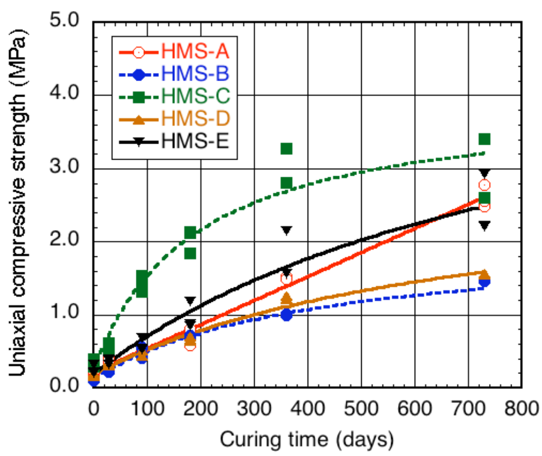


Figure 4: Relationships of uniaxial compressive strength with curing time

settle as the period of curing becomes longer but the strength in HMS-A continues to increase.

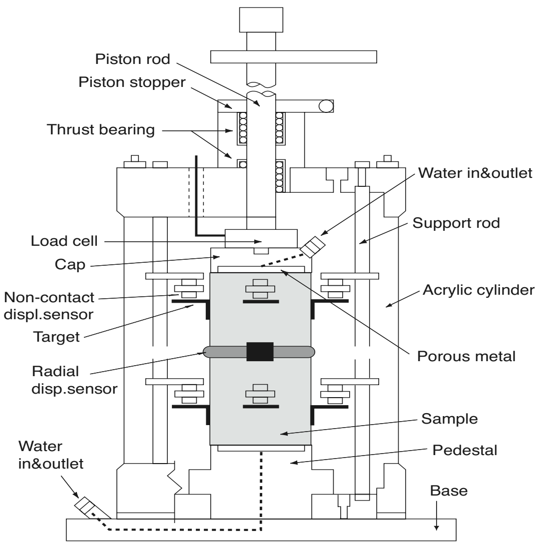
The currently dominant empirical design method assigns a specific value of 0.55 to the layer equivalency conversion coefficient for HMS base-course material and the Japanese industrial standard, as seen in Table 2, specifies only the lower bounds for mechanical indices: however, for rational use of HMS, it seems to be reasonable to take into account such difference in the development of hydraulicity among HMS as observed above.

Recalling the uniaxial compressive strength designated in the Japanese industrial standard (Table 2), one may think that the HMS tested in this study may either be underestimated or not be qualified. But it is not the case; unlike the strength designated in the standard, which is based on the test results on the specimens with a height-diameter ratio of much smaller than two and compacted at their maximum dry densities, the strength in this study was obtained on the longer specimens with a lower compaction effort.

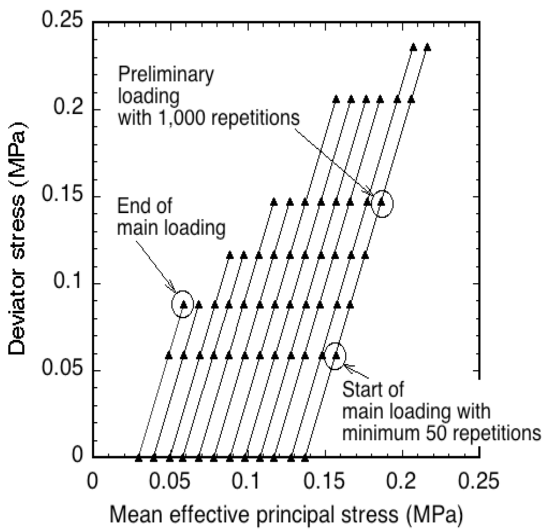
4.2 Resilient deformation characteristics

Repeated loading triaxial compression test was carried out in the same way as previous studies (*e.g.*, Yoshida *et al.*, 2006, 2008). The repeated loading triaxial compression test system consists of axial loading, lateral loading, triaxial cell and control units. Compressed air is used for axial loading and is converted to water pressure for lateral loading. Repeated axial load is applied onto the sample with a double-action Bellofram air cylinder by controlling the compressed air by an electro-pneumatic transducer through a servo-amplifier. A load cell is installed between the loading piston and the cap inside the triaxial cell as shown in Figure 5. The deformation of sample was measured as follows. For the axial displacement measurement, 8 non-contact displacement sensors were used with targets attached on the side of the sample: 4 on the upper portion and 4 on the lower portion of a sample. The radial displacement was measured, as shown in Figure 5, at the mid-height of sample using a radial displacement ring manufactured locally with strain gauges, steel spring, *etc.* (Sugita, 2006).

For repeated loading, the loading and pausing durations are 0.4 and 1.2 seconds, respectively, due to constraints from the use of compressed air, and the applied waveform is a



(a) Triaxial cell



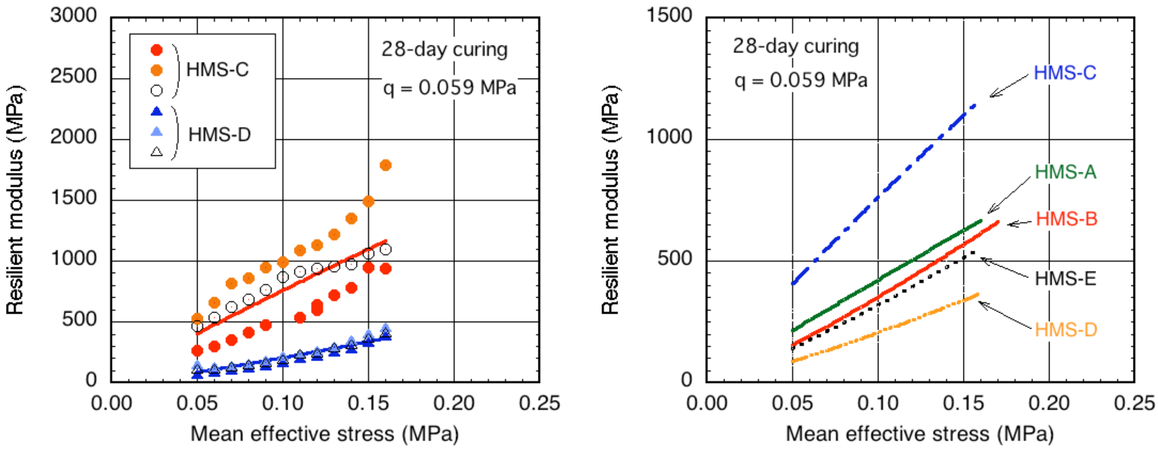
(b) Applied stress conditions

Figure 5: Triaxial cell and applied stress conditions for repeated loading triaxial compression tests

harversine shape. The loading sequence basically follows AASHTO Designation T292-91 (AASHTO, 1998) but the magnitude of applied deviator and confining stresses and the number of stress conditions differ as shown in Figure 5: the deviator stress ranges from 0.059 to 0.236 MPa and the mean principal effective stress from 0.049 to 0.216 MPa (Yoshida *et al.*, 2006). The test was conducted basically on three samples for each curing condition for each HMS.

Relationships of resilient modulus with mean effective stress, $p = (\sigma_1' + 2\sigma_3')/3$, for a deviator stress, $q = (\sigma_1' - \sigma_3')$, of 0.059 MPa are shown in Figure 6 (a) for HMS-C and HMS-D at curing time of 28 days, and in Figure 6 (b) five HMS are compared in terms of regression curves. From Figure 6 (a), it is seen that the resilient modulus for both HMS increases with mean effective stress and that HMS-C shows larger resilient modulus, although the results are scattered among samples for HMS-C. The resilient modulus for the other three HMS is also seen to exhibit a similar stress-dependency in Figure 6 (b) and it is seen that the resilient modulus of HMS-C is the largest and that of HMS-D the smallest.

Figure 7 shows increase of resilient modulus with curing time for HMS-C and HMS-D in terms of regression curves, together with an enlarged portion for resilient modulus smaller



(a) HMS-C and HMS-D with data (b) Five HMS in terms of regression curves

Figure 6: Relationships of resilient modulus with mean effective stress for 28-day curing

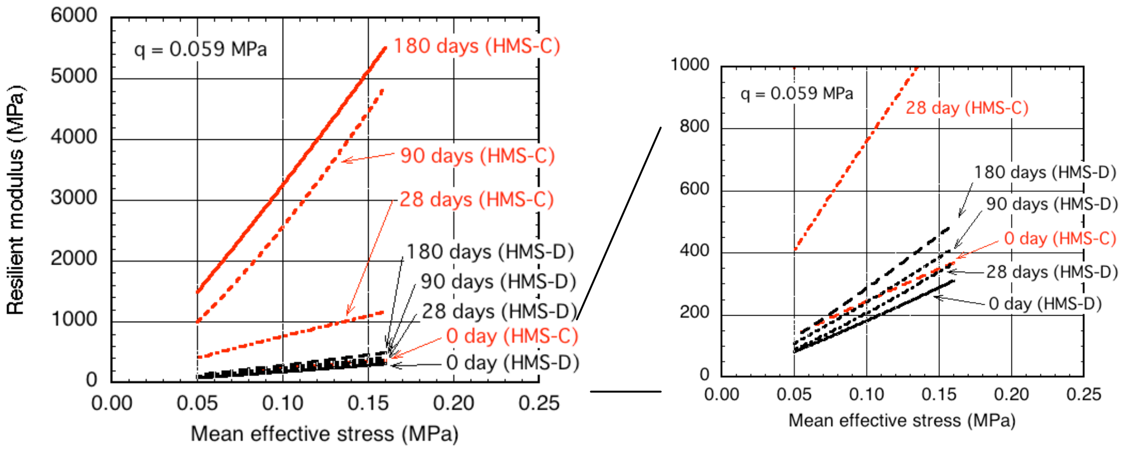
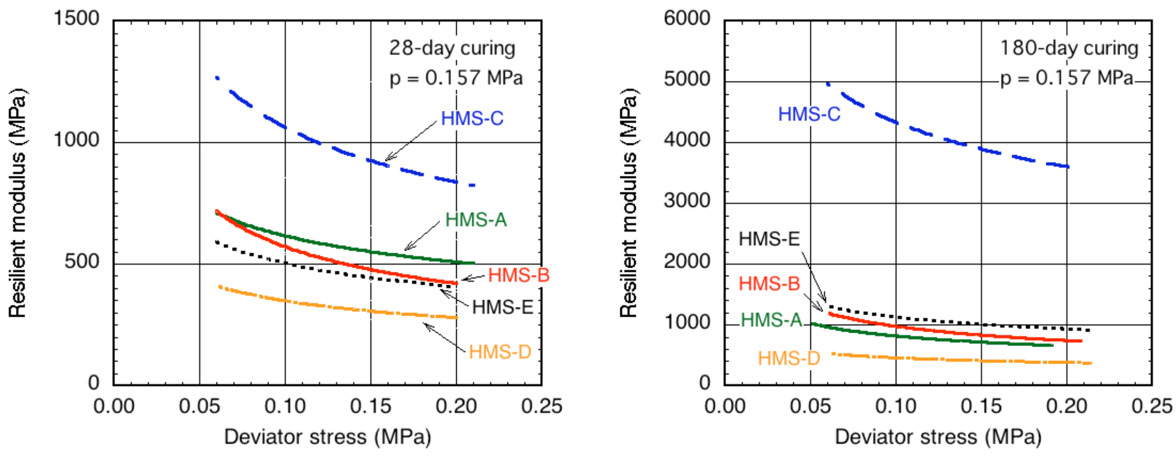


Figure 7: Relationships of resilient modulus with mean effective stress for HMS-C and HMC-D at curing time from 0 to 180 days



(a) 28-day curing (b) 180-day curing

Figure 8: Relationships of resilient modulus with deviator stress for five HMS

than 1000 MPa. It is seen that the stress-dependency of resilient modulus observed above is sustained regardless of curing time and that as curing time increases the degree of stress-dependency in resilient modulus increases. HMS-C exhibits much larger increase in resilient modulus with curing time than HMS-D.

Relationships of resilient modulus with deviator stress for all five HMS are shown in Figure 8 in terms of regression curves at curing time of 28 and 180 days. It is seen that, regardless of the type of HMS, resilient modulus depends on deviator stress and that the resilient modulus is the largest for HMS-C and the smallest for HMS-D as deduced from the resilient modulus - mean effective stress relationships presented earlier.

It is well known that the resilient modulus of untreated granular materials depends mainly on the sum of principal stresses and that clayey soils exhibit resilient modulus which depends on deviator stress (*e.g.*, Hicks and Monismith, 1971; Monismith, 1992; Lekarp, *et al.*, 2000). The results presented above suggest that HMS possesses the resilient characteristics observed in not only unbound granular but also clayey materials. Gradual development of hydraulicity inherent in HMS is considered to serve just like cohesion in clayey soils.

Furthermore, in order to use HMS as base-course material effectively, although the results for other stress conditions are not shown here, it appears better to reflect the difference in long-lasting increase of resilient modulus among five HMS in the design method. For this, it seems important to devise a simple method for evaluating or an index for estimating to what extent resilient modulus increases with time for any HMS.

5 CONCLUSIONS

In this paper, hydraulic, graded iron and steel slag, which is commonly termed HMS, is briefly introduced referring to the national industrial standard and the pavement design guide in Japan with a focus on the specifications. Then, five different HMS produced by five design in Japan are tested, and their compaction, uniaxial strength and resilient deformation characteristics are compared. All the five HMS satisfy the items specified by the national industrial standard; nonetheless, the followings can be pointed out.

- The density of solids for all five HMS lies within a narrow range from 2.93 to 3.15 g/cm^3. The maximum dry density ranges from 1.91 to 2.31 g/cm^3 and the optimum water content

from 10.0 to 15.8 %; but one HMS has a lower dry density and higher optimum water content than other four HMS.
- Uniaxial compressive strength increases with curing time regardless of the type of HMS and to what extent the strength increases differs among HMS; at two-year curing, the difference between the two extreme HMS is more than double.
- It is confirmed that, regardless of HMS, resilient modulus increases with mean effective stress and decreases with deviator stress, just as previous studies.
- One HMS has much higher resilient modulus than the other four HMS and its difference increases with curing time.

The national industrial standard and pavement design guide specify only the lower bounds in terms of uniaxial compressive strength for hydraulic nature of HMS for a quality control purpose. In order to use HMS effectively as base-course material, however, it is indicative that differences in uniaxial compressive strength and resilient modulus among HMS, which result from varying development of hydraulicity, should be reflected in the pavement design method.

REFERENCES

Communities and Local Government, 2007. *Survey of arisings and use of alternatives to primary aggregates in England, 2005*. Communities and Local Government, London, UK, pp. 42-47.

Hicks, R.G. and Monismith, C.L., 1971. *Factors influencing the resilient response of granular materials*. Highway Research Record 345, TRB, National Research Council, pp. 15-31.

Japan Road Association, 2006. *Pavement Design Manual*. (in Japanese)

Japan Slag Association, 2004. *Application of Iron and Steel Slag to Road Construction*. Technical Brochure, fs-89. (in Japanese)

Japan Slag Association, 2009. *Iron and Steel Slag*. Annual Report. (in Japanese)

Japanese Standards Association, 1992. *Iron and steel slag for road construction*, JIS A 5015.

Japanese Standards Association, 2009. *Method for unconfined compression test of soils*, JIS A 1216. (in Japanese)

Japanese Standards Association, 2009. *Test method for soil compaction using a rammer*, JIS A 1210. (in Japanese)

Lekarp, F., Isacsson, U. and Dawson, A., 2000. *State of the art. I: Resilient response of unbound aggregates*. Journal of Transportation Engineering, ASCE, pp. 66-83.

Monismith, C.L. 1992. *Analytically based asphalt pavement design and rehabilitation: theory to practice, 1962-1992*. Transportation Research Record 1354, TRB, National Research Council, pp. 5-26.

Sugita, T. 2006. *Resilient Characteristics of Hydraulic Base-Course Material*. M.Sc. Thesis, Graduate School of Science and Technology, Kobe University. (in Japanese)

USGS, 2010. *Iron and steel slag*, Advance release, 2008 Mineral Yearbook, U.S. Geological Survey, USA, pp. 69.1-69.8.

Yoshida, N., Sugita, T., Kawano, K., Ioku, T. and Hirotsu, E., 2006. *Physical, mechanical and resilient properties of two types of hydraulic graded iron and steel slag for base-course construction*. Proceedings, 10th International Conference on Asphalt Pavements, Quebec, Canada, No. 0445.

Yoshida, N., Sugita, T., Miyahara, T. and Hirotsu, E., 2008. *Influence of hydraulicity on resilient modulus and Poisson's ratio of hydraulic, graded iron and steel slag base-course material*. Proceedings, 1st International Conference on Transportation Geotechnics, Nottingham, UK, pp. 765-770.