Granulated Blast Furnace Slag in Base Course of Low-Volume Roads

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The use of granulated blast furnace slag (GBFS) mixed with an old base and wearing course aggregate on a low-volume gravel road is presented. GBFS is a poorly graded by-product of the iron industry and has latent hydraulic properties. The purpose of using this product was to increase the bearing capacity in spring and decrease frost heave differences. In preliminary tests, the compressive strength of compacted specimens increased as a function of GBFS content (10, 30, and 50 percent). The rate of strength gain was slow; considerable development was not noted until after 91 days of curing. In the test section the aggregate consisted of 30 percent lime-activated GBFS and 70 percent mixed wearing and base course aggregate. All control test specimens showed increased strength with increased curing time. The rate of strength gain was slow and affected by the density of the specimens and curing conditions. Decreased density or curing temperature (field conditions) as well as water immersion before testing decreased the compressive and tensile strengths. Once up to ultimate load, stressed specimens were recompressed after a predetermined curing time. In many cases, the strength was on the same or an even higher level than in the first compression. The strength was influenced by the recovering time, the water content of the specimen, and the recuring temperature. Both in spring and autumn the total surface deflection in FWD measurements was 0.2 mm smaller on the GBFS-aggregate section than on the reference section with normal aggregate layers. The difference in maximum and minimum frost heave was on the same level before and after construction.

Road 3424 is situated in central Finland and has an average daily traffic (ADT) of 590 including heavy vehicles transporting timber to the nearby wood-processing industry. The wearing course is made of gravel and there are sections with low bearing capacity, especially during the thawing period. The road also has uneven frost heave. Road 3424 is one among seven low-volume roads in a project to examine different ways of reducing the afore-mentioned problems. The methods applied were strengthening the base course by stabilizing it with hydraulic binders based on industrial by-products or by using geogrids, improving the drainage with gravel and vertical or horizontal drains, and preventing frost penetration by using thermal insulation. On Road 3424, two sections were stabilized using either activated granulated blast furnace slag (GBFS) or hydraulic binder based on desulfurization waste. In one section, geogrid was used, and one section was isolated with expanded clay pellets. In this paper, only the results of the use of GBFS are presented.

MATERIALS AND METHODS

The grain size distributions of the aggregate and GBFS are presented in Figure 1. The aggregate of the test section is a well-graded mixture of old wearing (crushed rock) and base course aggregates. Compared with the grading envelope for wearing course aggregate for

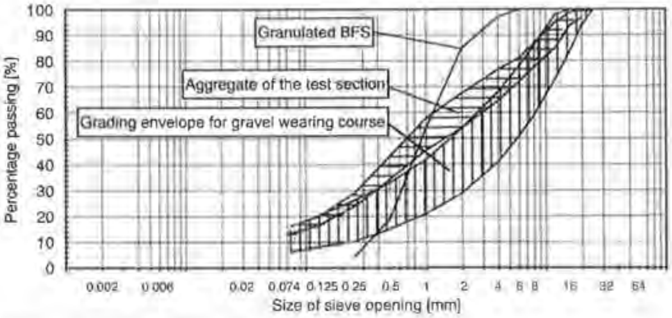

FIGURE 1 Grading of aggregates.

gravel roads, the aggregate mixture was somewhat too sandy. When determined using 3 percent NaOH solution, the amount of organic impurities in the aggregate was high. The grading of the GBFS is typical for granulated slags; it is poorly graded with small fines content. According to the chemical composition, the basicity determined as the ratio between $CaO + Al_2O_3 + MgO$ and SiO of the used GBFS was 1.6. In many specifications the basicity is used as a factor defining the hydraulic activity: increased basicity means increased activity (*1*). The hydraulics also increases the finer and more glassy the slag is. When attention is paid to the glass content (90 percent) and basicity, the used slag can be considered active with hydraulic properties, but when used without grinding, slow-strength gain and low strength level are expected.

Test specimens with a diameter of 100 mm and height of 115 mm were compacted using a gyratory compactor, sealed in plastic bags, and cured at 60 percent relative humidity and 22°C. The loading rate in compression was < 0.14 MPa/sec.

Surface deflections of the test sections were measured using a Kuabfalling weight deflectometer and applying an impulse load of 5000 kg. The deflections were measured at a distance of 0, 0.2, 0.45, 0.6, 0.9, and 1.2 m from the loading center.

PRELIMINARY TESTS

Tests Without Activator

In the tests without activator, the GBFS content was 10, 30, and 50 percent of the total amount of aggregate. The aggregate-GBFS mixture was compacted with 6 percent excess water to a wet density of 22.3 kN/m³. The water content of GBFS was not taken into account; therefore, the dry density of the specimens decreased with increased GBFS content (Table 1). Since compressive strength is a function of dry density (*1*), it should lead to decreased strength. The compressive strength did, however, increase when the GBFS content increased (and density decreased). Because of the slow strength progress, this result is most clearly seen after a long curing time.

The addition of poorly graded granulated slag to well-graded aggregate reduces the fines content and impedes the compactibility by increasing the sand content. In this study a six-times-higher compactive effort was needed to achieve the desired wet density when GBFS content was increased from 30 to 50 percent. Increasing the content from 10 to 30 percent tripled the needed compactive effort. With 10 percent GBFS content the compactibility was about the same as without slag. When constant compactive effort (20 revolutions) was used, the aggregate was compacted about 7 percent denser without GBFS than with 30 percent of GBFS.

Tests with Unslaked Lime Activator

The rapid hydration and strength gain of GBFS require the use of alkali activators. In blended cements, $Ca(OH)_2$, produced in the hydration of portland cement, serves as an activator (2). In France the unground GBFS is generally activated using lime (*3*). In this study, unslaked lime (CaO) was used to accelerate the hydration and remove water from GBFS. The aggregate mixture contained 30 percent GBFS, and the effects of lime

TABLE 1 Results of Preliminary Tests

GBFS - content [%]	Compaction effort [number of revolutions]	Dry Density [kN/m³]	Compressive Strength [kPa]				
			0 d	7 d	28 d	91 d	154 d
10	10	21.0	60	90	100	150	140
30	35	20.7	70	100	140	190	350
50	222	20.5	90	100	160	280	670

TABLE 2 Test Results with Activated GBFS

CaO		Dry Density [kN/m^3]	Compaction effort [number of revolutions]	Compressive Strength [kPa]		
content [% of GBFS]	mixing moment			7 d	28 d	91 d
1		20.8	60	90	90	120
3		20.7	43	80	100	120
	premixed	20.8	-	120	190	240
10		20.9	115	560	580	740
	premixed	20.7	23	250	290	370
		21.4	396	810	840	770

content, lime mixing moment, and the specimen density on the compressive strength were studied. According to the results presented in Table 2, the activation effect was observed only with a content of 10 percent. Compressive strengths were then improved considerably. When the lime was added to GBFS one week before it was mixed with aggregate, the activation effect was decreased to half the activation effect with simultaneous but separate mixing.

CONSTRUCTION

Short (50-m) test sections were constructed in August 1992. A schematic cross section of the structure is seen in Figure 2. The old wearing course and part of the layer below it were loosened and premixed with a backhoe loader and grader. About 100 kg/m^2 of GBFS (activated two weeks before with 2 percent of unslaked lime) was spread with a horizontal sand spreader in two stages. After each stage, the layers were mixed by driving a spring tooth harrow three or four times over them. The layers were compacted with a backhoe loader and loaded lorries. The upper layers of crushed rock aggregate were constructed immediately after compaction to prevent drying of the stabilized layer.

CONTROL TESTS

Tests with Specimens

The control specimens were compacted using the aggregate mixed in the test section. According to the sieve analysis, the aggregate was equivalent to the 70/30 percent mixture used in the preliminary laboratory tests. The control tests included studies of the effect of specimen density, curing conditions, and water immersion on the compressive and tensile strength. The results (Figure 3) again prove the remarkable influence of density, not only on the achieved strength level but also on the rate of strength gain. Between 28 to 91 and 91 to 182 days, it was two times faster with dense than with loose specimens. Also, the unfavorable effect (low curing temperature) of the late construction date (August) is noted when laboratory- and field-cured specimens are compared. During the first 1.5 months, the average daily air temperature near the test section fluctuated between 8 and 17°C. After 1.5 months of construction, the temperature decreased permanently to ≤ 5°C, causing retarded hydration reactions and stopping the strength development.

Immersing the specimens for one day in water before testing also had a harmful influence on the compressive strength. Immersion doubled the water content of the specimens to 9 percent and decreased the strength to 40 percent of the nonimmersed specimens. The relation of the water content to compressive strength can also be examined using the results from the specimens compressed when as dry as possible. Even though these specimens were older when compressed, they were cured between 182 and 270 days in unfavorable conditions for hydration reactions so that the greater strength of the "dry" specimens is obviously not due to hydraulic strength gain.

The compression up to ultimate load-stressed specimens was repeated once or twice after the first com-

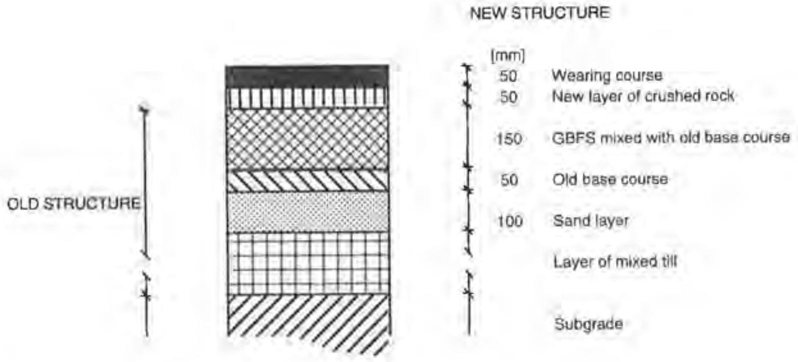

FIGURE 2 Compression results of control specimens.

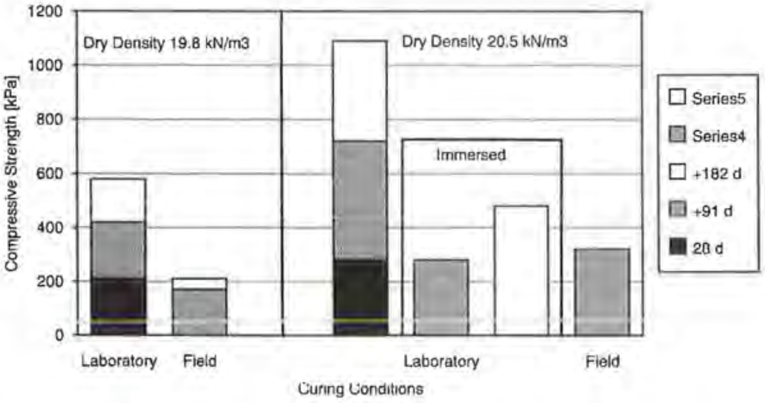

FIGURE 3 Strength after recuring.

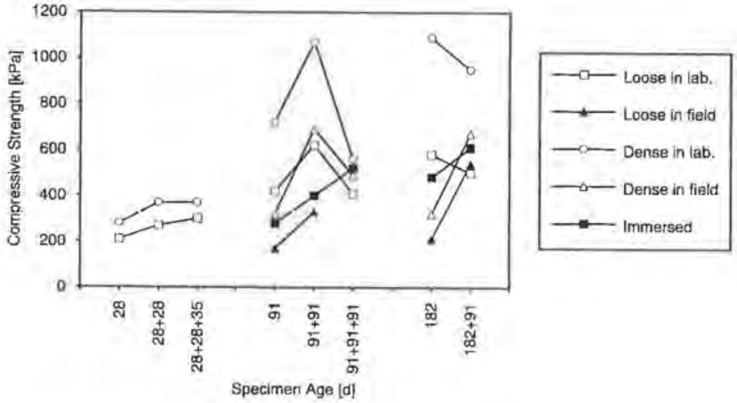

FIGURE 4 Cross section of structure.

pression. The recuring conditions were maintained the same as before the first compression and the recuring time varied from 1 to 3 months depending on the first compression age. Only the curing temperature of the field-cured specimens (recured in the laboratory) and the moisture content of the immersed specimens were different. The aim of this recompression procedure was to see if the GBFS-aggregate mixture had any self-cementing competence after the first or second failure.

The results (Figure 4) are interesting. If the curing conditions were unchanged, the strength in the second compression could still increase to a higher level during the recuring time when the first breakdown happened at a fairly young age (28 or 91 days). Changing the curing conditions to conditions more favorable for hydration reactions, that is, increasing the recuring temperature or water content of the specimen, led to the same results even with specimens compressed for the first time after a half year of curing. In unchanged recuring conditions, the strength of these specimens decreased. In some cases, the specimens were also compressed after the second breakdown. The strength of the younger (28 + 28 days) specimens was increased at least to the same level as in the previous compression. After the second compression, the strength of the older (91 + 91 days) specimens was increased only when the specimens were immersed before the first compression.

Tensile strength was determined by a splitting tensile test. The results (Table 3) indicate the same kind of in-

TABLE 3 Tensile Strength of Control Specimens

Dry Density [kN/m^3]	Cured	Splitting Tensile Strength [kPa]							
		Age of the specimen [d]							
		28	91	182	28+28	28+28+35	91+91	91+91+91	182+91
19.8	L	11		67	17	18			46
	F		9	12			24	28	23
20.5	L	17		119	25	26			95
	LI		30	70			39	37	80
	F		21	19			70	67	52

L = in laboratory, F = in the field, LI = in the laboratory; immersed before test

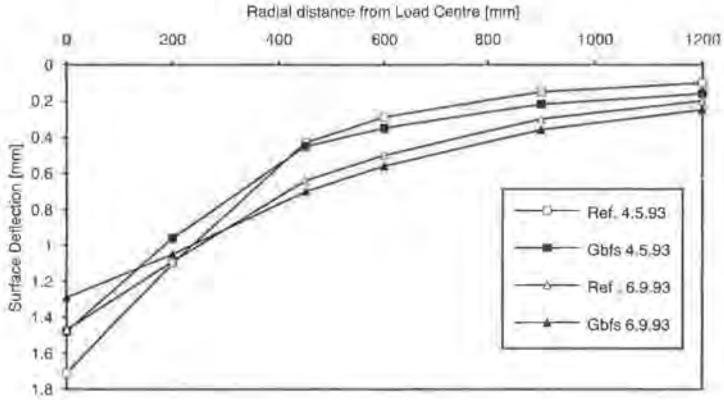

FIGURE 5 Deflection curves according to FWD measurements.

creasing development of strength as a function of curing time as in compressive strength. The ratio of tensile and compressive strength was about 0.06 for young specimens and increased to 0.12 for older specimens. A reducing effect of decreased curing temperature, lower dry density, and water immersing was also seen in tensile test results. Some recovering after the first failure was also noticed.

Falling Weight Deflectometer

The surface deflections of the FWD measurements in May and September are presented in Figure 5. In the load center, the difference between spring and autumn deflections is about 0.2 mm in both sections. In both seasons, the total deflection of the GBFS section is, however, 0.2 mm smaller than on the reference section. The difference is mainly formed between the first and the second deflections. In spring, the surface curvature index (SCI) (4) is 0.52 for the GBFS section and 0.61 for the reference section. In autumn, SCI is, respectively, 0.24 and 0.42.

Frost Heave

Frost heave of the test sections was measured twice before construction and once after construction. Before construction, the difference in the maximum and minimum frost heave of the GBFS section was 5 to 11 cm (Figure 6). The next year, after stabilization, the difference was still 8 cm even though the total frost heave was smaller than before construction. Decreased total frost heave was also observed on the reference section, so it is mainly due to milder climatic conditions in the winter of 1993 than in the winter before construction.

DISCUSSION OF RESULTS

The increasing compressive and tensile strengths of compacted specimens in preliminary as well as in con-

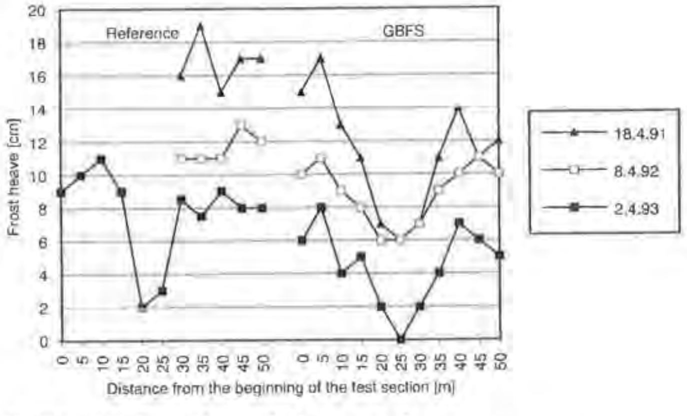

FIGURE 6 Frost heave before and after construction.

trol tests indicate that, mixed with ordinary wearing and base course aggregate of a low-volume road, unground GBFS works as a hydraulic binder and results in slow strength gain even though the aggregate contains organic impurities. Concerning bearing capacity, the hardening property of GBFS compensates for the negative effects on grading of mixing this poorly graded by-product with well-graded aggregate. Mixing can, however, have a positive influence, for example, on the drainage of the base layer, when the aggregate gradation becomes poorer and the permeability increases. Because of a decreased fines content, the amount of water the layer is able to absorb also decreases, which reduces bearing problems caused by excess water. GBFS can also be used to proportion an aggregate with open-graded to well-graded aggregate with good compactibility, which leads to a dense layer. In Finland this effect has been used successfully in some crushed rock aggregates on two test roads.

The self-healing property after the first and sometimes even the second failure was interesting and makes one think that it should be used in road construction. However, this property requires more research to be understood properly. One advantage of this self-healing property is that the strengthening of structure is not as susceptible to the disturbing effects of site traffic as normally stabilized structures.

The constructed layer of mixed GBFS-aggregate material is now only $1^1/_2$ years old, so its effects on bearing capacity and frost heave cannot yet be properly evaluated. FWD measurements indicate, however, that the mixed GBFS-aggregate layer is working as a semirigid layer decreasing the total deflection of the road surface compared to structures built with unstabilized aggregate. The GBFS stabilization has, however, not been able to decrease the difference between maximum and minimum frost heave.

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