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Additives to increase the sustainability of concrete paving blocks

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By

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List of Publications

1. *Limbachiya, V* & Claisse, P., 2013; Ternary cement blends for concrete paving blocks. *Proceedings of International Conference and Symposium on Advances in Science and Technology of Concrete- India Chapter of American Concrete Institution*, Mumbai, India, 20-21 December 2013. pp 352-360.

2. *Limbachiya, V*, Claisse, P & Ganjian, E ; The impact of variation in chemical and physical properties of PFA and BPD semi dry cement paste on strength properties- *Construction and Building Materials, Volume 96, 15 October 2015, Pages 248-255*

3. *Limbachiya, V*, Ganjian, E & Claisse, P; Analysis of semi-dry ternary blends consisting of PFA, GGBS, MK, SF and BPD to reduce the cement content of concrete paving blocks-*Construction and building materials (In Print)*

4. *Limbachiya, V*, Claisse, P & Ganjian, E ; Strength, durability and leaching properties of concrete paving blocks incorporating GGBS and SF- *Construction and building materials (In Print)*

Abstract

The aim of this study was to break through current limits with cement substitutes in concrete paving block and introduce high levels of cementitious constituents. As well as meeting the current strength and durability requirements stated in BS EN 1338:2003 the study reported on the effect of materials variability and leaching properties.

The cementitous materials used to replace Portland cement (PC) were Pulverised Fuel Ash (PFA also known as Fly Ash), Ground Granulated Blast Furnace Slag (GGBS), Metakaolin (MK), Silica fume (SF), Glass Powder (GP), Basic Oxygen Slag (BOS) and By Pass Dust (BPD). The first phase of the study analysed 11 groups of ternary cement paste blends using Minitab, a statistical programme to help determine mix designs and optimised mix.

Analysis of ternary cement pastes in the first phase concluded that mixes containing GGBS over PFA produced greater strengths at early ages. Mixes confirmed that PC-GGBS-GP provided good strengths due to the SiO_2 content within GP providing secondary CSH gel. PC-GGBS-BPD provided good strengths due to SO_3 within BPD activating the GGBS through sulphates. The best results in forms of strength were found in PC-GGBS-SF and PC-GGBS-BOS ternary pastes. The fine particles along with the high SiO_2 content of SF provided greater pozzolanic reactivity and a greater matrix densification.

Fourteen of the best mixes were then taken into the second phase. This is when concrete paving blocks were made from these mixes with the method that was developed at Coventry University. The two mixes with the greatest splitting tensile strength consisted of varying levels of PC-GGBS-SF and were known as the candidate mixes. The durability criteria set out in BS EN 1338:2003 was met, however the minimum strength requirement was not. The candidate mixes were still chosen to be produced in the factory as the manufacturing and curing procedure in the factory was more effective and efficient in comparison to the laboratory procedure. The site trial successfully achieved the minimum requirements for the

mechanical properties and durability performance stated in BS EN 1338:2003 and reduced the cement content of concrete paving blocks by 40% wt of PC, with a ternary blend consisting of 60% PC, 25% GGBS and 15%SF.

Analysis of material variability was conducted on PFA (regulated commercially available replacement) and BPD (replacement waste material). Results showed that when using regulated commercially available cementitious constituents the chemical composition of the material should be within a given range (For replacement by weight of 10%, 20%, 30%, difference in main oxide should be no greater than 1%, 2.5% and 3.5% respectively) and for the waste material the chemical composition (Limits as stated for regulated commercially available material) as well as fineness (Replacement by weight of 5% and 10% should not have a variability in average particle size of more than 15μm) should be within a range.

The two candidate mixes were finally tested for their leaching properties against a leachate that was derived from used oil concentrations. The increase in permeability with the use of GGBS and SF lead to the block absorbing less of the leachate in comparison to the control mix.

The study set out to introduce high levels of cementitious constituents in concrete paving blocks. Although it is known that high levels of replacement would cause deterioration, this was done in order for the study to create a database in which the company could refer to and determine which constituents performed well and what the maximum level of replacement could be. The study successfully replaced PC by 40% with 25% GGBS and 15% SF. With blocks actually producing greater strengths than the control mix (100% PC) at 28 days and meeting all the minimum requirements that were set out in BS EN 1338:2003.

Acknowledgements

List of acronyms

The following acronyms are used in the thesis

Supplementary Cementitious Materials	SCM
Portland cement	PC
Ground granulated blast furnace slag	GGBS
Pulverised Fuel Ash	PFA
Silica Fume	SF
Metakaolin	MK
By-Pass Dust	BPD
Basic Oxygen Slag	BOS
Glass Powdetr	GP
Calcium Hydroxide	CH
Water Cement or Cementitious ratio	w/c
Water Binder or Cementitious ratio	w/b
Sustainable Urban Drainage Sutems	SUDs
Scanning Electron Microscopy	SEM
Thermal Gravimetry	TG
Differential Scanning Calorimeter	DSC
X-ray Fluorescence	XRF
X-ray Diffraction	XRD
Particle size analysis	PSA
Particle size distribution	PSD

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Chapter 1

INTRODUCTION

1.1 Background

The UK government has set out plans to reduce CO_2 emissions from 1990-2050 by 80% (Climate Change Act 2008). In order to achieve the target, the construction industry which accounts for 47% (Department for Business, Innovation and Skills (2010)) of the total CO_2 emissions has a crucial role to play by leading the way with new and innovative designs and ideas. Within the construction industry one of the prime contributors to CO_2 emissions is cement, which is stated to account for up to 5% of all man-made carbon dioxide emissions (Huntzinger and Eatmon (2009)). In the construction industry there are many applications for concrete, one of these applications, which is the main focus of this study is in concrete paving blocks.

This research project was designed and carried out in partnership with Hanson Formpave UK who are leading innovators in permeable paving (Formpave). In 2013, Formpave stated that 85,980 tonnes of raw materials were used in their paving block factory based in Coleford, UK. Based on Figures reported by the Mineral Product Association (2009) this factory alone attributed to nearly 10,000 tonnes of CO_2 being emitted from solely the use of cement.

In recent years more attention has been paid to the production and application of concrete paving blocks with the introduction of Sustainable Urban Drainage Systems

(SUDS). SUDS systems can be applied to both domestic and non-domestic properties. As stated in a study by Poleto and Tassi (2012) the main aims for SUDS are;

- Conservation of natural characteristics of bodies of water;

- Quantitative control of surface runoff;

- Improvement in the quality of water from surface runoff;

- Balance of hydrological variables in watersheds.

SUDS technology is applied to pavements through permeable paving; it allows rain water to run through the openings in the paving and into layers below where pollutants such as oil are trapped and degraded. Figure 1.1 displays a typical schematic of a permeable paving system (Scholz and Grabowiecki(2007)). The importance of this new technology means that when improving the sustainability of concrete paving blocks you cannot be simply satisfied when the mechanical and durability properties meet the corresponding British Standards. As well as meeting standards the leaching aspects of the blocks must also be taken into consideration. This is in order to ensure that harmful metals from used oil does not pass through into the soils below with the use of these new materials.

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Figure 1.1 SUDS Schematic (Scholz and Grabowiecki ((2007))

Based on these facts and Figures, the motive of this research is to reduce the cement content to further increase the sustainability of concrete paving blocks. The justification is a need to better understand the effect of cementitious constituents at varying levels on the mechanical and durability properties of concrete paving blocks. These understandings allow the study to produce a mix design which can meet all the requirements set by British Standards as well as reduce the total CO_2 emissions of the concrete paving blocks.

The benefits, is that the study will review and determine the maximum quantity of cement that can be replaced in order to obtain concrete blocks that meet the minimum strength properties and durability performance stated by BS EN 1338:2003. As well as meeting standards it was important to report on the sustainability of the blocks produced in factory settings, this mean that as well as the environmental impacts it was important to consider the economic as well as social impacts.

1.2 Aim and Objectives

The prime aim of this research project was to increase the sustainability of concrete paving blocks by reducing the cement content.

Specific objectives were to;

1. Carry out a review of published literature to understand current practices in cementitious constituents, with respect to paving block production

2. Design mixes using several cementitous by-products and waste materials to reduce cement content in concrete paving blocks.

3. Conduct an extensive laboratory programme to examine the four key inter-related areas for concrete paving blocks; these are strength properties, durability performance, control of material variability and leaching properties of the block.

4. Carry out factory and site trials with constructed paved areas using actual factory made paving blocks and evaluate their performance.

1.3 Methodology used in this research

A systematic methodology (Figure 1.2) was adopted to examine the four key inter-related areas;

- Strength properties– Broken down into two phases. The first phase looked at different cement paste blends, which were designed and analysed with the use of statistical programme (Minitab 16.2.2). The second phase looked at the fourteen best mixes, produced concrete paving blocks and determined the splitting tensile strength.

- Durability performance-The two concrete paving block mixes with the greatest strength were the candidate mixes and these were tested for the durability performance stated in BS EN 1338:2003.

- Material variability – Pulverised fuel ash (PFA) and By-pass dust (BPD) were obtained from E.ON and Cemex respectively on a monthly basis over a 6 month period. The chemical and physical properties for the samples were obtained. The compressive strength of PFA (10%, 20% and 30% by weight replacement of PC) and BPD (5% and 10% by weight replacement of PC)

binary mixes were obtained at 14 and 28 days. The strengths were then analysed in accordance to the physical and chemical properties determined.

- Leaching - Concrete paving blocks are laid and placed where contaminants (used engine oil) can be spilled. The two candidate mixes were exposed to a leachate through the use of a high pressure flow test and then compared to the control mix (100% PC mix).

For the site trial the two candidate mixes were produced in the Hanson Formpave factory. The difference between laboratory and factory production was determined and the blocks were laid and observed over a period of 5 months during winter.

Additives to increase the sustainability of concrete paving blocks

Strength properties and durability performance

- 1st Phase
  - Design and analysis of cement paste blends with the use of Minitab
  - 11 ternary blends (131 mixes) tested for compressive and splitting tensile strength at 14 days
  - Contour plots produced and accuracy determined in order to find optimised mix.
  - 14 best mixes chosen and reviewed using XRF and XRD
- 2nd Phase
  - 14 best mixes from paste analysis used to produce concrete paving blocks
  - 14 and 28 day splitting tensile strength determined
  - 2 mix's with the greatest strength known as candidate mixes
  - Durability performance of 2 mixes determined in accordance with BS 1338:2003

Site trial

- Candidate mixes produced in factory conditions
- Tested in accordance with BS EN 1338:2003
- Laid over winter period to observe deterioration
- Blocks tested for leaching properties

Material Variability

- Commercially regulated source (PFA) and 'waste' material (BPD) chosen for analysis
- Variability in physical and chemical property of a monthly source determined over a period of 6 months
- Binary mixes produced with varying levels of replacement
- Determine 14 and 28 day paste strength and plot against physical and chemical variability
- Determine maximum variability that would be allowed for materials in the candidate mixes and ensure this is achieved

Figure 1.2 Flow diagram of systematic method

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1.4 Thesis Layout

Chapter 1-Breifly provides research background, principle aims and objectives of the work.

Chapter 2-Reviews the literature with regards to the practice of cement and cementitious constituents. Studies on the use of cementitious constituents in the application of paving blocks is limited, therefore studies analysing the effect of cementitious constituents in mortars, pastes and different purpose concretes were reviewed.

Chapter 3 -Details the methodologies that were used to analyse strength properties, durability performance, material variability and leaching.

Chapter 4 -Describes the materials that were used in this research and the effect of material variability.

Chapter 5 –Summarizes and presents the results that have been obtained for the paste mixes produced in the first phase.

Chapter 6 -Provides all the results that have been obtained for the concrete mixes produced in the second phase

Chapter7 –Describes and reviews the factory and site trials

Chapter 8 -Looks at possible leaching problems that could arise in the candidate mixes

Chapter 9 -Outlines the conclusion of the study and explains the practical implications of the main findings.

Chapter 10 Outlines the recommendations for the future work in this area and the contribution to knowledge.

Chapter 2

Literature Review

This chapter reviews published literature with regards to the practice of cement and cementitious constituents. Studies on the use of cementitious constituents in the application of paving blocks is limited, therefore studies analysing the effect of cementitious constituents in mortars, pastes and different purpose concretes were reviewed.

2.1 Concrete

Concrete is second to water as the most consumed material in the world. The advantages in terms of shape design, flexibility, strength and durability allow concrete to have a wide application in the construction industry.

2.1.1 Materials

Concrete consists of 4 main materials. These are Portland Cement (PC), aggregates (fine (Sand) and coarse (Crushed/uncrushed rock), water and admixtures.

2.1.1.1 Cement

The role of PC is crucial to understand in this study, as the main aim is to find a supplementary replacement for this material. CEM I Portland Cement produces strength primarily through the hydration of Di- and Tri-calcium silicates. The other

cements covered by BS EN 197-1 are CEM II- Portland-composite cement, CEM III-Blast furnace cement and CEM IV- Pozzolanic cement. The materials and process used to produce PC are shown in Figure 2.1. Although there is CO_2 produced during the mining of the raw materials (Limestone and clay) the main production of CO_2 occurs during cement production when the blended raw materials, after crushing, grinding and blending is heated in a kiln. As this part of the process is unable to be altered to produce PC, there is no other alternative way to reduce CO_2 than to find an alternative material i.e. reduce amount used. The alternative material should bind materials in the same way as PC and be compatible with it in order to provide the same levels of predictability and efficiency.

Raw Materials Limstone and clay

Quarrying/Crushning process

Crushed limestone+clay/shale are mixed and ground together

Mixture is heated in a kiln to temperatures of above 1000°C

Clinker

Gypsum is added and the mixture is ground to a powder resulting in OPC
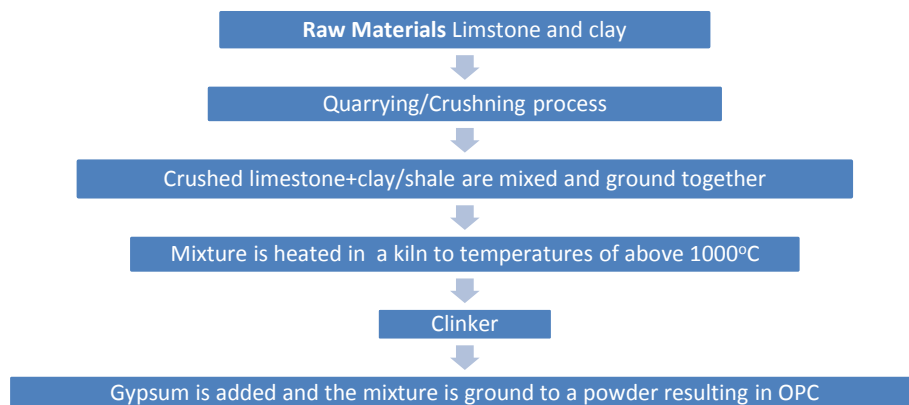
Figure 2.1 Material flow diagrams for the production of PC

2.1.1.2 Aggregates

Around 70% to 80% of the density of concrete consists of aggregates. As stated by Alexander and Mindess (2005) aggregates are defined, as mineral constitutes of concrete in granular or particulate form, usually comprising of coarse and fine fractions. Aggregate have two roles to play in concrete, the main role is to act as an inert filler which will give the performance and strength that is required. Secondly it is

to provide greater durability to the concrete by reducing factors such as shrinkage, alkali silica reaction (ASR) through the use of lesser reactive aggregates.

2.1.1.3 Water

Water binds PC and aggregates through hydration to produce the hardened material. The strength of concrete is attributed to the two calcium silicates of PC that are shown in Table 2.1 along with their abbreviations and properties. The reactions of hydration Equations for C_2S and C_3S along with the corresponding masses are shown in Equation 2.1 and 2.2 respectively. The two products produced from the reaction are Calcium Hydroxide ($Ca(OH)_2$) and Calcium Silicate Hydrate ($C_3S_2H_3$). When analysing the corresponding masses it is stated by Neville (1995-A) that both silicates require approximately the same amount of water for their hydration, but C_3S produces more than twice as much $Ca(OH)_2$ in comparison to C_2S.

Table 2.1 Compounds, compositions, abbreviations and properties of PC

Compound	Oxide Composition	Abbreviation	Property
Tricalcium silicate	3C.S	C_3S	Responsible for initial and early stage strength development Hydrates and hardens rapidly
Dicalcium silicate	2C.S	C_2S	Responsible for later stage strength development Hydrates and hardens over time

*C= CaO Calcium oxide S=SiO_2 Silicon Dioxide

$2\ C_3S + 6H^* \rightarrow C_3S_2H_3 + 3\ Ca(OH)_2$ Equation 2.1(Neville (1995-A))

Corresponding mass $100+24 \rightarrow 75 + 49$

*H= H_2O Water

$2\ C_2S + 4H \rightarrow C_3S_2H_3 + 3\ Ca(OH)_2$ Equation 2.2(Neville (1995-A))

Corresponding mass $100+21 \rightarrow 99 + 22$

The process of hydration converts calcium silicate to a Calcium Silicate Hydrate (CSH) gel which forms over time and fills up voids creating a hardened cement paste (Jennings (2000)). An important factor when reviewing water use in concrete is the water/ cement ratio. Excess water will make the concrete unworkable and weak while too little water will leave a greater quantity of un-hydrated cement resulting in reduced strength.

2.2 Physical and Chemical Properties

The physical and chemical characteristics of a material will determine its ability to be used as a cementitious constituent.

2.2.1 Physical property

Conventional   Optimum packing
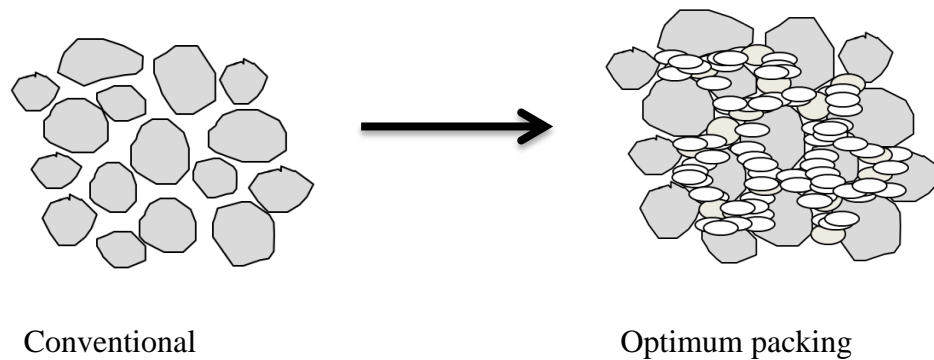
Figure 2.2 Result of optimum packing

Studies by Li and Wu (2005) and Binici et al (2007) stated that when using the same cementitious constituent, as particle fineness reduced the results reported a greater 'filler effect' resulting in increased strength. The finer particles also provide a higher specific surface area, which provides greater reactivity during the hydration process, resulting in increased strength. Figure 2.2 illustrates the conventional mix which contains solely PC and the optimum packing mix which may consist of a combination of PC, PFA and SF.

2.2.2 Chemical property

The chemical composition of a material provides the ability for it to be used as a supplementary material for cement. Materials that are able to be used as cementitious constituents are known as pozzolans. Varghese (2005) states that these are materials containing reactive silica (in amorphous form) which in themselves possess little or no cementitious value but which in combination with lime or other alkalis, in the presence of water produce cementing compounds.

Table 2.2 Chemical composition of PC from 3 different studies (Garcia-Lodeiro et al (2013), Cruz et al (2013), Kumar et al (2012))

	1	2	3
CaO (%)	62.79	62.87	62.66
SiO_2 (%)	20.26	20.21	19.50
Al_2O_3(%)	6.33	4.94	4.84
Fe_2O_3(%)	2.30	2.85	3.26
MgO(%)	0.18	1.05	4.19
SO_3(%)	2.82	3.54	1.80
K_2O(%)		0.92	0.54
Na_2O(%)	0.75	0.10	0.06

Table 2.2 shows the chemical composition of PC from 3 different studies. The chemical composition consisting largely of CaO , SiO_2, Al_2O_3, Fe_2O_3, and SO_3 with minor quantities of MgO, TiO_2, K_2O and Na_2O. Out of the minor compounds mentioned, the two that are of most interest are Na_2O and K_2O which are the alkalis and in combination with certain aggregates they are known to cause alkali silica reaction which deteriorates the concrete through expansion. Neville (1995-B) stated that it should be pointed out that even though they are referred to as minor compounds it does not necessarily refer to its importance.

The main oxides (SiO_2, CaO, Al_2O_3, Fe_2O_3 and SO_3) produce four main compounds which are shown in Table 2.3 for the 3 PC samples shown in Table 2.2, they are worked out using Bogue's equation (Neville (1995-A)) which are as follow:

- **Tricalcium silicate (C_3S)**

$$4.07(CaO) - 7.60(SiO_2) - 6.72(Al_2O_3) - 1.43(Fe_2O_3) - 2.85(SO_3) \quad \text{(Equation 2.3)}$$

- **Dicalcium silicate (C_2S)**

  $$8.60(SiO_2) - 0.75(CaO. SiO_2) \qquad \text{(Equation 2.4)}$$

- **Tricalcium aluminate (C_3A)**

  $$2.65(Al_2O_3) - 1.69(Fe_2O_3) \qquad \text{(Equation 2.5)}$$

- **Tetracalcium aluminoferrite (C_4AF)**

  $$3.04(Fe_2O_3) \qquad \text{(Equation 2.6)}$$

Table 2.3 Compounds based on the chemical composition

Compound	*Garcia-Lodeiro et al (2013)*	*Cruz et al (2013)*	*Kumar et al (2012)*
C_3S (%wt)	48	55	65
C_2S(%wt)	22	17	8
C_3A(%wt)	13	8	7
C_4AF(%wt)	7	9	10

The two major compounds (C_3S and C_2S) that make over 70% of the compounds have been discussed. Tricalcium aluminate and Tetracalcium aluminoferrite react with water and gypsum within the cement to produce calcium aluminates and calcium sulfoaluminates which as stated by Kurtis (2013):

- Includes ettringite, monosulfate hydration, calcium aluminate hydrates and ferric-aluminum hydroxide gels

- Comprises of 15-20% of solid volume of hydrated cement paste.

- Do not contribute much to strength

- In particular the formation of ettringite influences the setting time

- High heat of hydration for C_3A can be favourable or unfavourable depending upon application.

2.3 Paving Blocks

2.3.1 Production

Concrete paving block production differs from normal concrete products. The main difference with concrete paving blocks is the cement/aggregate ratio. The high aggregate content in paving blocks provides a semi dry mix. Secondly they differ in the manufacturing process, with normal concrete products when the concrete is poured into its location it is simply vibrated in order to remove the voids. With paving blocks when the mix is produced it is then vibrated and powerfully compacted simultaneously.

One of the biggest selling points of concrete paving blocks is their colour; therefore pigments are added in to the mix. If paving blocks have a darker colour which does not allow the pigment to produce the light colour that is required then blocks can be produced with a facing layer. Figure 2.3 taken from Ling and Nor (2007) displays the two different types of blocks that can be produced. The standard block which is one consistent block is the most common, however as mentioned if the finish is not to the required standard then a facing layer can be added.

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Figure 2.3 Paving blocks produced with single and facing layer. (Ling and Nor (2007))

The factory trail was conducted at the Hanson Forpave factory in Coleford, UK. The production for the two candidate mixes replicated the exact procedure that is currently used in the factory, with the exemption of cementitious constituents added. No facing layer was used

2.3.2 New applications - Sustainable Urban Drainage Systems (SUDS)

The main aim of SUDS is to allow water to flow steadily through permeable paving blocks and to the next stage of SUDS management or the drainage system. The role of SUDS has grown in importance because as stated by Interpave (2013) with urbanization and the increase in hard landscaping (roads, parking areas, driveways etc.) there has been a dramatic reduction in natural sustainable drainage. In the towns and cities 95% of rainfall becomes surface water runoff, overburdening the drainage system which already has to content with the fact that since the 1960s there has been a 50% increase in the number of 3 consecutive day storm occurrences.

(a) Total Infiltration

(b)Partial Infiltration

(c) No Infiltration

Figure 2.4 (a)(b)(c) schematic of different SUDS systems (Interpave (2013))

The three different types of systems which provide total infiltration, partial infiltration and no infiltration are shown in Figures 2.6(a)(b)(c) respectively. As can be seen from all Figures all systems consist of paving blocks, laying course (on which the blocks are laid and traps large pieces of sediment), Upper Geotextile (which traps any sediment that has filtered through), Permeable sub-base (Which is dependent on depth available and application, removes pollutant such as oil by allowing it to degrade over time in the sub base) and either a permeable or impermeable lower membrane (which allows the water to drain off or keep water to above the subgrade in order for to flow through the drainage pipe). The differences in roles for each system are as follows

- **Total Infiltration –** Figure 2.6(a) shows the system which has total infiltration and is also known as 'Zero Discharge system'. The advantage with this system is that no drainage pipes are required to be connected to the drainage system as all water is drained through the subgrade. This also results in cost savings.

- **Partial Infiltration-** Figure 2.6(b) shows the system which has partial infiltration. This system is similar to that of total infiltration, however it is used in areas where there is likely to be overflows due to excess rain and the subgrade is unable to absorb all the water. Therefore a drainage pipe in installed to allow the excess water to flow into sewers, watercourse etc.

- **No Infiltration-** Figure 2.6(c) shows the system which has no infiltration. This system has an impermeable lower membrane and can be used in two different scenarios. The first of these is when the subgrade maybe weakened by the addition of more water therefore it is drained of into sewers, watercourse etc. The second of these scenarios is where all the water is collected in an external storage tank and due to the filtration process through

the different layers the water can be used for day to day activities such as washing the car, external features etc.

2.3.3 BS EN 1338:2003

BS EN 1338:2003 is the British standard that specifies requirements and test methods required for concrete paving blocks. The scope as stated by BS EN 1338:2003 is "This European Standard specifies materials, properties, requirements and test methods for unreinforced cement bound concrete paving blocks and complementary fittings". It is applicable to precast concrete paving blocks and complementary fittings for pedestrian use, vehicular use and roof coverings, e.g. footpaths, precincts, cycle tracks, car parks, roads, highways, industrial areas (including docks and harbours), aircraft pavements, bus stations and petrol filling stations. One important note also stated is that this standard does not deal with permeable blocks; therefore the factors that affect permeable pavements have to be analysed. The properties and conformity criteria that are required by BS EN 1338:2003 are stated in Table 2.4. Greater detail into testing techniques and minimum requirements are given in sections 3.3.7-3.3.11.

Table 2.4 Conformity criteria for different aspects of concrete paving blocks (BS EN 1338:2003)

2.4 Properties of Cementitious Constituents

2.4.1 Pulverized Fuel Ash (PFA)

As stated by Joshi and Lohtia (1997), PFA is made up of very fine; predominantly spherical glassy particles collected in the dust collection systems from the exhaust gases of fossil fuel power plants. During the burning of coal for power stations there are two types of ashes produced, PFA is a finer particle that rises up with the flue gases and bottom ash are the heavier particles which do not rise. Out of the two ashes, PFA provides better suitability for cement replacement due to its finer particles and greater pozzolanic reactivity. When it comes to using PFA in construction, whether it is as a substitute for aggregate or cement, the UK has had standards from as far back as 1965 (McCarthy and Dhir (1999)).

Advantages of PFA as stated by Atici and Ensoy (2007) and McCarthy and Dhir (1999) are;

- Its production means that it improves the economic, environmental and social parameters of concrete

- The PFA consists of finer particles than PC therefore it can fill out voids increasing the durability of concrete

- Can be used with the addition of other additives to further increase the sustainability of concrete

Some of the disadvantages to fly ash are;

- The availability of a constant source

- For concrete paving blocks PFA tends to darken the colour of the blocks reducing its aesthetical appeal

- Develops strength over a longer period when compared to PC

It is important to note that within the American standards PFA broken up into two classes, Class C and Class F (ASTM C618). It is divided up by its chemical composition. If the combination of silicon dioxide, aluminum oxide and ferric oxide (Pozzolanic compounds) is greater than 70% of the chemical composition then it is Class F and if between than 50% and 70% is Class C. Both classes also vary by the quantity of lime (CaO), with Class F containing less than and Class C containing greater than 20%. This means that Class C is less likely to require an activator, although Class F PFA reacts with the excess lime after the hydration of cement. The British Standards states that PFA used in construction can only be Class F, therefore only Class F PFA will be used in this study. Table 2.5 shows the chemical and physical properties of PFA from different studies.

Table 2.5 Chemical composition of PFA from different studies (Papadakis (1999),Naik et al (2003),Uygunoğlu et al (2012),Atici and Ensoy (2007),Siddique (2004),Sabet et al (2013))

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2.4.1.1 Compressive strength

Papadakis (1999) conducted a study in which low calcium PFA was used to replace cement by 0%, 10%, 20% and 30% by weight of cement. To gain higher strength than that of the control mix (100%PC) it took 10% and 20% replacement around 6 months and 30 % replacement around 1 year. This improvement as stated in the study was down to the higher active silica content (40%) of calcium PFA in comparison with the cement (20%).

Naik et al (2003a) reviewed the performance characteristics of concrete paving blocks containing Class C and Class F PFA. Two blocks with Class C PFA were produced containing up to 70% replacement, 3 blocks with Class F PFA were produced with up to 67% replacement and a control mix that was specified by the State of Wisconsin Department of Transport containing 19% replacement Class C PFA was produced. The results showed that for early age strength the lower level replacement of Class C

PFA and the highest replacement Class F PFA would be preferred. For long term strength Class F PFA tended to gain greater strength. It was reported that this was due to Class F PFA making a greater contribution in pozzolanic C-S-H compared to Class C PFA, which resulted in a greater microstructure leading to more desirable long term perspective of using Class F PFA.

Atici and Ensoy (2007) reported the effect of PFA, GGBS and the combination of the two as cementitious constituents in concrete interlocking paving blocks. PFA was used to replace cement by up to 60% in increments of 10% and the blocks were tested on 3, 7, 28, 90 and 180 days. The early age compressive strength was lower than the control mix but as curing period increased there was a greater development in strength. The compressive strength achieved by the control mix at 28 days was 36.4 MPa. In comparison to the mixes containing PFA, no mix achieved a greater strength then the control mix and the greatest strength was achieved with 10% replacement (34.9MPa). The trend noted with PFA was that as the quantity of PFA increased the compressive strength decreased, the same trend was noticed when it came to the splitting tensile strength with replacements of up 30% being adequate.

2.4.1.2 Splitting tensile strength

Siddique (2004) studied the effect of high volume Class F PFA replacement in concrete. At 28 days as stated, splitting tensile strength of control mixture M-1 (0% PFA) was 4.1 MPa, whereas mixtures M-2 (40% PFA), M-3 (45% PFA), and M-4 (50% PFA) achieved splitting tensile strength of 3.0, 2.6, and 2.2 MPa respectively. This showed a reduction of 27%, 37%, and 46% respectively, in comparison with to

the control mixture. However, splitting tensile strength was found to increase with age. Mixtures M-1 (0% PFA), M-2 (40% PFA), M-3 (45% PFA), and M-4 (50% PFA) at 91 days, achieved splitting tensile strength of 4.2, 3.8, 3.3, and 2.6 MPa, respectively; an increase of 2%, 26%, 27%, and 18%, respectively. The results showed that after 28 days the control mix had little increase in strength and the mixes containing PFA continued to rise up to 365 days, with 40% replacement actually achieving the same splitting tensile strength at this stage, leading to the conclusion that over the long period 40% PFA replacement is sustainable.

2.4.1.3 Freeze thaw resistance

Uygunoğlu et al (2012) examined the effect of freeze thaw cycles on the splitting tensile strength of concrete paving blocks incorporating PFA. As stated the specimens were kept in a fully saturated condition with temperature cycling between −17°C and +20°C, each cycle took 6 h. Blocks were tested after 60 cycles. Figure 2.5 shows the splitting tensile strength of the blocks before and after the freeze thaw cycles. The results showed minimal impact after the freeze thaw cycles. It is assumed that this is due to the manufacturing process of paving blocks. Simultaneous compaction and vibration leads to a decrease in voids, therefore allowing less space for water to creep in to cause expansion. From these results it can be noted that after 60 freeze thaw cycles, up to 30% PFA replacement by weight of cement could still achieve the baseline standard for the splitting tensile strength (3.6Mpa) stated by BS EN 1338:2003.

Figure 2.5 Splitting tensile strength before and after freeze-thaw cycles. Uygunoğlu et al (2012)

2.4.1.4 Abrasion Resistance

Uygunoğlu et al (2012) also reported on the abrasion length (depth of damage) of the paving block as PFA ratio was increased. The control mix had a depth of 23mm and as the quantity of PFA replacement increased the abrasion length continued to increase. Abrasion results showed that PFA replacement had a negative effect. It was concluded in the study that the addition of recycled aggregates in combination with PFA replacement could increase the abrasion resistance through greater bonding of cement paste with the finer aggregates.

Figure 2.6 shows the abrasion resistance of concrete incorporating PFA at 28days (Siddique (2004)). The study reported that there was a key relationship between the compressive strength and abrasion resistance, this relation was that as compressive strength decreased the depth of wear increased. Figure 2.6 depicts that as PFA replacement increases the depth of wear increases. At no stage does any replacement level approach the values of the control mix and the reason for this was assumed to be due to the lower compressive strength. With early compressive strength known to be a

disadvantage of PFA, these results would be expected and as curing period increases (>28 days) the compressive strength is very similar to that of a control mix; therefore further work should be carried out on the long term abrasion resistance.

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Figure 2.6 Depth of wear versus abrasion time for HVFA concrete at 28 day (Siddique (2004))

2.4.1.5 Water Absorption

Sabet et al (2013) conducted a study to examine the effect of cement replacements on self-consolidating high strength concrete. PFA was used to replace cement by 10%wt and 20%wt. After 30 minutes water absorption rates were well below the good limits that are recommended by CEB-FIP (1989). The results showed that after 30 minutes 10% replacement had a lower absorption rate than 20% replacement as well as the control mix, however after 72 hours 20% replacement had a lower rate than 10% replacement and the control mix.

2.4.1.6 Summary of findings

- All studies noted that the early age compressive strength of concrete incorporating PFA would produce lower strengths than the control mix containing 100% PC. If

early age strength was to be taken into consideration then only 10%-20% would be the recommended, if the long term compressive strength of the concrete was to be considered than from the study conducted by Naik et al (2003a) up to 67% replacement has the potential to achieve good results.

- The outcome for splitting tensile strength is similar to that of the compressive strength, although during the early stages it can be seen that up to 30% replacement can meet requirements and at later stages this replacement has the possibility to increase up to 40%.

- The reason for the compressive and splitting tensile strength having this outcome is due to the finer particles providing greater reactivity at the early age and during the later stages the continuation of the pozzolanic reaction.

- PFA has the ability to be used as a high level replacement for cement; however it has positive effects on some factors and negative effect on others. During the analysis it is crucial to firstly make sure that the factors which result in a negative impact meet the standards and that the disadvantage of early age strength should be taken into consideration.

2.4.2 Ground Granulated Blast Furnace Slag (GGBS)

Siddique and Khan (2011) stated that GGBS is a by-product from blast furnaces used to produce iron. During the production of iron in a blast furnace one of the products produced is molten slag. This slag is cooled rapidly in order to prevent crystals forming, as if left to air cool then it would lose its cementitious properties, after drying and grinding the product produced is GGBS. Table 2.6 shows the chemical and physical properties of GGBS from different studies

Table 2.6 Chemical composition of GGBS from different studies (Hannesson et al (2012), Zhu et al (2012),Wainwright and Rey (2000),Atici and Ensoy (2007),Chidiac and Panesar (2008))

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Some of the advantages of GGBS as stated by Atici and Ersoy (2008) and Nazari and Riahi (2011) are:

- Greater compressive and flexible strengths

- Greater resistance to aggressive chemicals through lower permeability

- Lighter in colour

- Greater workability

- Develops durability

- Grinding process requires 75% less energy than that of PC

2.4.2.1 Compressive Strength

Hannesson et al (2012) conducted a study to see the effect on compressive strength as GGBS replaces cement in self-consolidating concrete. GGBS was obtained from two different sources and was used to replace cement by 100% in increments of 20%. The experiments showed that for both sources of GGBS, the early compressive strength

(14 days) at any replacement level was below that of the control mix. As curing time increased (28-168 days); replacement levels up to 60% were similar or greater to that of the control mix. The delay in strength as stated by Hannesson et al (2012) was down to the delay in C-S-H formation.

Zhu et al (2012) studied the effect of GGBS particle size on the compressive strength of concrete. 17 different mixtures were produced and the 3 different GGBS particle sizes were used (SA-particles between 200 and 300 meshes, SB- between 300 and 400 mesh and SC- smaller than 400mesh). The two trends reported were, that increases in slag decreases the strength and that decrease in particle size increases the strength. The results showed that 40% replacement with GGBS particle sizes falling within SC could achieve greater results than that of the control mix. The reason for this could be assumed to be due the particle distribution and compaction of the micro structure of hydration samples (Zhu et al (2012)). When it came to the combination of particle sizes, as the smaller particles became the majority the compressive strength increased and this assumed is due to greater reactivity with finer particles.

In a study conducted by Wainwright and Rey (2000) the compressive strength was calculated for GGBS from 4 different sources, replacing cement by 55% and 85% by weight, on 7,14 and 28 days. As reported by Atici and Ersoy (2008) the early strength of concrete containing GGBS was much lower than the control mix, although as time increases to 28 days the sample containing 55% was very similar to that of the control mix while 85% replacement was considerably lower. As stated by Wainwright and Rey (2000), the source of GGBS appeared to have little influence on the strength development with the possible exception of one source. Due to the similar GGBS

composition and fineness there was no obvious reason to why this could have occurred. This anomaly raises one of the issues of unpredictability with the use of any substitute material for PC.

2.4.2.2 Splitting Tensile Strength

Atici and Ersoy (2008) conducted a study to see the effects of GGBS on concrete interlocking paving blocks. GGBS was used to replace cement by up to 60% in increments of 10% by weight of cement. All mixes showed that as time increases the splitting tensile strength increases. The 28 day strength required to satisfy BS EN 1338:2003 and the best strengths are obtained for mixes containing between 20-60% GGBS replacement. However an anomaly was reported, as the strength was greater for replacements below and above 40% for which the reason is unknown. The study concluded that to achieve strengths greater than the control mix, 30% and 50% replacement would be required, although to achieve basic standards up to 60% replacement could be used.

Figure 2.7 reports the 28 day splitting tensile strength of concrete incorporating 0%, 20%, and 40% GGBS replacement by weight of cement, at different elevated temperatures. The heating and cooling regime of the blocks as stated by Siddique and Kaur (2012) was that they were cured in a tank for 28 days then taken out and air dried, the blocks were heated up in an electric oven to $100^{o}C$, $200^{o}C$ and $350^{o}C$ at a rate of $8^{o}C$/min. The temperatures were obtained for 1hr to achieve a thermally steady state and then allowed to cool naturally to air temperature. The results show that as GGBS levels are increased and the temperature is increased the strength decreases.

The study stated that the sensitivity of the splitting tensile strength to cracks on a micro or macro scale, which is increased by increasing temperature was the cause of decreased strength. When comparing the blocks without the elevated temperature to the study conducted by Atici and Ersoy (2008) the results obtained were the opposite. The assumption for this was due to the two different concrete products (High performance concrete and concrete interlocking paving blocks) being made. An important note to make from this is that not much has been done on concrete paving blocks and the effect of cementitious constituents. Therefore even though the mix might not work in certain applications of concrete every mix should be looked at in order to not only provide a mix that works but to also rule out the ones that will not work for the mix design required for paving blocks.

Figure 2.7 Splitting tensile strength of concrete containing GGBS at elevated temperatures.

Siddique and Kaur (2012)

2.4.2.3 Freeze thaw resistance

Table 2.7 reported in Chidiac and Panesar (2008) shows the cumulative weight loss of concrete after 50 freeze thaw cycles. Mixes contained up to 60% GGBS replacement by weight of cement with different w/cm ratios and tested at different curing ages.

When reviewing the long term freeze thaw resistance, the results show that there is not a clear pattern as the one reported at 28 days. However it can be assumed that 40%-50% replacement for long term resistance can still provide good freeze thaw resistance as these values are below the control mix. For long term resistance up to 60% replacement would not be recommended as this seems to cause deterioration which would reduce the long term life of the product (Chidiac and Panesar (2008)).

Table 2.7 Cumulative mass loss after freeze thaw cycles (Chidiac and Panesar (2008))

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2.4.2.4 Water absorption

El Nouhy (2013) investigated the effect and possibility of using Portland Slag cement in the production of paving blocks. The study analysed blocks that were produced with a facing layer. The types of cement used in this study were (1)CEM 1 52.5 N and Portland Slag cement (2)CEM11/A-S 32.5 N. Four mixes were produced which interchanged these cements in the facing and backing layer (Mix 1- Backing and facing layer (1), Mix 2- Facing layer (2) and Backing layer (1), Mix 3- Facing layer (1) and backing layer (2) and Mix 4- Facing and backing layer (2)). Figure 2.8 shows the blocks with highest water absorption rate at 28 days and 180 days. The results

show that at 28 days when incorporating GGBS only mix 2 can achieve the strength. When incorporating GGBS in the backing layer or both facing and backing layer the absorption rate is only achieved at 180 days.

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Figure 2.8 Water absorption percentages at 28 and 180 days (El Nouhy (2013))

Figure 2.9 reports results by Pavia and Condren (2008) on the water absorption rate at 28-day cycles over a period of 4 months as GGBS is used to replace PC by 30% and 50%wt. The results show that for all samples as time increases the water absorbed increases, however it can be seen that the increase in GGBS replacement reduces the water absorbed. It was stated in the study that this is possible because GGBS significantly decreases both the content and the size of Ca $(OH)_2$ crystals in the aggregate-paste interface, which makes the microstructure of the transition zone aggregate/binder dense and strong (Pavia and Condren (2008)).

Figure 2.9 Water absorption over a 4 month period containing GGBS (Pavia and Condren (2008).

2.4.2.5 Slip/Skid resistance

Slip/skid resistance is an important factor to consider with paving blocks as pedestrians are likely to walk across pavement, roads or driveways after/during times of rainfall. It is important to ensure that there is enough resistance on the surface of the block to prevent them falling. BS EN 1338:2003 states that any value from 40-74 and above 75 USRV (Unpolished slip resistance value) has a low and extremely low potential for slip respectively. Figure 2.10 taken from El Nouhy (2012) shows the slip/skid resistance at 28 and 180 days for mixes stated in 2.4.2.4. The results show that the best results were obtained by mix 4 which had Portland slag cement at both the facing and backing layer at 28 days. At 180 days it can be seen that the slip/skid resistance for all mixes decreased however the mixes containing Portland slag cement were still in the extremely low range while the solely PC mix fell into the low range.

Figure 2.10 Slip/Skid resistance at 28 and 180 days (El Nouhy (2012))

2.4.2.6 Summary of Findings

Studies have used GGBS to replace cement by up to 100% by weight (Hannesson et al (2012)) and the long term mechanical properties of an PC mix can be achieved with GGBS replacing PC by up to 60% by weight.

GGBS enhanced all durability properties (freeze thaw resistance, water absorption and slip/skid resistance).

GGBS provides good strength and durability properties because the pozzolanic properties use the $Ca(OH)_2$ after the cement hydration to produce C-S-H gel but due to the higher content of lime in GGBS it itself can be used in far higher replacement levels than other cementitious constituents.

2.4.3 Basic Oxygen Slag (BOS)

Steel is either produced in a basic oxygen furnace or an electric arc furnace. Figure 2.11 from Yildiirim and Prezzi (2011) displays these two processes and the waste materials which are produced. The two slags produced are electric arc furnace slag

(EAS) and basic oxygen furnace slag (BOS). Both have the chemical composition that allows it to be used as a substitute for cement. Chemical composition of EAS and BOS are shown in Table 2.8. Kourounis et al (2007) stated some of the reasons steel slag tends to be less popular is because of the high variability in the composition of the slag, the low content of reactive calcium silicate compounds and the high content of free calcium and magnesium oxides that may cause volume expansion problems.

Table 2.8 Chemical composition of EAS and BOS. Tossavainen et al(2007)

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One of the biggest advantages with re-using BOS and EAS is the prevention of material sent to landfill sites, which can also prevent further damage that is caused. The slag's contain harmful metals and toxic materials which can leak into the ground or surface water causing further harmful potential.

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Figure 2.11 Electric-arc and basic oxygen furnace steel process. (Yildiirim and Prezzi (2011))

As stated by Nemerow (2009), BOS is considered environmentally unfriendly when fresh because it gives of sulphur dioxide and in the presence of water, hydrogen sulphide and sulphuric acid are produced which are potentially very dangerous. As there are no current standards on the use of steel slag, Verhasselt and Choquet (1989) gave the following specifications if Belgian steel slags are to be used:

1. Steel slag should not have free lime (CaO) content of more than 45% at the time of production

2. Before use, the slag should be allowed to weather for one year.

3. Before use the volumetric stability should be checked by a volumetric swelling test.

This study obtained slag that was produced in a basic oxygen furnace and Table 2.9 shows the chemical and physical properties of BOS from different studies.

Table 2.9 Chemical composition of BOS from different studies (Altun and Yilmaz (2002),Wang et al (2012),Kourounis et al (2007),,Jallul (2014))

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2.4.3.1 Compressive strength

Altun and Yilmaz (2002) reported on BOS from two different sources (1 and 2 from Table 2.9), of which both had a high MgO content and replaced cement by 0%(C0), 15%(C1), 30%(C2) and 45%(C3). Table 2.10 shows the compressive strength that was achieved. The chemical composition showed encouraging signs as the blended mixes were very similar to that of PC; however as can be seen from the compressive strength this was not the case. Even though none of the mixes achieved greater results to that of the control mix, they did meet the minimum requirements set out by the Turkish standards (TS24). The cause of decreased strength was stated to be due to the impurities in the slag, the 2 and 7 day compressive strength decreases with the amount of Mn, but this decrease is lower in the 28 day compression strength. Similar results were found in a study done by Péra et al (1999) that concluded manganese has a negative effect on reactivity and strength of slag at the early stage, but it does not hinder long term activation.

Table 2.10 Compressive strength of BOS from two different sources Altun and Yilmaz (2002)
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Wang et al (2012) reported on the effect of BOS and GGBS as a substitute for PC. The study initially reviewed adding the materials individually and replacing by

22.5%, 45% and 60% by weight of cement. Figure 2.12 displays the compressive strength of these mixes. When compared to GGBS, BOS performs worse at all stage of curing and does not come close to the strength obtained by the control mix, while GGBS towards the later stages performs similar and greater than the control mix. Analysis of the pore size distributions by Wang et al (2012), showed that the proportions of pores of the hardening pastes smaller than 4.5nm of paste containing 22.5% GGBS, 45% GGBS, 22.5% BOS and 45% BOS was 14.8%, 55.3%, 10% and 9.8% respectively. This lead to the assumption that one of the factors for this, could be due to GGBS improving the pore structure at later stages by increasing fine pores and decreasing large pores.

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Figure 2.12 Compressive strength of GGBS and steel slag as cement replacement (Wand et al (2012))

Kourounis et al (2007) replaced PC with BOS by 0%, 15%, 30% and 45% by weight. The compressive strength was obtained at 3, 7, 28 and 90 days. At all stages of testing and replacement levels of BOS, the compressive strengths were lower than that of the control mix. As stated by Kourinis et al (2007) when compared to a study done by Altun and Yilmaz (2002) the development of strength at 28 days containing BOS was

higher due to the assumption that in the study the BOS had higher level of fineness and higher content of hydration component. The decrease in strength for the study conducted by Kourounis et al (2007) was also assumed to be occurring due to the fact that C_3S content in BOS is much lower than in PC.

2.4.3.2 Splitting tensile strength

Figure 2.13 displays the results by Jallul (2014) and reports the splitting tensile strength of cement paste paving blocks that were tested at 14 and 28 days. The results showed that in paste mixes containing up to 70% BOS replacement by weight of cement can achieve the minimum 3.6MPa splitting tensile strength that is required by BS EN 1338:2003. The optimum mix contained 60% PC and 40% BOS.

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Figure 2.13 Splitting Tensile strength of PC/BOS cement paving block pastes. Jallul (2014)

2.4.3.3 Summary of Findings

The physical and chemical properties of BOS allow it to be used as a cementitious constituent; however one of the key issues with the use of this material is impurities and variability in composition.

2.4.4 Metakaolin (MK)

As stated by Reeves et al (2006), many types of clay can be calcined to give highly reactive pozzolans. One of the most common of these is MK because its precursor, kaolin, is widely available commercially in a relatively pure form. Badogiannis et al (2005) reported that the pozzolanic property gained by the thermal treatment of kaolin allows MK to be used as a cementitious constituent. One of the main factors that influence the effectiveness of MK being used as an additive is its burning or calcining temperatures. As stated by Sabir et al (2001) the clay is in its most reactive state when the calcining temperature leads to loss of hydroxyls and results in a collapsed and disarranged clay structures, this state as shown by Li and Ding (2003) is between 600°C-800°C.

MK reacts with CH released by cement clinker hydration to produce secondary C-S-H gel inside the paste. The secondary formed C-S-H gel improves the microstructure of cement paste matrix (Li and Ding (2003)). Sabir et al (2001) stated that much of the interest has focused on the removal of CH, which is produced by the hydration of cement and which is associated with poor durability. Kostuch et al (1993) reported that up to 20% MK replacement at 28 days virtually removes all CH from the

concrete; however a study by Sabir et al (2001) showed that this Figure should be around 30-40%. Table 2.11 shows the chemical and physical properties of MK from different studies.

Some of the advantages of Metakoalin are:

- Reduction in CH content

- Increase in compressive and splitting tensile strength

- Reduction in expansion cause by alkali silica reaction

- Decrease in water penetration

- Increase in freeze thaw resistance.

Table 2.11 Chemical composition of MK from different studies (Güneyisi et al (2012),Güneyisi et al (2008),Hassan et al (2012),Vejmelková et al (2011),Mandandoust and Mousavi (2012))

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2.4.4.1 Compressive strength

Badogiannis et al (2005) reviewed MK from 4 different sources (K1-K4) and a commercially available (MKC), and replaced cement by 10% and 20% by weight. Table 2.12 shows the properties of these samples. The compressive strength was

tested on 1, 2,7,28, 90 and 180 days. Figure 2.14 and 2.15 shows the compressive strength for 10% and 20% replacement respectively. For 10% replacement all mixtures apart from 1 source at 2 days exceeded the control mix strength. At 20% replacement the early age strength was lower than the control mix; however there was greater development from 7 days onwards and from 28 days greater strength was noted for all mixes when compared to the control mix. A factor which was considered in this study was the relative strength which as stated was the ratio of the strength of MK to the strength of the control mix. Analyses of the relative strength lead to the conclusions that the reaction of MK with CH affects the strength even at the early stage, there is a possible effect on the long term strength with the addition of MK and that there is a clear increase in strength due to mainly the pozzolanic reaction of MK.

Table 2.11 Chemical composition of MK. Badogiannis et al (2005)

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The same conclusions as those noted by Badogiannis et al (2005) were found by Brooks and Johari (2001). Brooks and Johari (2001) found that incorporation of MK as a cementitious constituent had a positive effect on the compressive strength. MK was used to replace cement by 0%, 5%, 10% and 15 % and the 28 day cube strengths were 87MPa, 91.5MPa, 104MPa and 103.5MPa respectively.

Figure 2.14 Compressive strength with 10% MK. Badogiannis et al (2005)

Figure 2.15 Compressive strength with 20% metakoalin Badogiannis et al (2005)

2.4.4.2 Splitting tensile strength

Güneyisi et al (2012) studied the effect of MK replacing cement in reinforced concrete. The splitting tensile strength of MK replacing cement by 5% and 15% by weight for two w/cm ratios (0.25 and 0.35) was reviewed. The greater quantity of super plasticizer is assumed to be the reason why the lower w/cm ratio had greater strength. From both mixes it can be understood that the addition of MK increases the strength at all ages and replacement levels, apart from 3 days at 15% replacement. However at 7 days for this mix the strength was greater than the control mix. Overall

the results showed that increasing MK up to 15% increases the splitting tensile strength.

Güneyisi et al (2007) studied the effect of MK as a cementitious constituent on the splitting tensile strength of concrete. Mixes with two w/c ratios were analysed and MK was used to replace cement by 10% and 20%wt. Figure 2.16 illustrates the results for these mixes for up to 120 days curing. The results show that the introduction of MK has a positive effect on the splitting tensile strength and as the replacement level is increased to 20% by weight of PC the strength is still increasing. The study also commentated on the relationship between the compressive strength and splitting tensile strength, it was noted that the development patterns for both strengths were similar. The increase in compressive and splitting tensile strength was stated in the study to be due to the following factors 1) the dilution effect and 2) the pozzolanic reaction of MK with CH.

Figure 2.16 splitting tensile strength of reinforced   concrete containing metakaolin at two w/cm ratios (Güneyisi et al (2007))

2.4.4.3 Freeze thaw resistance

Hassan et al (2012) investigated the effect of MK on the durability properties of self-consolidating concrete. Table 2.12 shows the quantity of material that was scaled after 50 freeze thaw cycles and the visual rating (0-5) that was given as MK was used to replace cement by 3%-25%wt. The results show that MK had a positive effect on results; scaled material was reduced by 54% as replacement levels increased to 20%. Although the scaled material increased as replacement levels rose to 25% the quantity was still 40% below that of the control mix. The study concluded that the addition of MK in self compacting concrete improved the resistance to freezing and thawing and that the scaling resistance is greatly enhanced with the optimum level being 20%.

Vejmelková et al (2011) analysed the effect of CEM111/A 32.5 which consists of 56%wt GGBS (SCC-s) and a mix containing 60% CEM 1 32.5R and 40% MK (SCC-m) in self compacting concrete. Table 2.13 reports on the scaled material (kg/m^2) for the two mixes after 56freeze thaw cycles. The results show that the introduction of MK had an excellent effect with no material being scaled after 56 freeze thaw cycles within the accuracy of 0.001 kg/m^2. It was stated that the reason for the results could be due to presence of pores in the range of 10-100µm in SCC-m that enable the salt solution to penetrate deeper under the materials surface.

Table 2.12 Scaled material for SCC containing MK (Hassan et al (2012))

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Table 2.13 Scaled material for SCC containing MK (Vejmelková et al (2011))

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2.4.4.4 Water absorption

Mandandoust and Mousavi (2012) reported on the water absorption rate as MK was used to replace cement by 0-20%wt in self-compacting concrete. The results showed all mixes containing MK provided a reduction in water absorption when compared to the control mix and that they fell within the good limits set by CEB-FIP (1989) while the control at final absorption fell into the average. Similar tendencies were noted by Güneyisi et al (2012) which advocated the filling effect of MK and its pozzolanic reaction. Shekarchi et al (2010) conducted a study to determine the transport properties in MK blended cements. The study analysed the water absorption as MK was used to replace cement by 5-15%wt. The trends noted were the same as from Mandandoust and Mousavi (2012) which show that as MK is introduced the water

absorption rate is below the control mix and it can be once again assumed to be due to the finer particles resulting in greater pozzolanic activity.

2.4.4.5 Summary of Findings

MK successfully replaced cement in numerous studies analysing different types of concrete application

Replacing PC by up to 20% by weight successfully produced greater compressive and splitting tensile strengths and up to 40% by weight replacement successfully produced greater durability properties.

MK provides increased strength and durability properties as the fine particles allow for an increase in the filler effect and the chemical properties allow for it to react with the excess CH after the initial hydration process to produce the excess CSH gel.

2.4.5 Silica Fume (SF)

SF is a by-product of induction arc furnaces in the silicon metal and ferrosilicon alloy industries (Li (2011)). The three roles that describe the mechanism of SF in concrete as stated by Siddique (2011) are pore size refinement/matrix densification, reaction with free lime and cement paste-aggregate interfacial refinement. In order to get the best results when using SF it is recommended by Babu and Prakash (1997) that SF should meet certain minimum specifications:

- Greater than 85% SiO_2 content

- Average particle size of 0.1 to 0.2μm

- Very low content of unburnt carbon

A difficulty pointed out by Siddique (2011) is that the curing period of SF concrete is more sensitive when compared to normal concrete therefore greater control during the curing stage is required to optimize the strength and durability. The advantages of SF as stated by Mazloom et al (2004) are:

- High early compressive strength

- Good tensile/flexural strength and modulus of elasticity

- Increased toughness

- Increased abrasion resistance

- Enhanced durability

The particles of SF are very fine when compared to other cementitious constituents (GGBS, PFA etc.), therefore as well as powder form SF may also be provided in slurry form in order to provide greater workability. The fineness of SF plays a major role in its usability; many researchers have tried to understand the reaction of SF by viewing the particle characteristics and morphologies of hydration products. This has led to researchers (Yajun and Cahyadi (2003)) stating that the difference in mechanical and durability properties of concrete incorporating SF is likely to be due to its particle size rather than its chemical composition. The interfacial transition zone in concrete can be strengthened by the "micro filler effect" which is produced by the fine particles of SF. Table 2.14 shows the chemical and physical properties of SF from different studies

Table 2.14 Chemical composition of SF from different studies (Mazloom et al (2004),Wong and Razak (2005),Behnood and Ziari (2008),Köksal et al (2008),Sabet et al (2013))

2.4.5.1 Compressive strength

Mazloom et al (2004) observed high performance concrete substituted with SF by 6%, 10% and 15% by weight of cement for up to the age of 400 days. The compressive strength up to 90 days showed that as SF increased the compressive strength increased and when compared to the control mix at 90 days, 15% silica fume replacement was greater by 12MPa. When it came to the compressive strength at 365 days and 400 days the gap between the mixes had dramatically reduced but the strength at 15% replacement was still greater by 2MPa.

Wong and Razak (2005) reported on the effect of reducing the w/cm ratio in concrete containing 5%, 10% and 15% SF as replacement for cement for up to 180 days. When analysing the compressive strength there were two observations made. The first observation was that SF strength was only greater than the control mix from 7 days onwards and as stated was due to the effect of pozzolans, as well as the slow nature of

the pozzolanic reaction. The second observation was that after 90 days of curing the average strength enhancement with 10% SF achieved 17 % increment and that the water reduction did not trigger significant enhancement as expected.

Behnood and Ziari (2008) reviewed at the effect of SF on the compressive strength of heated and unheated specimens. Figure 2.17 illustrates the mixes that were prepared and the compressive strength that was gained at room temperature at 7 and 28 days. It is clear to see that the addition of SF had a positive effect on the compressive strength. As stated in the study this was down to the filler effect of the fine SF particles and due to the reaction of SF with CH formed during the hydration of PC that caused the formation of excess C-S-H. After exposure to heated conditions of 100-600°C the compressive strength of concrete is dramatically reduced, this was assumed to be occurring due to the weakened bond between the paste and the aggregate because as temperatures rose the cement pastes contracts and the aggregate expands.

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Figure 2.17 Compressive strength of concrete incorporating SF. Behnood and Ziari (2008)

2.4.5.2 Splitting tensile strength

Bhanja and Sengupta (2005) looked at the relationship between the addition of SF as a cementitious constituent and w/cm ratio on the 28 day splitting tensile strength. The

first observation reported was that as the w/cm ratio is reduced the splitting tensile strength increases.Secondly, increasing the quantity of SF increases the splitting tensile strength. The two observations made by Bhanja and Sengupta (2005) were also reported by Güneyisi et al (2012) who studied the effect on the mechanical properties as SF was used to replace PC by 0%, 5%, 10% and 15% of weight. For the optimum splitting tensile strength, 15%-20% SF replacement by weight was recommended by by Bhanja and Sengupta (2005). The study stated that the reason for the increase in strength for replacement levels between 0-20% is due to the SF filling voids. As replacement levels go beyond 20% the improvement tends to decrease, however for each case it should be noted that even at 30% replacement the strength was greater than that of the control mix.

Köksal et al (2008) studied the effect on the mechanical properties of high strength concrete as SF was used to replace cement by 0%, 5%, 10% and 15% of weight. The splitting tensile strength at 28 days for SF replacement at 0%, 5%, 10% and 15% was 3.48 N/mm^2, 3.82 N/mm^2, 5.36 N/mm^2 and 6.54 N/mm^2 respectively. The w/cm ratio used in this study was 0.38 and when comparing to the results obtained by Bhanja and Sengupta (2005) similar trends can be noticed. Both studies showed that the addition of SF provides a key enhancement on the splitting tensile strength as levels are increased to 15%.

2.4.5.3 Freeze thaw resistance

Table 2.15 from Hassan et al (2012) reports the scaled material after 50 freeze thaw cycles for cement in self consolidating concrete being replaced by 0%, 3%, 5%, 8% and 11% SF. Results show that as SF is used to replace cement by up to 8% of weight

the durability of the concrete is increased, however as replacement levels are increased beyond this point there is a sharp decrease in the durability. The reason for this was unknown; however the values were still below the control mix.

Table 2.15 Scaled material of concrete containing SF. Hassan et al (2012)

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2.4.5.4 Abrasion Resistance

Turk and Karatas (2011) analysed the abrasion resistance of self-compacting concrete as SF was used to replace cement by 0%, 5%, 10%, 15% and 20%wt. The loss on wear for the mixes is shown in Table 2.16. The results show that as SF was increased to 15% replacement the wear decreased by 34% when compared to the control mix however at 20% replacement it only decreased by 30%. The study stated that 20% replacement was still below the control mix however the reason for the increase between 15% and 20% was due to the low w/cm ratio. It was stated that SF improved abrasion resistance as it improves the bond between the aggregate particles and the paste phase due to its chemical and physical effects on the cement hydration process.

Table 2.16 Abrasion resistance of SCC containing silica fume (Turk and Karatas (2011))

2.4.5.5 Water Absorption

Figure 2.18 shows the water absorption rate that was determined based on ASTM C642 at 30 minutes and 24hrs as SF was used to replace cement by 10% and 20%wt in a study conducted by Sabet et al (2013). The results show that at 30 minutes SF levels were slightly below the control mix and were well within the good water absorption limit (3%) that is recommended by CEB-FIP (1989). At 24 hrs SF levels were well below the control mix and this as stated was attributed to limited pore connectivity and reduced porosity of the mixes. Similar conclusions were made by Valipour (2013) who also used ASTM C642 (2003) to determine the water absorption as SF was used to replace cement by 5%, 10% and 15%wt. The results showed that at 30 minutes the mixes containing SF were well within the good CEB limit and at 24hrs well below the absorption percentage of the control mix. Valipour (2013) concluded that the 24hr water absorption is highly dependent on the quantity of capillary pores and plays a more important role in water permeation, causing the specimens containing SF to permeate less water.

Figure 2.18 Water absorption rate for concrete incorporating silica fume. Sabet et al (2013).

2.4.5.6 Summary of Findings

The high SiO_2 content allows for secondary C-S-H gel to be produced increasing the strength and durability properties of the concrete.

Studies have noted that the strength is mainly attributed to the fineness of the particles as they allow for greater particle parking and increase the reactivity of SF.

SF has not been used to replace cement by more than 30% with studies showing the optimum levels to be around 15%

2.4.6 Glass powder (GP)

GP has predominantly been used as a replacement for fine or coarse aggregate, but if particle size is as fine as shown in Figure 2.19 (Schwarz et al (2008)), the high silica content provides the pozzolanic activity required for a cement substitute.

Figure 2.19 particle size distribution Schwarz et al (2008)

Glass mainly consists of SiO_2 and is therefore suitable as a cement substitute. Even though there are many types of glasses that are produced, (Chen et al 2002) concluded that after testing 32 types of glass with different colours and chemical compositions, the glass did not vary significantly but the strength that would be achieved would depend on its application. A concern with glass that was noted by Schwarz et al (2008) and Shi et al (2005) was the high alkali content in glass that has the potential to cause deleterious expansion through alkali-aggregate-expansion. Table 2.17 shows the chemical and physical properties of GP from different studies

Table 2.17 Chemical composition of GP from different studies (Shi et al (2005),Matos and Souse-Coutinho (2012),Vijayakumar et al (2013)).

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2.4.6.1 Compressive strength

4 different types of GP were used to replace cement by 20% of weight (Shi et al 2005). The four as stated in the study were from the screening of crushed waste glasses (GP-fine), from a dust collector of a glass crushing process (GP-dust) and two from further grinding of the powder from the dust collector in a ball mill (GP-4000 and GP-6000). As well as GP, PFA was also used as a reference point at the same level of replacement in order to compare to one of the most common substitutes. The assumption that particle size has a large effect on the compressive strength was noted, as replacements containing larger particles produced lower strengths at 28 days. From the results the study concluded that GP can be regarded as a pozzolanic material.

Matos and Souse-Coutinho (2012) investigated the durability of mortar using waste GP as a cementitious constituent. GP was collected from a local recycling plant and was used to replace PC by 10% and 20% by weight; these mixes were compared to the control mix containing 100% PC and an established pozzolanic material (SF)

which replaced PC by 10% of weight. When analysing the compressive strength of the mixes, early age strength is lower in the mixes containing GP, with 20% replacement having a lower strength than 10% replacement. The situation is reversed at 180 days with 20% replacement having a greater strength and both replacements at this age are similar to that of the control mix. When compared to SF, at no stage did the GP have the same level of strength, as SF was greater than the control mix from 28 days onwards. The results display similarities to the study conducted by Shi et al (2005) and concluded that GP has the potential to be a cementitious constituents as it has the pozzolanic attributes, even though SF performed better than the GP there are scenarios in which the all-round sustainability of GP would be better suited.

2.4.6.2 Splitting Tensile Strength

Figure 2.20 reports on the splitting tensile strength of concrete as GP is used to replace PC by up to 40% by weight in increments of 10% (Vijayakumar et al (2013)). The results show that at 28 days the control mix is greater than all mixes containing GP, however at 60 days 40% replacement increases the strength by 4.4%. The study concluded that the addition of GP increased the splitting tensile strength and that very finely ground glass has been shown to be excellent filler and may have sufficient pozzolanic properties to serve as partial replacement.

Figure 2.20 Splitting tensile strength of GP. Vijayakumar et al (2013).

2.4.6.3 Water absorption

Nwaubani and Poutos (2013) produced and analysed concrete which replaced PC with GP by 5%, 20% and 30% of weight. The water absorption values for 0%, 5%, 20% and 30% replacement was 0.45, 0.46, 1.25 and 0.82 respectively. The study had reported that Taha et al (2008) stated that glass by nature is an impermeable, therefore should reduce the water absorption. However the values obtained by Nwaubani and Poutos (2013) showed similar results for 0% and 5% replacement, with higher replacement being more absorbent. The study stated that performance depends on fineness of the waste GP used and that glass particles are evidently coarser than the concrete therefore pozzolanic activity correspondingly reduced to a lesser level than would be expected.

2.4.6.4 Summary of Findings

If GP is ground to a degree of fineness, the chemical properties (mainly SiO_2) allow it to be used as a cementitious constituent as it reacts with the excess CH from the initial hydration of PC to produce excess CSH gel.

Studies have successfully replaced PC with GP by up to 40% by weight and depending on the properties of the samples can produce similar or greater results when compared to the control mix.

2.4.7 By-Pass Dust (BPD)

Studies such as Kunal et al (2012) have mistaken By Pass Dust (BPD) to be the same as Cement Kiln Dust (CKD). The main difference between CKD and BPD is related to the temperature at which these materials are taken off the cement production process. CKD is taken out of the kiln during its initial length where the temperature is about 300°c, while BPD is from part of the kiln where the temperature is about 1000°C. As a result, BPD contains more cementitious phases compared with CKD, which contains a higher amount of calcium carbonate (limestone)(Ganjian et al 2008). Also due to the high temperatures that BPD experiences there is likely to be less salts(potassium chloride and sodium chloride) which are volatilized at about 770-800°C, this then leads to a lower LOI in comparison to CKD. Therefore when analysing papers for the literature review, based on material obtained for this study and the notes made above, if the LOI was to be lower than 10% the material was assumed to be BPD and not CKD.

One of the biggest disadvantages of BPD is that it can vary in particle size and chemical composition as a result of the materials, equipment and process adapted. This results in different BPD samples from one processor to another and in most cases even from the same source. Even though production has become much more efficient and it is now possible to incorporate BPD back into the clinker production, the

specifications give a maximum value on the alkali content in order to reduce alkali reactivity with aggregate; therefore there is still an excess of BPD which is sent to landfills. Table 2.18 shows the chemical and physical properties of BPD from different studies.

Table 2.18 Chemical composition of BPD from different studies (El-Mohsen et al (2014),Najim and Mahmood (2013),Ali and Yang (2011),Lachemi et al (2008))

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Some of the advantages of BPD as stated by Naik et al (2003) are:

- Opens a value added use option for utilization of BPD

- Helps in sustainable development by reducing demand of new landfills

- Uniform finer particle size is useful in manufacturing of self-consolidating concrete and high-performance concrete

- Manufacturing of blended cement

2.4.7.1 Compressive strength

El-Mohsen et al (2014) analysed the incorporation of CKD with partial cement replacement of 10%, 20%, 30% and 40% in Self Compacting Concrete (SCC) and compared it to a control mix of Normally Vibrated Concrete (NVC). The LOI for CKD in this study was 5.7, therefore it was assumed to be BPD. The specimens were tested at 7, 28, 56 and 91 days and Figure 2.21 shows the compressive strength at these ages. Mixes containing BPD at no stage obtained a greater strength than the control mix. The optimum blend containing BPD was found to be at 20% replacement with it achieving 97% ,93%, 96% and 93% of the compressive strength of NVC at ages of 7, 28, 56 and 91 days respectively. The cause for 20% replacement achieving the greatest SCC strength was due to a combination of fine powder and superplastisezer enhancing the self-consolidation action.

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Figure 2.21 Compressive strength of SCC containing BPD. El-Mohsen (2014)

Najim and Mahmood (2013) experimented on the use of CKD (assumed to be BPD) as a partial replacement for cement in self-consolidating concrete. The compressive

strength at 28 days for 0%, 10%, 20% and 30 % replacement was 57MPa, 55MPa, 52.5 MPa and 43MPa respectively. As CKD levels increased the compressive strength decreased and the assumed reasons for this as stated in the study were:

- Due to the reduction in C_3S and C_2S.

- Due to the increase in free lime content in cement dust, which in turn increases the amount of Ca $(OH)_2$ that weakened the hardened matrix

- The formation of chloro- and sulfoaluminate phases could make hydration products (C-S-H) softer and expand in comparison to with the cement hydration alone

- The high sulphate content can increase the porosity therefore decreasing the strength.

2.4.7.2 Splitting tensile strength

El-Mohsen (2014) analysed the splitting tensile strength of partial cement replacement of 10%, 20%, 30% and 40% with CKD in Self Compacting Concrete (SCC) and compared it to a control mix of Normally Vibrated Concrete (NVC). Figure 2.22 shows the splitting strength at 7 and 28 days for these mixes. Once again no mix achieved the same strength as the control mix and the best SCC strength was obtained with 20% replacement. The fineness of BPD was reported by El-Mohsen (2014)   to be the reason for 20% replacement achieving the greatest strength. It was also stated by El-Mohsen (2014) that the pozzolanic property of BPD, where the percentage of SiO_2 does not exceed 13.5%, was not significant in changing the mechanical properties of concrete.

Figure 2.22 Splitting tensile strength of SCC containing BPD. El-Mohsen (2014)

2.4.7.3 Water absorption

Ali and Yang (2011) produced concrete bricks that were made in 250 x 120 x 60 mm moulds. Figure 2.23 shows the water absorption rate as CKD (assumed to be BPD) is used to replace cement by up to 40% by weight in increments of 5%. The results showed that as replacement levels increased over 10% the water absorption increased. There was a sharp increase at 10% replacement, which then decreased at 15%. From Figure 2.23 it can be concluded that the optimum mix contained 5% CKD replacement as the water absorption decreased in comparison to the control mix.

Figure 2.23 Water absorption rate as CKD (Assumed to be BPD) is added to concrete bricks. Ali and Yang (2011)

2.4.7.4 Freeze thaw resistance

Lachemi et al (2008) incorporated CKD from various sources into controlled low strength materials (CLSM). Out of the 4 CKD samples obtained two had LOI values of 3.3% (Sample b) and 3.1% (Sample D) and therefore were assumed to be BPD. Samples B and D were used to replace PC by 4% and 10% respectively. The mass loss (%) for sample B at 4% and 10% replacement was 29.7% and 12.8% respectively. The mass loss (%) for sample D at 4% and 10% replacement was 11.8% and 18.55% respectively. The study stated that no definite conclusions can be drawn regarding the influence of types of CKD on the freeze thaw resistance of CLSM because sample B had positive effects when CKD was increased and sample D had negative effects as CKD was increased.

2.4.7.5 Summary of Findings

- Studies have mistaken BPD for CKD and vice versa however as stated there are large differences in the chemical composition which allow BPD to be better suited as a cementitious constituent.

- Experiments have replaced cement with BPD by up to 40% of weight, however with both mechanical and durability properties it is shown at such high levels of replacements there are negative effects on both properties.

- If taking both mechanical and durability properties are taken into account then it concluded that no more than 10% replacement would be suited to achieve greater properties than he control mix.

2.4.8 Ternary blends

2.4.8.1 Compressive strength

Li and Ding (2003) studied the effect of ternary blends consisting of PC, GGBS and MK. The blended mixes consisted of replacing PC with 10% MK / 10% and 20% GGBS by weight. The first advantage that was noted from using this combination was that there was a greater particle size distribution which increased the potential for greater strengths and the water demand was lower than that of the mix containing solely MK (10%wt of PC). When it came to the compressive strength at all stages tested the strength was greater than that of the control and solely MK (10%wt of PC) mix. It was stated in the study that the reason for this can be divided into two effects

- Physical effect- Which is that the ultra-fine particles fills the voids in concrete which makes the microstructure of concrete denser

- Chemical effect- Which is the reaction of MK and GGBS with the cement hydrates.

A review on the effect of MK in concrete was conducted by Sabir et al (2001). One of the studies reviewed was conducted by Sabir et al (1999), which observed the effect

of incorporating PFA and MK in concrete and its effects on the compressive strength. The mixes incorporated PFA by 0%, 10%, 20%, and 30% by weight of PC and MK by 0%, 10% and 20% of weight of PC. The biggest disadvantage with PFA as noted earlier is that at high replacement levels the early strength can be dramatically reduced. The incorporation of MK and its reaction with CH had a positive effect on this negative factor and the early strength lost with high levels of PFA (20-30%) was enhanced by 40% at 14 days when 20% MK was blended in the mix.

Barbhuiya et al (2009) studied the effect of ternary blends compromising of PC, PFA and SF. The mixes produced had solely PFA (30% by weight replacement of PC) in one mix and then a second mix contained PFA (27.5% by weight replacement of PC) and SF (3.5% by weight replacement of cement). The results showed that in the ternary blend not only did the early age (3-7 days) compressive strength increase significantly but so did the 28 day strength. This was stated to be assigned to the pozzolanic reaction of SF with the CH produced from the hydration of PC, the pore filling effects of the SF and the pozzolanic reactivity.

Wang et al (2012) reviewed BOS from four different sources and the effect of blended BOS - GGBS mineral admixture. The study shows similar results to the study conducted by Wainwright and Rey (2000) in which sourcing products from different sources has a minimal effect on the strength. The combination of BOS and GGBS gave encouraging results as the compressive strength was similar and greater in some cases than that of the control mix. These results can be assumed to be due to GGBS weakening the negative effect of BOS which as stated in the study, is its negative

effect on the early strength of concrete as well as the late age performance of concrete.

2.4.8.2 Splitting tensile strength

Figure 2.24 from Kim et al (2007) reports on the splitting tensile strength of high strength concrete incorporating PFA and MK/SF as cementitious constituents for up to 91 days curing. In this study the control mix contained 20% PFA replacement by weight of PC then either SF or MK was added to the control mix by 0%, 5%, 15% and 20% of weight of PC. The results show that for both SF and MK the early strength (1-7 days) showed similar or just lower splitting tensile strength; however from 28 days onwards all mixes produced similar or greater results than that of the control mix. Due to the efficiency of concrete decreasing above 10% MK replacement, as stated in the study this replacement level can be accepted as the optimum level, however the results do show that further replacement levels can be economic as they do produce better results than the control mix. When considering SF the results showed that up to 20% replacement by weight could achieve greater strengths than the control mix. Overall the study showed that the addition of SF or MK can improve the early age strength which is a disadvantage known with PFA.

Figure 2.24 Splitting tensile strength of ternary PC/PFA/MK and PC/PFA/SF blends. Kim et al

(2007)

2.4.8.3 Abrasion resistance

Rashad et al (2014) analysed the effect on abrasion resistance as SF is added to high volume PFA concrete. Figure 2.25 shows the wear depth up to 180 days for mixes F0 (100% PC), F70 (PC30%/FA70%), F60S10 (PC30%/FA60%/SF10%) and F50S20 (PC30%/FA50%/SF20%). The results show that none of the mixes obtained the same level as the control mix, however as the level of SF increased in the high volume PFA concrete the wear depth decreased. The conclusion was that the addition of SF had a positive effect due it having a greater hydration time and its greater pozzolanic reactivity which come from the finer particles and very high amorphous silicon dioxide content.

Figure 2.25 Abrasion resistance as SF is added to high volume PFA concrete. Rashad et al (2014)

2.4.8.4 Freeze thaw resistance

Figure 2.26 Scaling mass losses after 50 freeze thaw cycles Bleszynski (2002)

Figure 2.26 shows the scaling mass loss after 50 freeze thaw cycles for mortars incorporating GGBS and a combination of GGBS and SF as a replacement for PC. The study by Bleszynski (2002) was conducted using the standard, MTO (Ministry of Transport, Ontario) LS-412 - Scaling Resistance of Concrete Surfaces Exposed to De-icing Chemicals and the limit stated by MTO and British standards are outlined. The results show that the only mixture that exceeded the MTO and BS limit contained

50% GGBS replacement after 50 cycles; however one thing to note is that the British standards require the cumulative mass loss to be under 1kg/m3 after 28 cycles therefore under those conditions 50% GGBS replacement is sufficiently suiTable to be used. The only mix which performed better than the control mix contained solely 8% SF by mass, the additions of silica fume had a positive effect when incorporated with GGBS and as can be seen when 5.2% SF is introduced to 35% GGBS the mass loss decreases. The study concluded, in order have good resistance to freeze thaw and have high level of PC replacement, this can be achieved with by replacing GGBS (35-50%) with the addition on SF (5-8%) by weight of PC.

2.4.8.5 Concluding remarks

Ternary blends are a response to the economic and environmental pressure to reduce the cement content of concrete. Using two different cementitious constituents in addition to a remaining proportion of cement can deliver superior properties to a single replacement and make use of replacement materials that would otherwise not be successful

From review of individual materials it can be seen that some materials can replace PC by up to 10%wt. The aim of this study was to replace a high percentage of cement used in concrete paving blocks and in order to do this ternary cement blends provides the greatest solution.

Ternary cement blends have the potential to provide a greater microstructure because the particle size distribution of the different cementitous materials provides greater particle packing and reactivity.

The chemical composition which provides advantages for some cementitious constituents can help cementitious constituents for which the composition at early stage may be a disadvantage.

Chapter 3

Research Programme and Experimental Details

3.1 Introduction

Chapter 2, the literature review introduced the materials that are currently available to be used as cementitious constituents. The current standards (BS EN 1338:2003) state the strength and durability factors that are required in order for concrete paving blocks to be approved and this chapter goes through the adopted research programme (Systematic method shown in Figure 1.2) and experimental work undertaken. This will include the mix designs, laboratory work and method of analysis.

3.2 Research programme

The objectives of this study were to firstly, conduct trial mixes to examine the four key inter-related areas for concrete paving blocks. These are strength properties, durability performance, control of material variability and leaching properties of the blocks. Secondly, carry out two short run factory trials and site trials on actual constructed paved areas.

3.2.1 Strength properties

Due to the quantity of cementitious constituents being analysed to produce concrete paving blocks for each mix and to test for each property stated in BS EN 1338:2003 would be inefficient. Due to this the analysis was broken down into the first and second phase.

In the first phase the mixes derived from Minitab 16.2.2 were produced as 50mm cement paste (Cementitious materials + Water) cubes. Paste cubes allowed for the production of greater mixes in comparison to concrete paving blocks and a good indication to the trends that would be detected in concrete paving blocks. When introducing cementitious constituents to concrete paving blocks the most difficult and important property to obtain is the splitting tensile strength, which is the only mechanical property required in BS EN 1338:2003. For paste cubes the splitting tensile strength as well as the compressive strength was obtained, this was due to the compressive strength further reinstating the results of splitting tensile strength and contours produced. The pastes were tested at 14 days as the standards state no specific date on when the minimum strength should be achieved and from an industry perspective the mix with the greatest early age strength would be preferred.

In the second phase the cementitous mixes that produced the greatest strengths were then used to produce concrete paving blocks and tested for the splitting tensile strength at 14 and 28 days.

3.2.2 Durability Performance

From the 14 mixes that were tested in the second phase of the strength properties, the two with the greatest strength were known as the candidate mixes. The two candidate mixes were chosen and analysed in accordance with BS EN 1338:2003 for their durability performance (water absorption, freeze thaw resistance and slip/skid resistance).

3.2.3 Material Variability

Cementitious constituents are not the primary products that are produced but some like GGBS and PFA have quality control and standards to regulate the properties of the materials. Other possible replacement materials such as BPD and BOS are regarded as 'waste' and have no standards, therefore there is no control over the particle size distribution or chemical composition. When reviewing the materials in chapter 4, two materials (PFA and BPD) were obtained on a monthly basis over a 6-month period. PFA was chosen as it was a commercially available regulated cementitious constituent while BPD is regarded as a waste material. The effect on compressive strength at 14 and 28 days was plotted against the chemical and physical variability that was determined. This allowed for the study to determine a suitable range for the chemical composition and physical properties.

3.2.4 Leaching

The final of the four inter-related areas was to examine the leaching characteristics. Figures 2.4 (a) (b) (c) on page 17 illustrated the different SUDS systems offered. From these Figures it can be seen how contaminants such as oil and petrol can be absorbed by the permeable sub base and then degraded so not to cause any harm. If SUDS technology was not applied than heavy metals within these materials would simply leach through the blocks and into the soil below, therefore contaminating the soil. The leaching investigation carried out in this study determines if the heavy metals found in used oil are better absorbed when using the candidate mixes in comparison to the current Hanson mix.

3.2.5 Production trials

The project was in partnership with Hanson Formpave, who are innovators in permeable paving. The two candidate mixes that were determined were used to produce concrete paving blocks in the factory. As well as being tested to ensure they meet the current standards, the blocks were actually laid over the winter period to be analysed.

3.3 Strength/Durability

3.3.1 First phase

The mix designs were produced and analysed by a statistical programme (Minitab 16.2.2). The mixture design option in Minitab16.2.2 was used to establish and analyse the mix design and corresponding results.

3.3.1.1Theoretical basis

Currently the most common way of analysing ternary and binary cement blends is the matrix format. Table 3.1 from Kim et al (2007) shows how this matrix format is adapted for ternary blends. The Table illustrates how the variable (SF or MK) is increased in increments of 5%wt of PC to find the optimised mix. Increasingly studies are using mathematical modelling programmes to predict the strength of concrete. Two of these programmes/ models are Minitab which is a statistical package and

artificial neural networks which is used within programmes such as Matlab to derive the mathematical model.

Table 3.1 Matrix format of analysis. Kim et al (2007)

3.3.1.2 Response Surface Model

Response surface model within Minitab has been used in studies to predict the strength of concrete as well as determine which test parameters had impact on strength (Sadeghi-pouya et al (2007) and Ganjian et al (2014)). Khan and Lynsdale (2002) implemented the response surface model to predict the strength of concrete that had varying quantities of replacement materials, which produced ternary and binary blends. The models were based on the quadratic response surface model that had predictive capabilities. The response variable *f*(x) (Equation 3.1) which predicts the property analysed, is measured at a combination of values of two factor variables.

$$f(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{10} x_1^2 + \beta_{11} x_2^2 + \beta_{12} x_1 x_2 \text{ (Equation 3.1)}$$

Where f(x) is the observation of the response variable, β_1, β_2 ... β_{12} are the coefficients of the model and x_1 and x_2 are the experimental variables. Using this model the study successfully produced isoresponse contours showing the predicted strengths of mixes that were within the boundaries of the percentage material used. The accuracy of the model was reviewed based on the regression value between the results predicted from Minitab and the actual results produced.

Mermerdaş et al (2012) used Minitab to determine if the experimental variables (cementitious constituent level, age of concrete and type of calcined clay) had an influence on the compressive strength. The general linear model analysis of variance was used and in the case of this study the p-value was used to determine the significance of the results. The p-value is used in determining whether to reject the null hypothesis once regression values determine the correlation between actual and predicted results. Both studies showed positive outcomes and found the accuracy of the Minitab to be worthy.

3.3.1.3 Artificial Neural Networks

Artificial neural networks (ANN) solve very complex problems with the help of interconnected computer elements. It has been used to predict the strength of concrete based on many observed values (Uysal and Tanyildizi (2011)). The model process involves 5 main aspects (Duan et al (2013)):

1. Data acquisition, analysis and problem representation

2. Architecture determination

3. Learning process determination

4. Training of the networks

5. Testing of the trained network for generalization evaluation

An ANN model consists of 3 layers as shown in Figure 3.1 (input, hidden and output). The inputs in this case are the variables when mixing concrete and the hidden layer consists of neurons which recognises patterns and computes values from the input which predicts the response variable e.g. strength. Duan et al (2013) used ANN to predict the compressive strength of concrete containing recycled aggregate. The study created a model that was based on 17 different literature sources totalling 168 sets of experimental data (The ANN model used the back-propagation network which is one of the simpler models). The model produced had 14 different variables (water content, recycled aggregate, normal aggregate etc). The accuracy of the predictions was based on the regression values and the study found that the model provided a high level of accuracy.
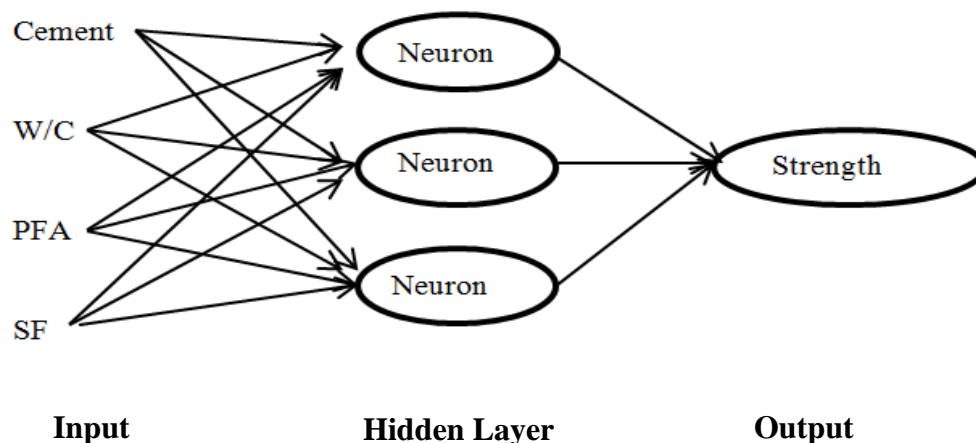
Figure 3.1 ANN set up

3.3.1.4 Systematic method- Minitab

The systematic method (Figure 1.2) designed in this study used the Design Of Experiments (DOE) technique within Minitab. It was found to be more efficient for the quantity of variables (PC + 2 replacements) that were being analysed and the quantity of results that would be available for analysis.

When reviewing past literature it was observed that many researchers that used mathematical programmes or models used them to analyse the results that were based on a mix design formulated based on the matrix format (Khan et al (2002), Mermerdaş et al (2012)). However in this study the systematic statistical analysis of results as well as the formulation of the mix design was designed by Minitab. This resulted in a greater accuracy level being achieved, by having the software design the mixes that were best suited for the statistical analysis within the boundaries of the material used.

The extreme vertices designs option which took into consideration the upper limits for each ternary blend was implemented. This as stated in Minitab, generates the vertices of the constrained design space (Lower Limit < Material < Upper Limit) and then calculates the centroid point up to the specified degree using Piepel's CONAEV algorithm. Piepel's CONAEV (Equation 3.2) (Cornell (2011)) calculates the extreme vertices and centroids, of an experimental region that is defined by constraints of the general form:

$$A_1x_1 + A_2x_2 + \text{.........} \ A_qx_q + A_o \geq 0 \qquad \text{(Equation 3.2)}$$

Where x_1, x_2 ...., x_q are the mixture component proportions and/ or the setting of other non-mixture variables. The A_1, A_2 ...., A_q are constants (Cornell (2011)).

The mixes designated by Minitab were produced and the strengths obtained were fed back into the software. To analyse the data, the model fitting method used was mixture regression and the terms of the model were given in a quadratic formula (as defined by Minitab) as shown in Equation 3.3, were f (x) is the strength, A,B and C are the quantities for the three different components and x_1, x_2.... x_5 are the variables.

$$f(x) = Ax_1 + Bx_2 + Cx_3 + ACx_5 + ABx_2 + BCx_5 \quad \text{(Equation 3.3)}$$

Once these steps were completed, contours plots were analysed to detect trends that would lead to the optimised mixes. In order to determine the accuracy of the model, the regression value and P-Value were derived. The regression value was determined based on the difference between actual results and predicted results. The P-value was obtained at a 95% confidence level and a limit of 0.05, it was used to help decide whether to reject a null hypothesis, therefore validate the analysis.

3.3.2 First phase mix designs

In the first phase the mixes derived from Minitab 16.2.2 were produced as 50mm cement paste (Cementitious materials + Water) cubes. Eleven combinations of ternary pastes were analysed, as detailed in the following section.

3.3.2.1 PC/PFA/GGBS

The first ternary combination to be analysed was PC, PFA and GGBS. The upper limits of material to be used for PC,PFA and GGBS was 60%,80% and 80% by weight respectively, all materials had lower limits of 0%. Figure 3.2 shows the simplex design plot that was developed by Minitab along with Table 3.2 which shows the mix designs that were determined. As the replacement levels were high for each material, this resulted in binary mixes also being produced

Table 3.2 Mix designs (PC/PFA/GGBS)

Cementitious Constituents	Mix Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
PC (%wt)	43	24	24	60	14	14	20	26	20	44	60	00	00
PFA (%wt)	38	58	18	40	28	58	00	37	80	18	00	80	20
GGBS (%wt)	19	18	58	00	58	28	80	37	00	38	40	20	80

It is important to note that accuracy of the analysis by Minitab is only accurate within the area which is outlined in the Figures, as this is the only section that correlation between actual results and predicted results can be analysed. These outlines are the upper and lower bound quantities of each material to be used. If this study was to be conducted looking at different upper limits and lower limits of each material than even though the strengths will be similar the analysis by Minitab would be different.

Simplex Design Plot PC/PFA/GGBS
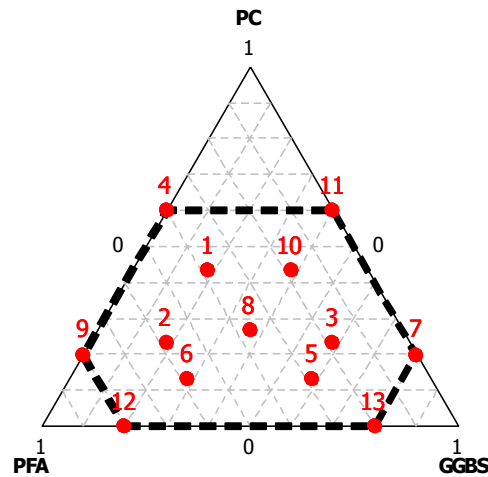
Figure 3.2 Simplex plot design (PC/PFA/GGBS)

3.3.2.2 PC/PFA/BOS

The second ternary combination to be analysed was PC, PFA and BOS. The upper limits of material to be used for PC,PFA and BOS was 60%,80% and 60% by weight respectively, all materials had lower limits of 0%. Figure 3.3 shows the simplex design plot that was developed by Minitab along with Table 3.3 that shows the mix designs that were determined. As the replacement levels were high for each replacement, this resulted in binary mixes also being produced

Table 3.3 Mix designs (PC/PFA/BOS)

Cementitious Constituents	Mix Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
PC (%wt)	5	30	60	35	45	45	40	0	25	20	15	60	0
PFA (%wt)	60	40	40	20	40	20	00	40	60	80	40	0	80
BOS (%wt)	25	30	0	45	15	35	60	60	15	0	45	40	20

Simplex Design Plot PC/PFA/BOS
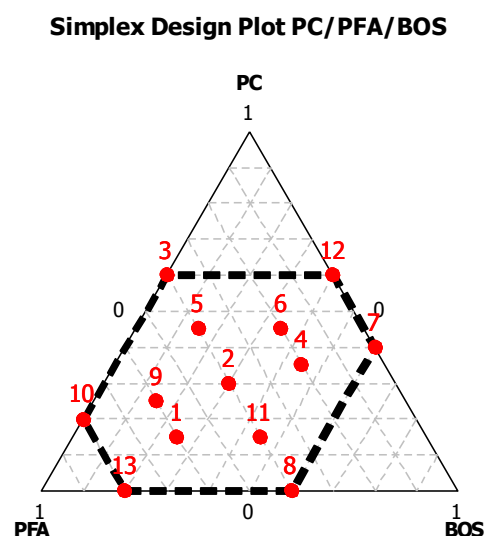
Figure 3.3Simplex plot design (PC/PFA/BOS)

3.3.2.3 PC/PFA/MK

The third ternary combination to be analysed was PC, PFA and MK. The upper limits of material to be used for PC,PFA and MK was 60%,80% and 40% by weight respectively, all materials had lower limits of 0%. Figure 3.4 shows the simplex design plot that was developed by Minitab along with Table 3.4 that shows the mix designs that were determined. As the replacement levels were high for each replacement, this resulted in binary mixes also being produced

Table 3.4 Mix designs (PC/PFA/MK)

Cementitious Constituents	Mix Number										
	1	2	3	4	5	6	7	8	9	10	11
PC (%wt)	20	0	14	14	24	44	60	60	44	0	28
PFA (%wt)	80	80	56	66	66	26	40	0	46	60	52
MK (%wt)	0	20	30	20	10	30	0	40	10	40	20

Simplex Design Plot PC/PFA/MK
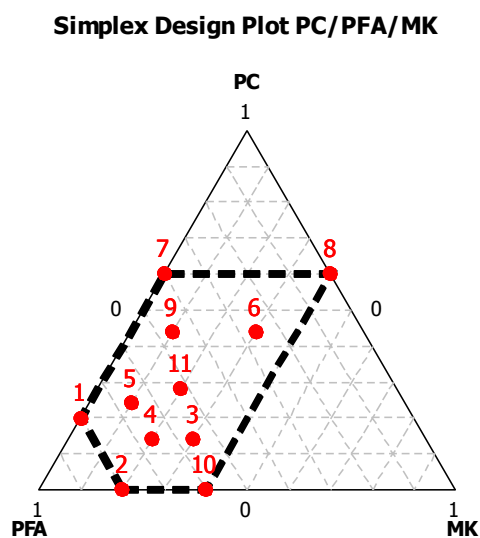
Figure 3.4 Simplex plot design (PC/PFA/MK)

3.3.2.4 PC/PFA/SF

The fourth ternary combination to be analysed was PC, PFA and SF. The upper limits of material to be used for PC,PFA and SF was 60%,80% and 15% by weight respectively, all materials had lower limits of 0%. Figure 3.5 shows the simplex design plot that was developed by Minitab along with Table 3.5 that shows the mix designs that were determined.

Table 3.5 Mix designs (PC/PFA/SF)

Cementitious Constituents	Mix Number										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
PC (%wt)	20.625	50	12.5	60	48.125	60	28.125	60	36.25	20	48.125
PFA (%wt)	68.125	80	80	25	48.125	32.5	68.125	40	56.25	80	40.625
SF (%wt)	11.25	15	7.5	15	3.75	7.50	37.5	0	7.5	0	11.25
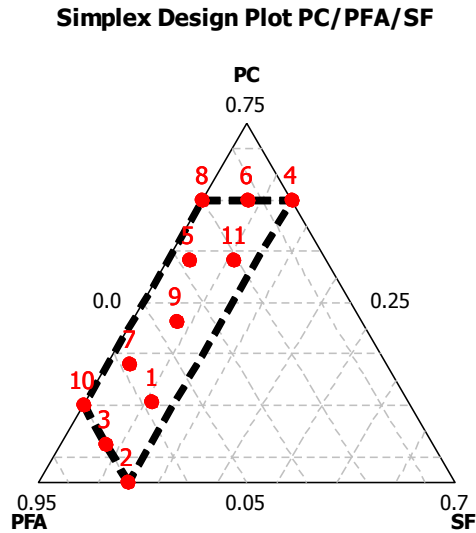
Figure 3.5 Simplex plot design (PC/PFA/SF)

3.3.2.5 PC/PFA/BPD

The fifth ternary combination to be analysed was PC, PFA and BPD. The upper limits of material to be used for PC,PFA and BPD was 60%,80% and 10% by weight respectively, all materials had lower limits of 0%. Figure 3.6 shows the simplex design plot that was developed by Minitab along with Table 3.6 which shows the mix designs that were determined.

Table 3.6 Mix designs (PC/PFA/BPD)

Cementitious Constituents	Mix Number										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
PC (%wt)	60	20	37.5	23.75	28.75	15	60	48.75	60	10	48.75
PFA (%wt)	40	80	57.50	68.75	68.75	80	30	48.75	35	80	43.75
BPD (%wt)	0	0	5	7.5	2.5	5	10	2.5	5	10	7.5

Simplex Design Plot PC/PFA/BPD
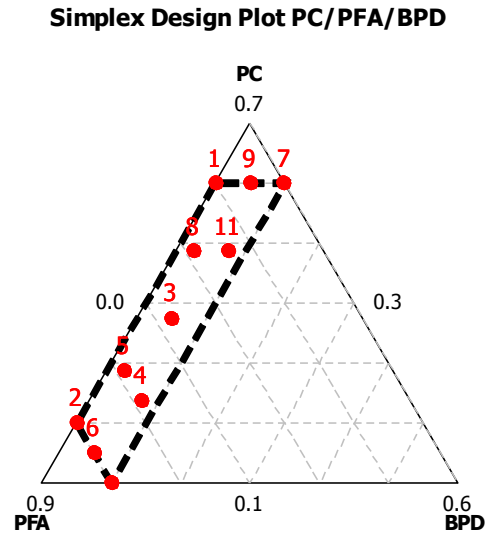
Figure 3.6 Simplex plot design (PC/PFA/BPD)

3.3.2.6 PC/PFA/GP

The sixth ternary combination to be analysed was PC, PFA and GP. The upper limits of material to be used for PC,PFA and GP was 60%,80% and 20% by weight respectively, all materials had lower limits of 0%. Figure 3.7 shows the simplex design plot that was developed by Minitab along with Table 3.7 that shows the mix designs that were determined

Table 3.7 Mix designs (PC/PFA/GP)

Cementitious Constituents	Mix Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
PC (%wt)	40	47.5	30	27.5	60	47.5	0	35	20	60	10	17.5	60
PFA (%wt)	60	47.5	50	67.5	40	37.5	80	55	80	20	80	67.5	30
GP (%wt)	0	5	20	5	0	15	.20	10	0	20	10	15	10
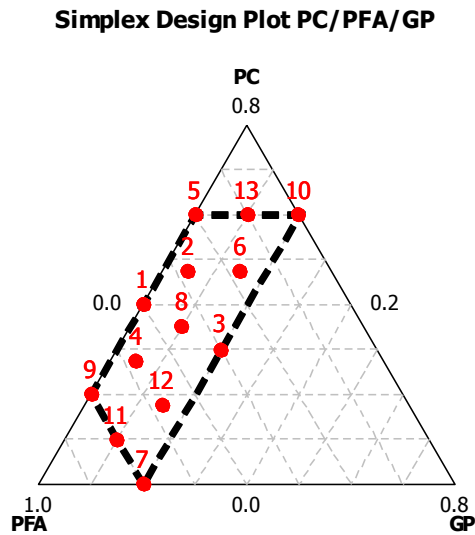
Figure 3.7 Simplex plot design (PC/PFA/GP)

3.3.2.7 PC/GGBS/BOS

The seventh ternary combination to be analysed was PC, PFA and BOS. The upper limits of material to be used for PC,PFA and BOS was 60%,80% and 60% by weight respectively, all materials had lower limits of 0%. Figure 3.8 shows the simplex design plot that was developed by Minitab along with Table 3.8 that shows the mix designs that were determined. As the replacement levels were high for each replacement, this resulted in binary mixes also being produced

Table 3.8 Mix designs (PC/GGBS/BOS)

Cementitious Constituents	Mix Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
PC (%wt)	35	60	60	30	40	45	0	15	15	25	20	45	0
GGBS (%wt)	20	0	40	40	0	20	40	40	60	60	80	40	80
BOS (%wt)	45	40	0	30	60	35	60	45	25	15	0	15	20

NOTE: The figure is a simplex design plot with labeled points.

Simplex Design Plot PC/GGBS/BOS
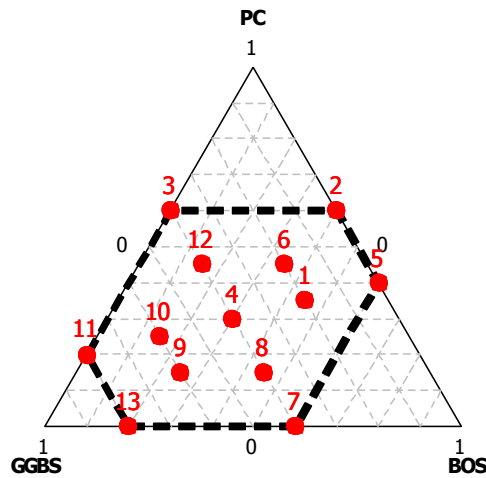
3.3.2.8 PC/GGBS/MK

The eighth ternary combination to be analysed was PC, GGBS and MK. The upper limits of material to be used for PC,GGBS and MK was 60%,80% and 40% by weight respectively, all materials had lower limits of 0%. Figure 3.9 shows the simplex design plot that was developed by Minitab along with Table 3.9 that shows the mix designs that were determined. As the replacement levels were high for each replacement, this resulted in binary mixes also being produced

Table 3.9 Mix designs (PC/GGBS/MK)

Cementitious Constituents	Mix Number										
	1	2	3	4	5	6	7	8	9	10	11
PC (%wt)	60	14	0	14	44	28	24	44	20	60	0
GGBS (%wt)	40	56	60	66	46	52	66	26	80	0	80
MK (%wt)	0	30	40	20	10	20	10	30	0	40	20

Simplex Design Plot PC/GGBS/MK
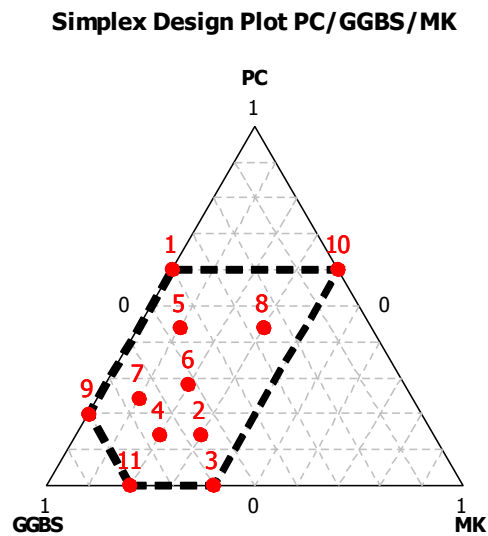
Figure 3.9 Simplex plot design (PC/GGBS/MK)

3.3.2.9 PC/GGBS/SF

The ninth ternary combination to be analysed was PC, GGBS and SF. The upper limits of material to be used for PC,PFA and SF was 60%,80% and 15% by weight respectively, all materials had lower limits of 0%. Figure 3.10 shows the simplex design plot that was developed by Minitab along with Table 3.10 that shows the mix designs that were determined.

Table 3.10 Mix designs (PC/GGBS/SF)

Cementitious Constituents	Mix Number										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
PC (%wt)	60	12.5	28.125	20.625	20	60	48.125	36.25	5	60	48.125
GGBS (%wt)	25	80	68.125	68.125	80	40	40625	56.25	80	32.5	48.125
SF (%wt)	15	7.5	37.5	11.25	0	0	11.25	7.5	15	7.5	37.5

Simplex Design Plot PC/GGBS/SF

Figure 3.10 Simplex plot design (PC/GGBS/SF)

3.3.2.10 PC/GGBS/BPD

The tenth ternary combination to be analysed was PC, GGBS and BPD. The upper limits of material to be used for PC,GGBS and BPD was 60%,80% and 10% by weight respectively, all materials had lower limits of 0%. Figure 3.11 shows the simplex design plot that was developed by Minitab along with Table 3.11 that shows the mix designs that were determined.

Table 3.11 Mix designs (PC/GGBS/BPD)

Cementitious Constituents	Mix Number										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
PC (%wt)	60	60	23.75	37.5	20	48.75	15	28.75	60	48.75	10
GGBS (%wt)	40	30	68.75	57.5	80	43.75	80	67.5	35	48.75	80
BPD (%wt)	0	10	7.5	5	0	7.5	5	2.5	5	2.5	10

Simplex Design Plot PC/GGBS/BPD
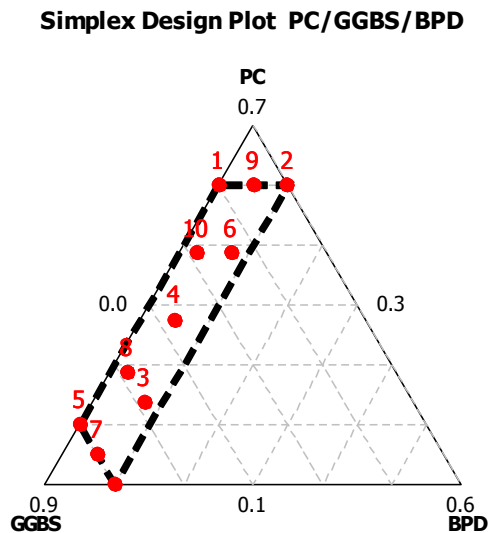
Figure 3.11 Simplex plot design (PC/GGBS/BPD)

3.3.2.11 PC/GGBS/GP

The eleventh ternary combination to be analysed was PC, GGBS and GP. The upper limits of material to be used for PC,GGBS and GP was 60%,80% and 20% by weight respectively, all materials had lower limits of 0%. Figure 3.12 shows the simplex design plot that was developed by Minitab along with Table 3.12 that shows the mix designs that were determined

Table 3.12 Mix designs (PC/GGBS/GP)

Cementitious Constituents	Mix Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
PC (%wt)	35	30	60	40	27.5	60	10	0	60	20	17.5	47.5	47.5
GGBS (%wt)	55	50	30	60	67.5	40	80	80	20	80	67.5	37.5	47.5
GP (%wt)	10	20	10	0	5	0	10	20	20	0	15	15	5
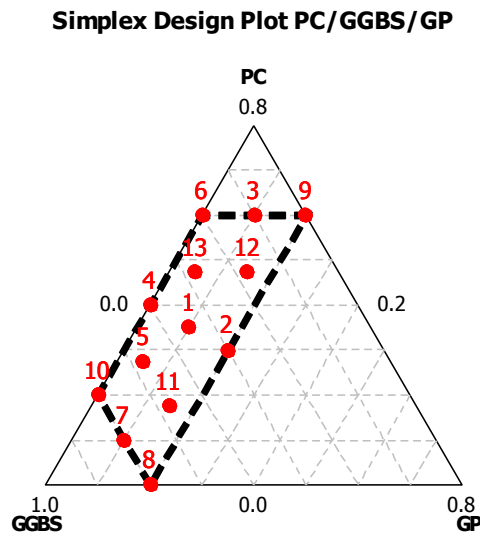
Figure 3.12 Simplex plot design (PC/GGBS/GP)

3.3.3 Casting and curing

Concrete paving blocks differ from normal concrete products as they are a semi-dry blend and are compacted and vibrated simultaneously into shape. The cementitious pastes analysed in this study were also in semi-dry form and as the laboratory did not have the facilities to compact and vibrate simultaneously the cubes were solely axially compacted. The compaction load was defined by comparing results from the industry and in the laboratory; this resulted in an accurate reproduction process.

The following steps were taken to produce the 50mm paste cubes.

1. The materials were weighed out and mixed.

2. The water was then added to the mix (w/cm ratio = 0.15)

3. It was important to note that the mix was consistent.

4. One 50mm cube mould was placed on top of another and fastened (Figure 3.13). The reason for this was due to the compaction, more material had to be inputted than what could manually be fitted into the mould to provide a 50 mm cube.

5. A compaction load of 52 kN for 3 minutes was applied by a Denison hydraulic machine to the individual cubes (Figure 3.14).

6. These cubes were then de-moulded after 24 hours and set to cure for 14days, after this they were tested for their compressive strength and splitting tensile strength.

Figure 3.13 50mm moulds construction (Showing a gang of 3 moulds)

Figure 3.14 50mm cube compaction at 52KN, each were loaded and compacted individually.

The curing procedure replicated the procedure by Jallul (2014). As stated, 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 de-moulded and stored in curing chambers at a constant air temperature of $22 \pm 2^{o}C$ and 98%RH until they were ready to be tested.

3.3.4 Compressive strength and splitting tensile strength

As previously mentioned the first phase would analyse the compressive and splitting tensile strength, as splitting tensile is the only mechanical property required by BS EN 1338:2003 and compressive strength further reinstates the results of splitting tensile strength results. The loading rate for compressive strength and splitting tensile strength was 2 kN/s and 0.2480 kN/s respectively. The equation used to calculate the splitting tensile strength is described in section 3.3.7.

3.3.5 Second phase

Fourteen mixes were chosen from the first phase to be taken into the second phase and these cementitous mixes were used in producing paving blocks with a technique that was developed at Coventry University (Jallul (2014)). All fourteen mixes were tested for their splitting tensile strength and two mixes that achieved the greatest strength were chosen as the candidate mixes and tested for the durability properties stated in BS EN 1338:2003.

3.3.6 Paving blocks production.

The technique used to produce concrete paving blocks at Coventry University was as follows:

1. The materials were weighed out and pre blended before water was added
2. The water was then added to the mix

3. It was important to note that the mix was consistent and that none of the material had been left at the bottom of the mixer.

4. A paving block mould was placed on top of another and fastened as more material had to be inputted then what could manually be fitted into the mould.

5. Apply a compaction load of 400 kN for 3 minutes.

6. These blocks were then de-moulded after 24 hours and set to cure (as stated in 3.3.3) for 14 and 28 days, after this they were tested for their compressive strength and splitting tensile strength

The difference in casting and curing conditions between the paving blocks produced in factory and in the laboratory would certainly have effect on the strength of the blocks. This effect was the reason for blocks being produced in the factory even if the minimum strength was not achieved following the procedure in the laboratory.

3.3.7 Splitting tensile strength

Figure 3.15 is taken from BS EN 1338:2003 and shows the principle set up required for obtaining the splitting tensile strength. Before the block was tested they were left in water at a temperature of $20\pm5^{o}C$ for 24 ± 3 hours and wiped with a cloth to remove excess water before testing. As stated in BS EN 1338:2003 the test is carried out along the longest splitting section of the block, parallel and symmetrical to the edges.

Figure 3.15 Splitting tensile principle of testing (BS EN 1338:2003)

The paving block moulds in the laboratory produced paving blocks with two different thicknesses and the loading rate for 75mm and 80mm thickness was 1.157 kN/s and 1.217 kN/s respectively. Once the failure load was obtained the calculation of strength (T) in Mega Pascal's was obtained for pastes and concrete blocks using the following equation (BS EN 1338:2003).

$$T = 0{,}637 \times k \times \frac{P}{S}$$ (Equation 3.4)

Where

T= Strength in MPa

k= is a correction factor for the block thickness calculated by the equation

k=1.3 – 30 (0.18 – t/ 1000) if 140 < t ≤ 180 mm

or:

k=1.3 if t> 180 mm

or:

for t ≤ 140mm determined from Table 3.13

BS EN 1338: 2003 states that the characteristic tensile splitting strength (T) shall not be less than 3.6 MPa. None of the individual results shall be less than 2.9 MPa, nor have a failure load less than 250 N/mm of splitting length.

3.3.8 Freeze thaw resistance

The freeze thaw resistance is one of two weathering resistance tests that is stated in BS EN 1338:2003 and was obtained in this study for the two candidate mixes and factory made blocks. Figure 3.16 is taken from BS EN 1338:2003 and shows the principle set up required for this test.

Figure 3.16 Freeze thaw set up (BS EN 1338:2003)

As stated in BS EN 1338:2003 the freezing medium consisted of 97% by mass of poTable water and 3% by mass of NaCl. After 28 cycles the mass loss per unit area of the specimen was to be calculated based on the mass (Kg) of the total quantity material scaled after 28 cycles and the area of the test surface (m^2). Each freeze thaw cycle was 24hrs with temperature exceeding 0^0c for each cycle for at least 7hrs but no more than 9hrs, the time temperature cycle is shown Figure 3.17.

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Figure 3.17 Freeze thaw time-temperature cycle (BS EN 1338:2003)

3.3.9 Water absorption

The second of the two weathering resistance tests noted in BS EN 1338:2003 is water absorption and was obtained for the two candidate mixes and factory made blocks. After 28 days the blocks were placed for 3 days in the water tanks with a temperature of 20 ± 5^oC. Thereafter for 3 days in the oven with a temperature of 105 ± 5^oC, until they reached their constant mass. BS EN 1338:2003 stated that constant mass shall be deemed to have been reached when the two weighing performed at an interval of 24h

show a difference in mass of specimen of less than 0.1%. The water absorption was then calculated based on the initial and final mass of specimen.

3.3.10 Slip/Skid resistance

As paving blocks are commonly used in locations used by pedestrians, an important durability as well as safety factor is the slip/skid resistance. The slip /skid resistance was only measured for the two candidate mixes and factory made blocks. Table 3.14 shows the measurement of slip/skid resistance required by BS EN 1338:2003 and Figure 3.18 displays the machine that was used to measure slip/skid resistance in this study. Just before obtaining the friction of the block the block was placed in water with a temperature of 20+- 2 ^{o}C for 30 minutes.

Table 3.14 Evaluation of pendulum test results

Pendulum test value	Potential for slip
Below 19	High
20-39	Moderate
40-75	Low
above 75	Extremely low

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Figure 3.18 Slip/skid resistance set up (BS EN 1338:2003)

3.3.11 Abrasion resistance

The abrasion resistance of blocks was only determined for the blocks produced in the factory as they had to be tested by an external source. The abrasion resistance was determined using the principle of wide wheel abrasion test. The test procedure followed was the same one noted in Annex G of BS EN 1338:2003. The measurement of the abrasion resistance was in mm and Table 3.15 shows the class in which the block falls within. As stated by El Nouhy (2013) in areas subject to very heavy pedestrian and vehicular traffic, Class 4 should be used. In areas, subject to normal pedestrian and vehicle use, e.g., public pavements and roads, at least Class 3 products should be used. In areas subject to light pedestrian and vehicular use, e.g., garden, drives, at least Class1 products should be used.

Table 3.15 Evaluation of abrasion resistance

Class	Marking	Requirement
1	F	No performance measured
3	H	≤23 mm
4	I	≤20 mm

3.4 Leaching experimental programme

The leachate used in this study was derived from the mean used oil concentrations rather than the mean new oil concentration, as they had a greater concentration of heavy metals therefore having greater potential to contaminate the soil below. These concentrations were taken from Coupe et al (2006) as shown in Table 3.16

Table 3.16 Concentrations of used and new oil

Element	Used oil mean concentration (PPM) (n=3)	New oil mean concentration (PPM) (n=3)
Pb	2	<1
Zn	1300	950
Cr	2	<1
Cu	34	<1
Al	15	1
Mo	160	16
Mg	490	13
P	1000	870

The leachate was created from salts and solutions. Figure 3.19 shows the salts that were used to obtain Zn ($Zn\ (NO_3)2\ 6H_2O$), Cu ($Cu\ (NO_3)2\ 3H_2O$), K ($K\ H_2\ PO_4$) and Mg ($Mg\ SO_4\ 7H_2O$) and Figure 3.20 shows the solutions that were used for Pb, Cr, Al and Mo.

Figure 3.19 Salts for leachate

Figure 3.20 Solution for leachate

Once the solution was prepared, 50mm cores were drilled (Figure 3.21) from the blocks and tested. Figure 3.22 provides the setup of the experimental programme. The leachate was placed in a jug (**1**), thereafter by applying pressure the leachate was passed through the core, which was in the test chamber (**2**). For each sample the quantity of leachate that passed through was equal to the volume of the core. In the

final step (**3**) the last 25ml of leachate to pass through the block was collected and timed in order to determine the permeability of the blocks.

Figure 3.21 50mm cores drilled from blocks

Figure 3.22 Set up of leaching tests

Once the leachate was passed through the blocks, the samples were analysed using an Inductively Coupled Plasma (ICP). As stated by Hou and Jones (2000), the main analytical advantages of the ICP originate from its capability for efficient and reproducible vaporization, atomization, excitation, and ionization for a wide range of elements in various sample matrices. Figure 3.23 displays the set up for analysis and the procedure for ICP was as follows;

1. Elements and sample characteristics are inputted into the software

2. A calibration blank (distilled water) and calibration solution (consisted of the maximum concentration expected of each element) are produced to be initially analysed by ICP.

3. ICP disperses the atoms and ions which then emits a visible light. This visible light will be specific to the wavelength of a specific element.

4. From the calibration solution, ICP produces a linear chart which plots light emission (EM) vs concentration (mg/l)

5. After this the samples being tested are analysed. The concentration of each element is then dependent on the EM value that is measured

6. For each element an average is taken from 3 measurements.
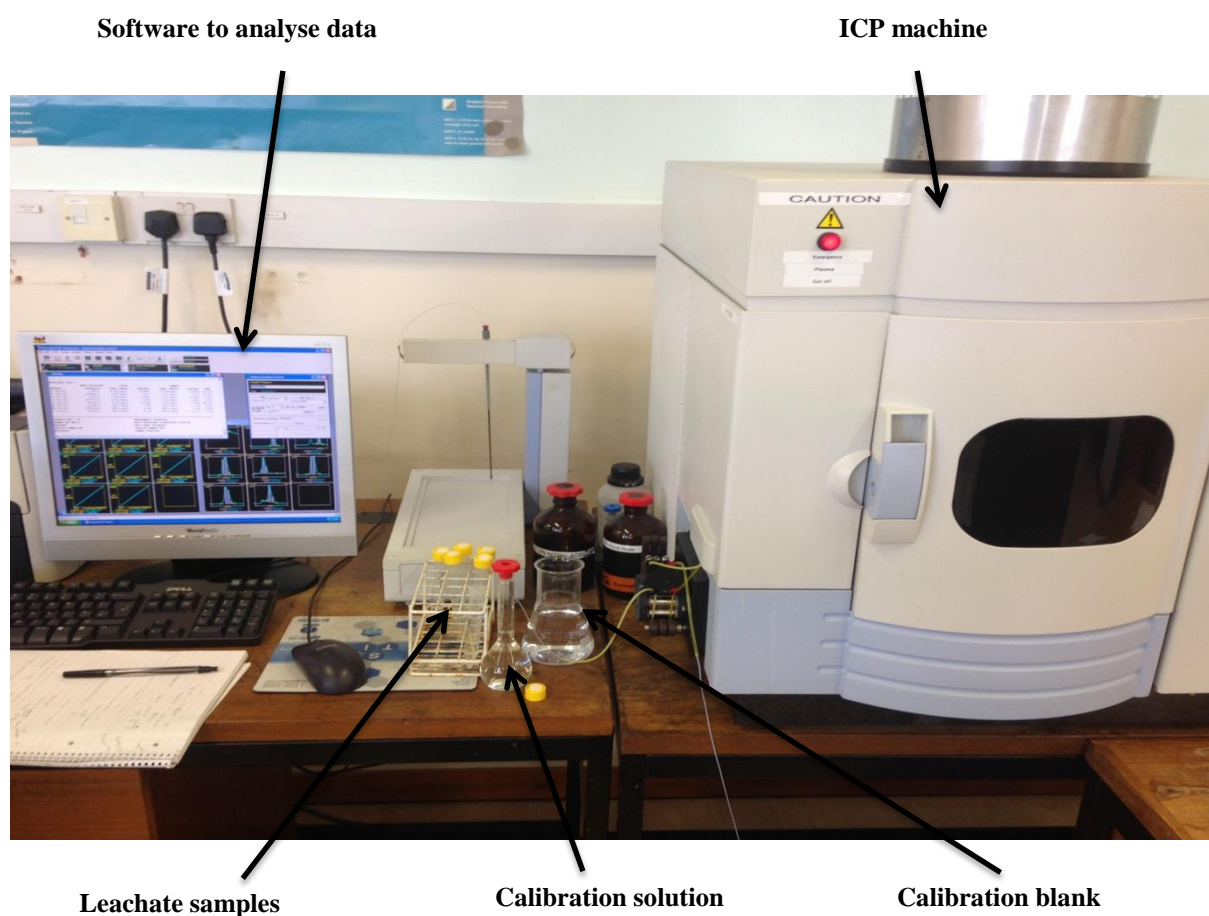
Figure 3.23 Set up of leachate analysis

3.5 Factory and site trial

The project was in partnership with Hanson Formpave who are innovators in permeable paving. The final part of the research programme was to carry out site trials with constructed paved areas using actual factory made paving blocks with the candidate mixes. The two candidate mixes were re-produced in factory conditions and settings.

The programme that was set out to do the trial was as follows;

1. Obtaining materials from manufactures and determine the most efficient and effective way of introducing the materials to the mix.

2. Produce blocks in the same manor that would be expected if they were to produce them on a mass scale.

3. Determine the exact differences between the casting and curing procedures in the laboratory and factory, therefore determine the effect on strength between the two methods.

4. Lay blocks over the winter period on the test bed were SUDS technology is being tested on site.

3.6 Concluding remarks

- To analyse the strength and durability of blocks the programme broke the analysis into two sections, first and second phase.

- The effect of material variability on compressive strength is to be determined for PFA and BPD that was obtained over a 6 month period on a monthly basis.

- A programme was developed for the two candidate mixes that were derived to be compared to the factory control block to determine if they provide a reduction in leaching.

- A programme was set out to conduct trail runs in the factory with the two candidate mixes that were developed.

Chapter 4

Materials used and material variability

This chapter provides details on the materials that were used in this study and the effect of material variability.

4.1 Cement and cementitious constituents.

4.1.1 PC

The PC fulfilled the requirements of BS EN 197-1 CEM I and was supplied by Hanson Heidelberg Cement group. Figure 4.1 and Table 4.1 shows the particle distribution and chemical composition respectively for PC. The average particle size was around 38μm. The particle distribution curve was developed using the Hydro 2000 and Mastersizer 2000 at Coventry University. The chemical composition of each material was determined using X-Ray Fluorescence (XRF) at the University of Leicester.
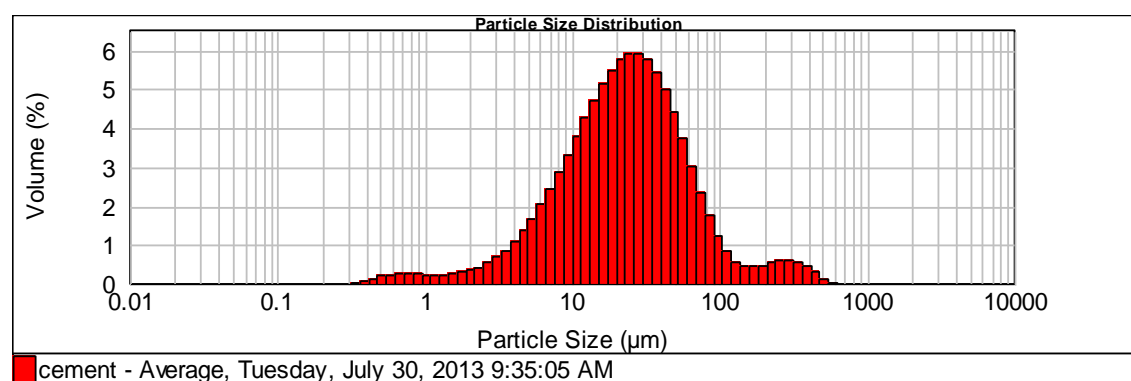
Figure 4.1 Particle distribution of PC

Table 4.1 Chemical properties of PC

Composition	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	LOI
Value(%wt)	19.42	0.36	4.55	2.49	0.023	1.03	60.60	0.22	0.568	0.201	3.62	0.75

4.1.2 PFA

The PFA was obtained from E.ON UK. They are a member of the United Kingdom Quality Ash Association (UKQAA) and have three coal fired power stations; the ash for this project was obtained from the Ratcliffe-on-Soar plant. The average particle size was around 55μm. Figure 4.2 and Table 4.2 shows the particle size distribution and chemical composition respectively for PFA.
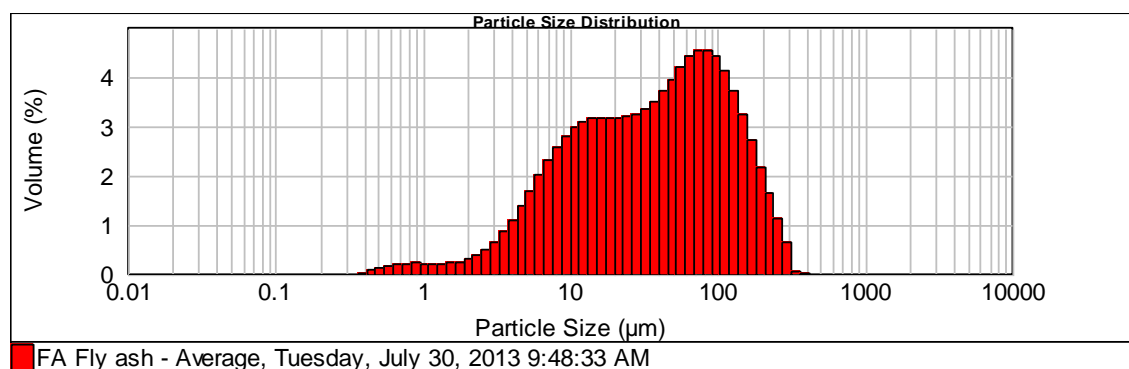
Figure 4.2 Particle distribution of PFA

Table 4.2 Chemical properties of PFA

Composition	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	LOI
Value(%wt)	47.75	0.97	24.12	10.22	0.160	1.72	3.25	0.73	2.440	0.240	0.654	7.45

4.1.3 GGBS

The GGBS for this study was provided by Hanson from the Port Talbot plant which is situated near the Port Talbot docks. The material was obtained from this plant because if this material was to be successful then this is closest source to the manufacturing plant and the GGBS from this plant is likely to be the one being used. Figure 4.3 and Table 4.3 shows the particle distribution and chemical composition respectively for GGBS. The average particle size was around 20µm.
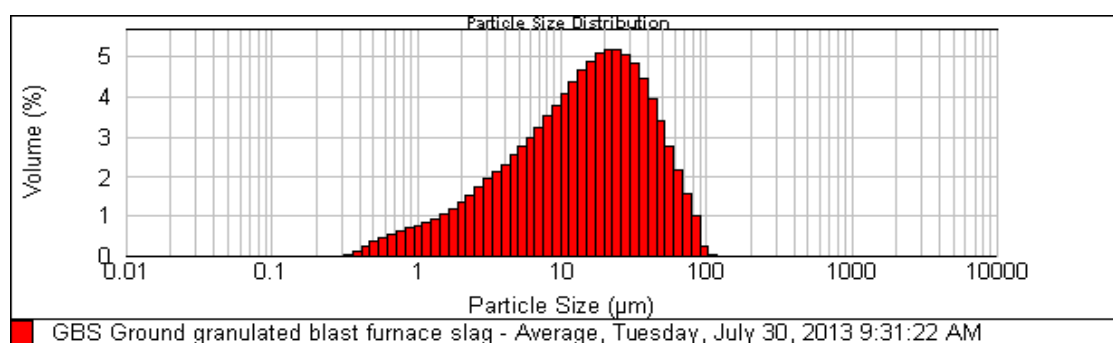
Figure 4.3 Particle distribution of GGBS

Table 4.3 Chemical properties of GGBS

Composition	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	LOI
Value(%wt)	33.28	0.57	13.12	0.32	0.316	7.74	37.16	0.33	0.478	0.009	2.212	4.42

4.1.4 BOS

The BOS used in this study obtained from the TATA steels operation in Scunthorpe. The slag was obtained in its purest form and therefore had to be ground in order to obtain particle sizes that would make it adequate to be used as a cementitious constituent. It was determined that the material passing below 150 µm would be

sufficient and therefore the ball mill was used to grind the material before it being sieved. The average particle size was around 30μm. Figure 4.4 and Table 4.4 shows the particle size distribution and chemical composition respectively for BOS.
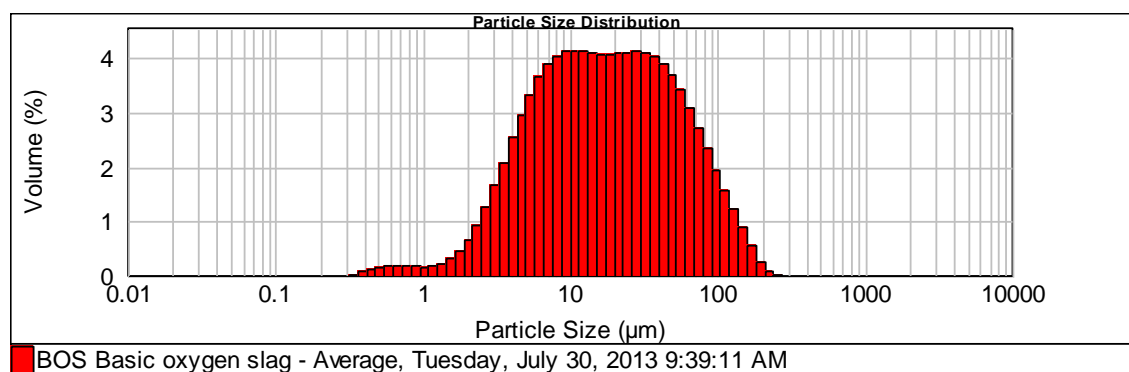
Figure 4.4 Particle distribution of BOS

Table 4.4 Chemical properties of BOS

Composition	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	LOI
Value(%wt)	13.94	0.70	2.98	25.99	3.166	6.56	39.57	0.06	0.027	1.516	0.277	1.42

4.1.5 MK

The MK was obtained from IMERYS who are based in Cornwall. As stated by IMERYS, the carefully controlled calcination process gives a specific form of MK which is highly reactive. Figure 4.5 and Table 4.5 shows the particle size distribution and chemical composition respectively for MK. The average particle size was around 7μm.
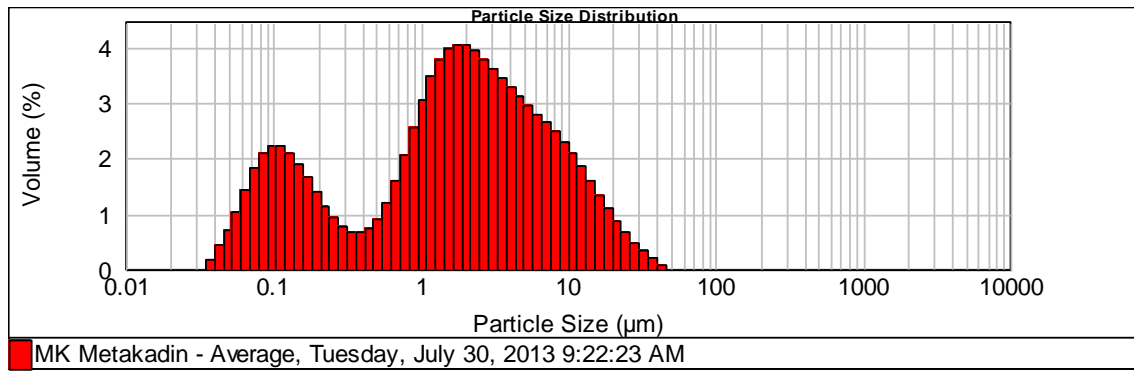
Figure 4.5 Particle distribution of MK

Table 4.5 Chemical properties of MK

Composition	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	LOI
Value(%wt)	54.06	0.02	40.65	0.77	0.008	0.23	0.03	0.17	1.888	0.161	0.016	2.55

4.1.6 SF

The SF in this study was obtained from Elkem materials that are based in Norway. As stated by Elkem the undesified grade 940 dry SF used in this study has a typical bulk density of 200-350 Kg/m^3.Elkem state that the quality assurance of the SF is covered by ISO 9001 and complies with ASTM C-1240 and CAN/CSA-A23.5 standards for SF and with new European standards prEN 13263. Figure 4.6 and Table 4.6 shows the particle size distribution (supplied by Elkem) and chemical composition respectively for SF. The average particle size was around 0.7μm.
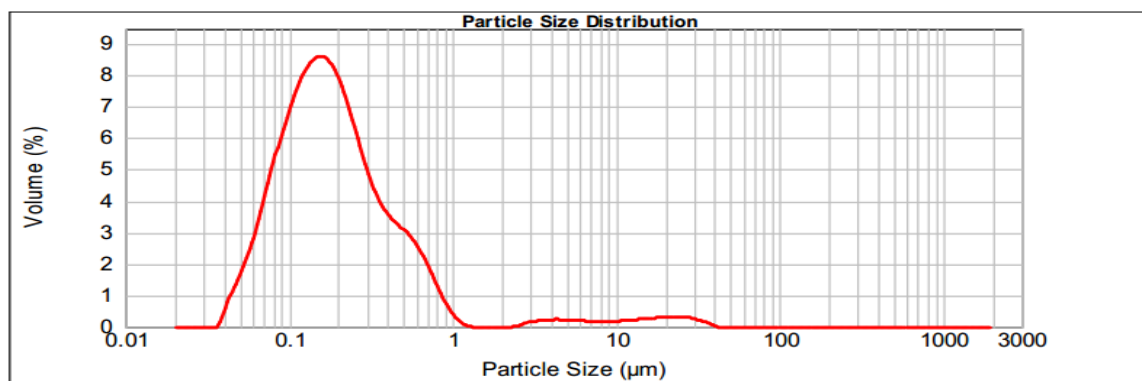
Figure 4.6 Particle distribution of SF

Table 4.6 Chemical properties of SF

Composition	SiO$_2$	TiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	MnO	MgO	CaO	Na$_2$O	K$_2$O	P$_2$O$_5$	SO$_3$	LOI
Value(%wt)	94.21	0.01	0.48	0.71	0.013	0.55	0.37	0.35	1.153	0.040	0.166	2.31

4.1.7 GP

The GP was provided by the Day group Ltd based in London. As with the BOS the GP did not come in the particle size which would directly allow it to be used as a cementitious constituent. The 4mm-dust GP obtained from Day Group went through the same grinding procedure with the ball mill as BOS and the same limit of maximum particle size of 150µm was set. Figure 4.7 and Table 4.7 shows the particle size distribution and chemical composition respectively for GP. The average particle size was around 100µm.
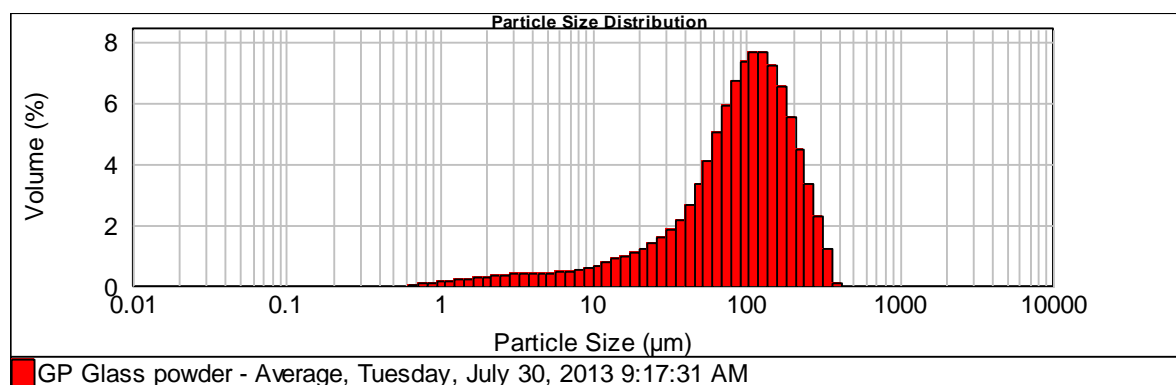
Figure 4.7 Particle distribution of GP

Table 4.7 Chemical properties of GP

Composition	SiO$_2$	TiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	MnO	MgO	CaO	Na$_2$O	K$_2$O	P$_2$O$_5$	SO$_3$	LOI
Value(%wt)	69.56	0.07	2.01	0.65	0.0.32	1.19	10.61	12.28	0.979	0.032	0.181	1.24

4.1.8 BPD

The BPD was obtained from the Cemex plant in rugby. Cemex is one of the UK's biggest building materials company and the BPD was obtained from there cement plant in Rugby. Figure 4.8 and Table 4.8 shows the particle distribution and chemical composition respectively for BPD. In Figure 4.8 the particle size distribution is stated to be for CKD, however it is for BPD (LOI<10%). This is due to the initial confusion in thinking that these materials were the same, when in fact as described in 2.4.7 they were different. The average particle size was around 56μm.
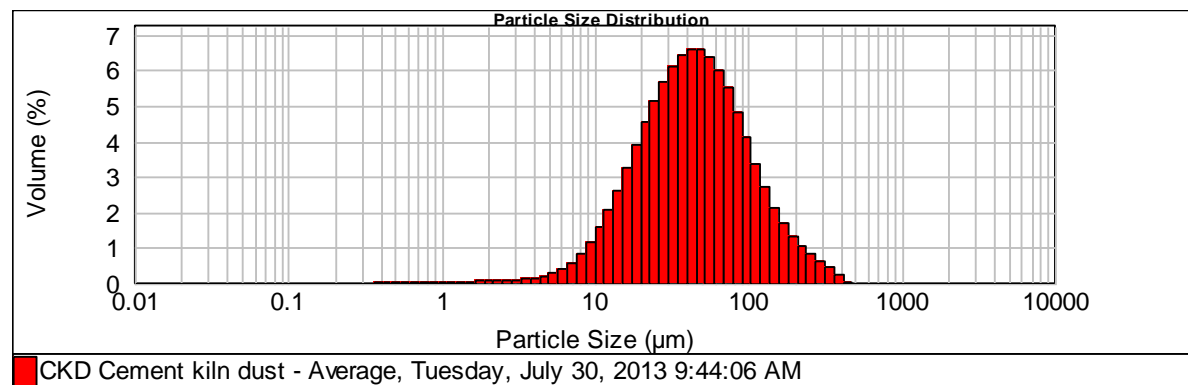
Figure 4.8 Particle distribution of BPD

Table 4.8 Chemical properties of BPD

Composition	SiO$_2$	TiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	MnO	MgO	CaO	Na$_2$O	K$_2$O	P$_2$O$_5$	SO$_3$	LOI
Value(%wt)	16.85	0.23	4.16	2.36	0.043	1.04	53.60	0.50	4.278	0.147	6.661	6.76

4.2 Aggregates

In the production of paving blocks Hanson Formpave use three different types of aggregates. These are 4mm-dust, 6mm and sand. In order to get as accurate results the

aggregates were obtained from Hanson Formpave and used to produce the concrete paving blocks manufactured in the laboratory. Table 4.9 shows the sieve analysis and density of the three different aggregates.

Table 4.9 Sieve analysis and density of aggregates.

Aggregate	Sieve size							Density (Kg/m^3)
	10mm	5mm	2.35mm	1.18mm	600μm	600μm	600μm	
4mm-dust	100	100	71	42	8	3	0	2718
6mm	100	54	20	17	16	14	8	2691
Sand	100	100	99	96	88	33	3	2021

4.3 Analysis of material variability

4.3.1 Introduction

Cementitious constituents are not the primary products that are produced but some like GGBS and PFA have quality control and standards to regulate the properties of the material. Other possible replacement materials such as BPD and BOS have no standards and therefore there is no control over the particle size distribution or chemical composition. This section of the thesis analyses the effect of material variability on the compressive strength and the two materials that were analysed were PFA and BPD.

From an industry point of view it is assumed that greater concern would come from having variability from a single source on a monthly basis. Therefore the variation in chemical/physical properties of material obtained on a monthly basis over a period of

6 months was analysed and the effect of this on the compressive strength in semi-dry cement paste was determined.

4.3.2   Materials investigated.

The two materials investigated were PFA and BPD. The reason for this was because it allowed for the investigation of one material (PFA) that is regulated and one material (BPD) that regarded as waste. The study would therefore be able to conclude what is likely to have greater impact on each type of material, as well as this it would allow the study to review the replacements in the candidate mixes and ensure that they are within a suitable range.

4.3.2.1 PFA

The PFA was obtained from E.ON UK who is a member of the United Kingdom Quality Ash Association. UKQAA represent the producers and promotes the use of coal ash and biomass ash products. The particle distribution (carried out at Coventry University) of the PFA obtained over the 6 months is shown in Table 4.10. It can be seen from the Table that there is a slight variability in the fineness of PFA from month to month. The difference is not immense, with fineness of each sample looking to have similar averages. However this does not rule out the fact that if there were to be differences in strengths as replacement level increased, than one of the potentials factors for this could be due to some samples having finer particle. Li and Wu (2005) reported that due to average particle sizes of PFA increasing from 12.1 to 18.8 μm it resulted in 28 day strengths decreasing from 36.4 to 33 MPa.

Table 4.10 percentage of PFA passing given meshes

Mesh No	Aperture	Passing					
	µm	Below %					
		July	Aug	Sept	Oct	Nov	Dec
100	150	90	94	91	94	95	90
140	106	81	88	82	86	88	81
200	75	70	80	72	76	78	70
325	45	55	65	58	61	63	55
400	38	51	60	53	56	58	50

Table 4.11 shows the chemical composition of PFA for the 6 monthly samples, which was determined using XRF at the University of Leicester. PFA is a popular replacement material because of the high SiO_2 content, which reacts with the secondary CH from the initial hydration process. The four oxides that make up over 80% of the chemical composition are SiO_2, Al_2O_3, Fe_2O_3 and CaO. PFA consists of greater amounts of SiO_2 and the greatest difference was noted between November and August, which had SiO_2 quantities of 45.85% and 52.29% respectively. The difference between largest and smallest quantity for Al_2O_3, Fe_2O_3 and CaO was 4.67%, 2.83% and 3.32% respectively.

Table 4.11 Chemical composition of PFA from July to December.

Composition	SiO_2 (%)	TiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	SO_3 (%)
PFA-JUL	46.53	0.92	24.43	9.12	0.06	1.62	2.81	0.91	2.75	0.29	0.49
PFA-AUG	52.29	0.93	22.57	10.38	0.07	1.44	3.00	0.77	2.35	0.22	0.51
PFA-SEPT	50.49	0.98	22.75	7.55	0.08	1.54	3.95	0.73	2.27	0.37	0.57
PFA-OCT	49.82	0.89	22.08	9.57	0.10	1.53	4.20	0.63	1.97	0.32	0.61
PFA-NOV	45.85	0.82	19.76	8.42	0.10	2.09	6.13	0.79	2.05	0.51	0.84
PFA-DEC	46.78	0.97	21.82	8.46	0.11	1.79	5.12	0.63	2.02	0.35	0.48

Tables 4.10 and 4.11 show that although samples were procured from the same source there was variability in both chemical composition and fineness on a monthly basis. The reasons for this variability could be due to samples being obtained from a different manufacturing batch, new batch of raw material being burned, change in machinery setting etc. The exact reason is unknown however if industry was to implement the use of these materials, this level of variability would be likely to occur and therefore it is important to note the effect the variability would have on the strength.

4.3.2.2 BPD

The BPD used was obtained from the Cemex plant in Rugby. The particle distribution of the BPD obtained over the 6 months is shown in Table 4.12. It comparison to Table 4.10 it can be seen that the variability of fineness for BPD is larger than that of PFA. The reason for the higher variability is assumed to be due to BPD being a waste material, therefore no control over the particle distribution when supplied for use. It shows the main difference occurs when the material is passed through the 38µm mesh; the largest differences are between the September/November and October samples at 31.95% and 32.68% respectively. With such large differences it is likely that there will be a larger degree of strength change due to the particle size distribution when analysing BPD in comparison with PFA.

Table 4.12 percentage of BPD below given meshes

Mesh No	Aperture µm	July	Aug	Sept	Oct	Nov	Dec	BPD
					Passing Below %			
100	150	91	96	88	96	86	93	93
140	106	83	89	74	91	73	85	86
200	75	79	78	58	85	57	72	74
325	45	48	56	34	67	34	48	50
400	38	41	48	28	60	27	39	42

Table 4.13 shows the chemical composition of BPD samples. The chemical properties of BPD are similar to that of PC; however BPD contained greater quantities of alkalis (K_2O) and sulphur trioxide (SO_3). It can be seen from Figure 4.32 that there were noticeable variability's in the chemical composition over the 6 months period. The four oxides which make up over 80% of the composition are CaO, SiO_2, K_2O and SO_3. BPD consists largely of CaO and the largest difference was between July and October, which had CaO quantities of 44.03% and 53.13% respectively. The difference between largest and smallest quantity for SiO_2, K_2O and SO_3 was 4.58%, 5.97% and 7.18% respectively.

Table 4.13 Chemical composition of BPD from July to December.

Composition	SiO₂ (%)	TiO₂ (%)	Al₂O₃ (%)	Fe₂O₃ (%)	MnO (%)	MgO (%)	CaO (%)	Na₂O (%)	K₂O (%)	P₂O₅ (%)	SO₃ (%)
BPD-JUL	12.79	0.19	3.47	1.88	0.04	0.82	44.03	1.16	10.06	0.12	12.22
BPD-AUG	15.58	0.22	4.26	2.26	0.04	0.98	50.32	0.70	5.80	0.13	9.23
BPD-SEPT	14.85	0.20	3.70	2.11	0.04	0.85	47.43	0.88	7.46	0.12	13.42
BPD-OCT	15.13	0.21	3.84	2.24	0.04	0.93	53.13	0.66	5.09	0.14	6.25
BPD-NOV	16.52	0.23	4.17	2.29	0.05	1.11	49.57	0.71	6.29	0.14	11.18
BPD-DEC	17.34	0.20	3.75	2.35	0.05	1.05	52.75	0.52	4.03	0.15	9.94
BPD-T	16.85	0.23	4.16	2.36	0.04	1.04	53.60	0.50	4.28	0.15	6.66

The variability noted for chemical composition and fineness of BPD was larger than PFA. This is due to BPD being a defined as a 'waste material', while PFA is regulated (BS EN 197-1) to a degree where it can be used as a cementitious constituent. This results in no control over the material that is provided for use and the variability's stated in analysis of PFA occurring to a greater degree.

4.3.3 Mix Design

From review of PFA and BPD literature (Papadakis (1999), Uygunoğlu et al (2012), Siddique et al (2012), (Siddique (2006), Maslehuddin (2009)), reports showed that they can be used effectively as replacement but the replacement levels at which they can be used varies. The analysis of material variability focused on binary blends instead of ternary blends as this would allow the sole reason for the variability to be due to that one material. In this study PFA was used to replace cement by up to 30%wt in increments of 10% and BPD was used to replace cement by up to 10% in increments of 5%. Table 4.14 shows the cement paste mixes that were produced. The water/cementitous ratio was 0.15.

Table 4.14 Mix proportions for PFA and BPD samples

Mix	July	August	September	October	November	December
Cement:PFA10	90:10	90:10	90:10	90:10	90:10	90:10
Cement:PFA20	80:20	80:20	80:20	80:20	80:20	80:20
Cement:PFA30	70:30	70:30	70:30	70:30	70:30	70:30
Cement:BPD5	95:5	95:5	95:5	95:5	95:5	95:5
Cement:BPD10	90:10	90:10	90:10	90:10	90:10	90:10

4.3.4 Results and discussion

Table 4.15 shows the compressive strength at 14 and 28 days for PFA and BPD paste mixes. The compressive strength for the control mix (100% PC) was 64.3 MPa and 70.7 MPa for 14 and 28 days respectively. The results show that as PFA levels increased the strengths decreased for all 6 months analysed. The reduction in strength is assumed to be due to SiO_2, which reacts with the excess lime from the initial hydration to produce C-S-H gel, accumulating within the inner PFA particles where it is unable to react (Barbhuiya et al (2009)), resulting in a slow pozzolanic reaction and dilution effect (Wongkeo (2014)). In comparison to the control mix no PFA mix achieved greater strengths and the sample that came closest to the control mix was the August sample at 10% replacement. BPD as a replacement material produced greater results than PFA and as replacement levels increased from 5% to 10% the strengths increased. The chemical compositions of BPD is very similar to that of PC, however it contains greater quantities of finer particles. It is therefore assumed that the same compounds as those produced within hydration by PC are also produced with BPD. However with the finer particles it increases the reactivity of oxides as well as increases particle packing which would lead to an increase in strength. The greatest compressive strength achieved with a mix containing BPD was the October 10% sample which had strengths of 70.4 MPa and 76.1 MPa at 14 and 28 days respectively. At 28 days all mixes containing BPD produced greater strengths than the control mix and at 14 days the mixes with the least amount of particles passing through the finest mesh (September and November) were below the strengths of the control mix.

Table 4.15 Compressive strength (MPa) for mixes

Mix	July		August		September		October		November		December	
Day	14	28	14	28	14	28	14	28	14	28	14	28
Cement :PFA10	55.8	63.4	59.3	68.4	57.0	66.9	58.7	64.5	55.1	60.6	56.0	64.3
Cement :PFA20	52.6	57.9	54.9	60.8	52.5	61.4	54.7	60.4	51.5	59.4	52.1	58.4
Cement :PFA30	45.2	52.9	49.9	57.7	45.9	53.4	48.4	54.6	47.0	52.9	45.9	52.1
Cement :BPD5	61.6	68.0	60.8	68.8	56.5	64.7	63.7	69.7	58.3	65.3	62.5	68.6
Cement :BPD10	64.5	73.2	67.5	74.5	59.8	72.0	70.4	76.1	63.3	72.9	65.3	74.4

4.3.4.1 Cement: PFA10

Figures 4.9-4.12 show the correlation between SiO_2/Fineness and 14/28 day compressive strength for 10% fly ash replacement. The fineness correlation is based on the average particle size. The results show that at 14 days there was greater correlation between SiO_2 ($r^2 = 0.83$) content than the particle size ($r^2 = 0.21$). At 28 days the same conclusion could be made but this time the gap was much greater between the regression values, with SiO_2 having 0.83 and fineness having 0.01. When analysing the fineness results it can be seen that results for November was a possible anomaly and if they were to be taken out the regression values for 14 and 28 days would be 0.96 and 0.49 respectively. This would have resulted in 14 day strength being a consequence of fineness and 28 day strength being down to the SiO_2 content.

It is assumed that the anomaly could be due to the SiO_2 content in November being the lowest out of all the samples, even though it had the 2nd highest average particle size. The reason for this anomaly backs up the assumption that at 10 % replacement the SiO_2 content is the main reason for strength gain.
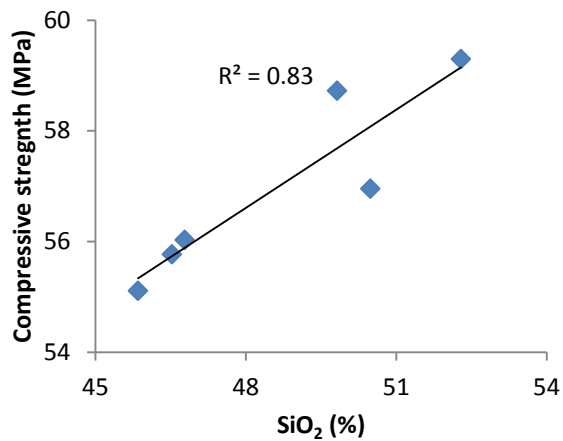
Figure 4.9 SiO$_2$ vs 14 day compressive strength PFA10
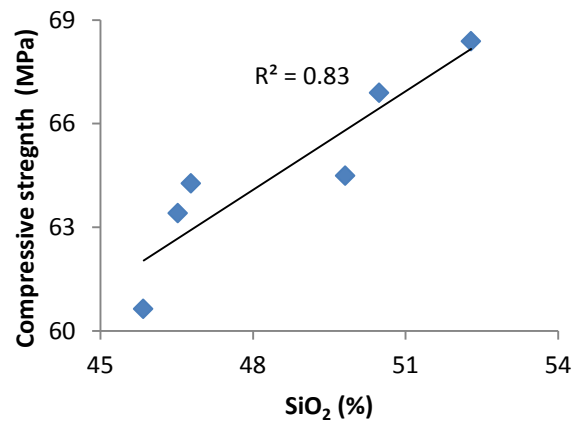
Figure 4.10 SiO$_2$ vs 28 day compressive strength PFA10
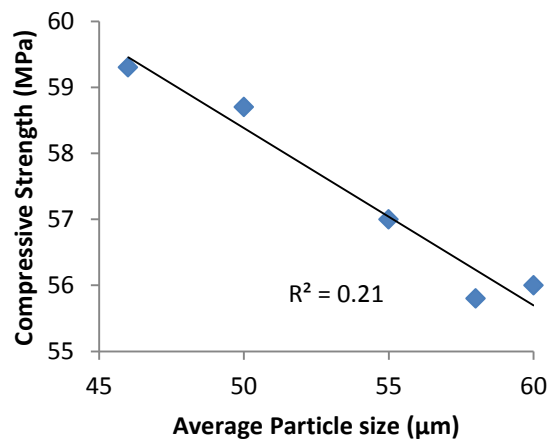
Figure 4.11 Fineness vs 14 day compressive strength PFA10
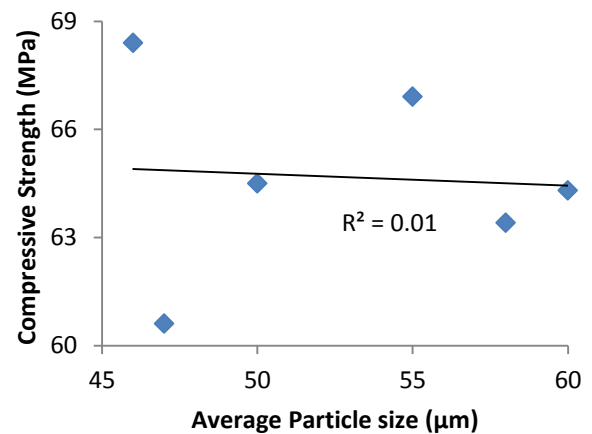
Figure 4.12 Fineness vs 28 day compressive strength PFA10

4.3.4.2 Cement: PFA20

Figures 4.13-4.16 show the correlation between SiO_2/Fineness and 14/28 days compressive strength for 20% fly ash replacement. The results show that at 14 and 28 days compressive strength, the SiO_2 had regression values of 0.64 and 0.69 respectively and for the fineness it was 0.2 and 0.31 respectively. The results showed at 28 days the correlation between SiO_2 content and strength was not as strong as at 10% replacement and fineness correlation was slightly higher. A possible reason for this could be due to the SiO_2 being deeper within the PFA particles therefore needing a longer time to react with the CH to create the extra C-S-H gel. Therefore if a greater quantity and larger particles of PFA is added the fineness should have greater influence. The same anomaly noted for the November sample at 10% PFA replacement was also relevant at 20% replacement because if this value was to be taken out then the regression values for fineness against strength would be 0.9 and 0.49 for 14 and 28 days respectively. This would result in concluding, at 14 days fineness has greater effect and at 28 days the SiO_2 has greatest influence.
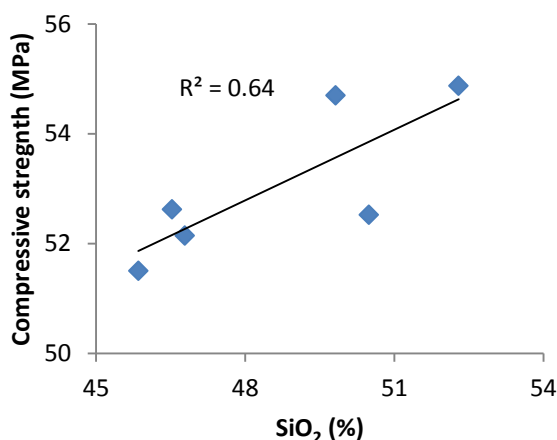
Figure 4.13 SiO_2 vs 14 day compressive strength PFA20
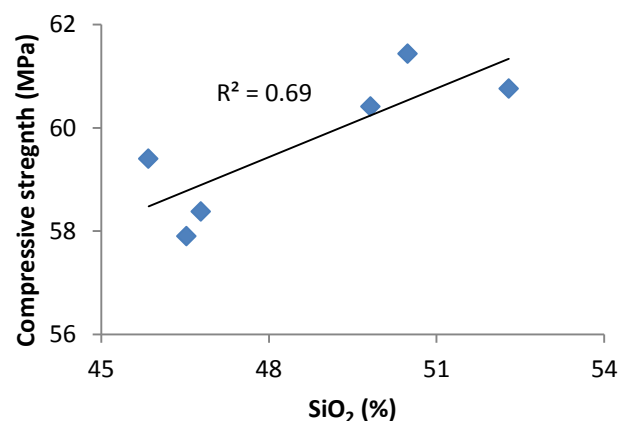
Figure 4.14 SiO_2 vs 28 day compressive strength PFA20
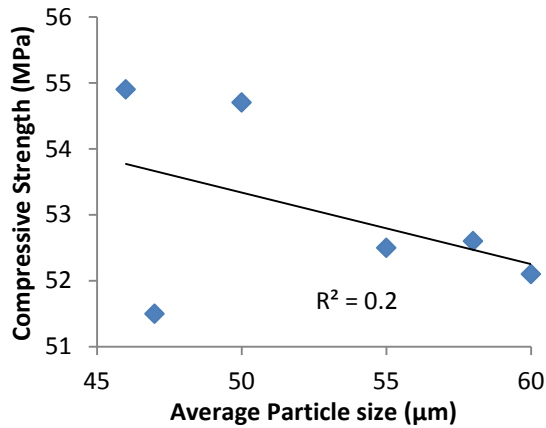
Figure 4.15 Fineness vs 14 day compressive strength PFA20
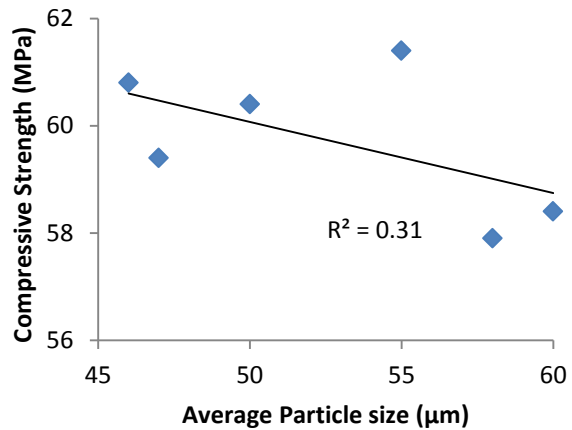
Figure 4.16 Fineness vs 28 day compressive strength PFA20

4.3.4.3 Cement: PFA30

Figures 4.17-4.20 show the correlation between SiO_2/Fineness and 14/28 days compressive strength for 30% fly ash replacement. The results show that at 14 and 28 days compressive strength the SiO_2 had regression values of 0.48 and 0.70 respectively and for the fineness it was 0.68 and 0.49 respectively. The results show that at 14 days the fineness has greater influence than SiO_2 and this is believed to be due to the particle packing and increase surface area, as well due to the extra time that is required for the excess CH to react with the SiO_2 which is within the inner parts of the PFA particles (Barbhuiya et al (2009)). At 28 days the SiO_2 content had greater correlation with strength however the fineness still had greater correlation than at 10% and 20% replacement. Fineness influences strength because the finer the particles are the greater the reactivity will be and at 28 days it can be assumed that the fly ash content has a significant effect on strength as both fineness and SiO_2 content have correlations with the strength.
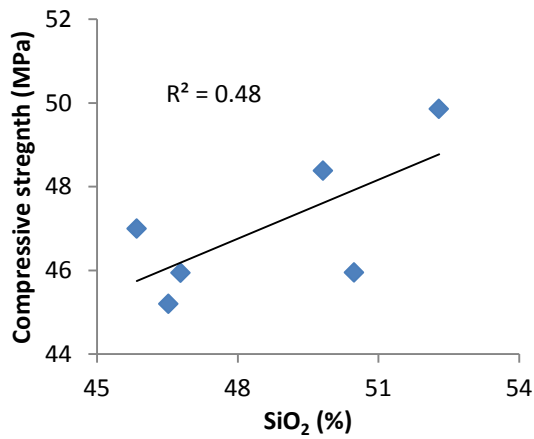
Figure 4.17 SiO₂ vs 14 day compressive strength PFA30
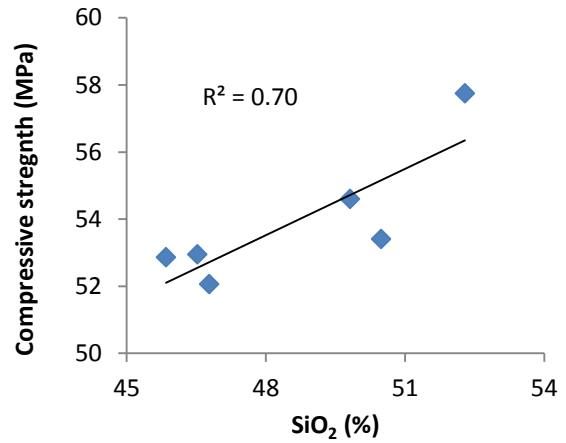
Figure 4.18 SiO₂ vs 28 day compressive strength PFA30
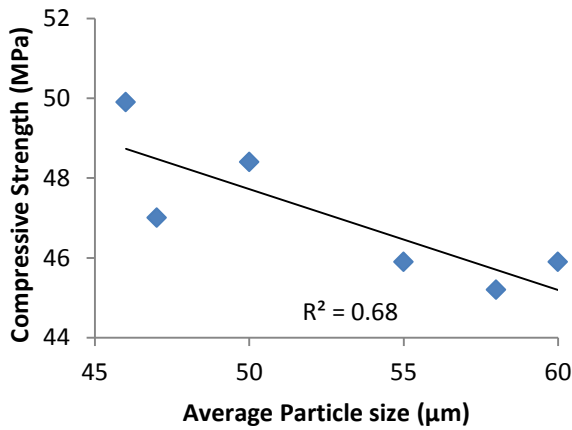
Figure 4.19 Fineness vs 14 day compressive strength PFA30
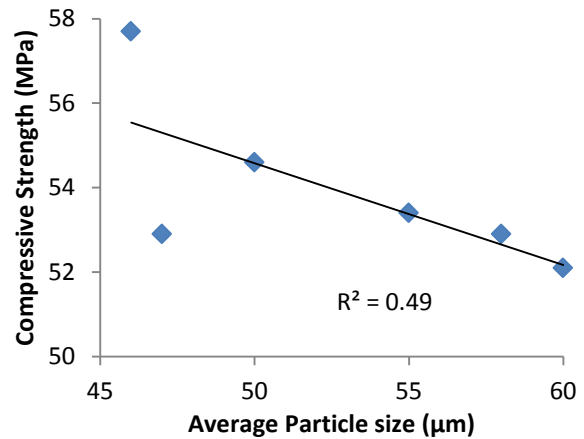
Figure 4.20 Fineness vs 28 day compressive strength PFA30

4.3.4.4 Cement: BPD5

Figures 4.21-4.24 show the correlation between Fineness/SiO_2 +CaO and 14/28 days compressive strength for 5% BPD replacement. The results show that at 14 and 28 days the strength of the paste was dependent on the fineness of the material. As

Figures 4.21 and 4.22 show, as time increased from 14 to 28 days the correlation increased from 0.72 to 0.89 respectively. CaO and SiO_2 are the two predominant oxides within BPD and during hydration it is assumed that these oxides are the predominant reason for strength increase through the production of CSH. When analysing the correlation between chemical properties and strength there was no significant correlation between the two, as correlation values were only 0.1 for 14 and 28 days respectively. The low impact of CaO and SiO_2 content is assumed to be due to the large differences within the particle distribution. This results in mixes containing finer particles providing a more intense reaction and denser hydrated structures and hence greater strengths. The effect of chemical composition can be seen when comparing samples obtained in July and December/ September and November as they have very similar particle distribution values. For July and December the CaO+SiO_2 content was 56.82% and 69.68% respectively and for September and November it was 62.28% and 66.09% respectively. In both comparisons it was noted that the greater content of CaO+SiO_2 resulted in a greater strength being achieved.
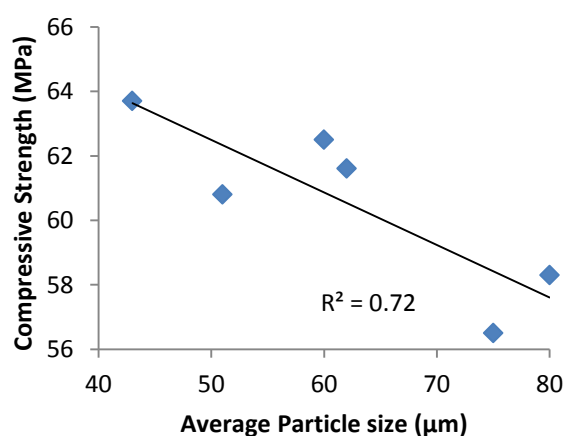
Figure 4.21 Fineness vs 14 day compressive strength BPD5
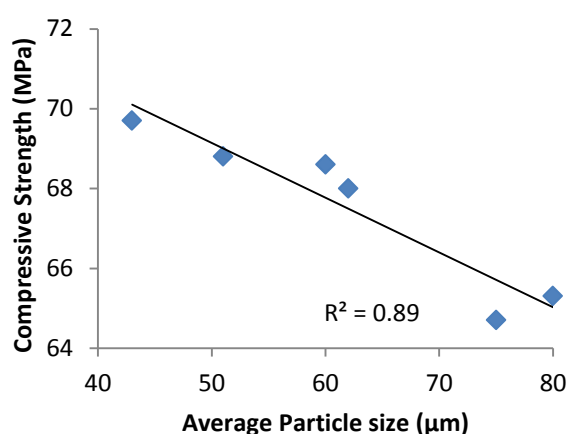
Figure 4.22 Fineness vs 28 day compressive strength BPD5
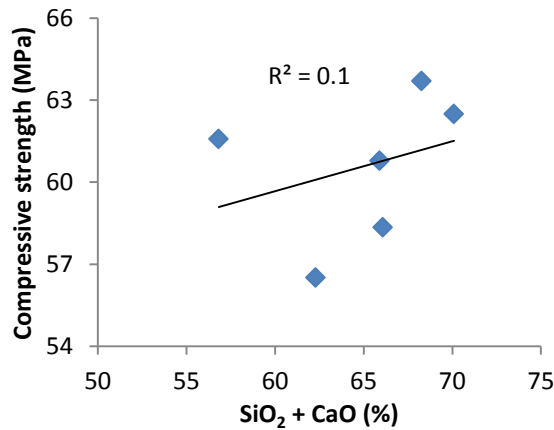
Figure 4.23 SiO$_2$ +CaO vs 14 day compressive strength BPD5
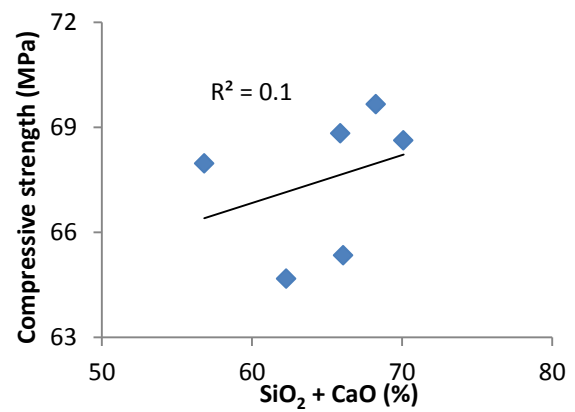
Figure 4.24 SiO$_2$ +CaO vs 28 day compressive strength BPD5

4.3.4.5 Cement: BPD10

Figures 4.25-4.28 show the correlation between Fineness/SiO$_2$ +CaO and 14/28 days compressive strength for 10% BPD replacement. In comparison to 5% replacement, 10% replacement showed an increase in the regression values for fineness and SiO$_2$ +CaO. The correlation between fineness and compressive strength for 14 and 28 days was 0.82 and 0.83 respectively and as noted in BPD1 the fineness of the material seem to dictate the strength achieved, as BPD had a greater average particle size the strength decreased. The correlation between SiO$_2$ +CaO and strength at 14 and 28 days was 0.19 and 0.32 respectively. Although at 10% replacement the oxide content seem to gain greater importance in strength development than at 5% the regression values were still low. When comparing the July and December/ September and November samples which had similar particle distribution values the same trend as noted in 5% replacement was noted, in which the samples with greater SiO$_2$ +CaO content produced greater results.
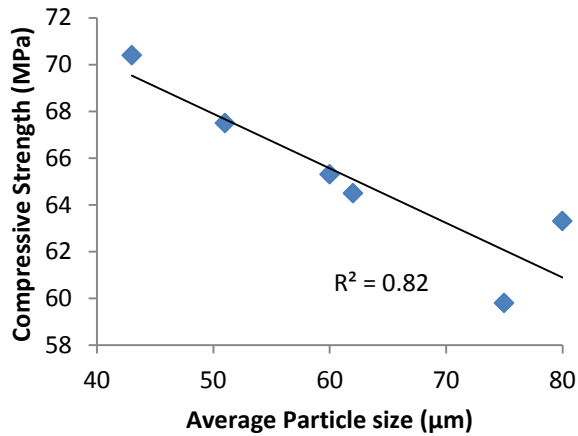
Figure 4.25 Fineness vs 14 day compressive strength BPD10
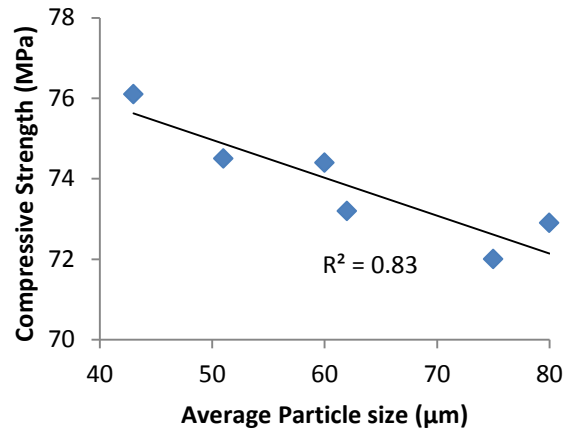
Figure 4.26 Fineness vs 28 day compressive strength BPD10
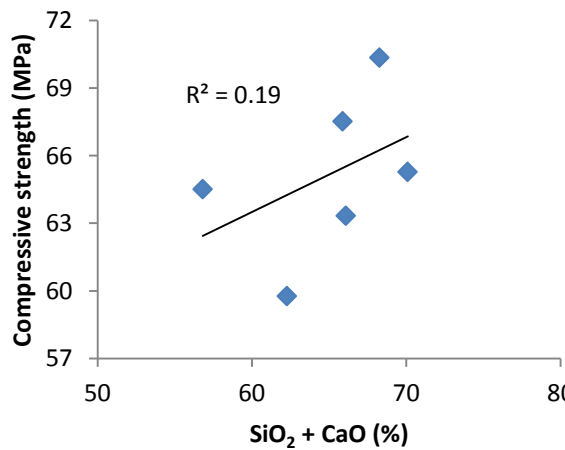
Figure 4.27 SiO₂ +CaO vs 14 day compressive strength BPD10
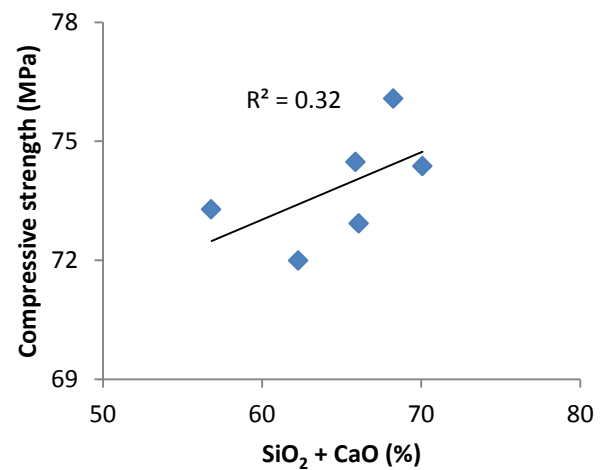
Figure 4.28 SiO₂ +CaO vs 28 day compressive strength BPD10

4.4 Concluding remarks

When analysing the 3 levels of replacement (PFA10, PFA20 and PFA30) it can be noted that as replacements levels increased, the average particle size increased to contribute to the strength. However the SiO_2 content at 28 days showed the greatest correlation to strength. In order to determine a suiTable range, the difference in

strength and difference in SiO_2 content were compared to the minimum 28 day compressive strength at each replacement level. At 10% replacement it is suggested that in order for there to be less than a 3% difference in strength the SiO_2 difference should be no greater than 1%. At 20% replacement it is suggested for there to be less than a 3% difference in strength the SiO_2 difference should be no greater than 2.5%. At 30% replacement it is suggested for there to be less that a 3% difference in strength the SiO_2 difference should be no greater than 3%. It can be seen that as PFA levels increase the SiO_2 difference suggested also increases. This is because the fineness increases to have impact on strength as replacement levels increase however as seen in Figures 4.9-4.20 the SiO_2 at 28 days still provides a greater correlation to strength.

As PFA is a controlled substance under BS 3892: Part 1, the fineness of the material is controlled as the manufacturer has a greater control over this process. With regards to the chemical composition the PFA is dependent on the batch of material that is being burned. Therefore in a cementitious constituent that is regulated the chemical composition of the material should be considered to a greater degree than the fineness.

When analysing the 2 levels of replacement (BPD5 and BPD10) it can be noted that as replacements levels increased, the average particle size was the main contributor to strength. The reason for this is because BPD is referred to as a 'waste material' therefore the material that is provided for use does not have to meet any standards. It is suggested that as well as the chemical regulations stated in the analysis of PFA, there should also be a suiTable range on the average particle size. In order to determine a suiTable range, the difference in strength and difference in fineness content were compared to the minimum 28 day compressive strength at each

replacement level. It is suggested that for both 5% and 10% replacement the average particle size should not vary by more than 15μm.

4.5 Summary of Main Findings

The aim of this chapter was to review the material being used as well as analyse the effect on strength of variation in chemical/physical properties.

- The materials being used in the first and second phase of the study were analysed and there chemical and physical properties were obtained through the use of particle size distribution and XRF.

- Two materials were analysed to determine the effect of chemical and physically variability. The first of these was a commercially available replacement (PFA) and secondly a material which has no control over its properties when delivered as a replacement (BPD)

- The project successfully obtained samples over a 6 month period and analysed the effect of variability in chemical and physical composition on the compressive strength of semi dry cement paste cubes.

- For both PFA and BPD the chemical composition of the major oxides had similar variability's over the 6 months being analysed, however the particle distribution was much more variable for BPD than PFA.

- With PFA the trends noted were that as PFA levels increased in replacement the fineness of material played a greater role in strength development, however the chemical composition had the greatest correlation to the strength at 28 days for each replacement.

- It is suggested that if the candidate mixes were to use a material that was regulated than the chemical composition should be analysed. This is in order

to ensure that the limits fall within the limits stated in 4.4 to ensure that there is no difference in strength greater than 3%.

- The high variability in BPD particle distribution played a major role in the strength development at both 5% and 10% replacement. The samples with finer particles produced the greatest strength and this is assumed to be due to particle packing as well as finer particles having greater reactivity.

- It is suggested that if the material in the candidate mixes is a waste material than there should be limits on chemical composition as stated in 4.4and to a greater degree on the fineness of the material. For a material that is used in low level replacement (up to 10%) an average particle size difference of 15µm is suggested to ensure that there is no difference in strength greater than 3%.

Chapter 5

First phase- Cement paste results

5.1 Introduction

This chapter provides the results that were obtained in the first phase, with the mixes derived from Minitab 16.2.2 and produced as 50mm cement paste (Cementitious materials + Water) cubes.

5.2 Results

5.2.1 Compressive and splitting tensile strengths.

5.2.1.1 PC/PFA/GGBS

Table 5.1 gives the results for the 14 day compressive and splitting tensile strengths, for the paste mixes designated by Minitab containing PC/PFA/GGBS. The compressive and splitting tensile strength values were entered into Minitab and the contour plots generated are shown in Figures 5.1 and 5.2 respectively. The results show that binary mixes containing PC/GGBS provided greater strengths than PC/PFA. Although presence of PFA within the matrix produces CSH from the free lime after the PC hydration it assumed that due SiO_2 being within the inner part of particles (Barbhuiya et al (2009)) the formation of strength occurs over a longer period of time in comparison to PC/GGBS. Furthermore the chemical composition of GGBS allows it to be self cementitous and it also increases the density of the

microstructure by reducing the content and size of calcium hydroxide crystals. In ternary pastes (PC/PFA/GGBS) as the quantity of GGBS increased in relation to the PFA the strengths were greater. The same trends detected in this study for binary and ternary paste mixes was also noted by Atici and Ersoy (2008), results in this study exhibited that GGBS in concrete interlocking paving blocks could be used in a higher percentage than PFA and provide greater strength. When used in a ternary mix it was shown that at the same PC level as GGBS increases in comparison to PFA the strengths increased. The mix that produced the greatest compressive strength (37.3 MPa) and splitting tensile strength (4.1 MPa) consisted of 60% PC and 40% GGBS.

Table 5.1 Compressive and splitting tensile strength for PC/PFA/GGBS paste mixes at 14 days.

	Mix number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
PC (%wt)	43	24	24	60	14	14	20	26	20	44	60	0	0
PFA (%wt)	38	58	18	40	28	58	0	37	80	18	0	80	20
GGBS (%wt)	19	18	58	0	58	28	80	37	0	38	40	20	80
Compressive Strength (MPa)	28.5	14.4	16.9	34.0	6.0	4.2	19.8	16.6	14.8	30.6	37.3	0.0	0.0
Splitting Tensile strength (MPa)	2.9	1.8	2.3	3.7	0.7	0.8	2.6	2.2	1.7	3.3	4.1	0.0	0.0
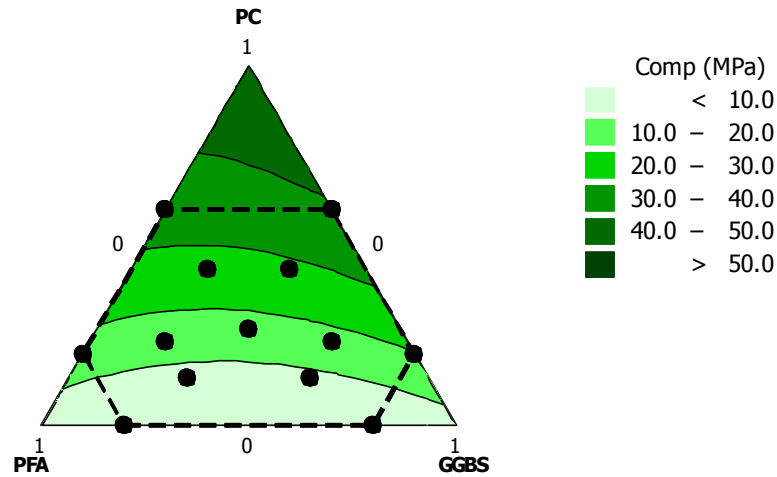
Figure 5.1 14 day compressive strength contour plot (PC/PFA/GGBS)
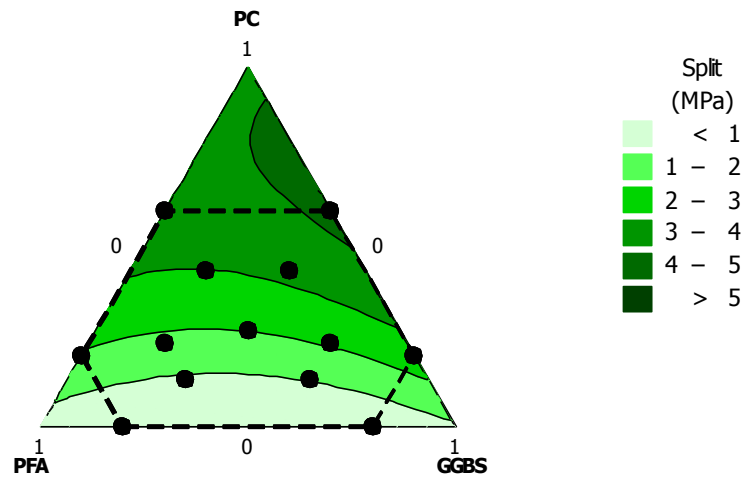
Figure 5.2 14 day splitting tensile strength contour plot (PC/PFA/GGBS)

As stated in the methodology, to analyse the data the model fitting method used was mixture regression. The terms of the model were given in a quadratic formula (as defined by Minitab) as shown in the equation below, were $f(x)$ is the strength, A, B and C are the quantities of the three different components and x_1, x_2.... x_5 are the variables.

$$f(x) = Ax_1 + Bx_2 + Cx_3 + ABx_4 + ACx_5 + BCx_5 \text{ (Equation 5.1)}$$

The equations that predicted the strength $f(x)$ and produced the contour plots for compressive strength and splitting tensile strength were:

Compressive strength

$f(x) = 46.28(PC) + 3.49(PFA) + 5.61(GGBS) + 22.32(PC*PFA) + 36.8(PC*GGBS)$

$– 36.91(PFA*GGBS)$ (Equation 5.2)

Splitting tensile strength

$f(x) = 3.696(PC) + 0.476 (PFA) + 0.827(GGBS) + 4.877 (PC*PFA) + 7.001 (PC*$

$GGBS) – 4.682 (PFA*GGBS)$ (Equation 5.3)

The accuracy of contour plots were based on the regression values, r^2 which was determined based on the predicted and actual results and the p-value which allows us to rule out a null hypothesis. The r^2 value for compressive strength and splitting tensile strength was 97.96% and 94.31% receptively. As values were above 90% it was determined that the contour plots gave an accurate representation for trends to be noted and validated. The p-values were used to help decide whether to reject a null hypothesis, therefore validate the analysis. With a 95% confidence level the p-value for compressive strength and splitting tensile strength was 0.000 and 0.000 respectively. As these values were below 0.05 it could be assumed that the hypothesis determined from the contour plots can confidently be assured.

5.2.1.2 PC/PFA/BOS

Table 5.2 reports on the 14 day compressive and splitting tensile strength for paste mixes containing PC/PFA/BOS. Mix 12 consisted of 60% PC and 40% BOS and

produced the greatest compressive strength (40.7 MPa) and splitting tensile strength (4.5 MPa). Figures 5.3 and 5.4 show the contour plots that were generated in Minitab. The results showed that mixes containing PC/BOS (mix 6 & 12) produced greater strengths than mixes containing PC/PFA (mix 1 & 11). As stated by Kourinis et al (2007) when compared to a study done by Altun and Yilmaz(2002) the development of strength at 28 days containing PC/BOS was higher due to the assumption that the slag had higher level of fineness and higher content of hydration component. When analysing Figure 4.4 and Table 4.4 it is believed that this is the same occurrence in comparison to PC/PFA. The results for ternary blends (PC/PFA/BOS) showed that mixes containing a greater quantity of BOS over PFA at PC levels over 35% provided good results. Li et al (2000) stated when there is a proper ratio between PFA and BOS, and at the same mill time in mixtures containing 45% clinker, the strength and pore structure properties all exceed the BOS cement. It is expected that this is occurring in the mixes produced.

Table 5.2 Compressive and splitting tensile strength for PC/PFA/BOS paste mixes at 14 days

	Mix number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
PC (%wt)	15	30	60	35	45	45	40	00	25	20	15	60	0
PFA (%wt)	60	40	40	20	40	20	0	40	60	80	40	0	80
BOS (%wt)	25	30	0	45	15	35	60	60	15	0	45	40	20
Compressive Strength (MPa)	7.4	14.7	34.0	29.7	24.5	31.2	36.4	0.0	13.6	13.8	8.0	40.7	0.0
Splitting Tensile strength (MPa)	0.7	1.9	3.7	2.8	1.8	3.5	4.2	0.0	1.6	1.7	1.2	4.5	0.0

Compressive Strength PC/PFA/BOS
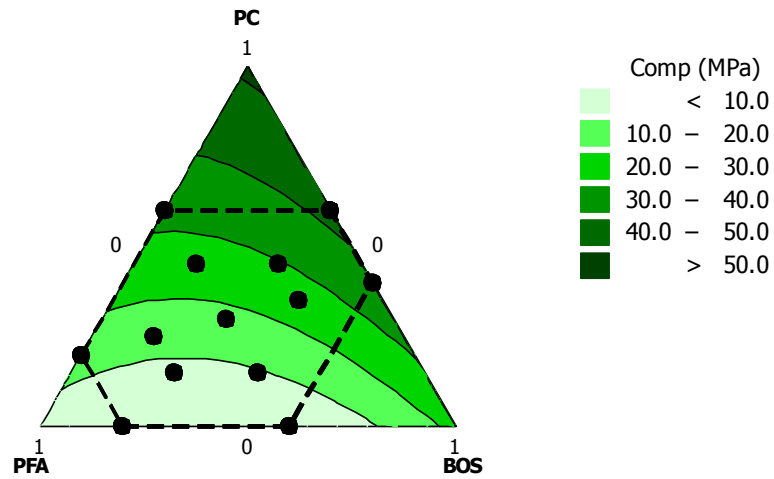
Figure 5.3 14 day compressive strength contour plot (PC/PFA/BOS)

Splitting Tensile Strength PC/PFA/BOS
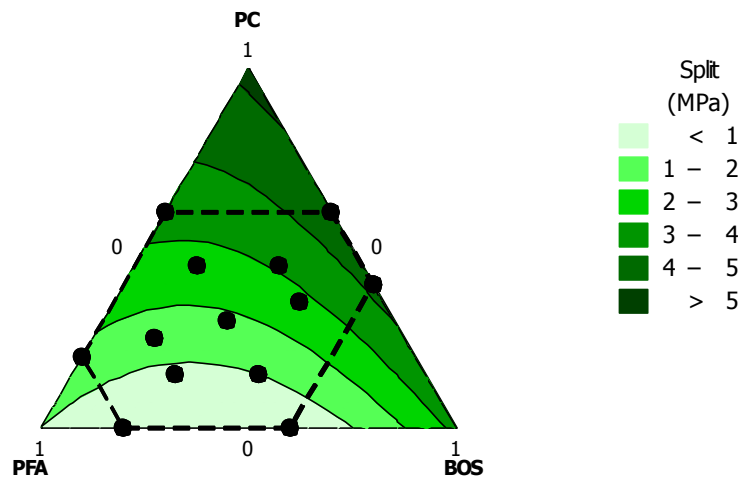
Figure 5.4 14 day splitting tensile strength contour plot (PC/PFA/BOS)

The equations that predicted the strength *f (x)* and produced the contour plots for compressive strength and splitting tensile strength were:

Compressive strength

$f(x) = 51.5(PC) + 5.29(PFA) + 22.98(BOS) - 0.90(PC*PFA) + 10.46(PC*BOS) -$

$64.22(PFA*BOS)$ (Equation 5.4)

Splitting tensile strength

$$f(x) = 5.212(PC) + 0.979(PFA) + 3.286(BOS) - 0.583PC*PFA) + 0.788(PC*BOS) - 9.247(PFA*BOS)$$
(Equation 5.5)

The r^2 value for compressive strength and splitting tensile strength was 97.86% and 92.71% receptively. As values were above 90% it was determined that the contour plots gave an accurate representation for trends to be noted and validated. The p-values with a 95% confidence level for compressive strength and splitting tensile strength was 0.000 and 0.000 respectively. As these values were below 0.05 it could be assumed that the hypothesis determined from the contour plots can confidently be assured.

5.2.1.3 PC/PFA/MK

Table 5.3 gives the results of the 14 day compressive and splitting tensile strength for paste mixes containing PC/PFA/MK. The mix that produced the greatest compressive strength (34.0 MPa) and splitting tensile strength (3.7 MPa) consisted of 60% PC and 40% PFA. The results showed that mixes containing PC/PFA (mix 6) produced better strength than the mixes containing PC/MK (mix 8). Güneyisi et al (2007) and Badogiannis et al (2005) had noted that MK produced better strengths then the control mix and the greatest pozzoalanic reactivity occurred during 7-14 days. Based on this the results seemed unusual, however Snelson et al (2003) stated that PFA has a negligible effect on the water demand of PC/PFA blends whereas for PC/MK blends, increasing MK levels results in an increasing water demand. Therefore it is assumed that low MK strengths are due to the semi-dry mix which stays at a contestant water

to cement ratio of 0.15. With ternary blends at the same PC level as mixes increased the quantity of MK the strengths decreased. This once again was unexpected as firstly particle packing would be expected to increase the strength as the MK particles (7µm) are much finer than the PFA (55µm) and PC (38µm) particles .Secondly, that the high SiO_2 (54.06 %) content of MK would produce greater quantities of C-S-H gel in the early stage from the CH after the initial cement hydration. The positive effect of MK is unable to be noted due to the low water content, hydration products required could not be produced to increase strength and the filler effect could not account for the loss of this. The compressive and splitting tensile strength values were entered into Minitab and the contour plots generated are shown in Figures 5.5 and 5.6 respectively.

Table 5.3 Compressive and splitting tensile strength for PC/PFA/MK paste mixes at 14 days

	Mix number										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
PC (%wt)	20	0	14	14	24	44	60	60	44	00	28
PFA (%wt)	80	80	56	66	66	26	40	0	46	60	52
MK (%wt)	0	20	30	20	10	30	0	40	10	40	20
Compressive Strength (MPa)	14.8	0.0	2.6	3.6	17.0	22.7	34.0	26.0	21.4	0.0	13.0
Splitting Tensile strength (MPa)	1.7	0.0	0.7	0.9	1.7	2.9	3.7	2.9	2.8	0.0	1.9

Compressive Strength PC/PFA/MK
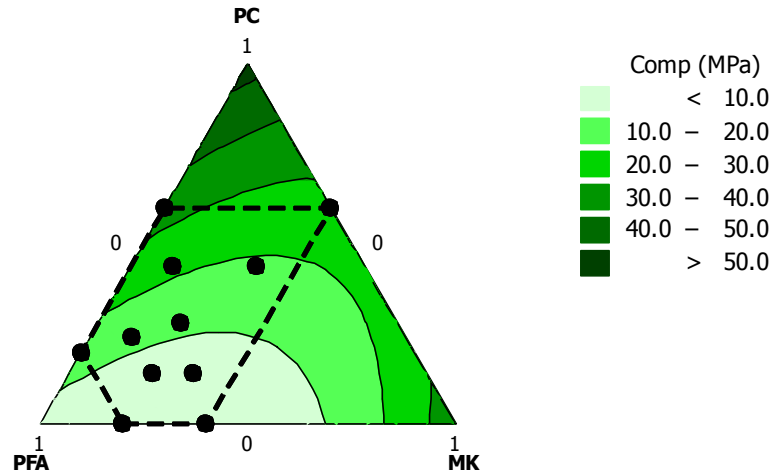
Figure 5.5 14 day compressive strength contour plot (PC/PFA/MK)

Splitting Tensile Strength PC/PFA/MK
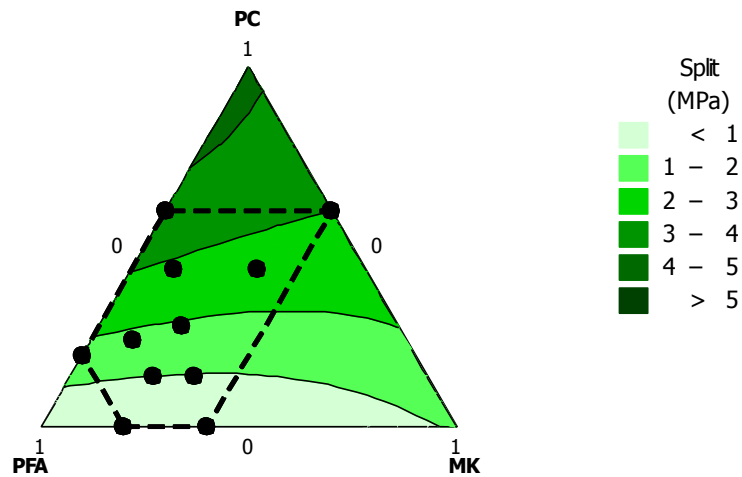
Figure 5.6 14 day splitting tensile strength contour plot (PC/PFA/MK)

The equations that predicted the compressive strength *f*(x) and produced the contour plots for compressive strength and splitting tensile strength were:

Compressive strength

f(x) =53.88(PC) + 5.67(PFA) + 36.6(MK) – 1.98(PC*PFA) – 84.78(PC*MK) – 78.86

(PFA*MK)   (Equation 5.6)

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Splitting Tensile Strength

$$f(x) = 4.207(PC) + 0.069(PFA) + 1.133(MK) + 4.738(PC*PFA) + 0.07(PC*MK) - 2.362 (PFA*MK)$$

(Equation 5.7)

The r^2 value for compressive strength and splitting tensile strength was 98.2% and 97.02% receptively. As values were above 90% it was determined that the contour plots gave an accurate representation for trends to be noted and validated. The p-values with a 95% confidence level for compressive strength and splitting tensile strength was 0.001 and 0.018. As these values were below 0.05 it could be assumed that the hypothesis determined from the contour plots can confidently be assured.

5.2.1.4 PC/PFA/SF

Table 5.4 gives the results for the 14 day compressive and splitting tensile strengths for paste mixes containing PC/PFA/SF. Mix 6 consisted of 60% PC, 25% PFA and 15% SF and produced the greatest compressive strength (35.2 MPa) and splitting tensile strength (3.8 MPa). Studies such as Barbhuiya et al (2009) have reported on the pore filling effects and the pozzolanic reactivity of SF, which provides greater strengths and can increase the early age strength of mixes containing PFA. It can be seen that as PFA levels increased and PC levels decreased, the increase in SF continued to have a negative effect and this could be due to two possibilities. Firstly it could be due to as Bagheri et al (2013) reported, in mixes containing 30% PFA the nucleation effect and fast pozzolanic action of SF has not been able to compensate for reduced PFA activity caused by lower pore solution alkalinity. Secondly Bagheri et al

(2013) reported that as SF levels increased in ternary mixes containing PFA, the water/binder ratio increased. Figures 5.7 and 5.8 show the compressive and splitting tensile contour plots respectively that were generated in Minitab.

Table 5.4 Compressive and splitting tensile strength for PC/PFA/SF paste mixes at 14 days

	Mix number										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
PC (%wt)	20.625	5	12.5	60	48.125	60	28.125	60	36.25	20	48.125
PFA (%wt)	68.125	80	80	25	48.125	32.5	68.125	40	56.25	80	40.625
SF (%wt)	11.25	15	7.5	15	37.5	7.5	37.5	0	7.5	0	11.25
Compressive Strength (MPa)	**16.5**	**0.0**	**0.0**	**35.2**	**27.9**	**33.9**	**17.7**	**34.0**	**23.5**	**14.8**	**29.9**
Splitting Tensile strength (MPa)	**1.5**	**0.0**	**0.0**	**3.8**	**3.1**	**3.6**	**1.7**	**3.7**	**3.0**	**1.7**	**3.4**
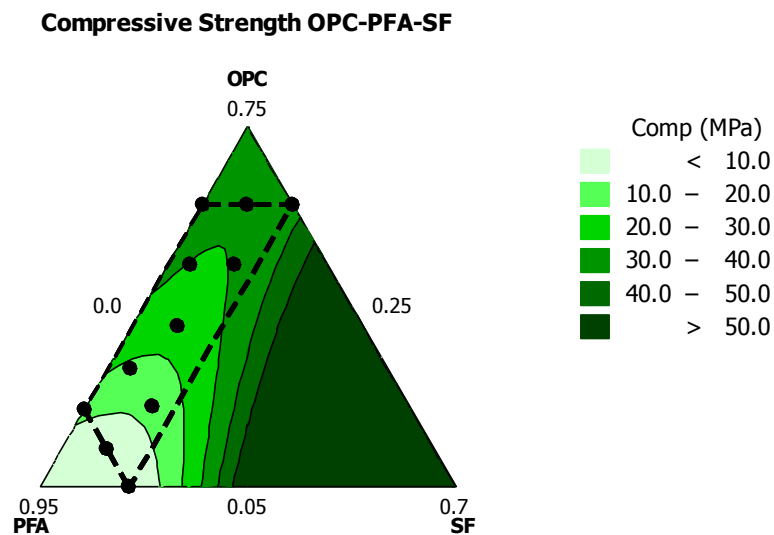
Figure 5.7 14 day compressive strength contour plot (PC/PFA/SF)

Splitting Tensile Strength PC/PFA/SF
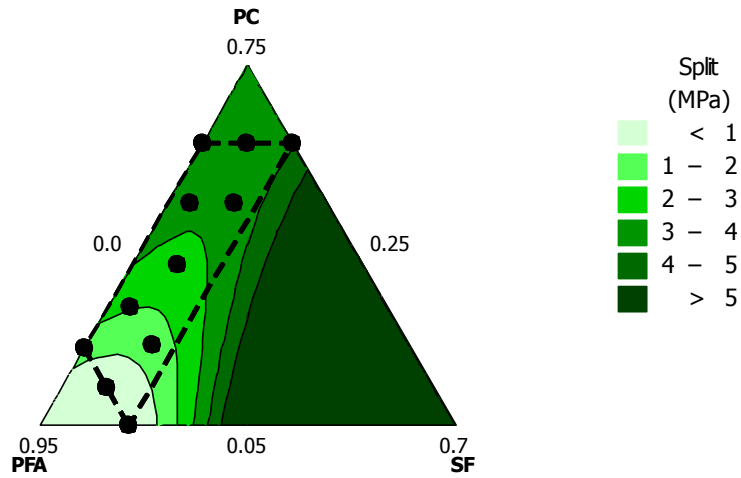
Figure 5.8 14 day splitting tensile strength contour plot (PC/PFA/SF)

The equations that predicted the strength $f(x)$ and produced the contour plots for compressive strength and splitting tensile strength were:

Compressive strength

$f(x) = 17(PC) -12.2(PFA) + 688.1(SF) + 121.9(PC*PFA) -701.3(PC*SF) - 782 (PFA*SF)$ (Equation 5.8)

Splitting Tensile Strength

$f(x) = 1.02(PC) -1.59(PFA) + 82.54(SF) + 15.82(PC*PFA) -84(PC*SF) - 93.84 (PFA*SF)$ (Equation 5.9)

The r^2 value for compressive strength and splitting tensile strength was 97.53% and 97.06% receptively. As values were above 90% it was determined that the contour plots gave an accurate representation for trends to be noted and validated. The p-values with a 95% confidence level for compressive strength and splitting tensile

strength was 0.000 and 0.000. As these values were below 0.05 it could be assumed that the hypothesis determined from the contour plots can confidently be assured.

5.2.1.5 PC/PFA/BPD

Table 5.5 gives the results for the 14 day compressive and splitting tensile strengths for paste mixes designated by Minitab for blends containing PC/PFA/BPD. Figures 5.9 and 5.10 show the contour plots that were generated in Minitab for compressive and splitting tensile strength respectively. The mix that produced the greatest compressive strength (34.0 MPa) and splitting tensile strength (3.7 MPA) consisted of 60% PC and 40% PFA. Due to the low percentage of BPD being used, all mixes consisting of BPD were in forms of ternary paste with PFA. The effect of BPD can be seen when analysing mixes 1, 7 and 10 in which PC content remains constant and BPD is used to replace PFA by 0%, 5% and 10% respectively. The results showed that 5% BPD replacement provided very close strengths (31.9 MPa) to that of 0% BPD (34.0 MPa) and that 10% BPD replacement (30.0 MPa) was lower than both BPD replacements. However no mix containing BPD achieved greater strengths than PC-PFA mix. When comparing Table 4.1 (chemical properties of PC) and Table 4.8(chemical properties of BPD) it can be seen that the chemical composition of the two materials are very similar. The only difference between the two is that BPD has higher quantities of alkalis mainly K_2O and higher quantities of SO_3. As there was no aggregate used in this stage of the research the alkali silica reaction could be ruled out as the reason for decreased strength. It is therefore assumed that the decrease in strength is due to the high SO_3 content which as stated by Najim and Mahmood (2013) can increase the porosity therefore decrease the strength.

Table 5.5 Compressive and splitting tensile strength for PC/PFA/BPD paste mixes at 14 days

	Mix number										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
PC (%wt)	60	20	37.5	23.75	28.75	15	60	48.75	60	10	48.75
PFA (%wt)	40	80	57.5	68.75	68.75	80	30	48.75	35	80	43.75
BPD (%wt)	0	0	5	7.5	2.5	5	10	2.5	5	10	7.5
Compressive Strength (MPa)	34.0	14.8	14.0	12.3	14.0	3.5	30.0	22.4	31.9	0.0	22.2
Splitting Tensile strength (MPa)	3.7	1.7	1.7	1.3	1.8	0.3	3.2	2.4	3.5	0.0	2.3
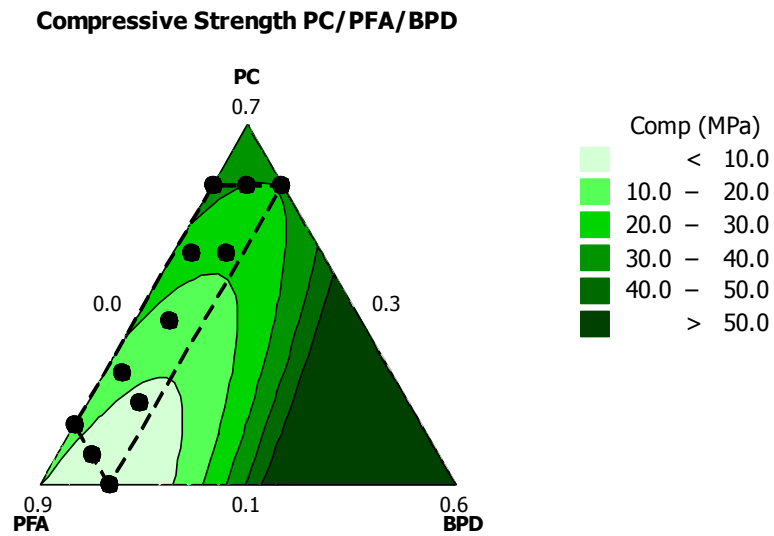
Figure 5.9 14 day compressive strength contour plot (PC/PFA/BPD)
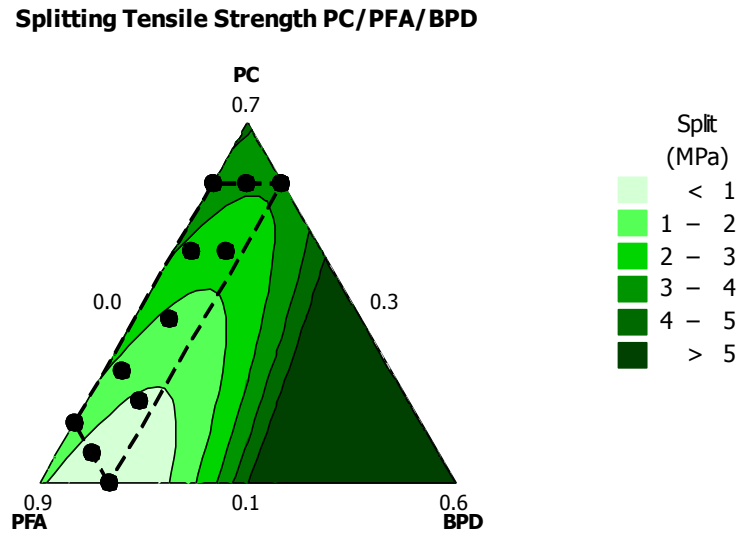
Figure 5.10 14 day splitting tensile strength contour plot (PC/PFA/BPD)

The equations that predicted the strength f(x) and produced the contour plots for compressive strength and splitting tensile strength were:

Compressive strength

$f(x) = 62.2(PC) + 7.1(PFA) + 784.6(BPD) – 27.3(PC*PFA) – 879(PC*BPD) – 979.9(PFA*BPD)$ (Equation 5.10)

Splitting Tensile Strength

$f(x) = 6.1(PC) + 0.8(PFA) + 96.3(BPD) – 1.1(PC*PFA) –107(PC*BPD) – 120.7$ $(PFA*BPD)$ (Equation 5.11)

The r^2 value for compressive strength and splitting tensile strength was 96.48% and 95.22% receptively. As values were above 90% it was determined that the contour plots gave an accurate representation for trends to be noted and validated. The p-

values with a 95% confidence level for compressive strength and splitting tensile strength was 0.005 and 0.02. As these values were below 0.05 it could be assumed that the hypothesis determined from the contour plots can confidently be assured.

5.2.1.6 PC/PFA/GP

Table 5.6 gives the results for the 14 day compressive and splitting tensile strengths for paste mixes containing PC/PFA/GP. Figures 5.11 and 5.12 show the contour plots that were generated in Minitab for compressive and splitting tensile strength respectively. The mix that produced the greatest compressive strength (34.0 MPa) and splitting tensile strength (3.7 MPa) consisted of 60% PC and 40% PFA. The results show that the GP had a pozzolanic reaction; however it was not strong enough to offset the early strength lost with the use of PFA. The effect of GP in ternary blends with PFA can be seen clearly in Mix 5, 10 and 13. These mixes show that when PC levels remain constant at 60% and GP levels are 0%, 10% and 20% the compressive strengths are 34.0 MPa, 31.3 MPa and 27.4 MPa respectively and for splitting tensile strength are 3.7 MPa, 2.6 MPa and 2.6 MPa respectively. This shows that as GP levels increase there are negative effects on both compressive and splitting tensile strengths. When analysing the chemical composition of GP in this study, Table 4.7 shows that the SiO_2 content was 69.56% and based on this it would be assumed that greater CSH gel would be produced from the secondary hydration of CH and SiO_2 from the initial cement hydration: however this is was not the case. It is therefore assumed that the reason GP did not achieve its potential is because of the particle distribution of the replacement. In this study GP and BOS were ground with a ball mill and sieved to get particles below 150 µm and from Figures 4.4 and 4.7 it can be seen that much finer

particles were achieved for BOS and GP had the majority of particles over 100 μm. Shi et al (2005) had noted the importance of fineness of GP and stated that higher percentage of larger particles resulted in decreasing compressive strengths and this is assumed to be the case in this study, if finer particles were produced than it is presumed that strengths would increase.

Table 5.6 Compressive and splitting tensile strength for PC/PFA/GP paste mixes at 14 days

	Mix number												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
PC (%wt)	40	47.5	30	27.5	60	47.5	0	35	20	60	10	17.5	60
PFA (%wt)	60	47.5	50	67.5	40	37.5	80	55	80	20	80	67.5	30
GP (%wt)	0	5	20	5	0	15	20	10	0	20	10	15	10
Compressive Strength (MPa)	**23.5**	**16.6**	**12.9**	**8.5**	**34.0**	**24.6**	**0.0**	**10.8**	**14.8**	**27.4**	**0.0**	**6.14**	**31.3**
Splitting Tensile strength (MPa)	**1.8**	**2.1**	**1.5**	**1.1**	**3.7**	**2.5**	**0.0**	**1.2**	**1.7**	**2.6**	**0.00**	**0.8**	**2.6**
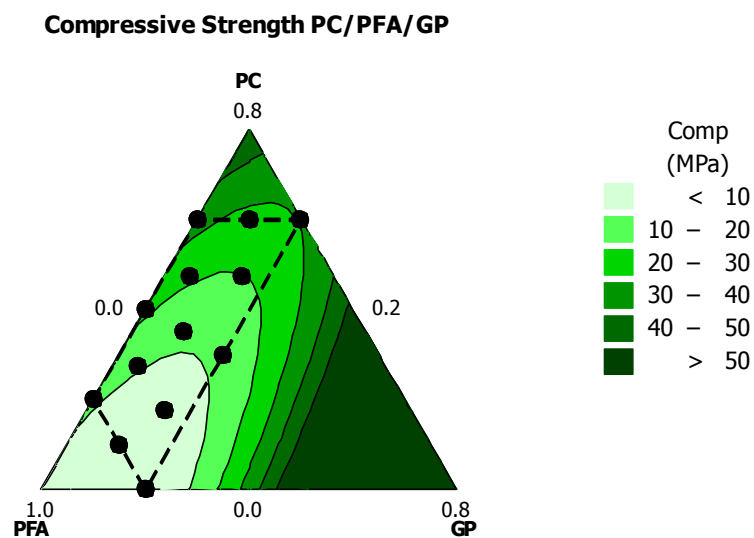
Figure 5.11 14 day compressive strength contour plot (PC/PFA/GP)

Figure 5.12 14 day splitting tensile strength contour plot (PC/PFA/GP)

The equations that predicted the compressive strength f(x) and produced the contour plots for compressive strength and splitting tensile strength were:

Compressive strength

$$f(x) = 65.6(PC) + 5(PFA) + 371.2(GP) - 30(PC*PFA) - 507.4(PC*GP) - 487.2 (PFA*GP) \qquad \text{(Equation 5.12)}$$

Splitting Tensile Strength

$$f(x) = 5.6(PC) + 0.29(PFA) + 39.75(GP) - 0.37 (PC*PFA) - 54.11(PC*GP) - 50.46 (PFA*GP) \qquad \text{(Equation 5.13)}$$

The r^2 value for compressive strength and splitting tensile strength was 92.94% and 90.72% receptively. As values were above 90% it was determined that the contour plots gave an enough representation for trends to be noted and validated. The p-values with a 95% confidence level for compressive strength and splitting tensile strength

was 0.000 and 0.002. As these values were below 0.05 it could be assumed that the hypothesis determined from the contour plots can confidently be assured.

5.2.1.7 PC/GGBS/BOS

Table 5.7 gives the results for the 14 day compressive and splitting tensile strengths for paste mixes containing PC-GGBS-BOS. The mix that produced the greatest compressive strength (41.2 MPa) and splitting tensile strength (4.9 MPa) consisted of 45% PC, 20% GGBS and 35% BOS. Figures 5.13 and 5.14 show the contour plots of the compressive and splitting tensile strength respectively. The results show that the binary mixes of PC/BOS produced greater strengths than binary mixes of PC/GGBS. Marriage (2009) at 28 days had 40%wt replacement of GGBS greater by 10Mpa than BOS in binary mixes and Wang et al (2012) concluded that GGBS produced greater strengths than BOS due to GGBS improving the pore structure at later stages by increasing fine pores and decreasing large pores. These trends were not detected in this study, when analysing Figure 4.6 (particle distribution of GGBS) and Figure 4.9 (particle distribution of BOS) it can be seen that BOS had a greater quantity of finer particles. It is therefore assumed that the greater reactivity due to this is the reason for greater strengths in binary mixes containing PC/BOS. Overall ternary mixes produced the greatest results and it can be seen from the contour plots how greater strengths are achieved as BOS becomes greater than GGBS. It is assumed that ternary blends produced greater strengths because of the particle distribution of all materials providing a greater impact on the filler effect and also the chemical properties of GGBS and BOS complimenting each other to provide greater hydration products.

Table 5.7 Compressive and splitting tensile strength for PC/GGBS/BOS paste mixes at 14 days

	Mix Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
PC (%wt)	35	60	60	30	40	45	0	15	15	25	20	45	0
GGBS (%wt)	20	0	40	40	0	20	40	40	60	60	80	40	80
BOS (%wt)	45	40	0	30	60	35	60	45	25	15	0	15	20
Compressive Strength (MPa)	35.9	40.7	34.0	31.4	36.4	41.2	0.0	8.4	10	29.9	14.8	38.5	0.0
Splitting Tensile strength (MPa)	4.1	4.5	3.8	3.52	4.2	4.9	0.0	1.3	1.4	2.8	1.7	3.8	0.0
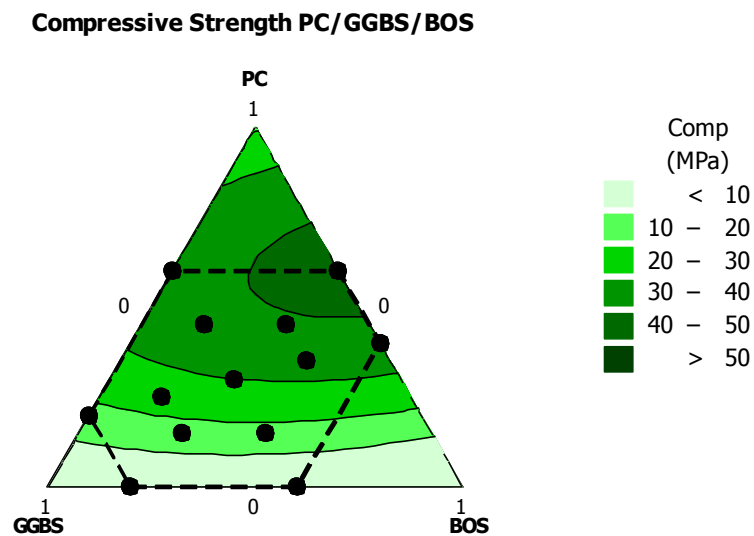
Figure 5.13 14 day compressive strength contour plot (PC/GGBS/BOS)

Splitting Tensile Strength PC/GGBS/BOS

Figure 5.14 14 day splitting tensile strength contour plot (PC/GGBS/BOS)

The equations that predicted the compressive strength $f(x)$ and produced the contour plots for compressive strength and splitting tensile strength were:

Compressive strength

$f(x) = 18.79(PC) - 6.01(GGBS) - 12.85(BOS) + 111.96(PC*GGBS) + 151.86(PC * BOS) + 28.50(GGBS*BOS)$ (Equation 5.14)

Splitting Tensile Strength

$f(x) = 1.694(PC) - 0.66(GGBS) - 1.219(BOS) + 12.276(PC*GGBS) + 17.857(PC* BOS) + 3.246(GGBS*BOS)$ (Equation 5.15)

The r^2 value for compressive strength and splitting tensile strength was 93.36% and 95.54% receptively. As all were above 90% it could be assumed that the contour plots gave an accurate representation for trends to be noted and validated. The p-values

with a 95% confidence level for compressive strength and splitting tensile strength was 0.000 and 0.000. As these values were below 0.05 it could be assumed that the hypothesis determined from the contour plots can confidently be assured.

5.2.1.8 PC/GGBS/MK

Table 5.8 gives the results for the 14 day compressive and splitting tensile strengths of paste mixes containing PC/GGBS/MK. The mix that produced the greatest compressive strength (37.3 MPa) and splitting tensile strength (4.1 MPa) consisted of 60% PC and 40% GGBS. The result showed that with 60% PC replacement the mix consisting of PC/GGBS (mix 3) produced greater strengths than mixes consisting of PC/MK (mix 10). The results of ternary pastes showed at a specific PC level as the replacement of MK reduced and GGBS increased, greater strengths were achieved. Khatib and Hibert (2005) reported that the GGBS content in concrete that gave maximum compressive strength reduces as the MK content increases; they found that as MK was increased from 10% to 20%, the GGBS content that gave the best compressive strength was 30% and 20% respectively and that as GGBS increased at those MK levels the strength decreased. These results can be seen clearly in Figures 5.15 and 5.16 which show the contour plots for the compressive and splitting tensile strength respectively. Results showed that MK performed better in combination with GGBS than PFA. It is assumed that the finer MK particles have an effect in both ternary blends (PFA and GGBS). However the difference is with the greater amount free lime in GGBS, Khatib and Hibert (2005) reported that MK is highly reactive pozzolana, it begins to react with free lime at very early stages of hydration, thus resulting in a high early strength.

Table 5.8 Compressive and splitting tensile strength for PC/GGBS/MK paste mixes at 14 days

|	Mix Number										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
PC (%wt)	60	14	0	14	44	28	24	44	20	60	0
GGBS (%wt)	40	56	60	66	46	52	66	26	80	0	80
MK (%wt)	0	30	40	20	10	20	10	30	0	40	20
Compressive Strength (MPa)	37.3	11. 9	0.0	15.5	28.5	19.3	23.0	28.8	15.8	26.0	0.0
Splitting Tensile strength (MPa)	4.1	1.1	0.0	1.8	3.2	2.6	2.9	3.0	2.5	2.9	0.0
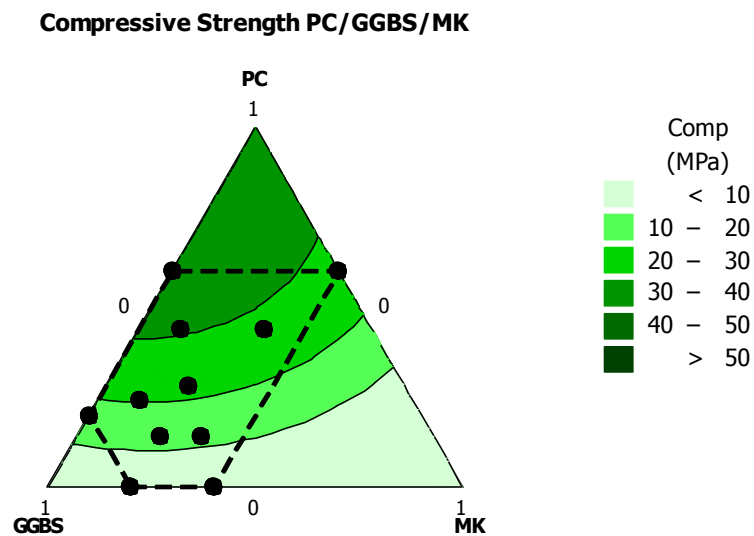
Figure 5.15 14 day compressive strength contour plot (PC/GGBS/MK)
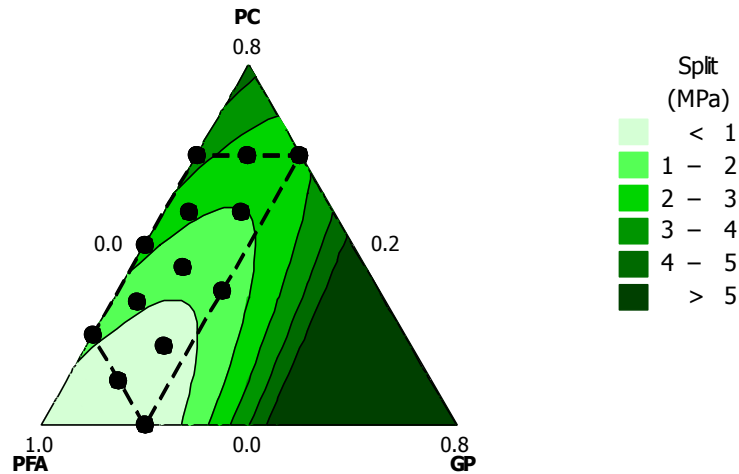
Splitting Tensile Strength PC/GGBS/MK

Figure 5.16 14 day splitting tensile strength contour plot (PC-GGBS-MK)

The equations that predicted the compressive strength *f*(x) and produced the contour plots for compressive strength and splitting tensile strength were:

Compressive strength

f(x) = 33.83(PC) – 1.66(GGBS) – 22.77(MK) + 70.12(PC*GGBS)+ 62.87(PC*MK) + 42.56(GGBS*MK) (Equation 5.16)

Splitting Tensile Strength

f(x) = 2.05(PC) +0.626(GGBS) + 1.118(MK) + 10.637(PC*GGBS) + 4.922(PC*MK) – 3.788(GGBS*MK) (Equation 5.17)

The r^2 value for compressive strength and splitting tensile strength was 95.20% and 96.65% receptively. As all were above 90% it could be assumed that the contour plots gave an accurate representation for trends to be noted and validated. The p-values with a 95% confidence level for compressive strength and splitting tensile strength

was 0.000 and 0.000. As these values were below 0.05 it could be assumed that the hypothesis determined from the contour plots can confidently be assured.

5.2.1.9 PC/GGBS/SF

Table 5.9 gives the results for the 14 day compressive and splitting tensile strengths of paste mixes containing PC/GGBS/SF. The mix that produced the greatest compressive strength (39.2 MPa) and splitting tensile strength (4.3 MPa) consisted of 60% PC, 25% GGBS and 15% SF. The contour plots generated by Minitab are shown in Figures 5.17 and 5.18 for compressive and splitting tensile strength respectively. The results showed that as SF replacement increases so did the strength. It is assumed that this is due to as stated by Bagheri et al (2012), SF having two different effects on development property. The first of these if is the high specific surface area and the second of these is its micro-filler effect results in strength enhancement from 7 days onwards. As well as the particle distribution of SF having positive effects on strength, the chemical composition of SF is also assumed to produce excess CSH gel through the reaction of SiO_2 in the SF and the CH after initial hydration of PC as well as the CaO in the GGBS. When comparing ternary blends of PC/PFA/SF and PC/GGBS/SF, the ternary blend with GGBS produced better results and this is assumed to be due to the free lime ($CaOH_2$) in the GGBS in addition to the lime left over after hydration reacting with the high SiO_2 content of silica fume.

Table 5.9 Compressive and splitting tensile strength for PC/GGBS/SF paste mixes at 14 days

|	Mix number										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
PC (%wt)	60	12.5	28.125	20.625	20	60	48.125	36.25	5	60	48.125
GGBS (%wt)	25	80	68.125	68.125	80	40	40.625	56.25	80	32.5	48.125
SF (%wt)	15	7.5	3.75	11.25	0	0	11.25	7.5	15	7.5	3.75
Compressive Strength (MPa)	**39.2**	**2.9**	**20.3**	**17.5**	**19.8**	**37.3**	**34.1**	**23.2**	**0**	**36.7**	**34.1**
Splitting Tensile strength (MPa)	**4.3**	**0.5**	**2.4**	**1.6**	**2.6**	**4.1**	**3.4**	**2.4**	**0.0**	**4.1**	**3.0**
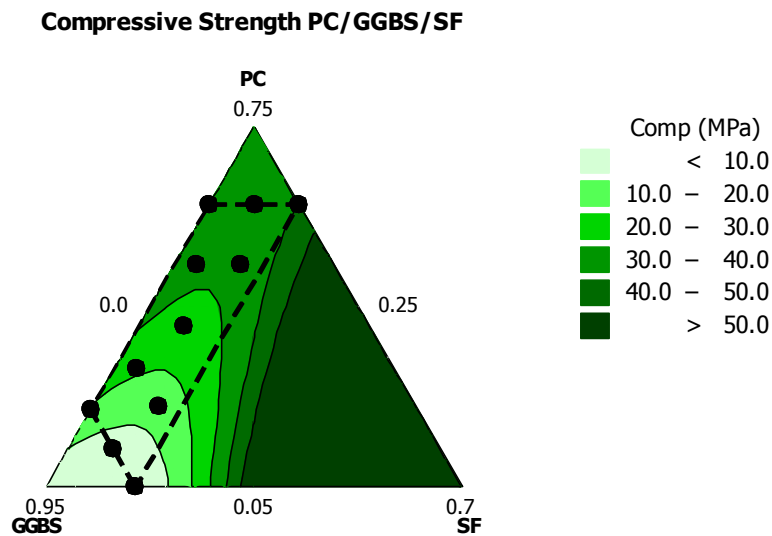
Figure 5.17 14 day compressive strength contour plot (PC/GGBS/SF)
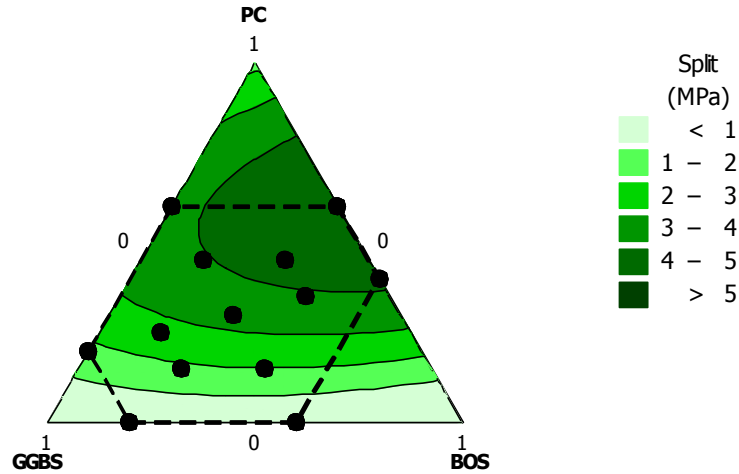
Splitting Tensile Strength PC/GGBS/SF

Figure 5.18 14 day splitting tensile strength contour plot (PC/GGBS/SF)

The equations that predicted the compressive strength f(x) and produced the contour plots for compressive strength and splitting tensile strength were:

Compressive strength

$$f(x) = 23.1(PC) - 5.8(GGBS) + 742.6(SF) + 112.8(PC*GGBS) - 743.1(PC*SF) - 890.6(GGBS*SF)$$ (Equation 5.18)

Splitting Tensile Strength

$$f(x) = 4.56(PC) + 1.15(GGBS) + 73.19(SF) + 3.89(PC*GGBS) - 71.55(PC*SF) - 98 (GGBS*SF)$$ (Equation 5.19)

The r^2 value for compressive strength and splitting tensile strength was 97.75% and 96.29% receptively. As all were above 90% it could be assumed that the contour plots gave an accurate representation for trends to be noted and validated. The p-values with a 95% confidence level for compressive strength and splitting tensile strength

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was 0.000 and 0.000. As these values were below 0.05 it could be assumed that the hypothesis determined from the contour plots can confidently be assured.

5.2.1.10 PC/GGBS/BPD

Table 5.10 gives the results for the 14 day compressive and splitting tensile strengths of paste mixes containing PC/GGBS/BPD. The mix that produced the greatest compressive strength (37.3 MPa) and splitting tensile strength (4.1 MPa) consisted of 60% PC and 40% GGBS. However mixes containing PC/GGBS/BPD were not far off from these Figures. When comparing mix 1, 9 and 2 in which PC levels remain constant it can be seen that as BPD levels increase from 0-10% the optimum level is 5%, which is only 0.5 MPa and 0.3MPa below the compressive and splitting tensile strength of mix 1 which has the greatest strength. As previously mentioned BPD had very similar values to PC however the main difference was the quantity of SO_3 in BPD. It is assumed that due to the high SO_3, as levels get above 5% it causes greater expansion and also delays the set time by delaying the hydration of C_3A. In comparison to PC-PFA-BPD blends the PC-GGBS-BPD blends produced greater strengths and this assumed to be due to as stated by Jallul et al (2014) the high volume of SO_3 in the BPD could have improved the strength as a result of the sulphates activating the GGBS. Figures 5.19 and 5.20 show the contour plots that were generated my Minitab for the compressive and splitting tensile strength respectively

Table 5.10 Compressive and splitting tensile strength for PC/GGBS/BPD paste mixes at 14 days

|	Mix Number										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
PC (%wt)	60	60	23.75	37.5	20	48.75	15	28.75	60	48.75	10
GGBS (%wt)	40	30	68.75	57.5	80	43.75	80	67.5	35	48.75	80
BPD (%wt)	0	10	7.5	5	0	7.5	5	2.5	5	2.5	10
Compressive Strength (MPa)	37.3	31.0	16.7	28.5	19.8	36.9	12.5	24.0	36.8	35.1	0.0
Splitting Tensile strength (MPa)	4.1	3.6	2.0	3.2	2.5	3.7	1.2	2.7	3.8	3.1	0.0
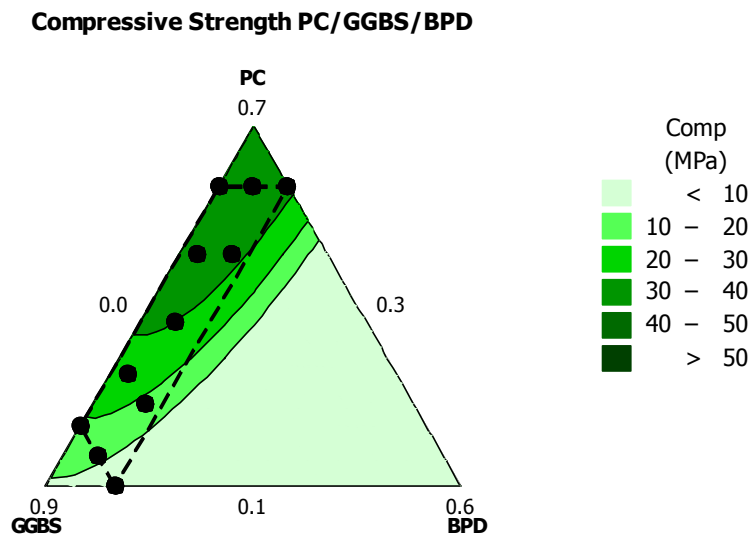
Figure 5.19 14 day compressive strength contour plot (PC/GGBS/BPD)
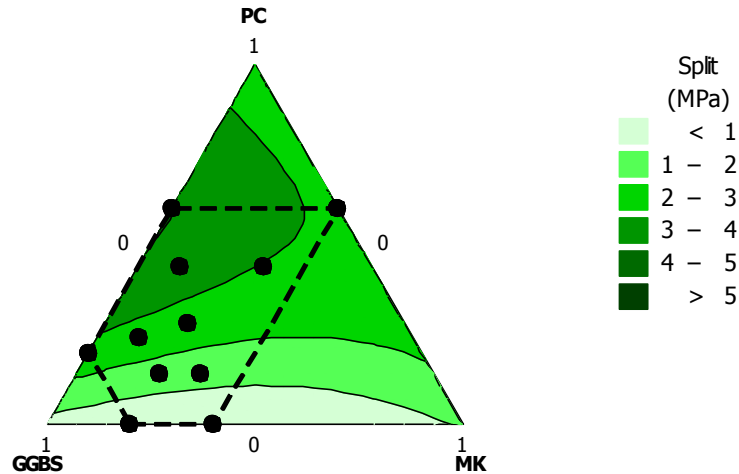
Splitting Tensile Strength PC/GGBS/BPD
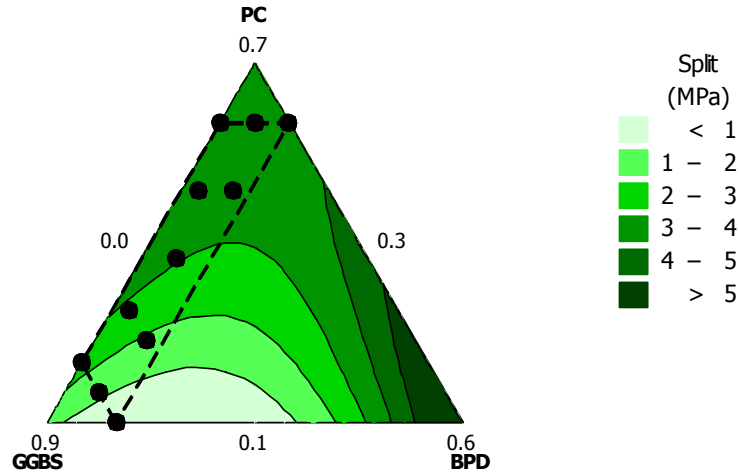
Figure 5.20 14 day splitting tensile strength contour plot (PC/GGBS/BPD)

The equations that predicted the compressive strength *f*(x) and produced the contour plots for compressive strength and splitting tensile strength were:

Compressive strength

f(x) = 20.6(PC) – 3.7(GGBS) – 901.7(BPD) + 110.1(PC*GGBS) + 1074.8(PC*BPD) + 892.6(GGBS*BPD) (Equation 5.20)

Splitting Tensile Strength

f(x) = 1.43 (PC) + 0.16(GGBS) + 26.32(BPD) +12.41 (PC*GGBS) – 11.02(PC* BPD) –46.26 (GGBS*BPD) (Equation 5.21)

The r^2 value for compressive strength and splitting tensile strength was 97.56% and 95.85% receptively. As all were above 90% it could be assumed that the contour plots gave an accurate representation for trends to be noted and validated. The p-values with a 95% confidence level for compressive strength and splitting tensile strength

was 0.000 and 0.000. As these values were below 0.05 it could be assumed that the hypothesis determined from the contour plots can confidently be assured.

5.2.1.11 PC/GGBS/GP

Table 5.11 gives the results for the 14 day compressive and splitting tensile strength of mixes containing PC/GGBS/GP. Figures 5.21 and 5.22 show contour plots generated my Minitab for the compressive and splitting tensile strength respectively. The greatest compressive strength (39.5 MPa) and splitting tensile strength (4.4 MPa) was obtained by the mix consisting of 60% PC, 20% GGBS and 20% GP. The effect of GP can be determined when analysing mixes 3, 6 and 9. As GP levels increased at 60% PC from 0%, 10% and 20% the compressive strengths were 37.3MPa, 35.8 MPa and 39.4 MPa respectively. In comparison to PC/PFA/GP mixes, PC/GGBS/GP provided greater strengths and this is assumed to be due to two possibilities. Firstly as stated in the PC/PFA/GP mixes the SiO_2 content of GP could not offset the early age disadvantages of PFA, however in this case the SiO_2 content is assumed to produced excess CSH from the secondary CH after the hydration of cement as well as the CaO in GGBS. Secondly as noted in mixes also containing BOS, the GP which was ground and sieved to give particles below 150 μm is assumed to have provided greater particle reactivity therefore increasing the strength.

Table 5.11 Compressive and splitting tensile strength for PC/GGBS/GP paste mixes at 14 days

|	Mix Number												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
PC (%wt)	35	30	60	40	27.5	6	10	0	60	20	17.5	47.5	47.5
GGBS (%wt)	55	50	30	60	67.5	40	80	80	20	80	67.5	37.5	47.5
GP (%wt)	10	20	10	0	5	0	10	20	20	0	15	15	5
Compressive Strength (MPa)	**16.8**	**20.9**	**35.8**	**23.5**	**21.8**	**37.3**	**2.4**	**0.0**	**39.5**	**19.8**	**5.7**	**25.0**	**29.9**
Splitting Tensile strength (MPa)	**1.9**	**1.5**	**3.9**	**1.8**	**1.8**	**3.7**	**0.3**	**0.0**	**4.4**	**1.7**	**0.5**	**2.4**	**2.9**
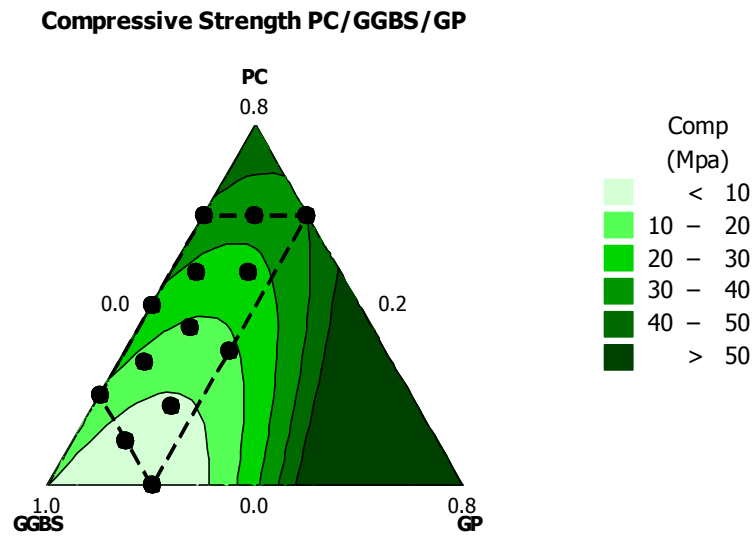
Figure 5.21 14 day compressive strength contour plot (PC/GGBS/GP)
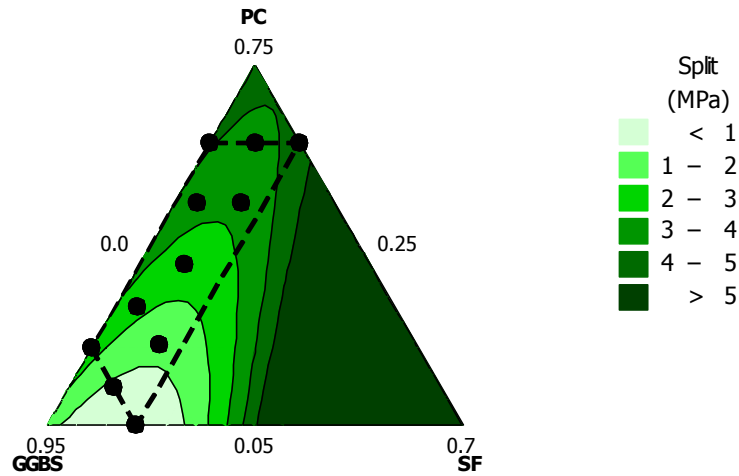
Splitting Tensile Strength PC/GGBS/GP
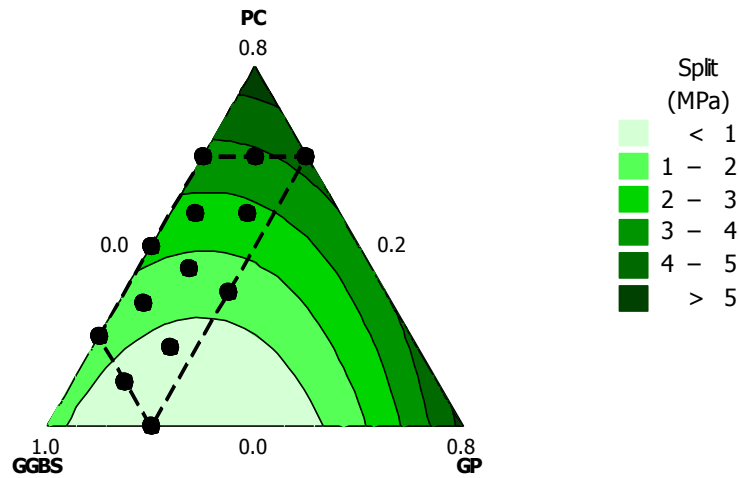
Figure 5.22 14 day splitting tensile strength contour plot (PC-GGBS-GP)

The equations that predicted the compressive strength f(x) and produced the contour plots for compressive strength and splitting tensile strength were:

Compressive strength

f(x) = 61.1(PC) + 10.4(GGBS) + 358.7(GP) – 12.5(PC*GGBS) – 404.5(PC*GP) –
506.1(GGBS*GP)   (Equation 5.22)

Splitting Tensile Strength

f(x) = 8.36(PC) + 1.4(GGBS) + 10.37(GP) – 7.92(PC*GGBS) – 9.95(PC*GP) –
20.75(GGBS*GP)   (Equation 5.23)

The r^2 value for compressive strength and splitting tensile strength was 95.71% and 95.72% receptively. As all were above 90% it could be assumed that the contour plots gave an accurate representation for trends to be noted and validated. The p-values with a 95% confidence level for compressive strength and splitting tensile strength

was 0.000 and 0.000. As these values were below 0.05 it could be assumed that the hypothesis determined from the contour plots can confidently be assured.

5.2.2 Concluding remarks

It is important to note that the equations and values noted in this study are only valid for mixes that are within the upper and lower boundaries set and have the same w/cm ratio, chemical and physical properties as the materials used. If the values were to be different then this model could not be used for predicting mixes, advanced models (ANN) which take into account greater quantities of variables, would have to be used.

When considering the relative merit of optimisation methods, in this study Minitab was successfully used to detect trends in ternary cement paste blends. As well as detecting trends the analysis allowed us to prove through regression and p-values that the contour plots had a degree of validity. This allowed us to confidently assume which blends and percentages have the potential to go on and be the optimised mix. If this study was to go further and analyse other factors such as w/cm ratio, superplastisizer quantity, addition of recycled aggregate etc. then Minitab could be used, as an optimisation method within the software allows for a combination of contour plots to be analysed in order to detect the optimised mix. Another option for multiple variables is artificial neural networks if there is sufficient amount of data, as this is when greatest accuracy can be achieved.

5.3 Chemical Analysis

Table 5.12 provides the fourteen best mixes that were derived from the analysis of ternary blends. This section of the thesis analyses these mixes with the aid of XRF and XRD. The Table shows that some of the mixes with the greatest strength were taken from the same group of ternary blends being analysed. Therefore, when determining properties of these ternary blends using XRF and XRD, not all mixes had to be analysed as they would provide similar values therefore conclusions. It can be noted from the Table that strengths for some mixes were derived from the equations. The reason for this was because after a discussion with Formpave about optimum mixes, it was decided that these mixes would be easier to produce if found successful.

Table 5.12 Fourteen mixes chosen to be taken onto the second phase

Mix	Cementitious constituents (% wt)							Compressive strength (MPa)	Splitting Tensile Strength (MPa)
	PC	GGBS	PFA	GP	BOS	BPD	SF		
1	60	40	-	-	-	-	-	37.3	4.1
2	60	20	-	20	-	-	-	39.5	4.4
3	45	20	-	-	35	-	-	41.2	4.9
4	60	20	-	-	20	-	-	39.5*	4.4*
5	60	35	-	-	-	5	-	36.8	3.8
6	50	45	-	-	-	5	-	35.3*	3.6*
7	50	40	-	-	-	10	-	33.1*	3.5*
	60	-	-	-	40	-	-	40.7	4.5
9	60	-	40	-	-	-	-	34	3.7
10	60	-	25	-	-	-	15	35.2	3.8
11	60	25	-	-	-	-	15	39.2	4.3
12	60	30	-	-	-	-	10	35.4*	3.9*
13	50	40	-	-	-	-	10	33.3*	3.4*
14	60	32.5	-	-	-	-	7.5	36.7	4.1

*Strengths derived from equations

5.3.1 XRF analysis

Table 5.13 provides the oxide composition of the 11 ternary blends that were tested at 14 days. XRF results were carried out at the University of Leicester. The results show the largest difference was found to be in the silica content that was ranging from 16.51-35.49 %wt. From review of XRF it is clear to see that different combinations gained strengths from different reactions occurring. It is important to note that the oxide composition provided in XRF results does not take into account the particle size of each combination, as this is likely to have impact through greater matrix densification and greater reaction provided by a greater surface area.

The three binary blends analysed were PC60/GGBS40, PC60/BOS40 and PC60/PFA40. It was stated in section 2.4.2 that PC60/GGBS40 provided good strengths as GGBS itself was self-cementitious and from analysis of oxides when compared to Table 4.1 (chemical properties of PC) it can be seen that the combined oxides value were very similar. Taylor (1997) stated that a flux is an agent that promotes a reaction by increasing the quantity of liquid at a given temperature; Al_2O_3 and Fe_2O_3 are fluxes for the formation of Alite. The high Al_2O_3 and Fe_2O_3 values of PC60/BOS40 are believed to produce good strengths through this process to help form greater quantities of tricalcium silicate. The oxide composition of PC60/PFA40 showed encouraging signs with good quantities of CaO and SiO_2 however this was not reflected in the strength. This is assumed to be due to SiO_2 particles forming in the inner particles of PFA and therefore unable to react to form CSH gel (Barbhuiya et al (2009)).

PC60/GGBS20/GP20 showed good strengths and this was due to the high CaO and SiO$_2$ content as well as the high alkaline content (Na$_2$O and K$_2$O=2.94%), which would have created a more intense reaction. A combination of the self-cementitious properties of GGBS and the formation of tricalcium silicate from Al$_2$O$_3$ and Fe$_2$O$_3$ in BOS are assumed to be the reason for the strength development of PC60/GGBS20/BOS20. The highest SiO$_2$ content was found in PC60/PFA25/SF15, which occurs, from the combination of SiO$_2$ in PFA and SF. However, this was not reflected in the strength as the nucleation effect and fast pozzolanic action of SF has not been able to compensate for reduced PFA activity caused by lower pore solution alkalinity ((Bagheri et al (2013)).

The ternary mixes consisting of PC/GGBS/BPD showed good concentrations of CaO and SiO$_2$ required for the production of CSH gel. However it also had high alkalinity, which would create a greater intensive reaction, as well as a high SO$_3$ content, which as stated by Jallul (2014) could improve strengths by activation of GGBS through sulphates. Ternary mixes consisting of PC/GGBS/SF from analysis of oxides produces strength primarily through the hydration of Di- and Tri-calcium silicates.

Table 5.13 XRF analysis of paste mixes

Mix	Chemical composition (%)										
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3
PC60/GGBS40	24.53	0.53	6.73	1.69	0.13	3.71	50.49	0.26	0.60	0.1	2.72
PC60/GGBS20/GP20	30.25	0.39	5.16	1.74	0.09	2.51	45.57	2.31	0.63	0.09	2.26
PC60/GGBS20/BOS20	20.62	0.50	5.33	6.31	0.64	3.48	50.27	0.21	0.46	0.37	2.32
PC60/GGBS35/BPD5	23.42	0.49	6.4	1.77	0.12	3.37	50.96	0.28	0.9	0.09	3.03
PC50/GGBS40/BPD10	23.96	0.51	6.69	1.64	0.14	3.66	49.23	0.29	1.13	0.09	3.36
PC60/BOS40	16.51	0.47	3.64	11.18	1.15	3.15	51.21	0.17	0.37	0.65	1.97
PC60/PFA40	27.98	0.55	10.19	4.65	0.05	1.35	38.42	0.35	1.077	0.21	2.13
PC60/PFA25/SF15	35.49	0.43	7.55	3.6	0.04	1.17	37.62	0.31	0.91	0.19	2.26
OC60/GGBS25/SF15	33.91	0.45	5.76	1.56	0.12	3.10	44.82	0.25	0.59	0.1	2.39
PC60/GGBS30/SF10	31.60	0.45	5.72	1.63	0.11	3.02	46.25	0.25	0.58	0.11	2.45
PC60/GGBS32.5/SF7.5	28.94	0.47	5.94	1.7	0.11	3.14	48.75	0.25	0.59	0.11	2.6

5.3.2 XRD analysis

Figure 5.23 reports on the results the XRD analysis for the 11 mixes analysed. Once again the XRD results were carried out at the University of Leicester. The phases reported are Ettringite (calcium sulfoaluminate), Portlandite ($(Ca(OH)_2$), Calcium Silicate (C_3S) and Larnite(C_2S).

Ettringite is the mineral name for calcium sulfoaluminate ($3CaO•Al_2O_3• 3CaSO_4•32H_2O$), which is normally found in Portland cement concretes (Portland Cement Association (2001)). The highest intensity of ettringite was detected in PC60/PFA40. This is assumed to be due to this mix having the highest levels of

tricalcium aluminate (C_3A), which is a result of the high Al_2O_3 content that can be seen in Table 5.13. As well as the high C_3A, it can be seen that the intensities of calcium silicate for this mix were not high and therefore the CSH gel that would fill the voids was left empty, allowing for ettringate to form.

As stated in equation 2.1(page 11) ($2\ C_3S + 6H^* = C_3S_2H_3 + 3\ Ca(OH)_2$) and 2.2 (page 11) ($2C_2S + 4H = C_3S_2H_3 + 3\ Ca(OH)_2$) and by Neville (1995-A), Portlandite is ($Ca(OH)_2$) is a byproduct from the formation of di-calcium silicate and tri-calcium silicate. It was noted from the literature review that in order to create a higher quantity of CSH, the SiO_2 content the cementitious constituent should produce this hydrate by reacting with the portlandiate. The lowest intensity of portlandite can be seen in mix PC60/GGBS25/SF15. The reason for this is assumed to be due to the silica fume having very fine particles as well as a high %wt. of SiO_2 that would maximise the reaction with portlandite to create calcium silicate. Although PC60/PFA25/SF15 had a higher quantity of SiO_2 (Table 5.13) the portlandite had a greater intensity as the SiO_2 particles formed in the inner particles of PFA and therefore unable to react to form CSH gel(Barbhuiya et al (2009)).

Calcium silicate (Ca_3SiO_5) also known as tricalcium silicate is the most abundant phase that was reported. It is responsible for initial and early stage strength development. The highest intensity of tricalcium silicate was reported in ternary blends consisting of PC,GGBS and SF. The reason for this is assumed to be due to the combination, of the initial hydration process of PC as well as the hydration products produced from the high levels of CaO in GGBS and SiO_2 in silica fume.

Larnite (Ca_2SiO_4) also known as Dicalcium silicate and is responsible for later stage

strength development and hydrates and hardens over time. The highest intensity of Dicalcium silicate was also reported in ternary blends consisting of PC,GGBS and SF. This is once again assumed to be due to a combination of the initial hydration process of PC as well as the hydration products produced from the high levels of CaO in GGBS and SiO_2 in silica fume.

KEY

E= Ettringite $Ca_6Al_2(SO_4)3(OH)12(H_2O)26$ P= Portlandite $Ca(OH)_2$ C= Calcium Silicate Ca_3SiO_5
L =Larnite Ca_2SiO_4
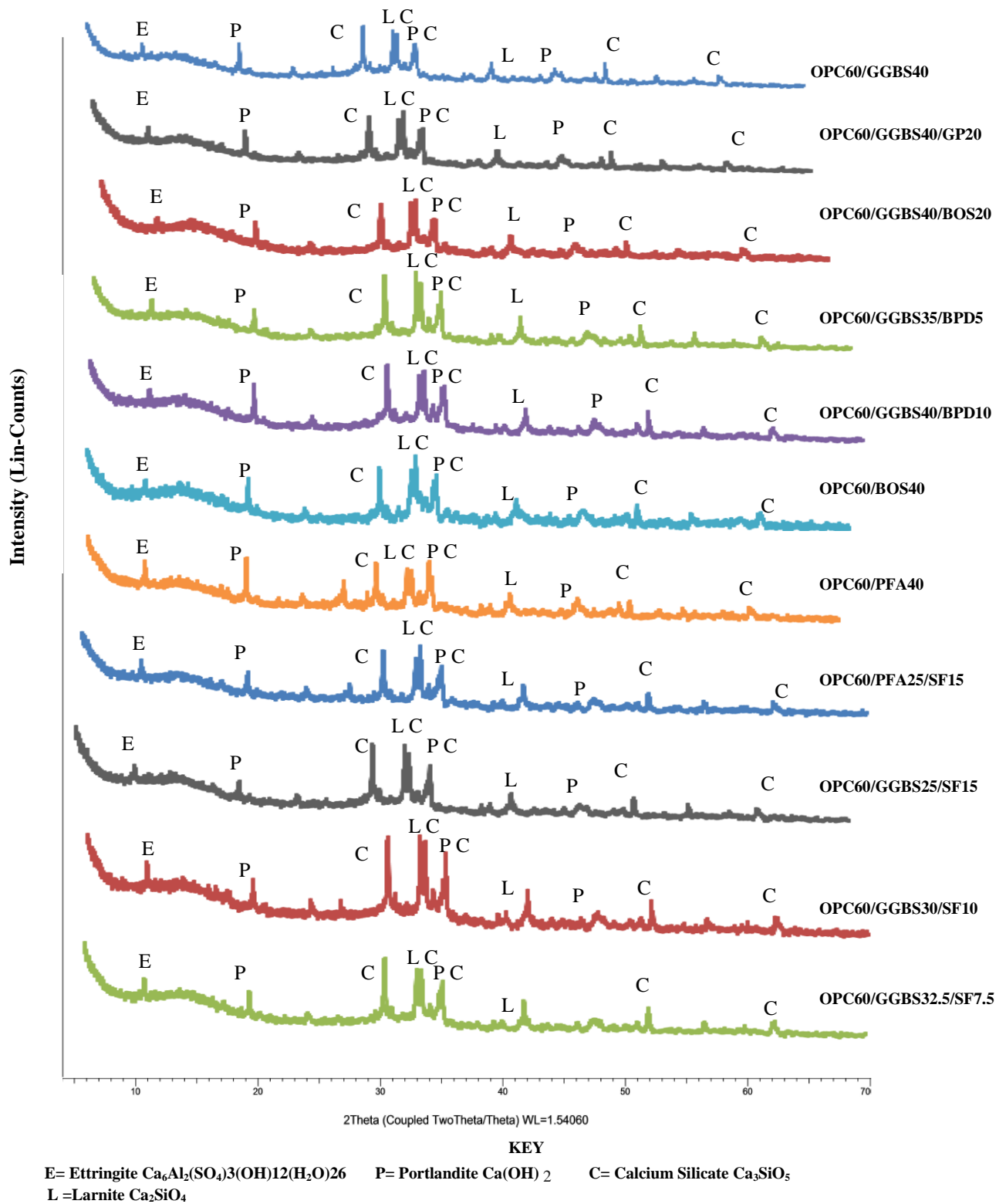
Figure 5.23 XRD analysis of 11 paste mixes tested at 14 days under curing procedure stated in

3.3.3

Chapter 6

Second phase-Concrete paving block results

This chapter provides results on the second phase where the cementitious paste mixes that produced the greatest strengths were than used to produce concrete paving blocks and tested. The two with the greatest strength were known as the candidate mixes and tested for the durability factors stated in BS EN 1338:2003.

6.1 Paving block mixes

Based on paste test results, in total fourteen different cementitious constituent blends were selected in this part of the study to asses splitting tensile strength properties of paving blocks and 14 and 28 days. The two mixes which had the greatest splitting tensile strength and potential to achieve the minimum required strength in factory casting and curing conditions were then known as the two candidate mixes. These two candidate mixes were tested for durability tests that are stated in BS EN 1338:2003. Table 6.1 shows the mix design for the fourteen concrete paving block mixes that were produced and tested. The w/c ratio remained constant at 0.25. The fourteen mixes were chosen based on trends detected on blends produced and analysed using Minitab.

Table 6.1 Mix design for paving blocks.(% by weight)

Mix	Cementitious constituents (% wt)							4mm-dust (%wt)	6mm clean (%wt)	Sand (%wt)
	PC	GGBS	PFA	GP	BOS	BPD	SF			
1	8.4	5.6	-	-	-	-	-	53	9	24
2	8.4	2.8	-	2.8	-	-	-	53	9	24
3	6.3	2.8	-	-	4.9	-	-	53	9	24
4	8.4	2.8	-	-	2.8	-	-	53	9	24
5	8.4	4.9	-	-	-	0.7	-	53	9	24
6	7	6.3	-	-	-	0.7		53	9	24
7	7	5.6	-	-	-	1.4	-	53	9	24
8	8.4	-	-	-	5.6	-	-	53	9	24
9	8.4	-	5.6	-	-	-	-	53	9	24
10	8.4	-	3.5	-	-	-	2.1	53	9	24
11	8.4	3.5	-	-	-	-	2.1	53	9	24
12	8.4	4.2	-	-	-	-	1.4	53	9	24
13	7	5.6	-	-	-	-	1.4	53	9	24
14	8.4	4.55	-	-	-	-	1.05	53	9	24

6.2 Results and discussion

6.2.1 Visual

As well as achieving the mechanical and durability properties that are required by BS EN 1338:2003, one of the key factors to the success of paving blocks in industry is the colour of the block. By having a lighter colour block the pigments have the ability to have a greater depth of colour, therefore be more appealing to the customer and therefore the supplier. Table 6.2 shows the picture and brief description of the 14 blocks produced. With mixes referring to those stated in Table 6.1 When judging the visual aspects, the blocks were examined according to annex J in BS EN 1338:2003,

which stated that in natural daylight the observer, shall stand in turn at a distance of 2m from each edge of the blocks laid in a square and record any block showing cracks or failing.

Table 6.2 Picture and description of concrete paving block mixes

Mix	Picture	Description
1		• Light in colour (Due to GGBS being white) • No cracks or flakes noted • Good uniformity in colour of blocks
2		• The addition of GP had no clear effect on the colour of the block in comparison to mix 1 • No cracks or flakes noted • Good uniformity in colour of blocks
3		• Dark in colour (Assumed due to high quantity of BOS) • No cracks or flakes noted • Good uniformity in colour of blocks
4		• Lighter in colour than mix 4, assumed due to reduction in BOS • No cracks or flakes noted • Good uniformity in colour of blocks
5		• Light in colour • No cracks or flakes noted • Good uniformity in colour of blocks
6		• Increasing the GGBS made the block slightly lighter than mix 5 • No cracks or flakes noted • Good uniformity in colour of block

7		• Light in colour (similar to that of mix 5) • No cracks or flakes noted • Good uniformity in colour of blocks
8		• Dark in colour (due to colour of BOS) • No cracks or flakes noted • Good uniformity in colour of blocks
9		• Dark in colour (due to colour of PFA) • No cracks or flakes noted • Good uniformity in colour of blocks
10		• Dark in colour (due to colour of PFA and SF) • No cracks or flakes noted • Good uniformity in colour of blocks
11		• Lighter in colour in comparison to mix 10 due to GGBS instead of PFA • No cracks or flakes noted • Good uniformity in colour of blocks
12		• Light in colour (similar to that of mix 11) • No cracks or flakes noted • Good uniformity in colour of blocks
13		• Light in colour (similar to that of mix 11 and 12) • No cracks or flakes noted • Good uniformity in colour of blocks
14		• Light in colour (similar to that of mix 11, 12 and 13) • No cracks or flakes noted • Good uniformity in colour of blocks

6.2.2 Splitting Tensile Strength

Figures 6.1 and 6.2 show the splitting tensile strength for the 14 concrete paving block mixes at 14 and 28 days respectively. The strengths are averages from 3 blocks that were tested at each age of testing. At 14 days no mix achieved the minimum splitting tensile strength of 3.6MPa required by BS EN 1338:2003. The three binary mixes produced contained PC/GGBS (Mix 1), PC/BOS (Mix 8) and PC/PFA (Mix 9) and they had 14 day splitting tensile strengths of 1.6, 1.2 and 1.5 MPa respectively. It is long-established that the strengths are due to the hydration products in the replacement materials because as they decrease so does the strength. Although the particle fineness must have some effect on the strength, due to the mix design having such large quantities of aggregate the density is largely down to the aggregate content of the mix. The three ternary paste blends (2, 3 and 4) that produced the lowest splitting tensile strength (1.5, 1.3 and 1.5MPa respectively) contained GGBS along with GP and BOS. The low hydration products were assumed to be the reason for the low strengths achieved with BOS. The best ternary mixes at 14 days contained GGBS along with BPD (mixes 5,6 and7) and SF (mixes 11,12,13 and 14) and PFA along with SF fume (mix 10). As PC levels decreased (mix 6) and BPD levels increased (Mix 7) in ternary PC/GGBS/BPD blends the strengths decreased, therefore the optimum level replacement was found to be 5% BPD replacement. It was assumed that the 5% BPD replacement (mix 5) was due to the quantity of free lime decreasing after the hydration process, also it has been noted by Jallul et al (2014) the high volume of SO_3 in the BPD could have improved the strength as a result of the sulphates activating the GGBS. The greatest strength (2.5MPa) at 14 days of all mixes was obtained by mix 11 which contained PC60/GGBS25/SF15 and this is assumed to

be due to the finer particles of SF and the greater quantity of C-S-H gel which is produced during hydration due to the greater quantity of reactive silica that is available with SF.
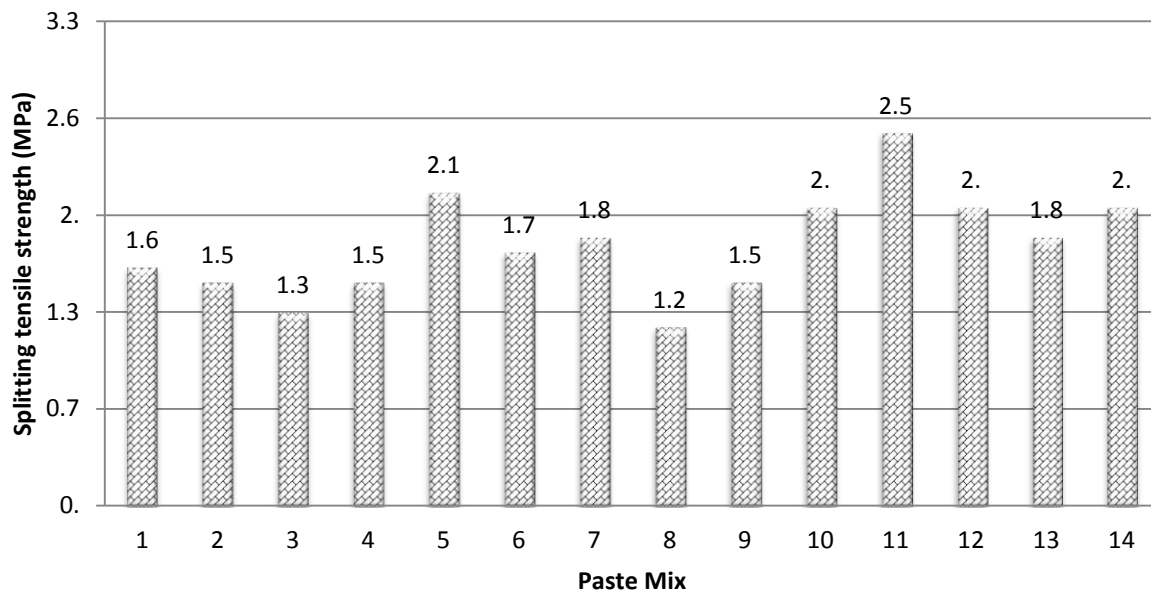
Figure 6.1 Splitting tensile strength at 14 days

Figure 6.2 shows the 28 day splitting tensile strength for all concrete paving block mixes. It is noted that none of the mixes achieved the minimum requirement of 3.6MPa that is expected by BS EN 1338:2003. Most mixes had gained between 60-90% of their 28 days strength at 14 days and the mix that had the greatest enhanced strength contained PC/GGBS/GP (mix 2). This is assumed to be due to the hydration taking longer because of the larger GP particle sizes. When analysing the binary blends the same trends were noted as those at 14 days. The two greatest strengths were achieved by mix 11 (PC60/GGBS25/SF15=3.2MPa) and mix 12 (PC60/GGBS30/SF10=2.8MPa) and this is once again due to the very fine SF particle sizes and high quantity of silica which reacts with the excess CH produced during the

initial hydration process to produce excess C-S-H gel. In order to get these mixes to

obtain the minimum strength required by BS EN 1338:2003 it is suggested that a

superplastisizer be used. Therefore the two candidate mixes were

PC60/GGBS25/SF15 and PC60/GGBS30/SF10 and these were tested for the

durability properties stated in BS EN 1338:2003.
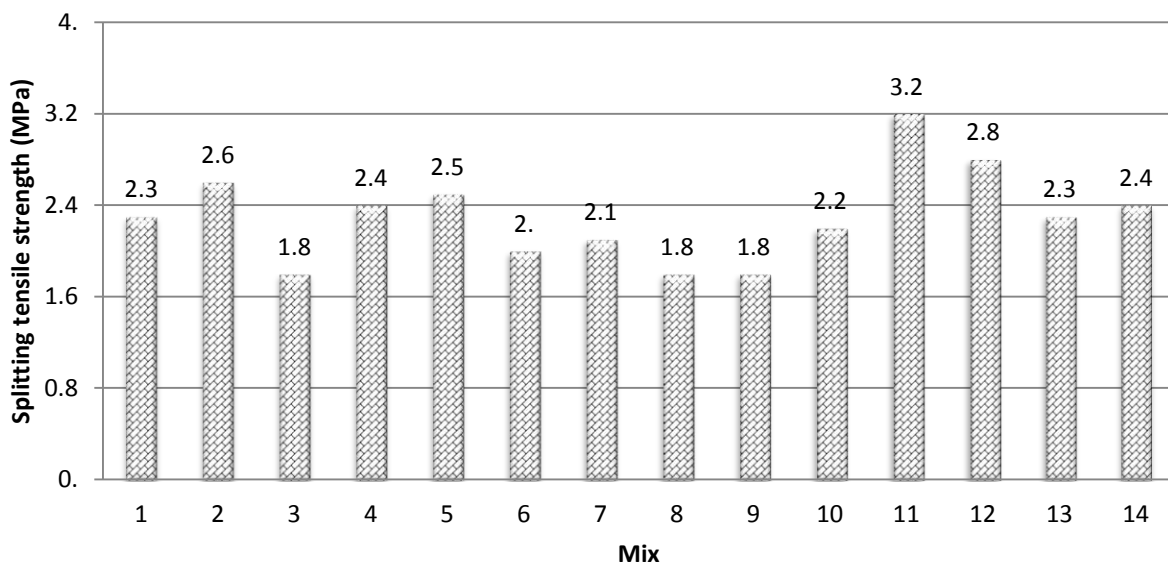
6.2 Splitting tensile strength at 28 days

6.2.3. Water absorption

Table 6.3 shows the weight of blocks after 3 days in water, 3 days in the oven at $100^{o}c$

and therefore the total water absorption after 28 days of curing. BS EN 1338:2003

states that no block should have water absorption greater than 6%. Table 6.3 shows

that all blocks tested for both mixes produced results that were below the required rate

and hence are all satisfactory. It is assumed that the introduction of SF and GGBS into

the mix provided a greater distribution of particles, resulting in an increase in the filler

effect, as well as greater quantities of C-S-H gel being produced, which overall meant
that there were less pores available for water to be stored in therefore absorbed.

Table 6.3 Water absorption of 2 candidate mixes

Mix	Weight after 3 days in water (kg)	Weight after 3 in oven at 100°c (kg)	Water absorption rate (%)
PC60/GGBS30/SF10	3474.2	3307.7	4.8
	3476	3290.6	5.3
	3486	3307.2	5.1
PC60/GGBS25/SF15	3473.6	3300	5
	3488.8	3309.3	5.1
	3489.8	3314.5	5

6.2.4 Freeze-thaw resistance

Figure 6.3 and 6.4 shows the blocks after 28 freeze thaw cycles for mixes
PC60/GGBS30/SF10 and PC60/GGBS25/SF15 respectively. BS EN 1338:2003 states
that after 28 cycles the mass loss should be no greater than 1kg/m3. Both mixes
showed excellent results and as can be seen from both Figures there were minimal
amount (both below $1g/m^3$) of material that had scaled of the blocks. The blocks
therefore achieved the required values stated by BS EN 1338:2003. Positive effect
with the addition of GGBS and SF has also been noted by Bleszynski (2002) and it is
stated in a study by Barbhuiya et al (2009) which analysed the addition of PFA and
SF that SF had a positive effect due it having a quicker hydration time and its greater
pozzolanic reactivity which came from the finer particles and very high amorphous

silicon dioxide content. It is assumed that the positive effects of SF were achieved in combination with GGBS resulting in high freeze thaw resistance.
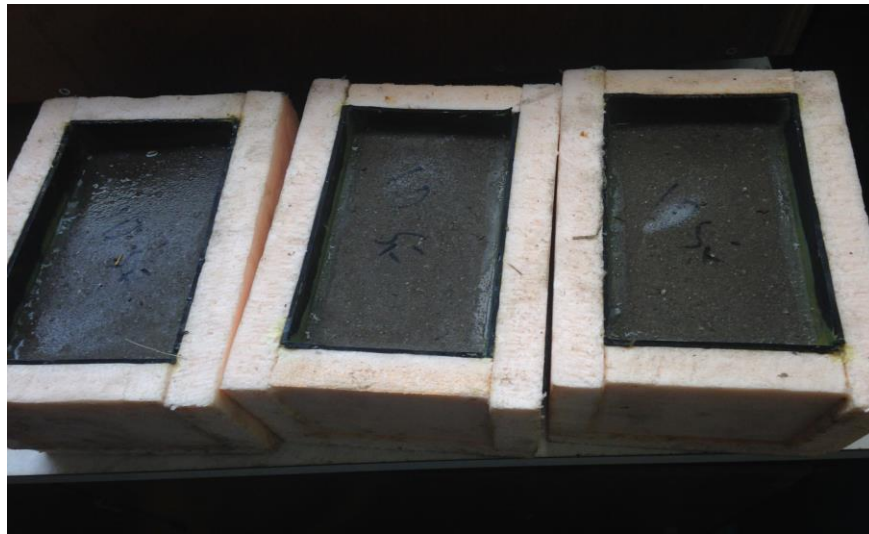
Figure 6.3 blocks after 28 freeze cycles for mix containing PC60/GGBS30/SF10

Figure 6.4 blocks after 28 freeze cycles for mix containing PC60/GGBS25/SF15

6.2.5 Slip/skid resistance

The final test conducted was the slip/skid resistance and Table 6.4 shows the slip skid values that were obtained. Table 3.44 shows the potential for slip that is stated by BS EN 1338:2003 in correlation to the Pendulum test value.

Table 6.4 Slip/Skid resistance of candidate mixes (USRV)

Mix	Block 1	Block 2	Block 3
PC60/GGBS30/SF10	95	100	101
	100	102	105
	102	104	102
	96	107	99
	96	104	98
Average	**97.8**	**103.4**	**101**
PC60/GGBS25/SF15	90	100	103
	92	98	99
	90	96	96
	96	95	95
	99	99	95
Average	**93.4**	**97.6**	**97.6**

The mix containing PC60/GGBS30/SF10 performed slight better than the mix containing PC60/GGBS25/SF15; however both mixes had a value much greater than 75 which meant that they both had extremely low possibilities for potential slipping.

6.3 Concluding remarks

- 14 concrete paving blocks produced using the optimised mixes in chapter 5 did not achieve the minimum splitting tensile strength required by BS EN 1338:2003 at 28 days.

- The 2 best mixes consisted of varying levels of GGBS and SF.

- It is suggested that the use of superplastizers will increase the splitting tensile strength.

- The 2 candidate mixes (Mix11 and 12) met the minimum durability properties required by BS En 1338:2003

Chapter 7

Factory and site trials

7.1 Introduction

The two greatest strengths, therefore candidate mixes from Table 6.1 were observed for mix 11 (PC60/GGBS25/SF15=3.2MPa) and mix 12 (PC60/GGBS30/ SF10= 2.8MPa). Even though these mixes did not achieve the minimum strength (3.6MPa) that is required by BS EN 1338:2003, the mixes were still used to produce blocks in the factory. The reason for this is due to the different manufacturing process (simultaneous compaction and vibration) and curing conditions, as well as this, when reviewing the process by the factory it was noted that they used a water reducing agent. These differences allowed for the possibility of the two candidate mixes achieving the minimum strength required. Therefore the two candidate mixes were used to produce concrete paving blocks in the factory and as well as being tested to ensure they meet the current standards, the blocks were actually laid over the winter period to be analysed.

7.2 Paving block production

7.2.1 Mix Design and materials

These mixes produced in the Hanson factory are shown in Table 7.1. The w/c ratio remained constant at 0.25. The conditions under which the blocks were made were exactly as though they would be produced if the factory was to make them on a

consistent basis. The aggregate grading at the factory is shown in Table 7.2. The chemical and physical properties of the cementitous materials are shown in Table 7.3 and Table 7.4 respectively. The water reducing agent used was supplied by Oscrete and met the specifications stated by BS 5075: Part 1.

Table 7.1 Mix Design for candidate mixes and control mix

Mix	Cementitious constituents (% wt)			4mm-dust (%)	6mm clean (%)	Sand (%)
	PC	GGBS	SF			
1	8.4	3.5	2.1	53	9	24
2	8.4	4.2	1.4	53	9	24
Control	14	0	0	53	9	24

Table 7.2 Aggregate properties

Aggregate	Sieve size (mm)						Density (Kg/m^3)
	10	8	6	4	2	1	
4mm-dust	100	100	100	100	62	31	2718
6mm	100	99	89	43	19	18	2691
Sand	100	100	100	100	99	98	2021

Table 7.3 Chemical composition of cementitous materials

Oxide	PC (%)	GGBS (%)	SF(%)
SiO_2	19.42	33.27	94.21
TiO_2	0.36	0.57	0.01
Al_2O_3	4.55	13.12	0.48
Fe_2O_3	2.49	0.32	0.71
MnO	0.023	0.316	0.013
MgO	1.03	7.74	0.55
CaO	60.60	37.16	0.37
Na_2O	0.22	0.73	0.33
K_2O	0.568	2.44	0.478
P_2O_5	0.201	0.24	0.009
SO_3	3.622	0.654	2.212

Table 7.4 Physical properties of cementitous materials

Mesh No μm	Aperture	Passing Below %		
		PC	GGBS	SF
100	150	95.65	100.00	100.00
140	106	94.00	99.99	100.00
200	75	89.90	98.05	100.00
325	45	76.19	87.89	100.00
400	38	69.69	82.70	100.00

One of the alterations between the mixes produced in the laboratory and in factory was that in the factory the SF was provided in a slurry form. The reason for this was because of the health problems that could occur with having a high quantity of fine material being used, however this was also an advantage as the efficiency of SF is improved in slurry form.

7.2.2 Casting and curing

In order to best disperse the slurry SF, GGBS and PC the following procedure was suggested by ELKEM (Manufacturer of SF):

1. Put all the coarse aggregate and 50% of the fine aggregate into the mixer with 75% of the water. Start the mixer.

2. When evenly mixed, add the microsilica. The preference here is to use undensified microsilica or slurry. Densified product can be used, but extra time must be allowed here to breakdown the particles. This would be approximately 2 minutes.

3. Once evenly mixed – a uniform grey colour – add the cement and allow mixing time.

4. Add any chemical admixtures (Plasticiser / superplasticiser etc.) diluted with some of the remaining water.

5. When evenly mixed, add the rest of the fine aggregate and allow to mix in.

6. Add the remaining water, slowly, until the required workability is reached.

Between the suggested procedure and actual procedure used there were two alterations. Firstly, the entire fine aggregate was added in the first stage. Secondly, the pigment used for the blocks produced was charcoal and in the factory the pigment is also added in the slurry form. This meant that for mix 1 around 95% of the water was added at the initial stage and for mix 2, 75% of the water was added at the initial stage. The water content of the mix is controlled by a sensor within the mixer which detects if additional water is required or not and therefore it is believed that this had no effect on strength.

Due to this being a trial mix, the quantity of GGBS and SF being used resulted in the use of silos being inappropriate. Therefore the material was ordered in barrels of 25Kg and 30 Kg for GGBS and SF respectively. The material was then introduced into the mix at the right time by pouring it directly into the mixer as shown in Figures 7.1 and 7.2.

Figure 7.1 Introduction of slurry SF to the mix   **Figure 7.2 Introduction of GGBS to the mix**
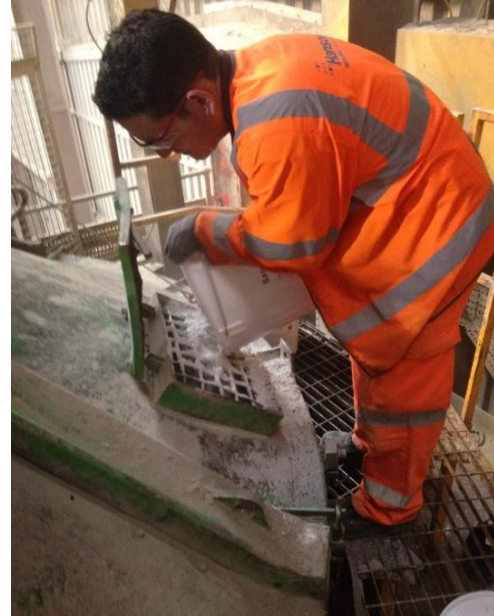
Once the materials had been evenly mixed in the mixer, the material was then transported along to the production line where it was placed into moulds ready to be compacted and vibrated simultaneously (Figure 7.3). The blocks after a few seconds emerged from the machine ready to be placed in the curing chamber (Figure 7.4). A tray of each batch was taken to the side to ensure that height of the blocks were 80±2mm (Figure 7.5), one thing to noted was that the blocks were very delicate and broke very easily if handled. Figure 7.6 shows the curing chamber that the blocks were placed in for 24 hrs before they were packed. The heat and humidity within the curing chamber comes from the exothermic reaction during hydration of the blocks.

The press simultaneously compacts and vibrates the materials in the mould

The semi dry concrete is placed in to moulds evenly

Figure 7.3 Material laid into moulds ready to be compressed and vibrated simultaneously.
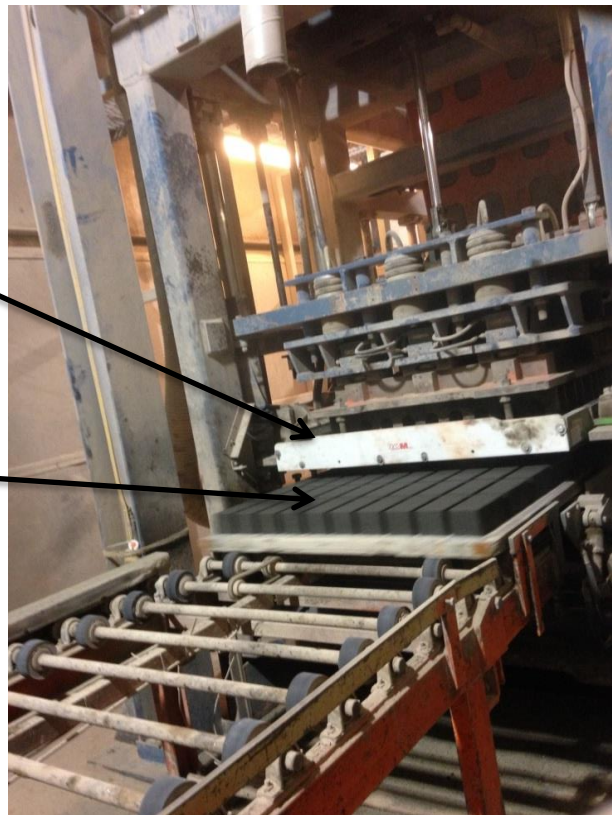
After a few seconds the mould is lifted

The blocks emerge ready to be cured in the chamber

Figure 7.4 Blocks emerging from the machine

Blocks still delicate to handle

Figure 7.5 Blocks are measured to ensure the height is between 80±2mm

After 24hrs curing, blocks are packed ready to be stored in the yard until being sent to site.

Figure 7.6 Automated system stores blocks on racks in the curing chamber

7.3 Strength and durability results

The strength (splitting tensile strength) and durability (water absorption, freeze/thaw resistance, slip/skid resistance and abrasion resistance) test recommended for concrete paving blocks by BS EN 1338:2003 was determined for the block produced in the factory

7.3.1 Splitting tensile strength

Table 7.5 provides the results for the splitting tensile strength for the two candidate mixes and control mix that were produced at the Hanson Form pave factory and tested at 2, 7, 14 and 28 days. The results show that production differences between laboratory and factory make a significant difference in the strength of the blocks. For mix 1 the difference between lab and factory results at 14 and 28 days was 1 MPa and 0.63 MPa respectively. For mix 2 the difference between lab and factory results at 14 and 28 days was 1.01 MPa and 0.7 MPa respectively. The cause for the difference between the two results is due to the specialist and designated equipment and curing conditions that the factory uses which cannot be replicated in the lab .As well as this it was initially reported that the factory did not use admixtures, however on the site trial it was noted that superplasticer was used in the process and this would have had impact on strength. However it can be assumed based on these mixes that at 14 days the strength between laboratory (without superplastisicer) and factory (with superplastisicer)will be on average 1.005MPa and at 28 days on average 0.665 MPa. The results showed that PC can successfully be reduced by 40% if it was to be

replaced by 25% GGBS and 15% SF and at 28 days the results for this mix actually produces greater strengths than a mix containing 100%PC.

Table 7.5 Splitting tensile strength- factory blocks.

Test age	Splitting Tensile Strength (MPa)		
	Control	**PC60/GGBS25/SF15**	**PC60/GGBS30/SF10**
2	2.95 (Fail)	2.4 (Fail)	2.35 (Fail)
7	3.3 (Fail)	3.17 (Fail)	2.87 (Fail)
14	3.63 (Pass)	3.5 (Fail)	3.01 (Fail)
28	3.7 (Pass)	3.83 (Pass)	3.5 (Fail)

7.3.2 Water absorption

Table 7.6 reports on the water absorption rate of the two candidate mixes and the control mix.BS EN 1338:2003 states that no block shall have a water absorption rate of greater than 6%. All blocks achieved this minimum requirement. The two candidate mixes produced lower absorption rates than the control mix, with the mix containing PC60/GGBS25/SF15 producing the lowest results of 3.43%. The reason for the lower absorption rate is assumed to be due the greater particle packing as well as a greater interface between the aggregate and cement paste which allows less pores to be accessible to store water.

When comparing blocks produced in the laboratory and the factory, the blocks produced within the factory had a lower water absorption rate. The difference between laboratory and factory results for PC60/GGBS25/SF15 was 1.6% and for

PC60/GGBS30/SF10 was 1.56%. The difference in result is assumed to be due the manufacturing process. The simultaneous vibration and compaction of the blocks in the factory are assumed to decrease voids and as well as the pores within the blocks, therefore reducing water absorption.

Table 7.6 Water absorption rate-factory blocks

Mix	Weight after 3 days in water (kg)	Weight after 3 days in oven at 100°C (kg)	Water absorption rate (%)
PC60/GGBS25/SF15			
	3.37	3.24	3.86
	3.43	3.32	3.21
	3.41	3.30	3.22
		Average	**3.43**
PC60/GGBS30/SF10			
	3.42	3.31	3.22
	3.39	3.26	3.83
	3.46	3.34	3.47
		Average	**3.51**
Control	3.43	3.31	3.50
	3.41	3.29	3.52
	3.42	3.29	3.80
		Average	**3.61**

7.3.3 Freeze thaw resistance

The quantity of scaled material for all blocks tested was minimal-zero (all below $1g/m^3$) and was well below the $1.0kg/m^3$ limit that was stated by BS EN 1338:2003. When testing blocks that were produced under laboratory conditions there was also minimal-zero being scaled of the blocks and therefore it was presumed that blocks being produced under greater intensity in the factory that there would be similar results.

7.3.4 Slip/Skid resistance

The measurement of the unpolished slip resistance value (USRV) on the blocks was made using the pendulum friction tester and tested in accordance to the method stated in BS EN 1338:2003. There was a slight variability in results however the slip/skid resistance is influenced greater by the finish of the block than the mix design itself. Table 3.14 from BS EN 1338:2003 provides the potential for slip in correlation to the pendulum test value. BS EN 1338:2003 states that any value above 75 results in a potential for slip being extremely low, it can be seen from Table 7.7 that all values were above this value therefore had extremely low possibilities for potential slipping.

Table 7.7 Evaluation of pendulum test results

Mix	Block 1	Block 2	Block 3
PC60/GGBS30/SF10	114	106	115
	109	110	114
	111	106	110
Average	**111.3**	**107.3**	**113**
PC60/GGBS25/SF15	109	109	111
	105	108	111
	103	108	106
Average	**105.7**	**108.3**	**109.3**
Control	100	105	102
	98	103	103
	99	103	106
Average	**99**	**103.7**	**103.7**

7.3.5 Abrasion resistance

The abrasion resistance of the blocks was measured in accordance in the test method

described in annex G of BS EN 1338:2003. Table 3.15 reports on the different classes that the blocks are subjected to, based on the results that were obtained. As stated by El Nouhy (2013) in areas subject to very heavy pedestrian and vehicular traffic, Class 4 should be used. In areas, subject to normal pedestrian and vehicle use, e.g., public pavements and roads, at least Class 3 products should be used. In areas subject to light pedestrian and vehicular use, e.g., garden, drives, at least Class1 products should be used.

Table 7.8 reports on the abrasion resistance of the two candidate mixes and control. The results showed all blocks fell within class 1 and should be used in areas of light pedestrian and vehicular use.

Table 7.8 Evaluation of abrasion resistance

Mix	Abrasion resistance (mm)
PC60/GGBS30/SF10	
	24.5
	23.5
	23.5
Average	**24**
PC60/GGBS25/SF15	
	23
	24
	24
Average	**23.5**
Control	
	23.5
	23.5
	23
Average	**23.5**

7.4 Site trial

7.4.1 Laying of blocks

Once blocks were produced, after 2 days they were laid on the test bed site at Hanson Formpave. The test bed was being used to analyse heated ground loops within the SUDS system. Figure 7.7 displays the blocks being removed and Figure 7.8 displays the test bed area. Figure 7.9 displays the blocks being laid and Figure 7.10 displays the completed laying of the blocks, with 1 and 2 within the area marking the mix design.

Figure 7.7 Removal of blocks on test bed   **Figure 7.8 Test bed prepared for laying of blocks**

Figure 7.9 Blocks being laid on site

Figure 7.10 Mix 1 and 2 laid on test bed

7.4.2 Condition of blocks following the winter period

The blocks were laid on 2nd October 2014 and the site was revisited on the 4th March 2015. Hanson Formpave had previously experimented with the use of SF as a

cementitious constituent and had noted difficulties arose in the form of 'dust balls' being created. The difficulty reported was that these 'dust balls' over the winter period rose to the top of the blocks causing deterioration. Figure 7.11 and 7.12 displays the blocks after the winter period.

Figure 7.11 Removal of blocks on test bed   **Figure7..12 Test bed prepared for laying of blocks**

Figure 7.13 provides images that were taken close up to the blocks on 4th March 2015. Assessment of the blocks showed that they had lightened in colour; however this was to be expected for all blocks that are produced. On closer inspection the 'dust balls' that were reported with previous use were not be detected. The dust balls were detected previously due to the agglomeration of the SF slurry as the silos in which the material was stored was not agitated correctly. As we had fresh material that was mixed well before use this problem did not occur. Overall the upper face of the blocks did not exhibit defects such as cracking or flaking over the winter period.

Figure 7.13 Close-up images of blocks

7.5 Material Variability

One of the biggest disadvantages with cementitious constituent are that they are not the primary products produced; therefore there can be variability in chemical composition on a monthly basis. The variability can have effect on both mechanical and durability properties. Chapter 4 reviewed the effect of material variability and concluded that if industry was to implement the use of materials that were commercially available, the chemical composition has greater effect as there seems to be a control on the fineness. If industry was to implement the use of waste material then to a much greater extent the particle distribution should be regulated in order to get a suiTable range for which industry could make predicted strengths.

The two cementitious constituent that were successful in this study were GGBS and SF. Both replacements have grown in popularity and due to this they are now commercially available. Based on this the chemical composition of the two materials was obtained over a 6 month period. Table 7.9 and 7.10 reports on the chemical composition of SF and GGBS respectively over a 6 month period (2013). The results show that these materials have low variability on a monthly basis, therefore when being used in a commercial setting the client can expect results of strength and durability to be consistent.

Table 7.9 Chemical properties of SF over 6 months

Chemical property	Month						Range
	Jul	Aug	Sep	Oct	Nov	Dec	
SiO_2 (%)	96.00	95.3	95.00	95.1	95.8	95.7	95.1-96
CaO (%)	0.30	0.31	0.40	0.33	0.22	0.38	0.22-0.40
Na_2O(%)	0.56	0.70	0.88	1.02	0.85	0.76	0.56-1.02
K_2O(%)	0.58	0.71	0.93	1.13	0.91	0.72	0.58-1.13
SO_3(%)	0.26	0.29	0.36	0.27	0.25	0.28	0.25-0.36

Table 7.10 Chemical properties of GGBS over 6 months

Chemical property	Month						Range
	Jul	Aug	Sep	Oct	Nov	Dec	
SiO_2 (%)	34.9	35.16	34.52	35.24	34.55	34.93	34.52-35.24
TiO_2(%)	0.67	0.65	0.69	0.69	0.62	0.64	0.62- 0.69
Al_2O_3(%)	12.93	13.25	11.93	12.86	14.46	14.22	11.93- 14.46
Fe_2O_3(%)	0.35	0.31	0.3	0.58	0.29	0.37	0.29-0.58
MnO(%)	0.39	0.36	0.33	0.41	0.34	0.39	0.33-0.41
MgO(%)	7.54	7.36	8.33	8.31	8.25	7.64	7.36-8.33
CaO(%)	39.68	39.79	39.23	39.5	39.46	39.82	39.23-39.82
Na_2O(%)	0.26	0.22	0.19	0.44	0.3	0.35	0.19-0.44
K_2O(%)	0.73	0.69	0.62	0.61	0.62	0.66	0.61-0.73
SO_3(%)	0.63	0.34	0.6	1.12	0.67	0.96	0.34-1.12

7.6 Sustainability

The final aspect of the site trial was to look at the overall sustainability of the blocks. Sustainability is analysed by looking at impact in three different areas.

Environmental Impact:

GGBS and SF are by products from the steel and silicon metal industries respectively. The reduction of 40% with the use of these materials results in a potential reduction of 4000 tonnes of CO_2 as the PC would not be required.

Social Impact:

The social impact with the use of the candidate mixes is that they make use of locally supplied products, the CO_2 emissions are reduced and more importantly the blocks they are using perform better than blocks produced with 100% PC.

Economic Impact:

Based on the factory using 12000 tonnes (Section 1.1) of PC a year, the use of the mix containing PC60/GGBS25/SF15 will result in an annual cost of around £1,461,420 and the 100%PC mix will have an annual cost of around £1,070,640. Figures are based on prices supplied by the factory and the suppliers. Financially this is a disadvantage to the factory and this is due to the current cost of SF. GGBS is currently around 10% cheaper than PC however SF in 2.5 times the price of PC.

Overall the use of the candidate mix containing PC60/GGBS25/SF15 shows a beneficial impact on the environment and social aspects. However financially due to

the current SF market prices the overall cost is nearly £5000 per month more expensive.

7.7 Concluding remarks

- The two candidate mixes were successfully produced in the Hanson Formpave factory and the mix containing PC60/GGBS25/SF15 at 28 days produced greater strengths than the control mix.

- All blocks produced were within the durability requirements stated in BS EN 1338:2003 and over the winter period the blocks laid on site showed no sign of deterioration.

- The variability of GGBS and SF over a 6 month period fall within the ranges recommended in section 4.4

- The sustainability of blocks showed advantages when reviewing the social and environmental impacts, however the cost of materials for the candidate mixes was higher.

Chapter 8

Leaching

8.1 Introduction
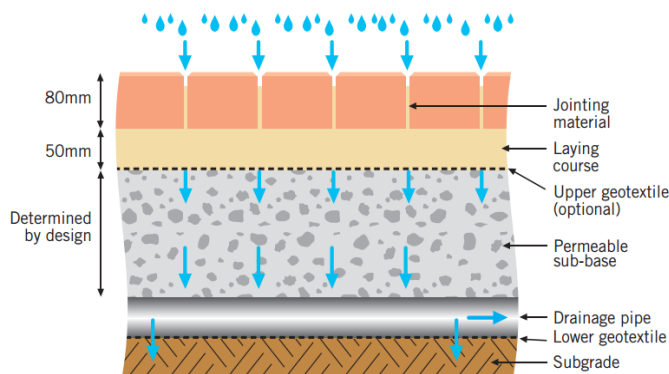
| Figure 8.1 SUDS-partial infiltration system | Figure 8.2 SUDS-No infiltration system |
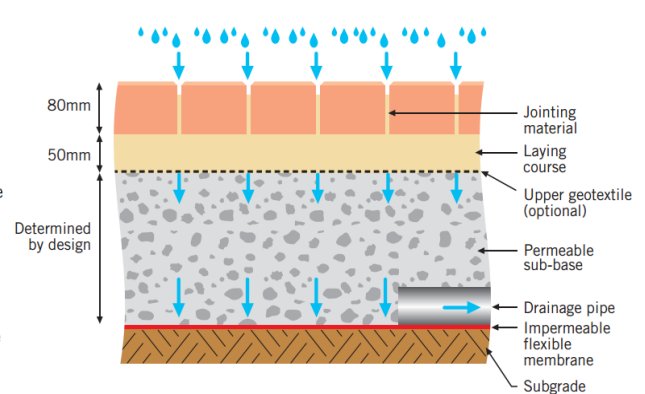
Figure 8.1 and 8.2 show the partial and no infiltration systems that are adopted in SUDS. These systems allow water to be stored and potentially re-used for domestic purposes. The SUDS system is designed in a way which allows contaminates such as oil and petrol to be filtered in between the blocks and be captured and degraded over time in the permeable sub-base. This section of the thesis focused on the leaching properties of the blocks if permeable system were not used, therefore determine the quantity of potential contaminants that could leach through the blocks themselves.

8.2 Results and Discussion

Figure 8.3 depicts the screen shot of the analysis that the software conducted in order to define concentrations. Point 1 illustrates the wavelength that was detected by ICP

from the calibration solution and element that it correlates with. Point 2 illustrates the plots for light emission vs concentration for each element. Point 3 defines the concentrations for each leachate sample and was calculated based on the plots in point 2.

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Figure 8.3 Screen shot of leachate analysis

Table 8.1 reports on the concentrations values for the different elements in the original sample (leachate developed) and the concentration that was in the leachate after a volume sample had been passed through the control mix, mix1 and mix 2.

When comparing the leachate produced to the values that were stated by Coupe et al (2006,) as shown in Table 8.1 the differences between the two for Al, Cr, Cu, Mg, Mo, P, Pb and Zn was 3%, 9%, 4%, 2%, 6%, 6%, 8% and 8% respectively.

The control mix absorbed 82%, 19%, 15%, 4%, 7%, 18%, 100% and 12% of Al, Cr, Cu, Mg, Mo, P, Pb and Zn respectively. Mix 1 absorbed 78%, 18%, 8%, 2%, 6%, 15%, 100% and 8% of Al, Cr, Cu, Mg, Mo, P, Pb and Zn respectively. Mix 2 absorbed 68%, 16%, 7%, 2%, 6%, 14%, 100% and 6% of Al, Cr, Cu, Mg, Mo, P, Pb and Zn respectively.

Table 8.1 Leachate concentrations of original sample and samples once passed through blocks

	Al 396.153 mg/L	Cr 267.716 mg/L	Cu 327.393 mg/L	Mg 285.213 mg/L	Mo 202.031 mg/L	P 213.617 mg/L	Pb 220.353 mg/L	Zn 206.200 mg/L
Original leachate	14.54	1.825	32.81	481.1	149.9	935.6	1.836	1200
Control mix	2.575	1.480	27.75	462.34	139.1	767.9	-0.313	1061
Mix 1	3.263	1.489	30.35	417.14	140.7	795.5	-.0307	1103
Mix 2	4.723	1.524	30.61	471.32	140.8	803.8	-0.229	1125

It is assumed that due to the higher permeability of the candidate mixes the leachate was able to pass at a higher rate through the blocks, therefore absorbing less of the contaminants. The permeability rates for the control mix, mix 1 and mix 2 were 1.05×10^{-7}m/s, 6×10^{-7}m/s and 6.65×10^{-7}m/s respectively. As it can be seen the permeability of mix 1 and 2 are about 6 times more than the control mix and this is reflected in the quantity of leachate absorbed.

From review of these Figures the most absorbed metals were Al and Pb and the metals which had similar concentrations both before and after testing were Cu, Mg, Mo, P, Cr and Zn. In order to put concentration values into perspective the top soil (between 51-203mm of the outmost layer of soil) concentrations for the elements, for England and Wales reported by UK Soil Observatory (UKSO) were analysed.

These concentrations were determined by UK Soil Observatory (UKSO) using wavelength X-ray fluorescence spectrometry with the lower limit of detection (mg/kg) being specific to each element. Table 8.2 shows the percentile scale each element falls within for each mix and original leachate.

Table 8.2 Percentile scale of elements in relation to top soil concentrations

	Al	**Cr**	**Cu**	**Mg**	**Mo**	**P**	**Pb**	**Zn**
	Percentile scale (%)							
Original leachate	>90%	0-10%	70-80%	>90%	>90%	>90%	<0%	>90%
Control mix	0-10%	0-10%	60-70%	>90%	>90%	>90%	<0%	>90%
Mix 1	0-10%	0-10%	70-80%	>90%	>90%	>90%	<0%	>90%
Mix 2	20-30%	0-10%	70-80%	>90%	>90%	>90%	<0%	>90%

Table 8.2 allows us to report that in comparison to current top soil concentrations, concrete paving blocks help reduce Al concentrations and that Cr and Pb concentrations are low in the used oil samples. However the results show that when analysing Cu, Mg, Mo, P and Zn concentrations are relatively high. The high concentrations of elements allows the study conclude that in locations where exposure

to such contaminants may occur, the use of SUDS systems would be recommended to avoid heavy metals concentrations increasing in the soil below. At minimum it would be recommended that some form of membrane that halts the flow of used oil be used.

8.3 Concluding remarks

- A leachate was successfully produced using salts and solutions and a sample volume was passed through 50mm cores.

- Results showed that the control mix absorbed a greater quantity of the leachate in comparison to mix 1 and 2. This is assumed to be due the permeability of the blocks being nearly 6 times greater for the candidate mixes.

- Overall the absorption of the leachate in the candidate mixes are quite high and are beneficial to absorb heavy metal ions.

- For all blocks it was concluded that in areas of vehicle use where such contaminates will be present the use of SUDS and at minimum some type of membrane be used.

Chapter 9

Conclusion and discussion

The prime aim of this project was to carry out trial mixes made with different cementitious constituent for concrete paving blocks and to devise and test mixes which will then be compared to the control mix (100% PC) to show which has the best outcome. The justification for the research is a need to better understand the effect of cementitious constituents at varying levels on the mechanical and durability properties of concrete paving block. This understanding was used to produce a mix design which met all the requirements set by BS EN 1338:2003 as well as increasing the all-round sustainability of the concrete paving blocks.

Based on this the specific objectives were to;

1 Carry out a review of past literature to understand current practices in cementitious constituents, in respect to paving block production

2 Design mixes with several by-products and waste materials to reduce cement content in concrete paving blocks.

3 Conduct laboratory trial mixes to examine the four key inter-related areas for concrete paving blocks, these are strength properties, durability performance, control of material variability and leaching properties of the block.

4 Carry out factory and site trials with constructed paved areas using actual factory made paving blocks with reduced cement content.

9.1 Objective 1

From review of past literature it was firstly noted that very little work had been done on reducing cement content in concrete paving blocks, therefore cementitious constituents in all types of concrete applications was reviewed. It was concluded that using two different cementitious constituents in addition to a remaining proportion of cement can deliver superior properties to a single replacement and make use of replacement materials that would otherwise not be successful.

9.2 Objective 2

The systematic method designed in this study used the design of experiments (DOE) technique within Minitab. The software allowed for the study to design and analyse mixes with high levels of cementitious constituents. Overall there were 11 different ternary groups that were analysed and these were PC-PFA-GGBS, PC-PFA-MK, PC-PFA-BOS, PC-PFA-SF, PC-PFA-GP, PC-PFA-BPD, PC-GGBS-MK, PC-GGBS-BOS, PC-GGBS-SF, PC-GGBS-GP and PC-GGBS-BPD. Out of the mixes analysed fourteen mixes which had the greatest strength at 14 days were chosen to be used in concrete paving blocks.

Analysis of ternary cement pastes concluded that mixes containing GGBS over PFA produced greater strengths at early ages. The advantages of MK that were reported during the literature review were unable to be re-created due to the nature of the semi-dry paste remaining at a consistent w/c ratio and MK requiring greater water content as replacement levels incresed. Mixes confirmed that OPC-GGBS-GP and OPC-

GGBS-BPD showed good strengths due to the SiO_2 content within GP proving secondary CSH gel and SO_3 within BPD activating the GGBS through sulphates. The best results were found in OPC-GGBS-SF and OPC-GGBS-BOS ternary pastes. The fine particles along with the high SiO_2 content of SF provided greater pozzolanic reactivity and a greater matrix densification. For OPC-GGBS-BOS blends the chemical composition of BOS along with the fineness which was achieved through grinding of raw material also provided good results. XRF and XRD tests were carried out to review the chemical properties of the greatest cement pastes mixes. This allowed for the validation of results that were produced.

9.3 Objective 3

When reviewing the strength and durability of the mixes produced in the laboratory it was concluded that

- The two mixes with the greatest splitting tensile strength in the mixes produced and therefore the candidate mixes were mix 11 (PC60/GGBS25/SF15) and mix 12 (PC60/GGBS30/SF10).
- The combination of PC/GGBS/SF provided greatest results due to the very fine SF particles and high quantity of silica which reacts with the excess CH produced during the initial hydration process to produce excess C-S-H gel.
- The two candidate mixes tested, successfully achieved the minimum requirements for freeze thaw resistance, water absorption and slip/skid resistance.

The review of material variability led to the following conclusions

- For both PFA and BPD the chemical composition of the major oxides had similar variability's over the 6 months being analysed, however the particle distribution was much more variable for BPD than PFA.

- It is suggested that if the material in the candidate mixes is a waste material than there should be limits on chemical composition as stated in 4.4. and to a greater degree on the fineness of the material. For a material that is used in low level replacement (up to 10%) an average particle size difference of 15µm is suggested to ensure that there is no difference in strength greater than 3%.

- It is suggested that if the candidate mixes were to use a material that was regulated then the chemical composition should be analysed. This is in order to ensure that the limits fall within the limits stated in 4.4.4.3 to ensure that there is no difference in strength greater than 3%.

The final of the four interrelated areas was the leaching properties. This testing was carried out on the concrete blocks produced in the factory and it was concluded that

- The permeability of the blocks incorporating GGBS and SF increases in comparison to the control mix. This results in a reduced quantity of leachate being absorbed when passing through the blocks.

- All blocks showed that in comparison to current top soil concentrations in the UK, used oil concentrations are in the high percentile and at minimum

it would be recommended that some form of membrane that halts the flow of used oil be used.

9.4 Objective 4

The candidate mixes were successfully used to produce concrete paving blocks in the Hanson Formpave factory. The conclusions from this site trail were

- The results showed that PC can successfully be reduced by 40% if it was to be replaced by 25% GGBS and 15% SF and at 28 days the results for this mix actually produces greater strengths than a mix containing 100%PC.
- When reviewing the durability tests recommended for concrete paving blocks by BS EN 1338:2003, Mix 1 consisting of PC60/GGBS25/SF15 produced similar or greater durability properties in comparison to the control mix and all properties fell with the boundaries set by the British Standards.

9.5 Practical implication of research

The title of the research project was additives to increase the sustainability of concrete paving blocks. This was to be achieved by reducing the PC content, which is the prime contributor to CO_2 emissions.

The research project analysed over 110 different cement paste mixes with vary levels of cementitious constituents. Thereafter, producing concrete paving blocks from the pastes which showed to have the greatest early age strength. The two mixes with the greatest strength were then used to produce blocks in factory settings.

Results showed that the cementitious mix consisting of OPC60/GGBS25/SF15 produced greater strengths than the control mix (100%PC) in factory production. This means that the practical implication of this research project is that the mix developed can help reduce PC content in concrete paving blocks by 40% if Hanson Formpave were to implements its use.

With considering the overall sustainability, with regards to the environmental impact, the reduction of 40% with the use of these materials results in a potential reduction of 4000 tonnes/per year of CO_2 as the PC would not be required. When considering the social impact, the cementitious constituents can make use of locally supplied products, the CO_2 emissions are reduced and more importantly the blocks they are using perform better than blocks produced with 100% PC. However economically due to the current SF market prices the overall cost is nearly £5000 per month more expensive.

CHAPTER 10

Recommendations for future study and contribution to knowledge

This chapter highlights the recommendations for future work and the contribution to knowledge from the research that was conducted

10.1 Recommendations for future study

The following recommendations are made based on research and conclusions, for any future studies that may be conducted.

1   Following the successful replacement of PC in this study, it is recommended that further research be carried out on the replacement of aggregates to further increase the sustainability.

2   Once candidate mixes were produced in the factory, it was reported that they used a water reducing agent in there mixes. It is recommended that an investigation be carried out into the use of different chemical admixtures and there effect on mechanical and durability properties.

3   It is recommended that an investigation be carried out into the effect of different curing conditions (elevated temperature, steam curing etc.)

4   It is recommended that the effect of material variability from different sources be looked at, in order to gain a greater quantity of data and allow for a more in depth analysis.

10.2 Contribution to Knowledge

The research conducted in this study had the prime aim to reduce cement content in concrete paving blocks and alongside this contribute to the current knowledge within the given field.

This research project contributed to knowledge in this field in the following ways

1. The new technique that was developed to analyse ternary blends provided a different perspective on how cementitious constituents can be analysed to provide a database and a predictive capability that can be assured to a high level of accuracy. The technique that was developed is thoroughly explained in the thesis and was presented at a conference in Mumbai, India.

2. The study also contributed to knowledge by reviewing the impact on strength of variation in chemical and physical properties of cementitious constituents. The constituents that were reviewed were sourced over a period 6 months on a monthly basis and were a commercially available regulated material (PFA) and a waste material (BPD). The work conducted in this research was published in a journal paper with Construction and Building Materials.

3. The research project provided a database for 11 combinations of ternary paste blends that were used to replace OPC by up to 100% by weight at a w/c ratio of 0.15. It provided a conclusion and analysis to the combination of materials that provided greater strength at 14 days and discussions on the reasons for this.

4. The study contributed to knowledge by reviewing the difference in strength properties and durability performance between laboratory testing and factory production for concrete paving blocks. As well as this the study was able to

provide a technique for determining the leaching properties of concrete paving, which should be determined if SUDs technology is not being applied in order to ensure contaminant are not leaching into the soil below.

5. The final contribution to knowledge that was derived by this study was the design of a cementitious mix that could reduce the cement content in concrete paving blocks by 40% by weight with the use of GGBS (25% by weight of OPC) and SF (15% by weight of OPC).

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