Reducing Cement Contents of Paving Blocks by Using Mineral Waste and by-Product Materials

Ganjian, E. , Jalull, G. and Sadeghi-Pouya, H

Uncorrected accepted proof deposited in CURVE January 2015

Original citation:
Ganjian, E. , Jalull, G. and Sadeghi-Pouya, H. (2014) Reducing Cement Contents of Paving Blocks by Using Mineral Waste and by-Product Materials . Journal of Materials in Civil Engineering, volume 27 (1): Article number 04014106. DOI 10.1061/(ASCE)MT.1943-5533.0001037

http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001037

Publisher
American Society of Civil Engineers ASCE

Reducing Cement Contents of Paving Blocks by Using Mineral Waste and by-Product Materials

Eshmaiel Ganjian, Ph.D.[1]; Ghassan Jalull[2]; and Homayoon Sadeghi-Pouya, Ph.D.[3]

Abstract: In the production of conventional paving blocks, it is usual to use a minimum of 210 $\mathrm{kg/m^3}$ of cement. However, when Portland cement is produced, it impacts negatively on the environment due to carbon dioxide emissions. Therefore, this paper investigates the use of waste and by-product materials, such as run-of-station ash (ROSA), basic oxygen slag (BOS), ground granulated blast-furnace slag (GGBS), plasterboard gypsum (PG), and cement bypass dust (BPD) to reduce the amount of cement in paving blocks. The combinations of binary and ternary blends in different mixes are considered. Tensile strength, skid/slip and freeze/thaw resistance of paving blocks, verified that a cementitious mix containing ROSA up to 60%, GGBS up to 55%, BPD up to 25%, and plasterboard gypsum PG up to 5% by weight can replace Portland cement without having any substantial impact on the strength or durability of the blocks. XRD and XRF tests of selected mixes have been presented and discussed. Concrete blocks prepared with OPC/GGBS/BPD can reduce cement content by up to 30% in comparison to the percent of cement used in factories. **DOI:** 10.1061/(ASCE)MT.1943-5533.0001037.

Author keywords: Blocks; Precast concrete; Tensile strength; Concrete; Stress; Environmental issues.

Introduction

In order to manufacture paving blocks, it is usual for a minimum of 210 $\mathrm{kg/m^3}$ of cement to be used. However, when Portland cement is produced it impacts negatively on the environment to a significant extent due to carbon dioxide emissions. Therefore, if it is possible to reduce the amount of Portland cement used by other cementitious materials, the carbon footprint of concrete products will be significantly reduced without adversely affecting its durability and other physical characteristics.

The significant emissions of carbon dioxide produced in the manufacture of Portland cement presents a problem. The production of every ton of Portland cement releases approximately 1 t of carbon dioxide—a major contributor to the greenhouse gas emissions that are responsible for global warming (Ghataora et al. 2004). Cement production accounts for roughly 8% of global CO_2 emissions (Olivier et al. 2012).

However, reduction of waste from industrial processes has become more complex and costly. Nowadays, mineral additives are attracting a great deal of attention as materials that contribute to the improvement of specific properties of concrete, as well as decreasing carbon dioxide emissions and energy generated in producing cement.

If it is possible to make use of existing waste materials, this would lead to the environmental impact being largely reduced as well as natural raw materials being preserved. This will mean that the overall energy required for the production of a cementitious material will be reduced, thus reducing the carbon dioxide emissions (Ganjian and Sadeghi-Pouya 2009).

This research aims to explore whether it will be possible to make paving blocks using a mixture of various waste materials, and in this way bring about a reduction in the percentage of Portland cement being used in the manufacturing material. This should bring about a reduction in CO_2 by reducing cement content. Furthermore, this should lead to a reduction in the stockpile of waste materials in order to decrease their impact on the environment, specifically, problems from the disposal of waste materials to landfill.

Background

Recycled materials have played a very important part in recent research; in particular, demolition waste, ceramic tile, crushed clay bricks, and recycled concrete have been studied as aggregate replacement. A great deal of research has also been carried out on the use of industrial waste and by-products as cement replacement in concrete paving block production (Chan and Poon 2006; Padmini et al. 2001; Torkittikul et al. 2010).

Cement content is a very important issue in the production of paving blocks. Researchers have investigated ways to reduce cement content in different construction products in order to reduce the environmental impacts of the products and to benefit in terms of the economic costs (Naik 2008).

Since 1970, researchers have been engaged in attempts to partially replace Portland cement with other suitable materials. Some pozzolans, limestone, and metakaolin are possible materials which occur naturally; others such as fly ash and steel slag are produced by various metallurgy processes, with silica and other materials being by-products of various industries (Menéndez et al. 2002).

Ganjian and Pouya (2008) conducted research on the viability of blending plasterboard gypsum waste with a range of industrial

---

[1] Dept. of Civil Engineering, Architecture and Building, Faculty of Engineering and Computing, Sir John Laing Building, Coventry Univ., Coventry CV1 5FB, U.K. (corresponding author). E-mail: E.Ganjian@Coventry.ac.uk

[2] Dept. of Civil Engineering, Architecture and Building, Faculty of Engineering and Computing, Sir John Laing Building, Coventry Univ., Coventry CV1 5FB, U.K.; and Dept. of Civil Engineering, Faculty of Engineering, Al Zawiya Univ., Al Zawiya, Libya.

[3] Dept. of Civil Engineering, Architecture and Building, Faculty of Engineering and Computing, Sir John Laing Building, Coventry Univ., Coventry CV1 5FB, U.K.

Note. This manuscript was submitted on June 13, 2013; approved on January 22, 2014; published online on January 25, 2014. Discussion period open until June 25, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Materials in Civil Engineering***, © ASCE, ISSN 0899-1561/(0)/$25.00.

wastes to produce a binder in the process of manufacturing paving blocks. It was found that pastes consisting of plasterboard gypsum (PG), cement-by-pass dust (BPD), and basic oxygen slag (BOS) with the same water content of 15% produced good strength development, and possible to produce paving blocks with desirable compressive strength and tensile strength. Furthermore, it was found that run of station ash (ROSA) had acceptable pozzolanic potential to be used with slag, plasterboard, and by-pass dust.

Materials Used in this Research

Run-of-Station Ash (ROSA)

For this research, dry run-off-station ash has been obtained from Rugby Ash. In this case, the run-off-station ash is derived from a power station with an average particle size of 20 μm.

Run-off-station ash is an unclassified fly ash collected from the chimney stacks of power stations. It is pozzolanic and reacts with calcium hydroxide and alkalis to form cementitious compounds, such as calcium silicate/aluminate hydrates.

The carbon content of fly ash affects the fresh and hardened properties of concrete mixes. Thermogravimetric analysis of ROSA indicated that the carbon content of the ash used was about 7%. This is about the average carbon content found in normal PFA.

Plasterboard Gypsum (PG)

For this research, crushed plasterboard gypsum waste was supplied by Lafarge plasterboard recycling plant in Bristol. Plasterboard gypsum waste had been sourced from a number of sources, such as construction and demolition sites, it was recycled and then carefully classified, ensuring that during the process all contaminants such as paper and glass had been eliminated. The big pieces of paper and other contaminations were separated by using a series of sieves before the gypsum was crushed using a metal tamper. Plasterboard was then grinded, sieved and conditioned to form a powder. The analysis of the particle size of the gypsum was made using a Malvern Mastersize 2000 laser analyzer with an accuracy of ±1%. As a result, the particle size was found to be between 1 μm and 1 mm in diameter, and mostly >300 μm.

Basic Oxygen Slag (BOS)

Basic oxygen slag or steel slag dust is a by-product that results when iron is converted to steel using a basic oxygen furnace or from melting scrap to make steel in an electric arc furnace (Caiju 2004). Currently, it is inevitable that basic oxygen steel slag will be produced as a result of the way that steel is produced, with nearly 150 kg resulting from the manufacture of each ton of steel. The basic oxygen slag for this research was obtained from the Corus plant at Scunthorpe, and the average particle size was 40–60 μm.

Cement by-Pass Dust (BPD)

By-pass dust (BPD) is collected from the kiln bypass. The main purpose of the kiln bypass is to bleed off volatile materials that would otherwise recirculate 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; it can only be removed from the kiln at 1,000°C. As a result, BPD contains numerous cement bound phases.

The BPD was provided in a powder form. However, the average size of fine particles is about 10 μm for the BPD, and the maximum particle size is 200 μm. BPD from a local cement works, Castle Cement (Heidelberg Cement Group, Rugby, U.K.), was obtained for this research.

Ground Granulated Blast-Furnace Slag (GGBS)

The ground granulated blast-furnace slag (GGBS) was obtained from Civil and Marine, a part of Hanson U.K., and the grain sizes were in the range of 0.3–0.1 mm, with an average particle size of 20 μm. The material was marketed under the BS EN 15167-1-2 standard (BSI 2006).

Ordinary Portland Cement (OPC)

The cement used for this research was CEM1 cement as defined by the European standard BSEN-197 (BSI 2011).

Chemical Analysis of Raw Materials

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

Experimental Work and Mix Proportions

The aim was to achieve the greatest tensile splitting strength for both binary and tertiary mixtures. For this experiment, the materials were compacted in one layer.

Mixes using four different combinations of resources were designed and used for paving blocks; they were then tested for tensile strength. For all groups, the water content was 15%. This water content was based on previous research carried out by the coauthors (Ganjian and Sadeghi-Pouya 2009) to obtain desirable density and flexural strength for manufactured blocks. The second phase of the study was to select the best results between all mixes and to add 4 mm and 6 mm aggregates that are similar to the mix design used by factories.

Casting, Curing, and Testing

The paving blocks had a 190 × 100 mm cross section and 80 mm thick. A compression machine was used to fully compact the materials in one layer with 150 kN of load. A mold collar was also used to retain the material within the mold, as shown in Fig. 1. Once cast, the specimens were covered with a polythene sheet so that there would be no loss of water. On the next day, all samples were demolded and then stored in curing chambers at a constant air temperature of 22° ± 2°C and 98% relative humidity until they were to be tested.

Table 1. Chemical Content of OPC, BOS, ROSA, PG, and PBD Used

Sample oxides	OPC (%)	BOS (%)	ROSA (%)	PG (%)	BPD (%)	GGBS (%)
SiO_2	20.00	11.43	45.91	2.43	21.86	37.28
TiO_2	—	0.39	1.41	0.03	0.29	0.58
Al_2O_3	6.00	1.60	26.51	0.81	3.85	10.79
Fe_2O_3	3.00	28.24	5.23	0.36	2.57	0.43
MnO	—	4.35	0.08	<0.01	0.02	0.68
MgO	1.50	8.27	2.13	0.40	1.13	8.83
CaO	63.00	41.29	6.88	37.30	53.40	40.12
Na_2O	1.00	0.02	0.61	0.03	0.41	0.27
K_2O	1.00	0.02	1.35	0.24	3.64	0.37
P_2O_5	—	1.48	0.98	0.02	0.08	<0.05
SO_3	2.00	0.44	1.37	53.07	7.10	0.15
LoI	0.50	3.12	7.11	4.09	5.64	1.03

Fig. 1. A mold collar used

To determine the split tensile strength of the paving blocks, BS EN 1338 (BSI 2003) was used and the 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; wooden pieces were placed on the top and bottom of the specimen to provide packing as shown in Fig. 2. The load was slowly applied at a rate of 0.05 ± 0.01 MPa/s until the point of failure. At this point, the specimen was divided into two halves. The failure load was noted and the tensile stress was calculated in MPa according to BS EN 1338 (BSI 2003). A minimum tensile strength of 3.6 MPa must be obtained for all paving blocks in order to comply with the British standard BS EN 1338 (BSI 2003). Paving blocks were tested after 14 and 28 days of age.

Fig. 2. Steel frame of split tensile strength test

The likelihood of pedestrians slipping and vehicles skidding is measured by determining its slip/skid resistance. In order to measure unpolished slip resistance use, is made of a standard rubber material which is attached to a pendulum friction tester; this is then tested under wet conditions; BS EN 1338 Annex I was used to find the unpolished slip resistance value. Concrete paving blocks have satisfactory slip/skid resistance provided that their whole upper surface has not been ground and/or polished to produce a very smooth surface.

Weathering resistance is an expression of the extent to which concrete paving blocks are able to withstand weathering where particular circumstances exist, such as surfaces being frequently subjected to contact with deicing salt when there is frost. It is possible to assess this capacity under laboratory conditions by making a measurement of the amount of spalled material accumulating on a surface when it has been subjected to repeated freezing and thawing with a deicing salt being used. Fig. 3 shows the specimens prepared for freeze/thaw test. Where there is no use of deicing salt, measurements should be made of the block's water absorption. The weathering resistance is determined by tests according to Annex D of BS EN 1338 for freeze-thaw resistance or annex E of BS EN 1338 for water absorption. Both tests have been carried out in this study.

Mix Designs for Paste and Concrete Paving Blocks

The mix design of all pastes made is shown in Table 2. Six different groups of paste blocks were made. The mix designs for concrete paving blocks made are given in Table 3. A constant ratio of paste to stone of 1:16.1 was used. Moreover, for all mixes between 120–140 L of water was added to a 1.5 m^3 mix, depending on the moisture contents of stones used.

Results and Discussion

Split Tensile Strength Results for Paving Blocks without Aggregate

In general, run-of-station ash (ROSA) showed satisfactory pozzolanic potential for use with basic oxygen slag, plasterboard gypsum, and cement bypass dust. In addition, using a ternary mixture of OPC/ROSA/BOS, OPC/ROSA/PG, and OPC/ROSA/BPD gave sufficient results that satisfied the 3.6 MPa requirements.

From Fig. 4, it can be seen that the development strength of paste mixtures using a range of ROSA and OPC indicated that

Fig. 3. Specimens for freeze/thaw test

Table 2. Mixes Proportions of Paving Blocks without Aggregates Giving Percentage by Weight

Mix code	OPC (%)	ROSA (%)	BOS (%)	GGBS (%)	PG (%)	BPD (%)	W/C
OPC70/ROSA30	70	30	—	—	—	—	0.15
OPC60/ROSA40	60	40	—	—	—	—	0.15
OPC50/ROSA50	50	50	—	—	—	—	0.15
OPC40/ROSA60	40	60	—	—	—	—	0.15
OPC30/ROSA70	30	70	—	—	—	—	0.15
OPC70/ROSA15/BOS15	70	15	15	—	—	—	0.15
OPC60/ROSA20/BOS20	60	20	20	—	—	—	0.15
OPC52/ROSA30/BOS18	52	30	18	—	—	—	0.15
OPC50/ROSA20/BOS30	50	20	30	—	—	—	0.15
OPC50/ROSA25/BOS25	50	25	25	—	—	—	0.15
OPC40/ROSA30/BOS30	40	30	30	—	—	—	0.15
OPC30/ROSA35/BOS35	30	35	35	—	—	—	0.15
OPC80/ROSA17/PG3	80	17	—	—	3	—	0.15
OPC80/ROSA15/PG5	80	15	—	—	5	—	0.15
OPC70/ROSA27/PG3	70	27	—	—	3	—	0.15
OPC70/ROSA25/PG5	70	25	—	—	5	—	0.15
OPC60/ROSA35/PG5	60	35	—	—	5	—	0.15
OPC50/ROSA45/PG5	50	45	—	—	5	—	0.15
OPC40/ROSA55/PG5	40	55	—	—	5	—	0.15
OPC70/ROSA20/BPD10	70	20	—	—	—	10	0.15
OPC60 /ROSA25/BPD15	60	25	—	—	—	15	0.15
OPC50 /ROSA30/BPD20	50	30	—	—	—	20	0.15
OPC50 /ROSA40/BPD10	50	40	—	—	—	10	0.15
OPC40 /ROSA35/BPD25	40	35	—	—	—	25	0.15
OPC40 /ROSA40/BPD20	40	40	—	—	—	20	0.15
OPC30 /ROSA60/BPD10	30	60	—	—	—	10	0.15
OPC30 /ROSA40/BPD30	30	40	—	—	—	30	0.15
OPC40/GGBS30/BOS30	40	—	35	35	—	—	0.15
OPC30/GGBS40/BOS30	30	—	30	40	—	—	0.15
OPC30/GGBS30/BOS40	30	—	40	30	—	—	0.15
OPC30/GGBS35/BOS35	30	—	35	35	—	—	0.15
OPC20/GGBS40/BOS40	20	—	40	40	—	—	0.15
OPC20/GGBS30/BOS50	20	—	50	30	—	—	0.15
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

a mixture of 50% ROSA and 50% OPC showed the highest strength at 14 and 28 days for the production of paving blocks, and it is shown that as the ROSA content increases the strength is reduced. This is due to the ash particles acting as filler without assisting the gel in a cement paste matrix of the paste. Moreover, splitting tensile strength was reduced as a result of increasing the ROSA content by more than 50%.

Table 3. Mix Proportions of Concrete Paving Blocks Giving Percentage by Weight

Mix	OPC (%)	GGBS (%)	PFA (%)	ROSA (%)	BOS (%)	4 mm (%)	6 mm (%)	Sand (%)
Factory mix I (Control mix I)	10.0	4.0	—	—	—	53	9	24
Factory mix II (Control mix II)	10.0	—	4.0	—	—	53	9	24
OPC/ROSA/BOS	7.3	—	—	4.2	2.5	53	9	24
OPC/ROSA	7.0	—	—	7.0	—	53	9	24
OPC/GGBS/BOS	2.8	4.2	7.0	—	—	53	9	24
OPC/GGBS/BPD	7.0	0.7	6.3	—	—	53	9	24

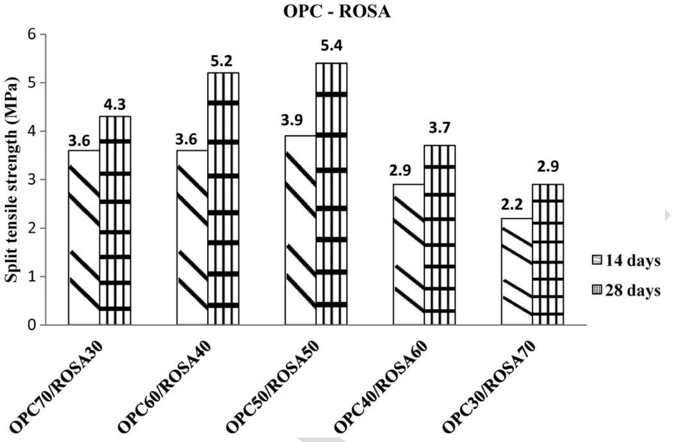

Fig. 4. Split tensile strength (MPa) of OPC-ROSA at 14 and 28 days

Even at 14 days, the characteristic strength of paving blocks prepared with a ternary mixture of OPC/ROSA/BOS shows better results than the minimum required tensile strength of 3.6 MPa. Furthermore, Fig. 5 shows that the use of run of station ash up to 35% and basic oxygen slag up to 35% replacement of cement shows sufficient results even at 14 days in the split tensile strength and confirmed that it is possible to reduce cement by up to 70%.

The 28-day split tensile strength of experimental mixes were analysed by using the response surface methodology (RSM), which is a collection of statistical and mathematical techniques that are useful for analyzing and modeling problems. A response is influenced by several variables and the objective of the method is to minimize this response (Montgomery 2005).

The RSM was constructed using plus/minus two standard deviations. The effect of mixtures on the 28-day tensile strength of pastes has been analyzed. For three-component mixtures, the mixture space is a triangle with vertices corresponding to formulations that are pure blends (mixtures that are 100% of a single component).

The results of splitting tensile strength were presented by using *Minitab 16* software to predict the optimum mixture. The actual optimization results for this group are shown in Fig. 6. Moreover, it can be seen that the maximum split tensile strength of 5.1 MPa is achieved by the optimum ternary mix 30% ROSA, 18% BOS, and 52% OPC at 28 days.

Dunster (2008) showed that the addition of gypsum at quantities greater than 5% SO3 (by weight of cement) to such cements (which

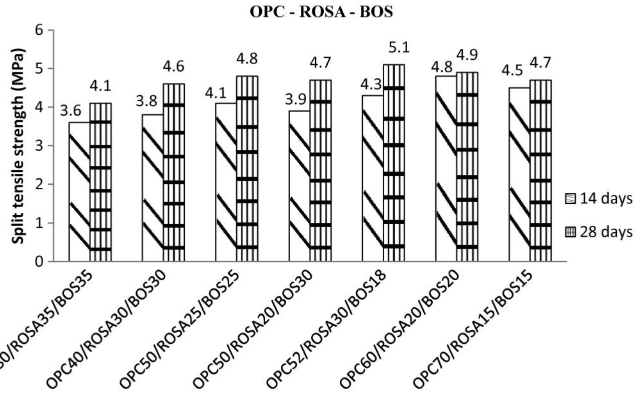

Fig. 5. Split tensile strength (MPa) of OPC-ROSA-BOS at 14 and 28 days

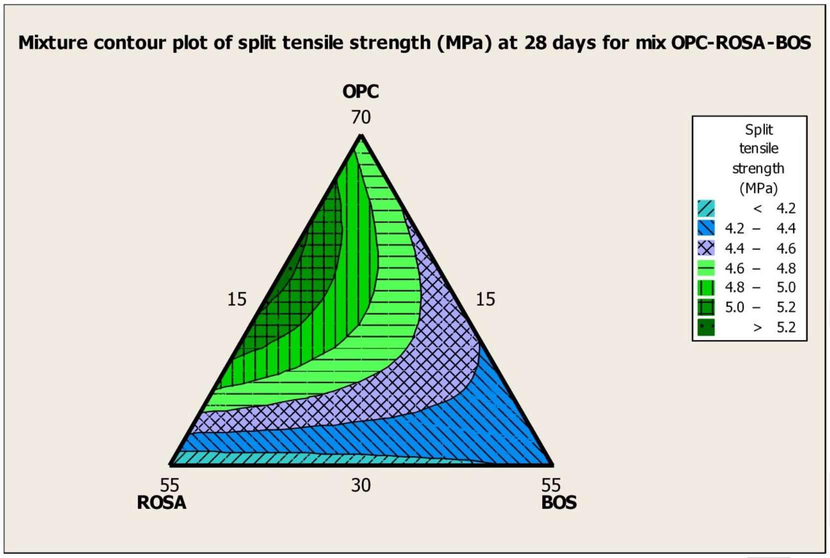

Fig. 6. Mixture contour plot of the ternary mix OPC-ROSA-BOS at 28 days

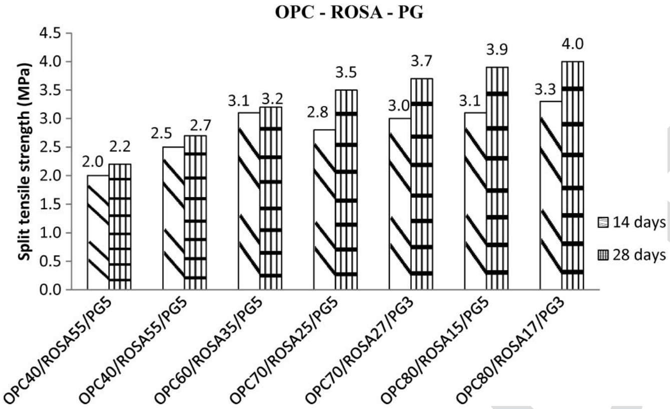

Fig. 7. Split tensile strength (MPa) of OPC-ROSA-PG at 14 and 28 days

contain calcium aluminate and calcium silicate hydrates) leads to a high risk of durability problems. This is because the excess sulfate reacts with the silicates and aluminates in the cement to form large amounts of expansive products, such as ettringite. Therefore, a maximum PG content of 5% is used in this investigation.

The results of OPC-ROSA-PG paste are shown in Figs. 7 and 8. The actual optimization result for OPC, ROSA, and PG group of pastes is illustrated in Fig. 8. The optimum ternary mix was obtained with the combination of OPC80/ROSA17/PG3, and this mixture achieved the highest split tensile strength of 4.0 MPa.

Fig. 9 confirms that the highest split tensile strength is 4.4 MPa, and this was achieved by using 40% ROSA, 10% BPD, and 50% OPC; the results were found to be higher than 3.6 MPa, which is required by the British standard BS EN1338 (BSI 2003). The paving blocks prepared with ternary mixtures of OPC/ROSA/BPD confirm the possibility of using up to 25% BPD and 35% ROSA as a replacement for cement, and the results are still higher than the minimum requirements after 28 days.

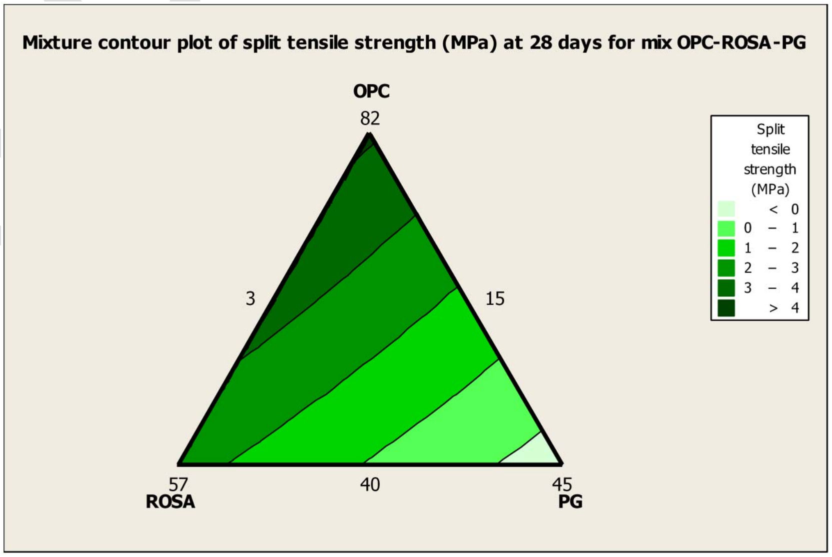

Fig. 8. Mixture contour plot of the ternary mix OPC-ROSA-PG at 28 days

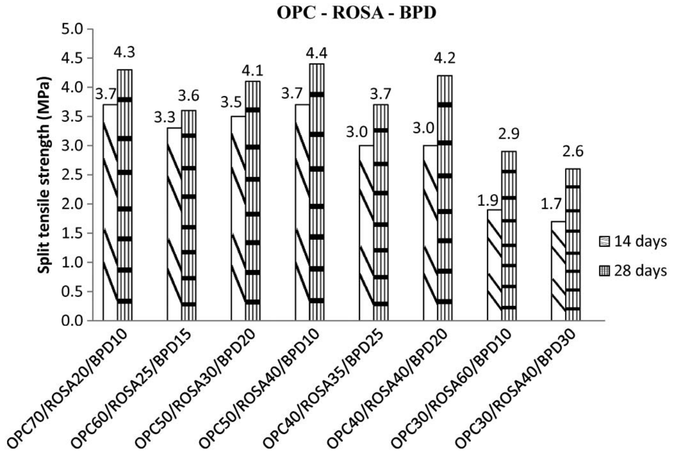

Fig. 9. Split tensile strength (MPa) of OPC-ROSA-BPD at 14 and 28 days

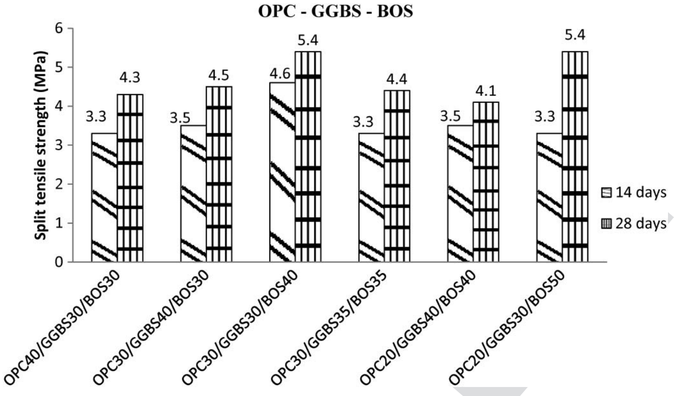

Fig. 11. Split tensile strength (MPa) of OPC-GGBS-BOS at 14 and 28 days

Alternatively, increasing the content of BPD by more than 25% in ternary combinations of OPC/ROSA/BPD resulted in a lower splitting tensile strength. This is due to an increase in the alkaline content of the paste resulting from BPD.

The results of OPC-ROSA-BPD paste are shown in Figs. 9 and 10. For this group, the actual optimization result is illustrated in Fig. 9. The optimum ternary mix was obtained with the mixture of OPC50/ROSA40/BPD10.

The characteristic strength of paving blocks prepared with ternary mixture of OPC/GGBS/BOS showed higher results than the minimum required tensile strength of 3.6 MPa after 28 days. Furthermore, Fig. 8 shows that the use of up to 40% ground granulated blast furnace slag and up to 40% basic oxygen slag as a replacement for cement shows sufficient results after 28 days in the splitting tensile strength; the results also confirmed that it is possible to reduce cement by up to 80%.

Moreover, it can be seen that the maximum split tensile strength can be achieved by using 30% GGBS, 50% BOS, and 20% OPC at 28 days.

The use of GGBS is well established in many cement applications, where it provides enhanced durability, including high resistance to chloride penetration, resistance to sulphate attack, and protection against alkali silica reaction (Wild et al. 1995).

The results of OPC-GGBS-BOS paste are shown in Figs. 11 and 12. The actual optimization result for this group is depicted in Fig. 12. In addition, it can be seen that the maximum split tensile strength of 5.4 MPa can be achieved by using the optimum range of the ternary mix OPC20/GGBS30/BOS50. Fig. 13 confirms that the highest results of split tensile strength can be achieved by using 20% GGBS, 5% BPD, and 75% OPC. Another ternary mix was obtained by combining 45% GGBS, 5% BPD, and 50% OPC; the results for this mix were higher than the required 3.6 MPa by the British standard BS EN1338. Paving blocks prepared with ternary mixtures of OPC/GGBS/BPD confirm the possibility of using up to 5% BPD and 55% GGBS as a replacement for cement, and the results are still higher than the minimum requirements after 28 days.

As it is well established, ground granulated blast furnace slag (GGBS) is a pozzolanic material that can be used as a cementitious ingredient in either cement or concrete composites. The hydration mechanism of a combination of GGBS and Portland cement is slightly more complex than that of Portland cement. This reaction involves the activation of the GGBS by alkalis and sulfates to form its own hydration products. Some of these combine with

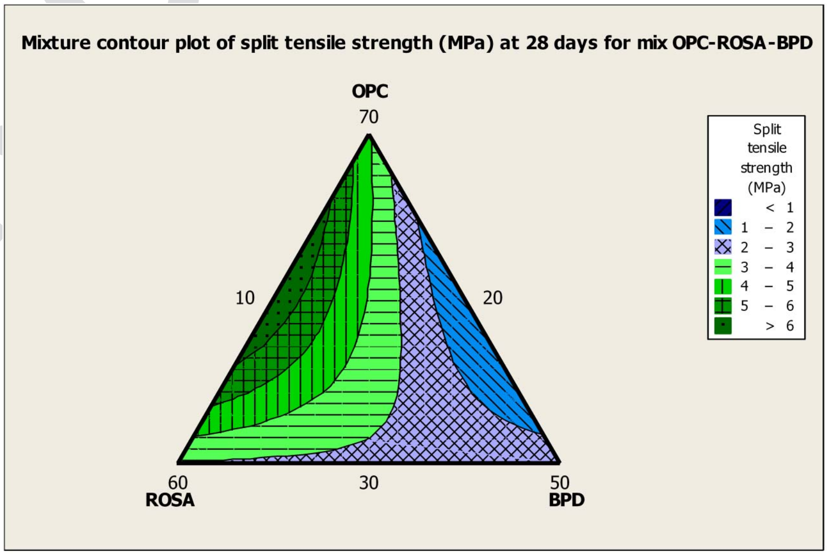

Fig. 10. Mixture contour plot of the ternary mix OPC-ROSA-BPD at 28 days

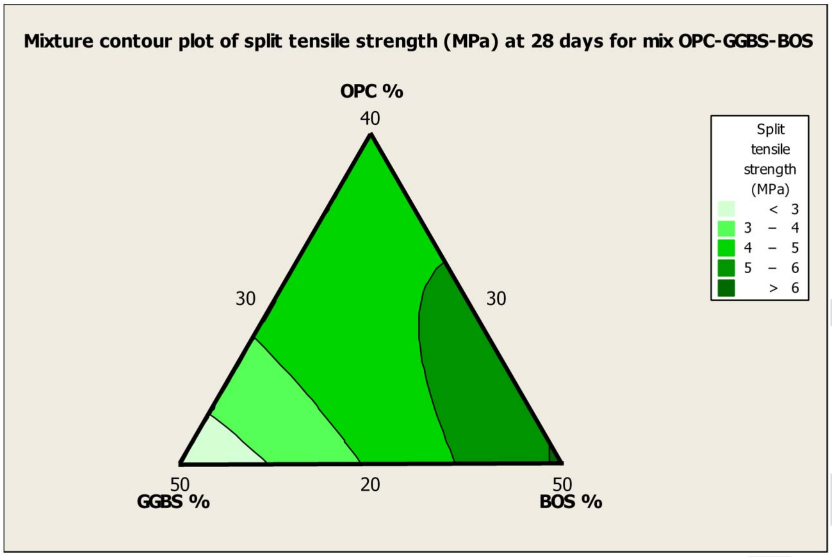

Fig. 12. Mixture contour plot of the ternary mix OPC-GGBS-BOS at 28 days

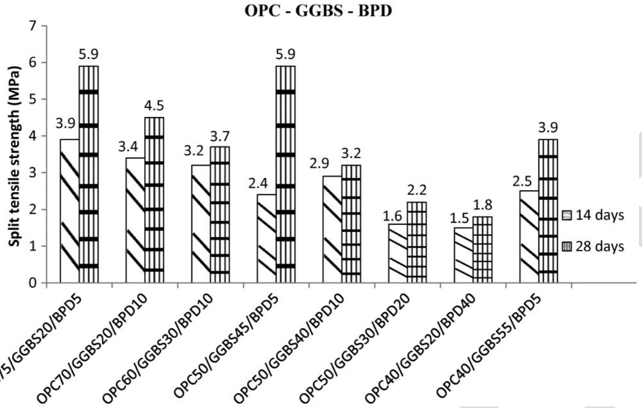

Fig. 13. Split tensile strength (MPa) of OPC-GGBS-BPD at 14 and 28 days

Portland cement products to form further hydrates which have a pore-blocking effect.

The result is a hardened cement paste that consists of a high concentration of tiny gel pores and a low concentration of large capillary pores, with the same total pore volume. Generally, the rate of strength development is slower than for a Portland cement mortar (Mortar Industry Association 2008).

In this mix, BPD is also acting as an alkaline and will improve the GGBS hydration with OPC further. The real optimization result for this group is illustrated in Fig. 14. It can be seen that the maximum split tensile strength is 5.9 MPa and this can be achieved by using the optimum ternary mix OPC75/GGBS20/BPD5.

The standard deviation of split tensile strength measured in all groups at 28 days was between 0.27 and 1.49.

Chemical Analysis of Raw Materials

Chemical analysis of the raw materials was carried out using XRF method. These are shown in Table 1.

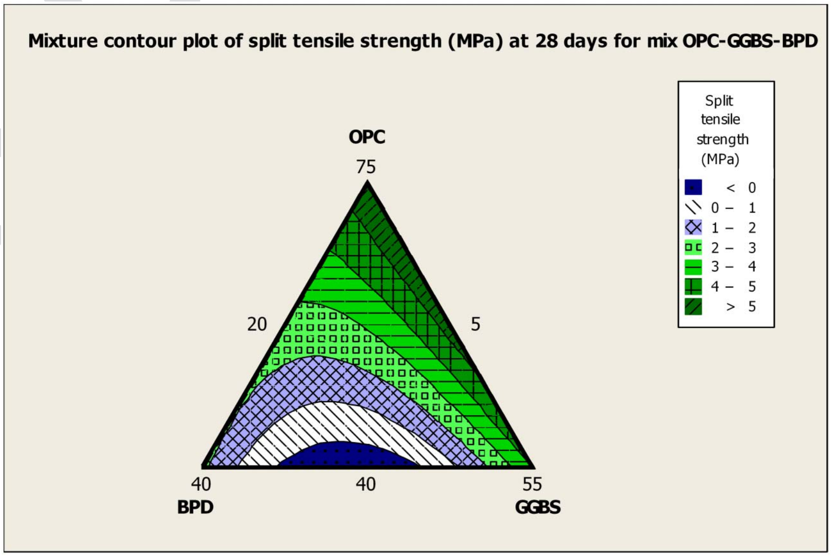

Fig. 14. Mixture contour plot of the ternary mix OPC-GGBS-BPD at 28 days

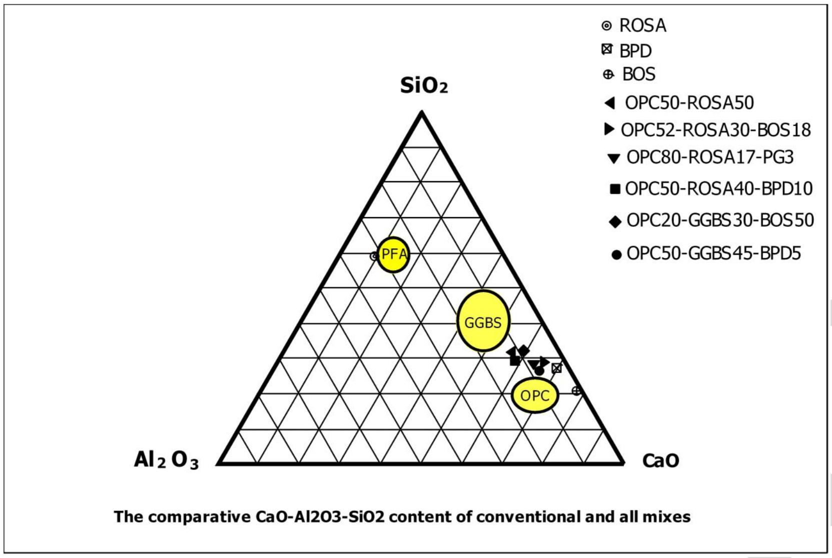

Fig. 15. The comparative CaO-Al_2O_3-SiO_2 content of conventional and all mixes

The typical chemical composition of pozzolanic materials, such as pulverized fuel ash (PFA) and ground granulated blast furnace slag (GGBS) is well understood, and their use as cement replacement is well-established in construction and concrete technology. Fig. 15 shows the comparative CaO-Al_2O_3-SiO_2 content of cementitious materials (OPC, GGBS and PFA), materials and the mixes used in this research. The figure shows that most of the raw materials used are placed near OPC and GGBS. The figure indicates GGBS and BPD is more promising to replace OPC.

Chemical Analysis of Mixtures

Four sets of pastes were studied and chemical analysis was determined using XRF method; the results are shown in Table 4.

Table 4 shows that for all mixes the silica content remained at 20%. On the other hand, as the presence of alkali in the pore solution causes dissolution of silica and is considered as one of the main contributors to strength development, it can be stated that the higher the amount of alkalis in the mix, the higher the strength. It should be noted that there is an optimum alkali content in the cementitious mix, above which the form and shape of the crystals, such as ettringite changes, reduce the dissolution rate of silica from slag. This will result in lower compressive and tensile strength.

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

Nevertheless, the higher alkalinity of the pore solution facilitates the dissolution of silica from the slag resulting in formation of higher amount of cementitious gel. Table 4 shows that the total alkalinity i.e., ($Na_2O + K_2O$) in OPC50/GGBS45/BPD5 is 1.14%.

Table 4. Chemical Analysis of the Materials, Carried Out Using XRF Method

Sample oxides	OPC	OPC50/ROSA50	OPC52/ROSA30/ BOS18	OPC80/ROSA17/ PG3	OPC50/ ROSA40/ BPD10	OPC20/GGBS30/ BOS50	OPC50/GGBS45/ BPD5
SiO_2	20.00	24.10	20.91	20.81	22.06	23.66	20.27
TiO_2	—	0.56	0.50	0.47	0.50	0.50	0.39
Al_2O_3	6.00	8.77	6.59	6.50	7.91	7.13	5.55
Fe_2O_3	3.00	4.39	5.46	3.46	4.00	6.32	1.97
MnO	—	0.06	0.35	0.05	0.06	1.00	0.15
MgO	1.50	1.93	2.09	1.47	1.73	5.08	2.30
CaO	63.00	44.92	49.07	51.15	44.77	45.27	52.84
Na_2O	1.00	0.21	0.19	0.19	0.27	0.22	0.24
K_2O	1.00	0.65	0.57	0.60	1.29	0.40	0.90
P_2O_5	—	0.32	0.33	0.22	0.29	0.32	0.08
SO_3	2.00	1.74	2.16	3.62	2.21	1.35	2.47
Lol	0.50	11.91	11.41	10.30	13.74	8.49	12.05
Total	98.00	99.57	99.62	98.85	98.82	99.75	99.20
$SiO_2 + Al_2O_3 + CaO$	89.00	77.79	76.57	78.46	74.74	76.06	78.66
CaO/SiO_2	3.15	1.86	2.35	2.46	2.03	1.91	2.61
Total alkalinity ($Na_2O + K_2O$)	2.00	0.86	0.76	0.79	1.56	0.62	1.14
CaO/Al_2O_3	10.5	5.12	7.45	7.87	5.66	6.35	9.52
Portlandite (Lin-counts)	—	3,200	3,200	4,000	3,000	2,300	3,300

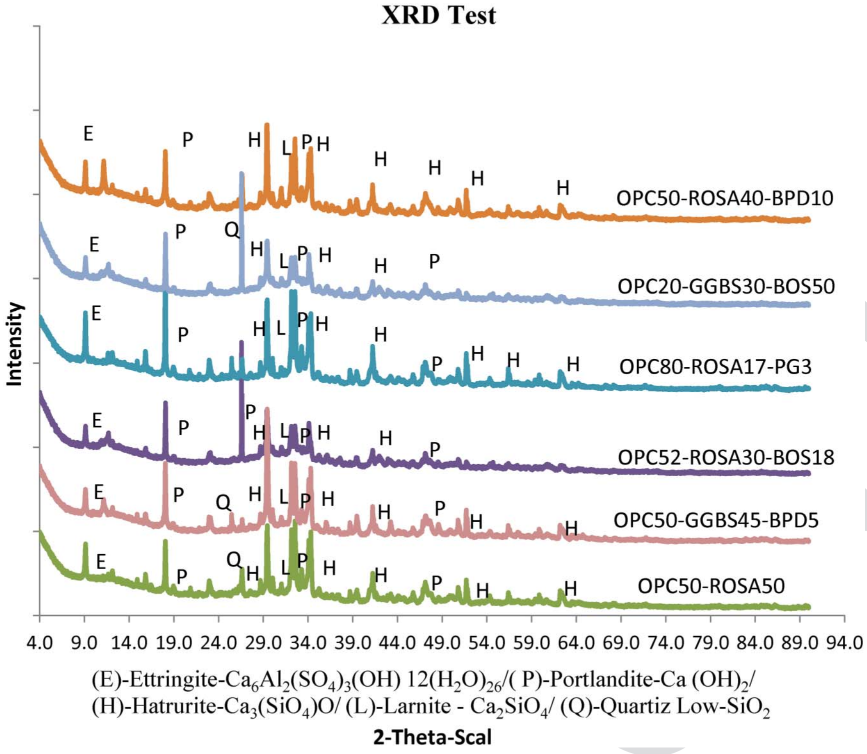

Fig. 16. The XRD test results of all mixes at 28 days

This suggests that more silica from slag dissolves in the pore solution to form more cementitious gel.

On the other hand, the total silica (SiO_2), aluminium oxide (Al_2O_3) and calcium oxide (CaO) content in the mix OPC50/GGBS45/BPD5 was 78.66%. In comparison to the other mixes tested, this mix had the highest percentage. This suggests that the combination of silica and calcium oxide contributed to the formation of CSH gel and increased the long-term split tensile strength of the paste specimen.

The C-S-H phase in cement paste is amorphous or semicrystalline calcium silicate hydrate and the hyphens denote that the gel does not necessarily consist of 1:1 molar CaO:SiO_2. The C-S-H of cement pastes gives powder patterns very similar to that of C3S pastes. The composition of C-S-H (in terms of C/S ratio) is variable depending on the time of hydration. At day one, the C/S ratio is about 2.0 and becomes 1.4–1.6 after several years (Ramachandran and Beaudoin 2001); furthermore, when the aqueous solution has a high silica concentration but low calcium, the C-S-H formed in the solution is expected to have a low C/S ratio (Gartner and Jennings 1987).

Moreover, the nanostructure of C–S–H is defined by its variations, and a comprehensive understanding requires an explanation of how variations of the Ca/Si ratio, the silicate structure, and the contents of Si–OH and Ca–OH are correlated (Jeffrey et al. 2004). According to studies by Puertas et al. (2004), microstructural analysis confirmed that aluminium is incorporated into the silicate chains of C–S–H formed and its Ca/Si ratio appears to be limited to about 1.1, which is low compared to that of Portland cement C–S–H.

Alternatively, the content of sulphate in mix OPC50/GGBS45/BPD5 calculated as SO_3 was 2.47%, suggesting that the improved strength may be as a result of activation of GGBS by sulfates. In addition, the ratio of CaO to Al_2O_3 in the same mix was 9.52, the highest in comparison with the other mixes tested and close to the same ratio of Portland cement, as shown in Table 4. Although the amount of portlandite in mix OPC50/GGBS45/BPD5 is the highest compared to the other mixes containing 50% OPC, it can postulated that part of all the portlandite from BPD reacted with GGBS to from CSH. This may be a reason for higher strength of this mix.

Fig. 15 below shows the comparative CaO-Al_2O_3-SiO_2 content of conventional with the waste materials used and all mixes in this research and commonly used cementitious materials (OPC, GGBS, and PFA).

The results of the XRD test showed that the presence of minerals affected the split tensile strength. The XRD diffractograms of the powder of paste samples are presented in Fig. 16. XRD analysis was carried out on samples at 28 days. The cementitious gel contributing to strength was not in a crystalline form and could not be detected by XRD. Obviously, it can be seen for all mixes that there were relatively large intensity peaks for portlandite, and in mixes with replacement 50% OPC the portlandite was high, while the mix with 80% OPC replacement had a reduction in portlandite, as shown in Fig. 16. Furthermore, the mix with 80% OPC had the highest portlandite content in comparison to the other mixes.

Density Results

The average measured densities of paving blocks were between 1,700 and 2,200 kg/m^3, as expected.

Split Tensile Strength of Selected Mixes with Aggregate

In the second phase of the study, the four highest strength mixes from the six paste groups were selected and aggregates were added to these groups having the same mix design as the factory, as shown in Table 3. Factory control mixes I and II are actual factory mix designs (with a constant cementitious to stone ratio of 1:16.1) used in production of concrete paving blocks in the laboratory. Control

Table 5. Test Results of Concrete Paving Blocks

	Split tensile strength (MPa)				Weathering resistance	
Mix	14 (days)	28 (days)	Slip/skid resistance (BPN)	Density $(\mathrm{kg/m^3})$	Water absorption (%)	Freeze/thaw resistance $(\mathrm{kg/m^3})$
OPC10/GGBS4 (Factory control mix I)	2.0	3.2	100	2,383	5.4	Allblocks < 1.0
OPC10/PFA4 (Factory control mix II)	2.0	2.6	92	2,396	5.8	
OPC7.3/ROSA4.2/BOS2.5	1.5	2.2	103	2,381	5.9	
OPC7.0/ROSA7.0	1.0	2.0	102	2,449	6.2	
OPC2.8/GGBS4.2/BOS7.0	1.5	1.9	102	2,395	4.7	
OPC7.0/GGBS6.3/BPD0.7	2.7	3.6	94	2,405	5.6	

Mix I is GGBS and OPC mix, and control Mix II is PFA and OPC (see Table 3).

Table 5 shows the results of tests that were carried out to determine the split tensile strength, slip/skid resistance, weathering resistance (water absorption and freeze/thaw) and density. From the results of split tensile strength presented in Table 5, it can be seen that only OPC/GGBS/BPD group achieved split tensile strength higher than 3.6 MPa, which is the limit of the British standard of BS EN1338 (BSI 2003). On the other hand, the factory control mixes and all other laboratory mixes containing OPC/ROSA/BOS, OPC/ROSA, and OPC/GGBS/BOS did not satisfy the minimum requirements of BS EN1338 (BSI 2003).

Durability Tests

The results of slip/skid resistance show that all paving block mixes made in the laboratory have excellent skid resistant surface and the potential for slip is extremely low according to the BS EN13383 (BSI 2003) definition, as results are above 75 BPN.

Table 5 shows the results of slip/skid resistance, weathering resistance (water absorption and freeze/thaw) and density. The result of freeze/thaw resistance shows that all mixes meet the British standard of BS EN1338 (BSI 2003). On the other hand, the water absorption test should show a result of less than 6% according to the BS EN1338 standard (BSI 2003). Therefore, the results in Table 5 show that only a mixture of OPC/ROSA did not satisfy the minimum requirements for the water absorption, and the result was 6.2% which is higher than the 6.0% limit set. However, the other mixtures met the minimum requirements and gave satisfactory results that varied from 4.7% and 5.8%.

Conclusions

The following conclusions can be drawn from the study:

1. Ternary materials such as run-off-station ash (ROSA), basic oxygen slag (BOS), and ground granulated blast furnace slag (GGBS) were more effective in reducing cement content than PG and BPD.
2. Concrete paving blocks prepared with OPC 50/GGBS 45/BPD 05 met the minimum requirements of 3.6 MPa and can be used to reduce cement content by up to 30% in comparison to the percentage of cement used in factories. This mixture showed good results in the slip/skid resistance test, freeze/thaw test, and water absorption test.
3. Concrete paving blocks prepared with OPC/ROSA, OPC/ROSA/BOS, and OPC/GGBS/BOS did not meet the minimum requirement of 3.6 MPa, but they did perform well in durability tests. However, these mixes would not be appropriate to be used on site as both physical/mechanical strength and weathering durability criteria should be met.
4. Results of the XRD test showed that the presence of minerals affected the split tensile strength. There were relatively large intensity peaks for portlandite, and in mixes with replacement 50% OPC the portlandite was high, while the 80% OPC replacement mix had a reduction in portlandite. Furthermore, the mix with 80% OPC had the highest portlandite content in comparison to other mixes.

References

British Standard Institute (BSI). (2003). "Concrete paving blocks requirements and test methods." *BS EN 1338*, London.

British Standard Institute (BSI). (2006). "Ground granulated blast furnace slag for use in concrete, mortar and grout." *BS EN 15167-1-2*, London.

British Standard Institute (BSI). (2011). "Cement, part 1: Composition, specifications and conformity criteria for common cement." *BS EN 197-1*, London.

Caiju, S. (2004). "Steel slag: Its production, processing, characteristics and cementitious properties." *J. Mater. Civ. Eng.*, 230–236. [11]

Chan, D., and Poon, C. S. (2006). "Using recycled construction waste as aggregates for paving blocks." *Waste Resour. Manage.*, 159(2), 83–91. [12]

Chen, J. J., Thomas, J. J., Taylor, H. F. W., and Jennings, H. M. (2004). "Solubility and structure of calcium silicate hydrate." *Cem. Concr. Res.*, 34(9), 1499–1519. [13]

Dunster, A. M. (2008). "Recycled gypsum in concrete construction product applications." Waste and Resources Action Program (WRAP) BRE. [14]

Ganjian, E., and Sadeghi-Pouya, H. (2009). "Investigation on the use of industrial and construction-demolition wastes as cement replacement in concrete paving blocks." *Proc., 4th Int. Conf. on Construction Materials: Performance, Innovations and Structural Implications*, Nagoya, Japan, 295–300. [15]

Gartner, E. M., and Jennings, H. M. (1987). "Thermodynamics of calcium silicate hydrate and their solutions." *J. Am. Ceram. Soc.*, 70, 743–749. [16]

Ghataora, G. S., Rischard, J., Hewish, F., and James, J. (2004). *Summary project report on the utilization of recycled aggregates generated from highway arising and steel slag fines*, Univ. of Birmingham, Birmingham, U.K.

Menéndez, G., Bonavetti, V., and Irassar, E. F. (2002). "Strength development of ternary blended cement with limestone filler and blast-furnace slag." *Int. J. Cem. Compos. Lightweight Concr.* [18]

Montgomery, D. C. (2005). *Design and analysis of experiments*, 6th Ed., Wiley. [19]

Mortar Industry Association. (2008). "The use of ground granulated blastfurnace slag and fly ash in mortar." ⟨http://www.mortar.org.uk⟩. [20]

Naik, T. R. (2008). "Sustainability of concrete construction." *Pract. Period Struct. Des. Constr.*, 10.1061/(ASCE)1084-0680(2008)13:2(98), 98–103.

[21] Olivier, J., Janssens-Maenhout, G., and Peters, J. (2012). *Trends in global* CO_2 *emissions*, PBL Netherlands Environmental Assessment Agency.

Padmini, A. K., Ramamurthy, K., and Mathew, M. S. (2001). “Behaviour of concrete with low strength brick as light weight coarse aggregate.” *Mag. Concr. Res.*, 53(6), 367–375.

[22] Pincha, T., and Arnon, C. (2010). “Utilization of ceramic waste as fine aggregate within Portland cement and fly ash concretes.” *Cem. Concr. Compos.*, 32(6), 440–449.

Puertas, F., Fernández-Jiménez, A., and Blanco-Varela, M. T. (2004). “Pore solution in alkali activated slag cement pastes. Relation to the composition and structure of calcium silicate hydrate.” *Cem. Concr. Res.*, 34(1), 139–148.

Ramachandran, V. S., and Beaudoin, J. (2001). “Handbook of analytical techniques in concrete science and technology.” *Build. Mater. Ser.*, 41. [24]

Taylor, H. F. W. (1997). *Cement chemistry*, 2nd Ed., Reedwood Books, Trowbridge, U.K.

Wild, S., Kinuthia, J. M., Robinson, R. B., and Humphreys, I. (1996). “Effect of ground granulated blast furnace slag on the strength and swelling properties of lime-stabilized kaolinite in the presence of sulphates.” *Clay Miner.*, 31, 423–433. [26]

Queries

1. Please provide the ASCE Membership Grades for the authors who are members.

2. NEW! ASCE Open Access: Authors may choose to publish their papers through ASCE Open Access, making the paper freely available to all readers via the ASCE Library website. ASCE Open Access papers will be published under the Creative Commons-Attribution Only (CC-BY) License. The fee for this service is $1750, and must be paid prior to publication. If you indicate Yes, you will receive a follow-up message with payment instructions. If you indicate No, your paper will be published in the typical subscribed-access section of the Journal.

3. Please provide author titles (e.g., Professor, Director) for all author affiliations.

4. Please provide check and confirm the heading levels are ok in this article.

5. The citation (Torkittikul et al. 2010) mentioned in this sentence is not present in the References list. Please provide the full details for (Torkittikul et al. 2010), and we will insert it in the References list and link it to this citation.

6. The citation (Ganjian and Pouya 2008) mentioned in this sentence is not present in the References list. Please provide the full details for (Ganjian and Pouya 2008), and we will insert it in the References list and link it to this citation.

7. Please provide manufacturer's location.

8. Please check expansion of XRF to X-ray fluorescence.

9. Please provide a reference for software Minitab 16.

10. The citation (Jeffrey et al. 2004) mentioned in this sentence is not present in the References list. Please provide the full details for (Jeffrey et al. 2004), and we will insert it in the References list and link it to this citation.

11. This query was generated by an automatic reference checking system. This reference (Caiju 2004) could not be located in the databases used by the system. While the reference may be correct, we ask that you check it so we can provide as many links to the referenced articles as possible.

12. Please confirm an issue number for all journal references.

13. This reference Chen et al. (2004) is not mentioned anywhere in the text. ASCE style requires that entries in the References list must be cited at least once within the paper. Please indicate a place in the text, tables, or figures where we may insert a citation to Chen et al. (2004) or indicate if the entry should be deleted from the References list

14. Please provide complete information (publisher name and location) for reference Dunster (2008).

15. Please provide the publisher or sponsor name and location (not the conference location) for the reference Gaqnjian and Sadeghi-Pouya (2009).

16. Please provide issue number for reference Gartner and Jennings (1987).

17. This query was generated by an automatic reference checking system. This reference (Menendez et al. 2002) could not be located in the databases used by the system. While the reference may be correct, we ask that you check it so we can provide as many links to the referenced articles as possible.

18. Please provide full information (volume, issue, and page numbers) for reference Menendez et al. (2002).

19. Please provide location of publisher for reference Montgomery (2005).

20. Please provide location of publisher and access date for reference Mortar Industry Association (2008).

21. Please provide location of publisher for reference Olivier et al. (2012).

22. This reference (Pincha and Arnon 2010) is not mentioned anywhere in the text. ASCE style requires that entries in the References list must be cited at least once within the paper. Please indicate a place in the text, tables, or figures where we may insert a citation to Pincha and Arnon 2010 or indicate if the entry should be deleted from the References list.

23. This query was generated by an automatic reference checking system. This reference (Ramachandran and Beaudoin 2001) could not be located in the databases used by the system. While the reference may be correct, we ask that you check it so we can provide as many links to the referenced articles as possible.

24. Please provide issue and page range for reference Ramachandran and Beaudoin (2001).

25. A check of online databases revealed a possible error in this (Wild et al.) reference. The year has been changed from '1995' to '1996'. Please confirm this is correct.

26. Please provide issue numnber for reference Wild et al. (1995).