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Slag bound materials in composite roads

JTG Richardson
Tarmac Quarry Products Ltd, Wolverhampton, UK
and
DJ Haynes
Independent Consultant, formerly British Steel plc (now Corus Group), Scunthorpe, UK

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Abstract

To date in the United Kingdom (UK), the production of granulated blast furnace slag has predominantly served the cement industry by providing a product which, when ground to a powder, can act as a cement replacement. Despite being a proven technique in other countries for many years, the use of granulated slag, in an unground form, as a hydraulic binder in road pavement courses and foundations has not been common in the UK.

Research is being undertaken in the UK on the utilisation of secondary materials in road pavements and foundations. Granulated slag is one such material and the findings of the research should encourage its greater use in this way.

This paper addresses the specific use of granulated slag in the construction of composite roads. Aggregates such as crushed rock, gravel and blast furnace slag are mixed with granulated slag and water in association with a basic catalyst such as lime to produce slag bound materials for incorporation in the lower layers of the composite construction.

Introduction

To date in the United Kingdom (UK), the production of granulated blast furnace slag has predominantly served the cement industry by providing a product which, when ground to a powder, can act as a cement replacement. Despite being a proven technique in other countries for many years, the use of granulated slag, in an unground form, as a hydraulic binder in road pavement courses and foundations has not been common in the UK. A type of slag stabilised product called *grave-laitier* (slag-bound aggregate) has been used widely in France for road base and sub base construction. It has been estimated that 65% of French roads have a layer of *grave-laitier* as a constituent [1]. The first French motorway built of composite construction with *grave-laitier* was the A8 in 1960. It consisted of 0 to 250mm of natural graded aggregate as sub base underneath 150mm of slag bound road base and 120mm of asphalt surfacing. Strengthening with asphalt overlay was planned as necessary over subsequent years.

A road trial of slag bound road base imported from Holland and using phosphorus slag as aggregate was undertaken in Kent in 1987 [2]. Such a product would be referred to as *grave-laitier tout laitier* if used in France. This led to a County specification for the material, which continues to be used today. The trial is described below.

Research is being undertaken elsewhere in the UK on the utilisation of secondary materials in road pavements and foundations. Granulated slag is one such material and the findings of the research should encourage its wider use in this way.

This paper addresses the specific use of granulated slag in the construction of composite roads. Aggregates such as crushed rock, gravel and blast furnace slag are mixed with granulated slag and water in association with a basic catalyst such as lime to produce slag bound materials for incorporation in the lower layers of the composite construction.

The production of slag

The production of molten iron in a blastfurnace involves the conversion of iron oxide feed materials by reduction at high temperature. During the smelting operation, a slag is formed from the non-ferrous components (gangue) of the iron oxide feed and the ash content of the carbon based fuels. The composition of the slag is controlled to specific metallurgical requirements, so that the iron composition meets the required compositional specifications. The final slag composition is also engineered so that as well as meeting the ironmaking compositional requirements, it also meets the chemical specifications required of the blastfurnace slag by-products.

Operating a large scale ironmaking operation necessitates a consistent supply of materials of known composition and quality, and a production operation that incorporates processes and systems that monitor the quantity and quality of feed materials, process consumables and intermediate products, as well as the final products.

Iron ores and coals are the basic raw materials for ironmaking and production of the necessary metallurgical coke required for the blastfurnace. They are supplied to meet the particular requirements specified by British Steel. The two types of materials are handled in separate systems incorporating bulk storage, large scale blending systems and pre-treatment processes. The coal is converted into high-grade metallurgical coke and the iron ores are generally agglomerated by a sintering process. All of the necessary process and quality controls are incorporated into these processes. An illustration of such a blending system is shown in Figure 1 as a schematic diagram of the iron ore blending operation at Scunthorpe Works.

Click here to view Figure 1

Figure 1. Iron ore blending operation

The blastfurnace operation uses a combination of closely sized and pre-screened, natural lump iron ore, pre-fired iron ore pellets and sinter as the ferrous feed materials. These are charged into the top of the blastfurnace along with the metallurgical coke, whilst hot air is blown in towards the base of the furnace through tuyeres. Supplementary fuel or reductants, such as oil, granular coal, pulverised fuel or natural gas, may also be injected with the hot blast. Oxygen enrichment may also be used. A flame temperature of approximately 2000°C is generated as some of the coke burns in front of the tuyeres and the hot reducing gases produced are forced up through the layered coke and ferrous burden, reducing the iron bearing materials and raising the temperature of the charged materials. A number of zones within the blastfurnace become established and by consistent operation of the furnace along with accurate weighing of the quality controlled, charged materials, a steady state of operation can be achieved. At one zone within the furnace, the cohesive zone, the reduced iron-bearing materials start to melt. It is here that the iron begins to separate from the non-ferrous components in the charged materials. Both components start to drip through the metallurgical coke, undergoing further changes as they descend. Below the tuyere region of the furnace, the non-ferrous liquid has absorbed the ash components from the combusted coke and the resultant slag absorbs metalloids from the percolating iron droplets. The iron settles through the slag layer in the hearth and both liquids accumulate according to the speed of operation of the blastfurnace. The liquids in the hearth are allowed to run out periodically from the taphole into a runner system where the iron and slag are separated by a system of weirs and dams.

The iron is run off into 300 tonne torpedo ladles that are transferred to the steel plant by rail. The slag is then either run into large pits at the side of the furnace for air-cooling into an aggregate product, or through a forced quenching system such as a slag pelletiser or a slag granulator.

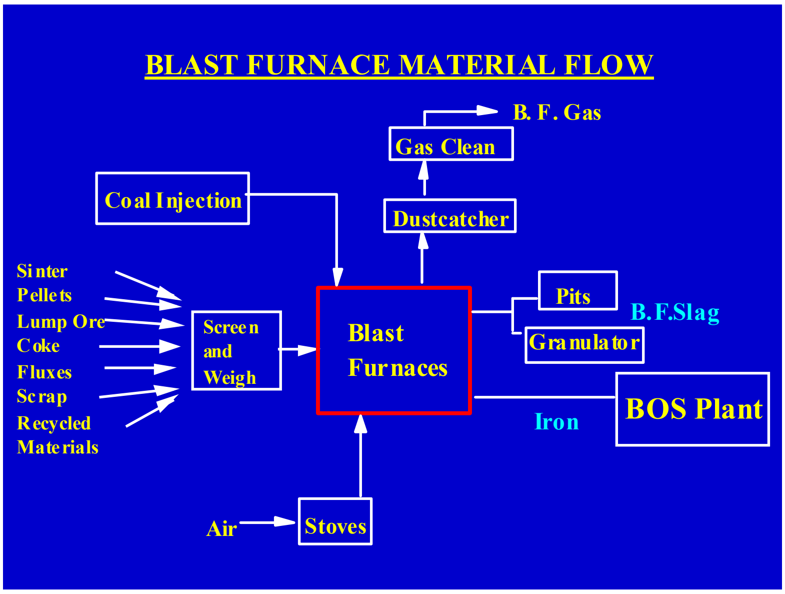

Figure 2. Material flow through ironmaking operation

The composition of both the iron and the slag are monitored on cast-by-cast basis and a wide variety of process control data is assessed to enable a stable process to be operated. A number of computer-based control schemes, operator guidance and feed-forward predictions are used to adjust the feed materials and the process variables accordingly.

Figure 2 is a diagrammatic view of the process material flow through the ironmaking operation. Figure 3 gives a diagrammatic view of the ironmaking process within a blastfurnace.

The Scunthorpe Works, operating four blastfurnaces, produces approximately 4 million tonnes of iron and 1.1 million tonnes of slag products on an annual basis. The production facilities, process control systems and quality monitoring procedures are designed to allow a stable, controlled process to be established and sustained over the many years of the life of the blastfurnace.

As an example of the variation in slag composition in terms of lime and silica content, a trend chart is shown in Figure 4 for one blastfurnace over one month. The quantity of slag represented in the diagram is approximately 30,000 tonnes.

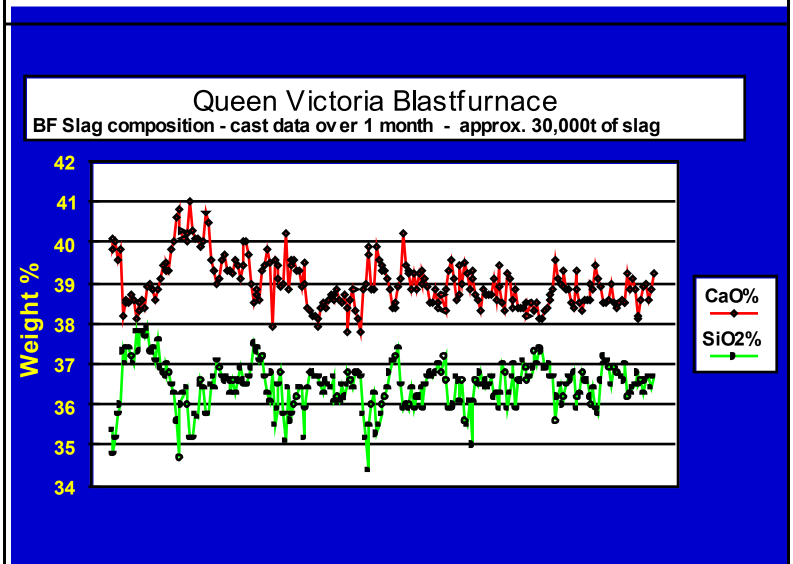

Figure 4. Variation in slag composition

Figure 3 Blastfurnace

Slag granulation

Figure 5 illustrates the main aspects of the process of granulating blast furnace slag. The molten slag at temperatures in the range of 1300 to 1500°C is either tapped from the blast furnace into pits and air cooled, as described above, or continuously fed into a granulator at a rate of about 10 tonnes per hour where it is suddenly quenched with water. The high water jet pressure and the thermal shock it causes fragments the slag into granulated particles. The rapid cooling hinders the formation of crystals and a glassy material is produced.

The granulated slag and water is then discharged as a form of slurry via a receiving hopper into a dewatering drum. This is a rotating drum within which the slurry is uniformly distributed along the length of the drum. Axial vanes on the inside of the drum lift the slag and deposit it onto a belt conveyor that removes it from the drum to a stockpile. Fine mesh on the vanes and exterior of the drum retain the slag granulate and allow the water to filter through.

The stockpiled product is 0-5mm size, but predominantly 2mm down to 600µm. It has a moisture content of initially 10-15%, but allowed to drain, this will reduce to below 8%.

The water that was used for quenching leaves the dewatering drum at a temperature of about 80-90°C and discharges into a cooling tower. The cooled water is reused with water drained from the stockpile area and pumped into the granulator at a temperature of about 40-50°C and at a rate of up to 4000 litres per minute.

The stockpiled material may then be transferred to a cement mill for the production of slag cement or alternatively be used in the production of slag bound mixtures for road construction.

Reference [3] has provided a large part of the information contained in the next two sections of the paper.

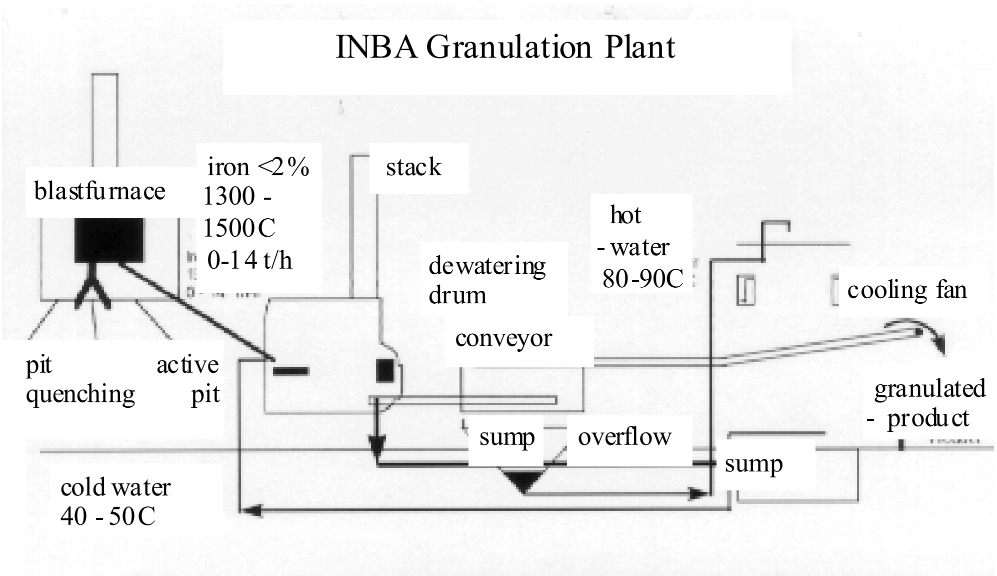

Figure 5 Granulation of blast furnace slag

Hydraulic property of granulated slag

Granulated slag has the appearance of concreting sand. Closer inspection, though, reveals its glassy, fibrous nature. There is no heat of crystallization in its formation and the material has a latent hydraulic property for forming solid hydration products - just like cement. However, whereas cement is soluble in water facilitating the hydration process, the vitrified slag is only soluble in alkaline solution. The alkaline condition may be produced by the addition of an activator or basic "catalyst", such as lime.

The hydration or setting process involves the partial dissolution of certain ions from the slag that produces a concentrated solution and then precipitation or crystallization of hydrated silicates and aluminates of calcium. The lime activator is not a true catalyst. It is more of a reagent that is consumed by the hydrate formation reactions. The simplified composition of slag is shown in Figure 6 using a convention of the cement industry by means of the formula C_5S_3A that represents a fairly good distribution of the three main oxides (C = CaO, S = SiO_2, A = Al_2O_3) [4].

The composition range of active constituents of granulated slag is shown in Table 1. A particular slag can be identified by the product of %CaO and % Al_2O_3. Three types are specified in French Standards by separating them with the limits 425 and 550. This may be explained by an example where the composition of a slag includes 50% of CaO and 10% of Al_2O_3, giving a product of $50 \times 10 = 500$ which lies between the two limits and is classified as type H. Type T slag is one for which the product is ≥ 550 and type A slag is one for which it is < 425 [5].

Simplified Hydration Equation

$$C_5S_3A + 2CaO + 16H_2O$$

Slag Lime Water

↓

$$C_4A.(H_2O)_{13} + 3CS.H_2O$$

Aluminate Silicate

pH > 12.6

C = CaO, S = SiO_2, A = Al_2O_3

Figure 6. Simplified composition of slag

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Table 1. Composition of Granulated Slag

Constituent	*% by mass of dry material*
SiO_2	27–39
Al_2O_3	8–20
CaO	38–50
MgO	≤ 10

The reactive properties of granulated slag depend upon a number of factors. The main factors that have been identified are as follows:

- Temperature of slag before granulation
- Chemical composition
- Condition during granulation (flow rates and temperature)
- Fines content

However, the reactive capacity of non-crystalline slag is the result of a surface phenomenon and is essentially a function of its specific surface. Studies in France led to the determination of the coefficient α from the following equation:

$$\alpha = S \cdot P \cdot 10^{-3},$$

where S is the Blaine specific surface of natural fines < 80 µm, expressed in cm^2/g, and P is a measure of friability, obtained by following a standard crushing test procedure.

The crushing test involves mixing of the granulated slag with porcelain beads in a ball mill and subjecting the mixture to 2000 revolutions, before washing and sieving it through an 80µm aperture sieve. The procedure is meant to simulate crushing that takes place during processing of the slag bound materials.

Properties of mixtures with granulated slag as binder

The alpha coefficient of granulated slag has been shown to give a good correlation with the strength of slag bound mixtures. Such a correlation for sand-slag mixtures is shown in Figure 7. The good correlation led to French Standards being established for classifying the potential reactivity of granulated slag as shown in Table 2.

Table 2. Activity Class of Granulated Slag

Class	α
1	< 20
2	≥ 20 & < 40
3	≥ 40 & < 60
4	≥ 60

Class 1 is not used for road construction. Class 2 is the most common type of slag used. Class 3 may be used for sands and gravels or other materials that are found to be difficult to handle. Class 4 would only be used in rare circumstances.

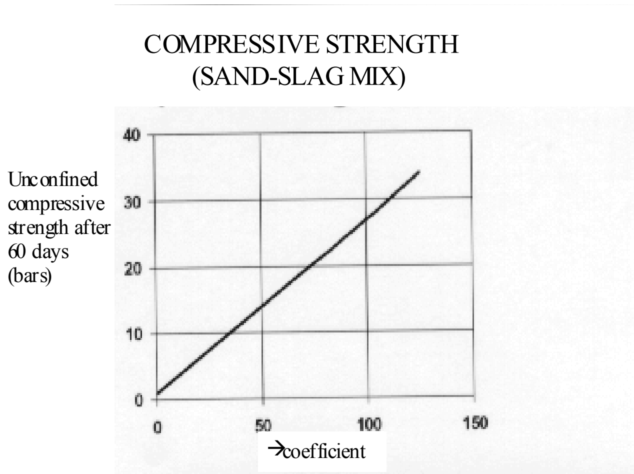

Figure 7 Compressive strength versus alpha coefficient

The setting or hydration process is somewhat slow and the reactive properties of the particles are only being brought partially into action. This means that the particles will remain active at a later stage and so, the non-mobilised parts will contribute to the mechanical stability of the product. The granulated slag is predominantly 2mm to 600µm size and will behave as coarse sand. The slow reaction and the mechanical stability of the aggregate are two of the reasons why slag bound materials are so versatile. They can, for example, adapt to limited, early deformations by self-healing due to the slow hydration process.

In general, a higher content of granulated slag and slag having a higher alpha coefficient lead to mixtures having higher strength. These effects are illustrated in Figure 8 for a limestone-slag mixture. In practice, the area of the curves between an alpha coefficient of 20 and 40 may be assumed for most cases. Increase in strength with time for a range of slag contents up to 30% is shown in Figure 9. Slag contents would typically lie between 10 and 25% depending upon the
application and the aggregates used.

Typical mechanical properties of slag bound mixtures in the hardened state have been reported as falling within the following ranges:
Compressive strength of 6-10 MPa
Tensile strength of 0.6-1.5 MPa
Elastic modulus of 15-20 GPa

The relatively high tension/ compression ratio can be considered important in order to hinder cracking and the high modulus is important for spreading traffic loads.

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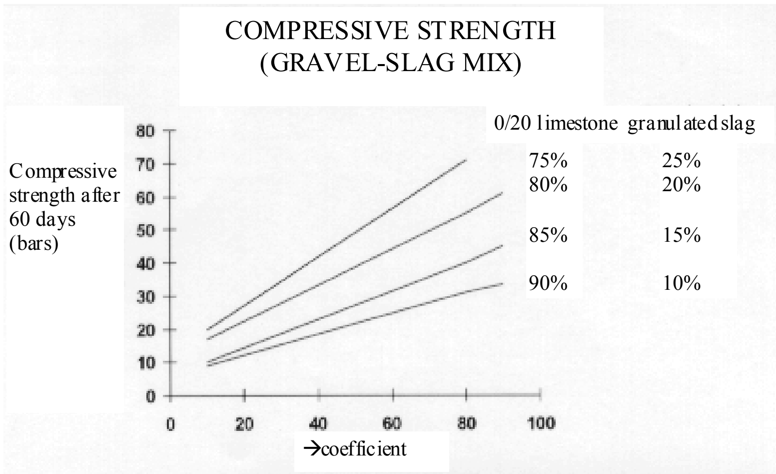

Figure 8. Effect of composition on compressive strength

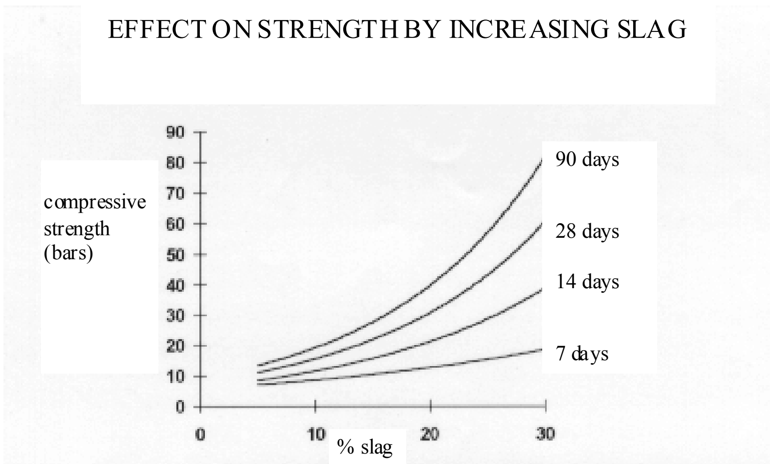

Figure 9. Effect of time on compressive strength

Experimental sites in the UK

A full-scale road trial of slag bound mixture was carried out on the Pembury Bypass in Kent in May 1987 [2]. A material called phosphoric slag was imported from continental Europe for use as the major component of the mixture. This is a blend of granulated blastfurnace slag and phosphorus slag aggregate. The hydraulic mixture was laid by mechanical paver at optimum moisture content and compacted with vibrating tandem rollers. It was constructed as both sub-base and road-base. Details of the construction are given in Table 3.

Table 3. Design of Full Scale Road Trial on the Pembury Bypass

Control Section	*Trial Section*
300 mm Asphalt	130 mm Asphalt 170 mm Phosphoric Slag Road Base
150 mm Type 1 Sub-base	150 mm Phosphoric Slag Sub-base
Capping	Capping
Subgrade	Subgrade

Deflectograph surveys have been carried out to monitor the performance of the trial pavement. Kennedy [2] reported that the increase in strength was greater than expected, with a predicted life far exceeding the design objective. Details of its deflection history are given in Table 4.

Table 4. Deflection History of Trial Pavement at Pembury Bypass

Date	*Average Deflection, mm × 0.01*	
	Southbound	*Northbound*
June 1987	50	60
February 1988	5.5	7
April 1992	7	6
June 1994	5	5

Experimental sections have also been laid in the works of British Steel.

In particular, funding was obtained by Wimpey Minerals (later Tarmac Quarry Products) in 1994 from the Department of the Environment through their Energy Best Practice Programme, that is managed by ETSU, for the development of slag bound mixture (SBM) as a low energy construction material. This entailed carrying out a series of laboratory investigations to determine optimum mixture designs and the installation and monitoring of the materials in pilot-scale road trials. In-situ deflection testing using a Falling Weight Deflectometer indicated that the performance of the SBMs after about one year in service were comparable with that of Heavy Duty Macadam asphalt bases of similar thickness and position in the pavement construction [6]. An energy audit suggested that energy savings of the order of 10 to 15% were feasible when compared with asphalt bases [7].

Subsequent testing of the road trial materials beyond the period of the ETSU project confirmed the continuing process of curing or stiffening of the SBMs, consistent with findings elsewhere in Europe.

An SBM construction also formed part of a road reconstruction project in the British Steel works at Redcar, Teesside. The road carries 1000 heavy goods vehicles per day with

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up to 35 tonne loads in one direction and 350 vehicles per day in the other direction with up to 50 tonne loads. The slag bound mixture was manufactured in a conventional asphalt plant and then left in a stockpile until the laying operation was due to take place a week later. The material was transported by truck to the site and laid by a standard asphalt paving machine. Compaction was completed using a Bomag 161 vibrating roller and it was noted that there was very little displacement of the material during rolling.

In this particular case, the mixture consisted of air-cooled blast furnace slag aggregates and a proportion of steel slag fine aggregate that provided free lime to aid activation of the hydration process. The addition of basic activators is not essential when slag aggregates are included in the mixture, but it may serve to improve early-life performance.

The SBM was covered by two layers of asphalt the following day and trafficked soon afterwards [8].

As part of a project carried out by the TRL on behalf of the Highways Agency to investigate the behaviour of industrial by-products in road bases, full-scale road trials have been planned to be constructed on the A485 link road on A40 Eastern Carmarthen by-pass, South Wales that include the use of SBM. One section will also incorporate SBM as sub-base. Installation of the SBMs is due to take place in the autumn of 1998.

Link research project

A similar type of slag bound mixture to that used on the Redcar site is one of the materials that are included in a research project as part of the LINK Transport Infrastructure and Operations Programme, investigating the use of secondary materials in pavement foundations.

The major aggregate components of the materials being examined are pulverised fuel ash, china clay sand and blastfurnace slag, mixed with various other components that constitute the binders.

The mixtures have been laid as sub-base in full-scale trials with control sub-bases of Type 1 and CBM1 materials at the pavement test facility in the grounds of the Transport Research Laboratory (TRL). Each trial sub-base was designed as a wedge of varying thickness along the trial section and laid over a weak subgrade. Wedge dimensions were chosen so that the thinner end was expected to fail and the thicker end was considered appropriate for the subgrade and traffic. Loading was applied by a dual wheel travelling at 20 km/h. Sub-bases are normally designed to support construction traffic loading of 1000 standard axles (80 kN each). In this case, however, the equivalent of 5000 standard axles was applied and if the foundations were still remaining intact, the wheel load was increased to 95 kN (190 kN axle load) to try and induce cracking in the layer. The trafficked test bed containing the slag bound mixture remained largely intact throughout and so, it was not possible to measure any reduction in stiffness due to cracking for this material.

The trials demonstrated that good performance can be achieved with these materials and all of the findings will be published by the TRL in due course [9].

Use and performance of slag bound mixtures in Europe

Granulated slag has been used as a hydraulic binder for road construction in a number of European countries, but particularly in France, Italy and the Netherlands. It is estimated that 65% of French roads have a pavement layer composed of SBM [1].

The first French motorway built of composite construction with SBM was the A8 in 1960. It consisted of 0 to 250mm of natural graded aggregate as sub base underneath 150mm of slag bound road base and 120mm of asphalt surfacing. Strengthening with asphalt overlay was planned as necessary over subsequent years. Details of some other French motorways built with SBM up until 1993 are given in Table 5.

SBM is used in French roads for both new construction and maintenance, including haunch repair, for light and heavy traffic intensities. Catalogues of pavement thickness design are available for the construction of roads suitable for carrying up to greater than 300 million 80 kN standard axles (some allowance would be needed to account for the slow curing of SBM for very heavy traffic) [10]. A variation of SBM incorporating sand only as the aggregate is also widely used as a base or sub-base in lightly trafficked areas [11]

A European standard specification for bound mixtures using slag is being developed by the European Committee for Standardization (CEN) and will be one of a series of specifications for mixtures bound with hydraulic binders other than cement [12]. The mixtures will be classified by performance testing. Three classifications have so far been identified:

- By California bearing ratio (CBR) test
- By compressive strength (R_c) test
- By tensile strength (R_t) and elastic modulus (E) tests.

It is the intention that the choice of classification will be according to national practice, but classification by the CBR test is meant to apply only to lightly bound mixtures of low stiffness.

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Table 5. French Motorways with SBM Pavements to 1993

Motorway	*Date built*	*Thickness, mm*			*1st inter-vention, years*	*Type (mm)*	*2nd inter-vention, years*	*Type (mm)*
		Sub-Asphalt Base	*SBM*					
A1	1967	250 (3)	180/210	150	14 (su)	ST	18 (su)	ST
A13	1970	280/300 (4)	230	100/120	10 (su)	CT	13 (su)	40/70 AC
A6	1970	200 (1)	200/250	80	3-5 (st)	30/80 AC	9-17 (st)	70/160 AC
A13	1973		370	70	8 (su)	CT	11 (su)	40 AC
A36	1973	170 (5)	200	80	6-7 (st)	80 AC	17 (su)	20 AC
A36	1973		350	60	3 (st)	80 AC	8 (st)	80 AC
A94	1974	230 (3)	200	120	7-11 (su)	40 AC	15-18 (su)	30/40 AC
A31	1974		400	80	7 (st)	80/200AC	15 (su)	ST
A94	1974	420 (3)	200	120	5-10 (su)	30/40 AC	14-15 (su)	30/40 AC
A94	1974-75	350 (3)	200	120	9-10 (su)	40 AC	17-18 (st)	70 AC
A4	1976		400	90	7-9 (su)	40 AC	9-14 (su)	CT/40 AC
A4	1976	250 (3)	250	150	10-11 (su)	40 AC	16 (su)	20 AC
A4	1976	300 (1)	250	80	8 (st/su)	80 AC	11-13 (su)	ST/ 40 AC
A4	1976	300 (1)	150	150	9 (st/su))	80 AC	13	ST/ 20 AC
A4	1976		500	80	9-10 (su)	CT	13 (su)	CT/ST
A36	1976		450	80	7 (st)	80 AC	14 (su)	ST
A26	1983		220	160	7 (su)	ST	>10	
A31	1983-84		220	160/210	4-8 (su)	20 AC	>10	
A40	1986		270	230	4-6 (su)	20 AC	>7	
A431	1990		420	80	>3			

Notes				
	1	Natural graded aggregate	su	Restoration of surface characteristics
	2	Lime stabilised gravel	st	Strengthening
	3	Sand cement	st/su	Improvement in both structural & surface characteristics
	4	Slag sand	ST	Surface treatment
	5	Cement bound granular material	AC	Asphalt concrete
			CT	Crack Treatment

Conclusion

The first SBMs were used in road construction almost forty years ago. Since then, their properties and the techniques used to manufacture and construct them have been continually improved. Their unique characteristics have provided the highway engineer with an invaluable option for a very wide range of paving applications and the choice of SBM has enabled its considerable benefits to be demonstrated.

About two thirds of the blast furnace slag produced in the UK is air cooled and processed as aggregate for use mainly in the roadstone industry. The rest is granulated or perhaps pelletised for eventual use as a cement replacement. However, it has been predicted that there will be continued pressure on environmental grounds to rely more on granulation as the preferred processing method. It is unlikely, though, that there will necessarily be a corresponding increase in demand from the cement industry. It is therefore timely to introduce granulated slag as a hydraulic binder to the UK roads industry and by so doing, present a very flexible, reliable solution.

Acknowledgements

This paper is presented with the permission of Tarmac Quarry Products and Corus Group. However, the views expressed are not necessarily those of Tarmac Quarry Products and Corus Group.

Figures 7,8 and 9 are derived from figures VII.2, VII.4 and VII.5 from reference [3] below, with permission from the Organisation for Economic Co-operation and Development (OECD).

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