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Using ground granulated blast-furnace slag and mineral wastes to reduce cement in paving block

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Portland cement production releases carbon dioxide; this has significant adverse effects on the environment and so a reduction in the content of Portland cement in concrete products will improve the carbon footprint. This investigation explored the use of by-product materials and waste in the production of paving blocks. The following materials were examined: ground granulated blast-furnace slag, basic oxygen slag, plasterboard gypsum and cement by-pass dust. Ternary blends were created for different mixes and tested. The tensile strength, skid/slip resistance and freeze/thaw of each paving block specimen were determined in accordance with British Standard BS EN 1338. It was found that about 30% cement replacement was achieved in comparison with current factory production in the UK without having any considerable impact on the strength and durability of the paving blocks. It was also found that a cement mix can contain ground granulated blast-furnace slag up to 55%, basic oxygen slag up to 70%, cement by-pass dust up to 10% and plasterboard gypsum up to 5% by weight.

1. Introduction

A minimum weight of 210 kg/m^3 of cement is used in the manufacture of paving blocks. However, production of Portland cement impacts the environment negatively owing to the production of carbon dioxide (CO_2) emissions. Recently, there has been extensive interest in potential methods for reducing the Portland cement content used in other cementitious materials without reducing the durability or affecting other physical characteristics.

Cementitious paste is used in the manufacture of pre-cast paving blocks which come in an assortment of shapes and sizes and are used for various purposes. Paving blocks are very durable and easy to walk on and have a prolonged life, which means that they are ideal for heavy duty use as they are able to withstand substantial loads and offer resistance to forces that may cause shearing or damage the surface.

Portland cement is an essential material used in almost all relevant civil engineering applications. In 2009, it was estimated that more than 3 Bt of cement are produced annually, and during 2010 this figure further increased by about 3·8% (USGS, 2011). Carbon dioxide is a key contributor to the greenhouse gas emissions that are causing global warming (Ghataora *et al.*, 2004). The production of every t of Portland cement releases approximately 1 t of carbon dioxide. Cement production accounts for roughly 8% of global carbon dioxide emissions (Olivier *et al.*, 2012). With such a large amount of cement being produced, the toxic carbon dioxide emissions produced during the manufacture of Portland cement are a major issue that must be tackled in the near future.

Currently, there has been a lot of attention focused on mineral additives, as these are materials that can improve specific properties of concrete. They also decrease the amount of energy required in the manufacture of cement and decrease carbon dioxide emissions.

Since 1970, attempts have been made to partially replace Portland cements with other materials. It was discovered that some types of pozzolans, limestone and metakaolin, which occur naturally, are possible alternatives to Portland cement. Other materials, such as fly ash and steel slag, which are produced by various metallurgy processes are also possible alternatives (Al-Chaar *et al.*, 2011; Courard *et al.,* 2003; Li and Ding, 2003; Menéndez *et al.*, 2003).

If an existing waste material can be used in a certain process, it will reduce the environmental impact of the waste and natural raw materials can be preserved. The use of waste materials will also lead to a reduction in the total energy required for the production of a cementitious material and therefore reduce carbon dioxide emissions (Ganjian and Sadeghi-Pouya, 2009).

The present research aimed to investigate the possibility of using a mixture of various waste materials with ground granulated blast-furnance slag (GGBS) to produce paving blocks, so that the percentage of Portland cement used during the manufacturing process can be further reduced. Any decrease in the percentage of Portland cement used will also lead to a reduction in the carbon dioxide emissions produced. Furthermore, it should decrease the supply of waste materials and their impact on the environment, which will in turn lessen the problems associated with disposing of waste materials in landfill sites.

2. Materials used in this research

2.1 Ground granulated blast-furnance slag

GGBS is a cement substitute; it is a by-product of the production of iron. Every year in the UK 2 Mt of GGBS is used in the cement industry (Dubey *et al.*, 2012), according to the Cementitious Slag Makers Association. Essentially, GGBS comprises silicates and alumina silicates of calcium and other bases that are manufactured in a blast furnace under molten conditions simultaneously with the iron. The chemical composition of oxides in GGBS is similar to that of Portland cement, but the proportion varies (Dubey *et al.*, 2012). There are many advantages to using GGBS in concrete including improved durability, workability and economic benefits (ACI, 2003).

The GGBS used in the present study was obtained from Civil and Marine, a division of Hanson UK. The material was marketed under BS 6699 (BSI, 1992).

2.2 Plasterboard gypsum

For this research crushed plasterboard gypsum (PG) waste was supplied by the Lafarge plasterboard recycling plant in Bristol. On a construction site, there are many reasons why plasterboard waste may occur, such as having a wasteful design, off-cuts being produced during installation, over-ordering or damaged boards (Dunster, 2008).

Plasterboard gypsum is obtained from a number of sources; construction and demolition sites are the most common sources. The plasterboard is recycled and all contaminants such as paper and glass are eliminated before a metal tamper crushes the gypsum. A series of sieves are used to separate contaminants and large pieces of paper before the plasterboard is ground, sieved and conditioned so that a powder is formed. Gypsum particle size analysis was performed using a Malvern Mastersize 2000 laser analyser ($\pm$ 1%). The average particle size was found to be > 300 μm; the range was between 1 μm and 1 mm. (Ganjian and Sadeghi-Pouya, 2009).

2.3 Basic oxygen slag

Basic oxygen slag (BOS), otherwise known as steel slag dust, is a by-product generated during the conversion of iron into steel. This process is done either in a basic oxygen furnace or an electric arc furnace (Shi, 2004).

During the current production of steel, it is inevitable that basic oxygen steel slag will be produced. For each t of steel produced, an estimated 300 kg of basic oxygen steel slag is consequently produced (Moreno, 1999). Each year in the UK approximately 1 Mt of BOS is produced; an estimated 10 Mt is stored for hydrating free lime through the process of weathering (Ghataora *et al.*, 2004).

For this research, the BOS was obtained from the Corus-Tata plant at Scunthorpe, UK.

2.4 Cement by-pass dust

By-pass dust (BPD) is collected from the kiln by-pass. The main purpose of the kiln by-pass is to bleed off volatile materials that would otherwise re-circulate around the kiln and pre-heater system. When by-pass dust is condensed in cooler parts of the kiln, it may lead to blockage of the kiln or eventually may end up in the cement clinker. The temperature is of utmost importance for the BPD as it can only be removed from the kiln at 1000°C. As a result, BPD contains numerous cement-bound phases.

BPD from a local cement factory; Castle Cement (Heidelberg cement group in Rugby, UK) was obtained for this research. The BPD was provided in powder form, the average size of fine particles was found to be 10 μm, and the maximum particle size was noted to be 200 μm.

2.5 Ordinary Portland cement

For this research CEM1 ordinary Portland cement (OPC) was used, as defined by BS EN 197-1 (BSI, 2011).

Bead sample	OPC: %	GGBS: %	BOS: %	PG: %	PBD: %
SiO_2	20·00	37·28	11·43	2·43	21·86
TiO_2	–	0·58	0·39	0·03	0·29
Al_2O_3	6·00	10·79	1·60	0·81	3·85
Fe_2O_3	3·00	0·43	28·24	0·36	2·57
MnO	–	0·68	4·35	$<$ 0·01	0·02
MgO	1·50	8·83	8·27	0·40	1·13
CaO	63·00	40·12	41·29	37·30	53·40
Na_2O	1·00	0·27	0·02	0·03	0·41
K_2O	1·00	0·37	0·02	0·24	3·64
P_2O_5	–	$<$ 0·05	1·48	0·02	0·08
SO_3	2·00	0·15	0·44	53·07	7·10
LoI	0·50	1·03	3·12	4·09	5·64

LoI, loss of ignition

Table 1. Chemical content of OPC, GGBS, BOS, PG and PBD used

Group	Mix code	OPC: %	GGBS: %	BOS: %	PG: %	BPD: %	W/C*
1	OPC40/GGBS30/BOS30	40	30	30	–	–	0·15
	OPC30/GGBS40/BOS30	30	40	30	–	–	0·15
	OPC30/GGBS30/BOS40	30	30	40	–	–	0·15
	OPC30/GGBS35/BOS35	30	35	35	–	–	0·15
	OPC20/GGBS40/BOS40	20	40	40	–	–	0·15
	OPC20/GGBS30/BOS50	20	30	50	–	–	0·15
2	OPC80/GGBS15/PG5	80	15	–	5	–	0·15
	OPC70/GGBS25/PG5	70	25	–	5	–	0·15
	OPC60/GGBS35/PG5	60	35	–	5	–	0·15
	OPC60/GGBS20/PG20	60	20	–	20	–	0·15
	OPC50/GGBS45/PG5	50	45	–	5	–	0·15
	OPC50/GGBS47/PG3	50	47	–	3	–	0·15
	OPC40/GGBS55/PG5	40	55	–	5	–	0·15
	OPC40/GGBS15/PG45	40	15	–	45	–	0·15
	OPC40/GGBS45/PG15	40	45	–	15	–	0·15
3	OPC75/GGBS20/BPD5	75	20	–	–	5	0·15
	OPC70/GGBS20/BPD10	70	20	–	–	10	0·15
	OPC60/GGBS30/BPD10	60	30	–	–	10	0·15
	OPC50/GGBS40/BPD10	50	40	–	–	10	0·15
	OPC50/GGBS45/BPD5	50	45	–	–	5	0·15
	OPC50/GGBS30/BPD20	50	30	–	–	20	0·15
	OPC40/GGBS55/BPD5	40	55	–	–	5	0·15
	OPC40/GGBS20/BPD40	40	20	–	–	40	0·15

*W/C, water/cementitious.

Table 2. Mix proportions of paving blocks without aggregates giving percentage by weight

Mix	OPC: %	GGBS: %	PFA: %	BOS: %	PG: %	BPD: %	4 mm: %	6 mm: %	Sand: %
OPC10/GGBS4 (Factory control mix I)	10·0	4·0	–	–	–	–	53	9	24
OPC10/PFA4 (Factory control mix II)	10·0	–	4·0	–	–	–	53	9	24
OPC2.8/GGBS4.2/BOS7.0	2·8	4·2	–	7·0	–	–	53	9	24
OPC7.0/GGBS6.3/BPD0.7	7·0	6·3	–	–	–	0·7	53	9	24

Table 3. Mix proportions of concrete paving blocks giving percentage by weight

2.6 Chemical analysis of materials

Chemical analysis of the raw materials was carried out using the X-ray fluorescence (XRF) method and the results are shown in Table 1.

3. Experimental work and mix proportions

A pressing action was performed using a compression machine and the materials were compacted into a single layer; the material was retained inside the mould by a mould collar. All mixes were then tested for compressive strength and tensile strength. The water content for all mixes was 15%.

Optimum results were then selected for the second phase of the study, 4 and 6 mm aggregates were then added to the mix; this is similar to the mix design used by factories.

3.1 Casting, curing and testing

All of the paving blocks produced had a cross section size of 190 mm × 100 mm, and the paving blocks were 80 mm thick. All cubes were 50 mm in size. The materials were fully compacted using a compression machine with a 150 kN load.

A polythene sheet was used to cover the specimens once they were cast; this ensured that no water was lost. The samples were left overnight and then removed from the mould and stored in curing chambers at a constant air temperature of 22 ± 2°C and 98% relative humidity. The samples were stored in the curing chambers until they were tested at 14 or 28 days.

The tensile strength of the paving blocks was tested using BS EN 1338 (BSI, 2003). A load was applied along the longest splitting section of the specimen block. Prior to the test, the block specimen was placed in a split tensile steel frame and pieces of wood were placed on the top and bottom of the specimen to provide packing. Between the plates of the loading machine and the top and bottom of the steel plates of the testing frame, contact was added before the load was slowly applied at a rate of 0·05 ± 0·01 MPa/s until the point of

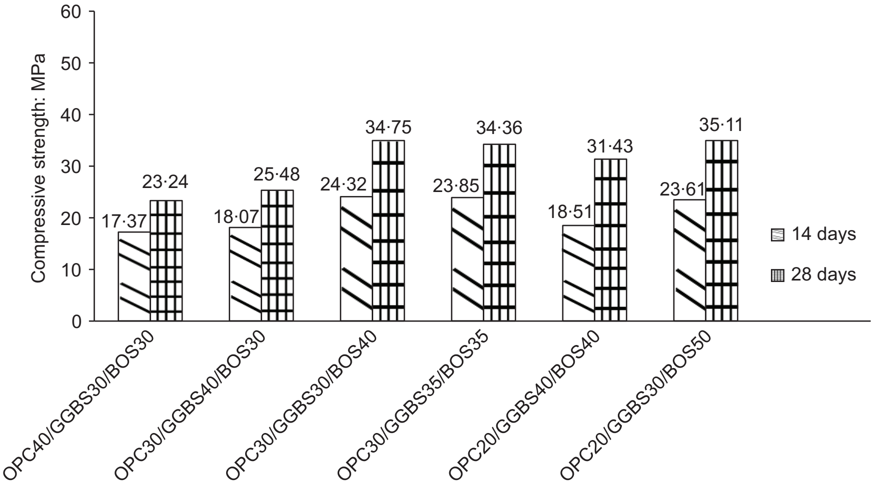

Figure 1. Compressive strength (MPa) of OPC/GGBS/BOS at 14 and 28 days

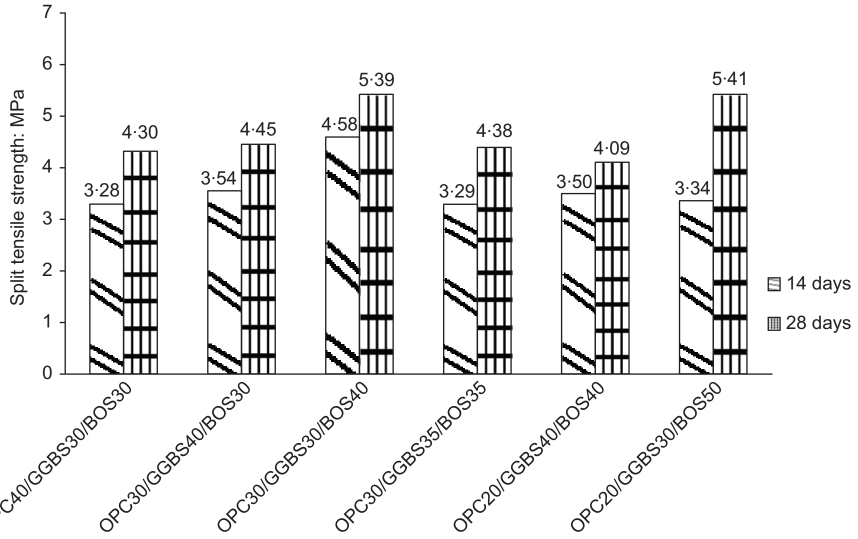

Figure 2. Tensile strength (MPa) of OPC/GGBS/BOS at 14 and 28 days

failure. At this point the specimen was divided into two, and then the two specimens were divided into two halves. The failure load was noted, and the tensile stress was calculated in MPa according to BS EN 1338 (BSI, 2003). In order to comply with industry regulations, the minimum tensile strength of the paving blocks must be 3·6 MPa.

The compressive strength of the specimens was determined using a compression testing machine with a maximum capacity load of 2000 kN, according to the BS EN 12390-3 (BSI, 2002) standard. For the cubes, the compression load was applied to the face with a nominal area of 2500 mm^2. Blocks and cubes were tested after 14 and 28 days. BS EN 1338 (BSI, 2003) specifies no requirements for the compressive strength but only the minimum tensile strength of 3·6 MPa for paving blocks as mentioned above. In this research the compressive strength of different mixes was tested as an indication for the required tensile strength.

3.2 Mix designs for paste and concrete paving blocks

Table 2 shows the mix designs of all the pastes made. The mix designs were based on previous research carried out by Ganjian and Sadeghi-Pouya (2009). It can be seen that three different

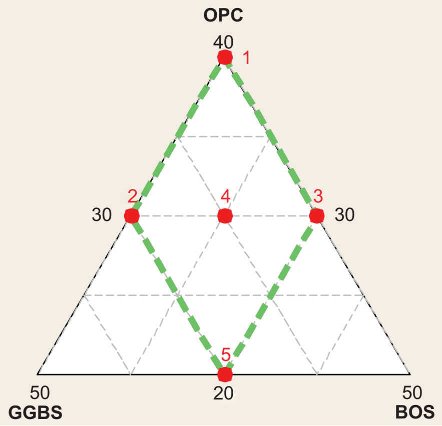

Figure 3. Simplex design plot in amount of OPC/GGBS/BOS at 28 days

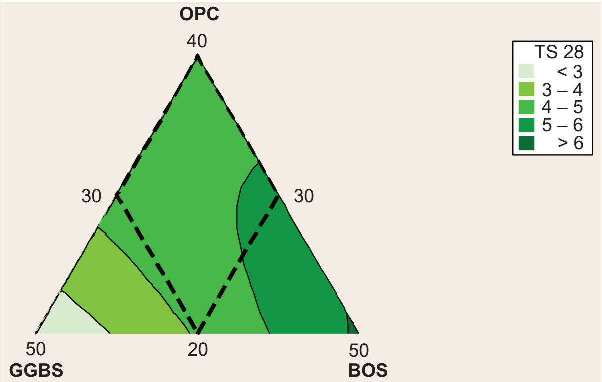

Figure 4. Mixture contour plot of tensile strength of OPC/GGBS/BOS at 28 days

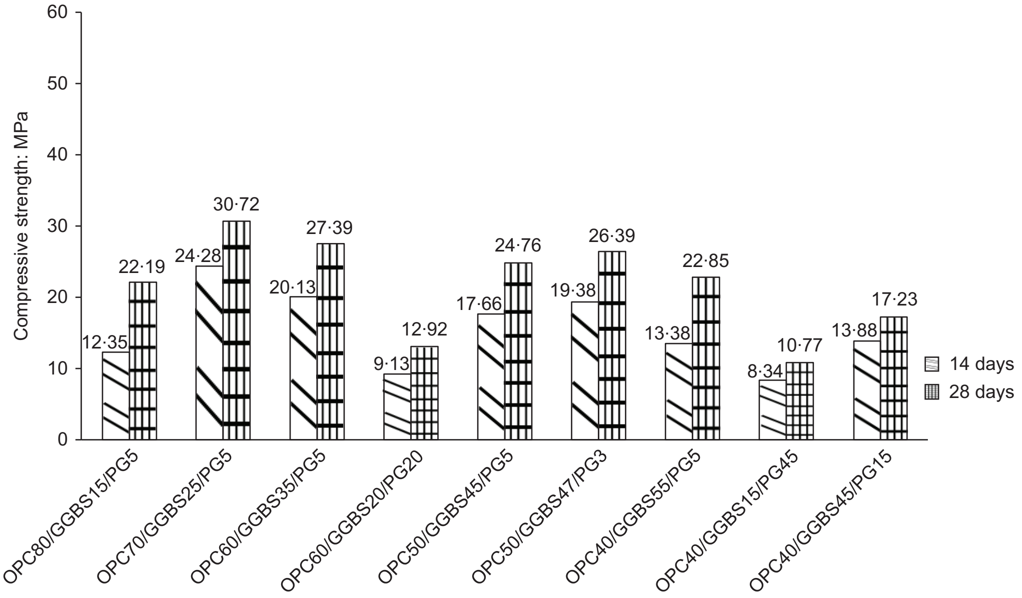

Figure 5. Compressive strength (MPa) of OPC/GGBS/PG at 14 and 28 days

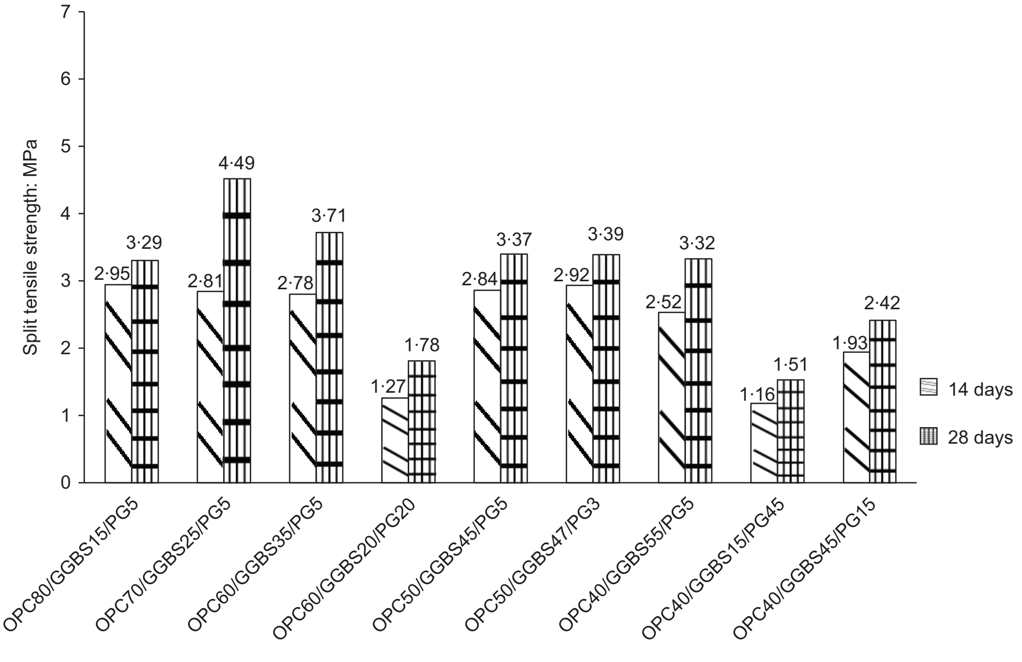

Figure 6. Tensile strength (MPa) of OPC/GGBS/PG at 14 and 28 days

groups of paste blocks and one factory reference paste block were made. For the second phase of the study, aggregates were added, and the resulting concrete paving block mixes are given in Table 3.

4. Results and discussion

4.1 Tensile and compressive strength for paving blocks and cubes without aggregate

Figure 1 shows the compressive strength of cubes prepared with a ternary mixture of OPC/GGBS/BOS, and Figure 2 shows the corresponding tensile strength of paving blocks of the same mix. The results of the tensile strength achieved in this mix were higher than the minimum required 28 day tensile strength of 3·6 MPa. Furthermore, using up to 40% GGBS and up to 40% BOS as a cement replacement yielded an adequate tensile strength after 28 days. The results indicate that it is possible to reduce the cement content by up to 80%. Moreover, at 28 days the mix with 30% GGBS, 50% BOS and 20% OPC, achieved the highest compressive strength and splitting tensile strength in comparison with the rest of the mix ratios used in the same group of mixes. In many cement applications, the use of GGBS is well established as it provides enhanced durability, high resistance to chloride penetration, resistance to sulfate attack and protection against alkali silica reaction (Wild *et al.*, 1996).

Response surface methodology (RSM) was used to analyse the experimental tensile strength of the mixes at 28 days. RSM is a collection of statistical and mathematical techniques that are used to analyse and model problems. Several variables influence a response; the objective of RSM is to minimise this response (Montgomery, 2005).

The tensile strength of paste at 28 days was analysed. For mixtures that contain three ingredients, the mixture space is represented as a triangle. The vertices represent pure blend formulations that contain 100% of a single ingredient. The splitting tensile strength results were presented using Minitab 16 software (Minitab, 2010); this software was used to predict the optimum mixture.

Figure 3 shows the simplex design plot for OPC/GGBS/BOS mixtures. The numbered points represent the five mixes used in this group. The actual optimisation results for this group of five mixes (given in Figure 2) are shown in Figure 4 as a mix contour plot. The plots shown in Figure 4 indicate that the optimum range of the ternary mix was OPC20/GGBS30/BOS50. In addition, a maximum compressive strength of 35·11 MPa and splitting tensile strength of 5·41 MPa was achieved by using this optimum range of the ternary mix. The results achieved by this mix are also shown in the last bar of the bar charts in Figures 1 and 2.

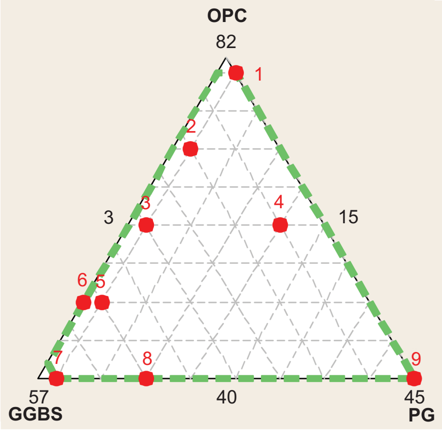

Figure 7. Simplex design plot in amount of OPC/GGBS/PG at 28 days

Figures 5 and 6 confirm that the highest compressive strength and tensile strength recorded was 30·72 and 4·49 MPa, respectively, for the mixture of 25% GGBS, 5% PG and 70% OPC. The results for this mix comply with the British standard BS EN 1338 (BSI, 2003), which requires the tensile strength of samples to be higher than 3·6 MPa.

As expected the compressive strength of the cube specimens in this group showed the same trend as the paving block specimens. The paving blocks prepared with ternary mixtures of OPC/GGBS/PG confirm the possibility of using up to 35% GGBS and 5% PG as a replacement for cement, and even after 28 days the results were still higher than the minimum requirements.

As an alternative, increasing the content of PG by more than 5% in ternary combinations of OPC/GGBS/PG resulted in

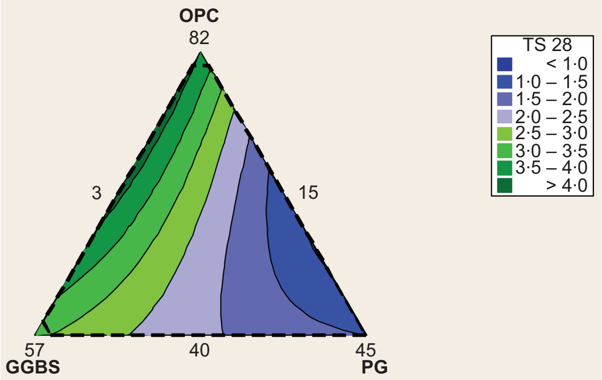

Figure 8. Mixture contour plot of tensile strength of OPC/GGBS/PG at 28 days

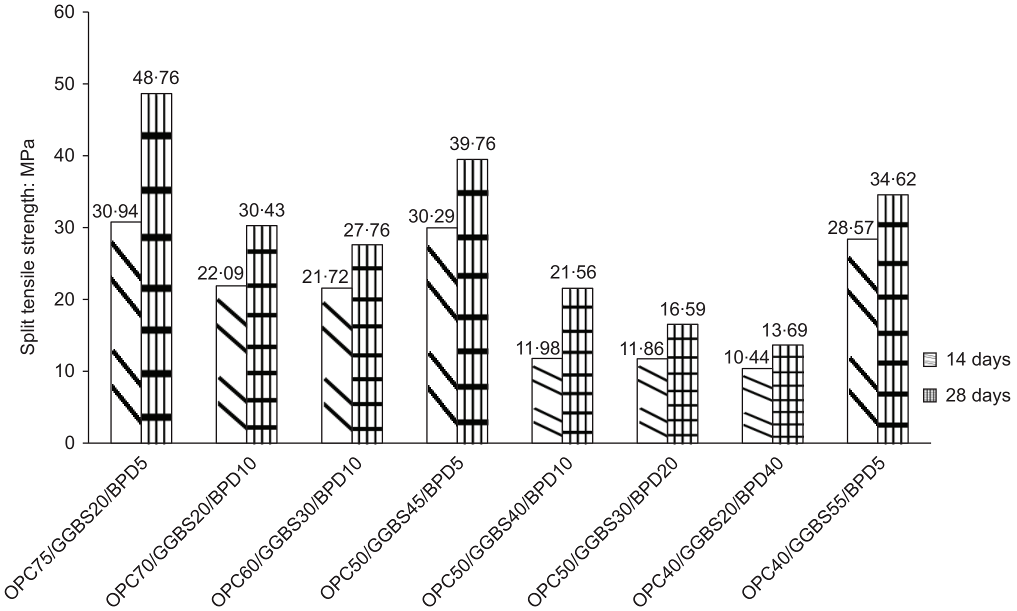

Figure 9. Compressive strength (MPa) of OPC/GGBS/BPD at 14 and 28 days

lower compressive strength and splitting tensile strength values. This was because of an increase in the sulfate content of the paste resulting from PG.

In previous research by Dunster (2008), it was shown that if gypsum that contained 5% or more SO_3 (5% weight in total volume of cement) was added to cements that contain calcium aluminate and calcium silicate hydrates, then there was a high risk that durability problems will occur in the cement. This was because of the high likelihood of formation of ettringite, which is an expansive product that forms as a result of the reaction between the excess sulfate with silicates and aluminates.

Figure 7 presents the simplex design plot for OPC/GGBS/PG mixtures. Figure 8 illustrates the actual optimisation result for the OPC, GGBS and PG group of pastes. The optimum

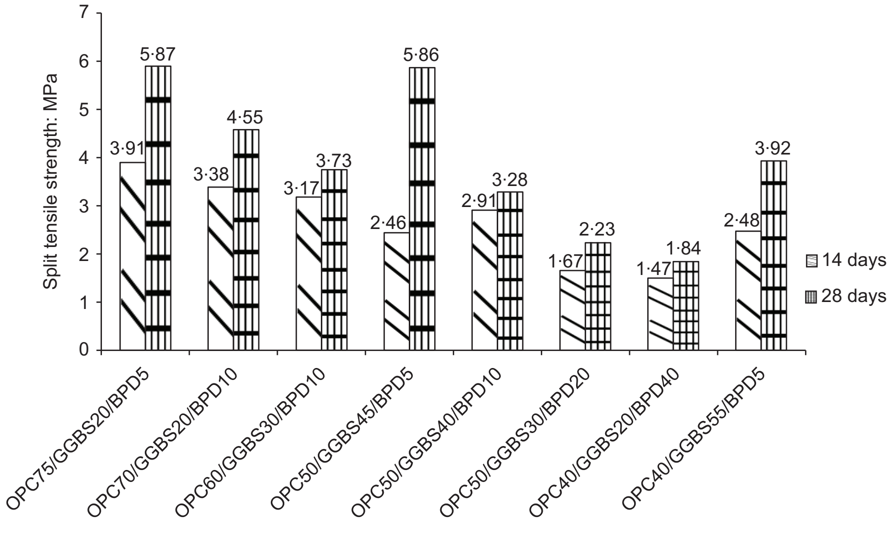

Figure 10. Tensile strength (MPa) of OPC/GGBS/BPD at 28 days

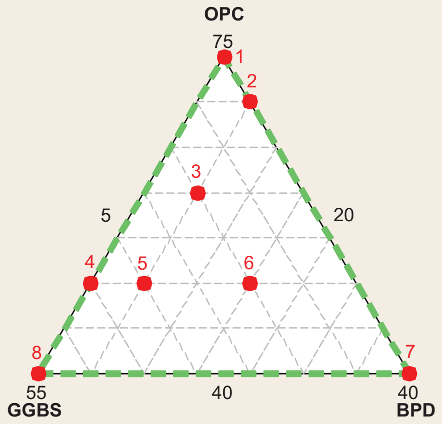

Figure 11. Simplex design plot in amount of OPC/GGBS/BPD at 28 days

ternary mix was obtained with the combination of OPC70/GGBS25/PG5 as this mixture achieved the highest compressive strength and splitting tensile strength as discussed previously.

Another ternary mix that passed the British standard requirements was OPC50/GGBS45/BPD5, for which the results are presented in Figures 9 and 10.The paving blocks prepared with ternary mixtures of OPC/GGBS/BPD confirmed that it is possible to use up to 5% BPD and 45% GGBS as cement replacement as the results were still higher than the minimum requirements after 28 days.

GGBS is a pozzolanic material that can be used as a cementitious ingredient in either cement or concrete composites. The hydration mechanism of cement containing a combination of GGBS and Portland cement is slightly more complex than that of just Portland cement as GGBS is activated by alkalis and sulfates and forms its own hydration products. These hydration products can lead to a pore blocking effect as they may combine with Portland cement products to produce further hydrates.

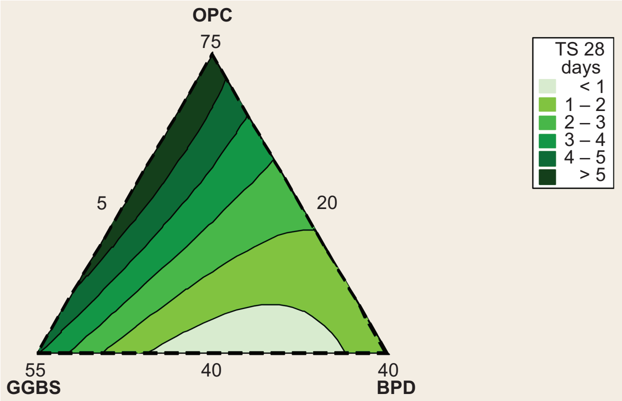

Figure 12. Mixture contour plot of tensile strength of OPC/GGBS/BPD at 28 days

This reaction will result in a hardened cement paste that consists of a high concentration of tiny gel pores and a low concentration of large capillary pores; however, it will still have the same total pore volume. Due to this reaction, the rate of strength development is slower for a combination of GGBS and Portland cement than just Portland cement (Mortar Industry Association, 2008).

In this ternary mix, BPD also acts as an alkali and improves the GGBS–OPC hydration further. The results also showed that the tensile and compressive strength fell as the BPD content of the ternary paste mixtures was increased. The lower strength due to high alkali metal content in the pore solution can be attributed to the morphology of the ettringite precipitation (Scrivener and Taylor, 1993). With an increase in alkali content more needle-shape ettringite crystals will be formed. This contributes to the lower strength of the mix. On the other hand, the lower alkali content results in shorter and denser ettringite crystals that help to improve the compressive strength.

Figure 11 shows the simplex design plot for the OPC/GGBS/BPD mixtures. The actual optimisation result for this mix is illustrated in Figure 12. A ternary mix of OPC75/GGBS20/BPD5 produced a maximum compressive strength of 48·76 MPa and a tensile strength of 5·87 MPa.

4.2 Chemical analysis

Three sets of pastes were studied as shown in Table 4. The chemical analysis of the optimum strength paste in each set was determined after 28 days of hydration in a humidity chamber using the XRF method and the results are shown below.

The chemical composition of the selected mixes (highest mix in each group) showed that the silica content remained about 20% at all mixes. However, as the dissolution of silica in the presence of alkalis into the pore solution is considered to be the main contributor to the strength development, the greater the amount of alkalis in the mix, the greater the strength. It should be noted that there was an optimum alkali content for the cementitious mix; above this the form and shape of the crystals, such as ettringite, changed, thereby reducing the dissolution of silica from slag. This will result in lower compressive and tensile strengths.

Ettringite forms hexagonal-prismatic crystals based on columns of cations of the composition $\{Ca_3[Al(OH)_6]\cdot 12H_2O\}^{3+}$

Bead sample	OPC20/GGBS30/BOS50	OPC70/GGBS25/PG5	OPC50/GGBS45/BPD5
SiO_2	23·66	20·34	20·27
TiO_2	0·50	0·41	0·39
Al_2O_3	7·13	5·39	5·55
Fe_2O_3	6·32	2·20	1·97
MnO	1·00	0·12	0·15
MgO	5·08	1·99	2·30
CaO	45·27	55·24	52·84
Na_2O	0·22	0·20	0·24
K_2O	0·40	0·54	0·90
P_2O_5	0·32	0·10	0·08
SO_3	1·35	4·60	2·47
LoI	8·49	8·49	12·05
Total	99·75	99·62	99·20

LoI, loss of ignition

Table 4. Results of the chemical analysis of materials carried out using XRF method

in which the $Al(OH)_6^{3-}$ octahedra are bound up with the edge-sharing CaO_8 polyhedra. This means that each aluminium ion, bound into the crystal, is connected to Ca^{2+} ions with which they share OH^- ions. The intervening channels contain the SO_4^{2-} tetrahedra and remaining water molecules. The water molecules are partly bound very close into the ettringite structure (Taylor, 1997).

However, in the absence of gypsum the higher alkalinity of the pore solution facilitates the dissolution of silica from the slag resulting in the formation of a greater amount of cementitious gel. Table 4 shows that the total alkalinity (i.e. $Na_2O + K_2O$) in OPC20/GGBS30/BOS50 and OPC50/GGBS45/BPD5 was 0·62 and 1·14%, respectively. This suggests that more silica from the slag dissolved in the pore solution to form more cementitious gel.

On the other hand, the aluminium oxide (Al_2O_3) content in the OPC20/GGBS30/BOS50 mix was higher than the OPC70/GGBS25/PG5 mix; therefore it appears that the higher aluminium resulted in more aluminium-bearing cementitious gel, such as aluminium silicate hydrate, which increased the strength in the OPC/GGBS/BOS group mixes. Furthermore, the content of sulfate, expressed as SO_3, in the

Mix code	Density: kg/m^3	Mix code	Density: kg/m^3
OPC40/GGBS30/BOS30	2191	OPC40/GGBS55/PG5	1943
OPC30/GGBS40/BOS30	2120	OPC40/GGBS15/PG45	1988
OPC30/GGBS30/BOS40	2238	OPC40/GGBS45/PG15	1894
OPC30/GGBS35/BOS35	2181	OPC75/GGBS20/BPD5	2185
OPC20/GGBS40/BOS40	2177	OPC70/GGBS20/BPD10	2055
OPC20/GGBS30/BOS50	2270	OPC60/GGBS30/BPD10	2040
OPC80/GGBS15/PG5	2077	OPC50/GGBS43/BPD7	1963
OPC70/GGBS25/PG5	2003	OPC50/GGBS45/BPD5	2097
OPC60/GGBS35/PG5	1977	OPC50/GGBS30/BPD20	2054
OPC60/GGBS20/PG20	1935	OPC40/GGBS55/BPD5	1934
OPC50/GGBS45/PG5	1949	OPC40/GGBS20/BPD40	2020
OPC50/GGBS47/PG3	2052		

Table 5. Density results for all paste mixes

Mix code	14 days	28 days
Factory control mix I	11·7	18·6
Factory control mix II	12·9	15·7
OPC2.8/GGBS4.2/BOS7.0	9·5	12·6
OPC7.0/GGBS6.3/BPD0.7	13·5	20·3

Table 6. Compressive strength test (MPa) of selected mixes with aggregate at 14 and 28 days

OPC50/GGBS45/BPD5 and OPC20/GGBS30/BOS50 mixes was 2·47 and 1·35%, respectively, suggesting that the improved strength may be as a result of activation of GGBS by sulphates.

4.3 Density

Table 5 presents the average measured densities of the paving blocks that were manufactured. The table shows that the density for each group changes depending on the specific gravity of each ingredient used in the mix. As expected, the range of values for density varied between approximately 1900 and 2200 kg/m^3.

4.4 Tensile and compressive strength of selected mixes with aggregate

The second part in this study included the investigation of strength development of the two highest strength mixes from the previous three paste groups with added aggregate. Aggregates were added in the same way as they were employed in a factory. Table 6 and Figure 13 show the two samples chosen and the factory controls. Factory control mixes I and II are actual factory mix designs used in the production of concrete paving blocks in the laboratory. Control mix I contains a GGBS and OPC mix, and control mix II contains pulverised fuel ash and OPC.

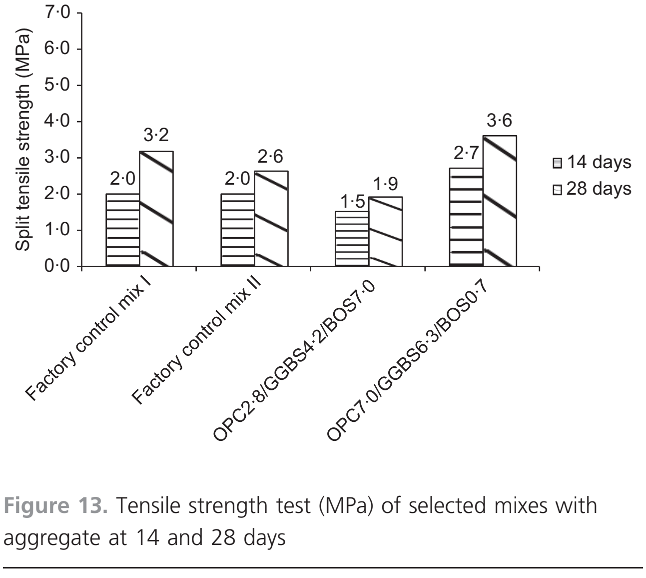

Figure 13. Tensile strength test (MPa) of selected mixes with aggregate at 14 and 28 days

The results of the splitting tensile strength are presented in Figure 13. It can be seen that only the OPC/GGBS/BPD group achieved tensile strength higher than 3·6 MPa. On the other hand, the factory control mixes made in the laboratory and other laboratory mixes containing OPC/GGBS/BOS did not satisfy the minimum requirements of BS EN 1338 (BSI, 2003). It should be noted that the production method used in the laboratory was different from the factory production method in terms of compaction, vibration and compression load, etc. It was understood that factory control mixes I and II made in the factory achieved the minimum tensile strength requirement of 3·6 MPa. Therefore, the 28-day tensile strength of the developed OPC/GGBS/BPD mix when produced in the factory is anticipated to be significantly higher than the minimum requirement.

4.5 Durability tests

Table 7 shows the slip/skid resistance, weathering resistance (water absorption and freeze/thaw) and density of the mixes. Furthermore, the results of slip/skid resistance show that all paving block mixes made in the laboratory had an excellent skid-resistant surface, and the potential for slip was extremely low according to the BS EN 1338 (BSI, 2003) definition, which is provided in Table 8.

In addition, the results of freeze/thaw resistance showed that all of the mixes met the British standard of BS EN 1338 (BSI, 2003). Furthermore, water absorption tests satisfy the minimum requirements of 6% by the BS EN 1338 (BSI, 2003) for water absorption, and the results vary between 4·7 and 5·8%.

5. Conclusion

The potential application of the results presented is a reduction of the amount of Portland cement content in the manufacture of paving blocks and thereby a reduction in the carbon footprint of the construction industry. Such a goal is desirable from the point of view of combating global warming. This research study provides further environmental benefit by re-using industrial/mineral waste materials. This will also lead to a reduction in the stockpile of such waste materials, thus decreasing their impact on the environment and easing the problems associated with the disposal of these waste materials to landfills. Economic benefits should also be felt by the industry due to the reduced waste disposal costs and freedom from complex laws and regulations relating to the disposal of such waste material. Concrete producers will also benefit from lower production costs from the ready availability and low cost of industrial waste.

			Weathering resistance	
Mix	Density: kg/m^3	Slip/skid resistance: BPN	Water absorption: %	Freeze/thaw resistance: kg/m^2
OPC10/GGBS4 (Factory control mix I)	2383	100	5·4	All blocks $< 1·0$
OPC10/PFA4 (Factory control mix II)	2396	92	5·8	
OPC2.8/GGBS4.2/BOS7.0	2395	102	4·7	
OPC7.0/GGBS6.3/BPD0.7	2405	94	5·6	

BPN, British pendulum number

Table 7. Durability test results of concrete paving blocks.

Pendulum test value: BPN	Potential for slip
Below 19	High
20 to 39	Moderate
40 to 74	Low
Above 75	Extremely low

BPN, British pendulum number

Table 8. Pendulum test values and definition given by BS EN 1338 (BSI, 2003)

The following conclusions can be drawn from this study.

- Cement and waste materials such as GGBS, BOS, PG and cement BPD can be used to prepare compressed paving blocks without aggregate.
- Ternary materials, such as BOS and GGBS reduced the cement content more than PG and BPD.
- Paving blocks containing up to 10% BPD in combination with GGBS or OPC without aggregate satisfied the tensile strength minimum requirements. The desired strength can also be achieved by paving blocks containing less than 5% PG.
- Unlike OPC/GGBS/BOS mixes, concrete paving blocks prepared with OPC/GGBS/BPD satisfied the minimum requirements of 3·6 MPa for tensile strength. This mix can be used in the factory to reduce cement content by up to 30%. This mixture performed well in the slip/skid resistance, freeze/thaw and water absorption tests.

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