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THE EFFECT OF QUARRY WASTE DUST AND RECLAIMED ASPHALT FILLER IN HYDRAULICALLY BOUND MIXTURES CONTAINING PLASTERBOARD GYPSUM AND GGBS

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Abstract

In this research, a novel Hydraulically Bound Mixture (HBM) is successfully developed using waste minerals and industrial by-products to fully replace cement in road (base) and foundation materials. HBM is a mixture that sets and hardens by hydraulic reaction and usually has compaction by rolling. The materials used were reclaimed asphalt filler (RAF), quarry waste dust (QWD), plasterboard gypsum (PG) and ground granulated blast furnace slag (GGBS). A statistical mixture design programme – Minitab 18, was used for the design of the experiment. Compressive strength, high pressure flow tests and freeze/thaw tests were carried out to determine the mechanical stability of the by-product binders and performance determined in the strength development by time. It was concluded that cement can be 100% replaced with the named industrial by-products. Test results revealed that the presence of GGBS is highly beneficial between 40 – 60% replacement by weight. Strength development on the hydraulic paste comprising of this GGBS replacement has a reduced strength during the first 28 days. After 28 days and up to 90 days when the maximum strength is gained, strength increases with the presence of GGBS of up to 60%. The results showed that the top four mixes in the two groups discussed in this research meet the standard requirements for road (base) and foundation materials.

Keywords: gypsum; reclaimed asphalt filler; quarry waste dust, GGBS; hydraulically bound mixtures; pavement

1 Introduction

As the world is becoming aware of climate change and, as environmental policies and public concerns over the manufacture of cement and the extraction of our natural

resources intensify, there is an increasing pressure and desperate need to use alternative materials to replace cement with by-product binders for pavement. Environmental concerns over our desires for using products that are manufactured from the continuous extraction of our natural resources has necessitated a growing use of secondary waste minerals such as coal-fired power station waste (PFA), municipal incinerator ash (IBA) and cement by-products (cement kiln dust – CKD and by-pass dust – BPD). Concerns about the depletion of our natural resources and the effect that meeting the demand for quarried materials may have on the environment has increasingly focused attention on the possibility of finding alternatives to naturally occurring materials (Sherwood 1995).

The research was to investigate alternative materials for cement in concrete to be suitable as road base and foundation layers. This paper looks at the potential use of Plasterboard Gypsum (PG), activated by GGBS, Quarry Waste Dust (QWD) and Reclaimed Asphalt Filler (RAF) in different proportions as ternary semi-dry pastes. Two of the eleven combinations of ternary binders in the research study, referred to as 'groups', were discussed in this paper. Group 2 (PG/RAF/GGBS) and Group 9 (PG/QWD/GGBS) were the two of the top three preferred groups that were considered to have potential and further explored. These various types of by-products were assessed to have potential for use in road (base) and road foundation. Combinations of natural and / or recycled aggregate concrete will be used with the novel paste to create concrete at the final stage of the study. The new replacement materials will reduce the impact the extraction of naturally occurring materials have on the environment.

Previous research studies have been carried out to explore the partial replacement of cement using different industrial by-product materials in the construction industry. Unlike previous studies investigated by Limbachiya, Ganjian and Claisse (2015); Raghavendra et al. (2016); Tan, Doh and Chin (2017), this paper draws attention to the full replacement of cement in concrete.

1.1 Background

The cement industry is one of the biggest pollution producer industries in the world (Modarres, Ramyar and Ayar 2015). Approximately, 7% of the global carbon dioxide emissions come from the manufacture of cement (Andrew 2018; Benhelal et al. 2013; Li et al. 2013; Meyer 2009; Siddique and Rajor 2012). The manufacture of Portland cement itself is ecologically harmful in that the production of one tonne of cement equates to approximately one tonne of carbon dioxide being expelled into the atmosphere (Neville 2011). The construction industry is identified by the UK Green Building Council as one of the most emission-intensive industries, accounting for approximately 50% of greenhouse gas production in the UK (Dadhich et al. 2015). There is no doubt an increasing demand for the use of industrial by-products and recycled materials due to the stress on our natural resources and environmental systems.

Raghavendra et al. (2016), investigated powdered board wastes with GGBS, cement

along with stone dust as fine aggregates to produce sustainable controlled low strength material (CLSM). Mix proportions were produced and water content varied from 45 – 60%. It was noted that binder blend of gypsum board wastes, GGBS, cement and less water, are effective in resisting the effect of sulphates in the gypsum board wastes. About 30 – 48%, 67 – 95% and 93 – 100% of maximum strength gained was observed at 3, 7 and 28 days respectively. The highest strength achieved at 56 days for the CLSM was 5.8MPa.

Lizarazo-Marriaga et al. (2011), studied the influence of Steel Basic Oxygen Slag (BOS) and Portland cement (OPC) on the compressive strength and hydration mechanisms of blended GGBS pastes. Laboratory tests were carried out at 7, 28 and 90 days. For the ternary group of OPC – GGBS – BOS mixes, the highest compressive strength (approximately 65MPa) obtained at 90 days corresponds to a mixture of 40%OPC, 30%GGBS and 30%BOS. It was observed for the ternary mixes, that the compressive strength increases as the percentage of OPC increases.

Limbachiya et al. (2015) reported the effect of Pulverised Fuel Ash (PFA), By-pass Dust (BPD) and OPC in a ternary semi-dry cement paste. The effect of BPD can be seen when analysing Mixes 1 (60%OPC/40%PFA/0BPD), 7 (60%OPC/30%PFA/10%BPD) and 9 (60%OPC/35%PFA/5%BPD) in which OPC content remains the same and BPD is used to replace PFA by 0%, 5% and 10%. The 28 days strength results showed that 5% BPD replacement provided very close strengths (31.9MPa) to that of 0% BPD (34MPa) and that of 10% BPD replacement (30MPa).

Bai Kamara et al. (2019), stated that waste management and the use of industrial by-products are important aspects of government policies around the world aimed at re-enforcing current trends regarding the conservation of our natural resources. Recent increase in the use of environmental controls meant that some of these wastes are recovered within the manufacturing process. Most of the wastes, however, are removed and disposed of to landfill sites. With the increasing shortage of land available for waste disposal, the penalties introduced by local authorities in disposing of waste, and the increased manufacturing of by-products, it is inevitable that increased use of these industrial by-products be explored in pavement and other construction applications to help prevent depletion of virgin materials, which is usually accompanied by environmental degradation and leads to economic problems.

The aim of this research study was to fully replace cement with industrial waste minerals. One of the research objectives was to identify industrial by-products that are being taken to landfill sites in the UK and investigate their use in pavement engineering. Other objectives include laboratory investigations to examine by-product suitability and obtain a novel blend that can be used as ‘Hydraulically Bound Mixture – HBM’ or ‘Cement Bound Granular Mixture – CBGM’ when used with sand and gravel. The novelty of this research is to close the knowledge gap in the use of gypsum waste, reclaimed asphalt filler and quarry waste dust.

2 Raw Materials used in the Study

2.1 Description of Raw Materials

The waste Plasterboard Gypsum (PG) was obtained from a local housing development site in Nuneaton, North Warwickshire, UK. The plasterboard waste arose from off-cuts and damaged boards.

The Reclaimed Asphalt Filler (RAF) and Quarry Waste Dust (QWD) were obtained from Tarmac. The materials were sourced locally from their Mancetter Quarry in Atherstone, North Warwickshire, UK. The RAF is produced by their Via Nova Asphalt Plant and conveyed to the plant reclaimed duct silo. The RAF material is activated by thermal treatment and is formed during the processing of asphalt using sedimentary rocks. The QWD on the other hand is a waste material, produced as a by-product of the screening and crushing processes of sedimentary rocks. QWD can also be referred to as Cyclone Filler Dust (CFD). The RAF and QWD are natural calcined pozzolan and natural pozzolan, respectively.

The Ground Granulated Blast Furnace Slag (GGBS) from Hanson Heidelberg Cement was obtained from Coventry University materials' inventory stock.

2.2 Chemical Compounds and Mineralogical Compositions of Raw Materials

For the X-ray diffraction analysis tests, the powdered raw materials were measured between 5-80° 2θ on a Panalytical Empyrean X-ray diffractometer equipped with Co Kalpha (1.790307Å) radiation. The phases were determined using Panalytical Highscore Plus software and the latest ICDD PDF4+ database. Table 1 shows the chemical compounds of the raw materials and Figures 1 and 2 show the mineralogical composition of RAF and QWD. The results showed high levels of gypsum ($CaSO_4 2H_2O$) and low levels of basanite ($CaSO_4$-$0.5(H_2O)$) in the PG. The RAF showed high levels of calcium carbonate ($CaCO_3$) and sodium aluminium silicate (Na Al Si_3 O_8).

Table 1: Chemical compounds of PG, RAF and QWD

Name	Chemical Formula	Weight (%)
PG		
Calcium Sulfate Hydrate	$Ca(SO_4)\ (H_2O)_2$	91
Calcium Sulfate Hydrate	$Ca(SO_4)\ (H_2O)_{0.5}$	2
Silicon Oxide	SiO_2	2
Iron Oxide Phosphate	$Fe_3O_4\ (PO_4)$	2
Calcium Sulfate	$CaSO_4$	3
RAF		
Calcium Carbonate	$Ca\ Co_3$	28
Sodium Aluminum Silicate	$Na\ Al\ Si_3\ O_8$	30
Zinc Aluminum Hexanedicarboxylate Hydrate	$C_{2.76}\ H_{9.68}\ Al\ O_{7.84}\ Zn_2 \cdot 2.36\ H_20$	21
Magnesium Aluminum Hydroxide Hydrate	$((Mg_6\ Al_2\ (OH)_{18}\ (H_2O)_4)_{0.325}$	1
Barium Aluminum Silicate Chloride Hydroxide	$Ba_3\ Al_{3.25}\ Si_{5.75}\ O_{16.75}\ Cl_2\ (OH)_{3.25}$	4
Lithium Titanium Oxide Silicate	$Li_2\ Ti\ (SiO_4)\ O$	8
Ammonium Gallium Phosphate Hydroxide	$(N\ H_4)\ Ga\ (PO_4)\ (OH)$	1
Zinc Phosphate Hydroxide	$ZN_2\ (PO_4)\ (OH)$	4
Manganese Phosphate Hydrate	$Mn\ (PO_4)\ (H_2O)$	3
QWD		
Calcium Carbonate	$Ca\ (CO_3)$	-
Sodium Aluminum Silicate	$Na\ Al\ Si_3\ O_8$	-
Magnesium Aluminum Silicate Hydroxide	$Mg_5\ Al\ (Si_3\ Al)\ O_{10}\ (OH)_8$	-
Copper Zinc Aluminum Sulfate Hydroxide	$(Zn_{1-x}\ Al_x\ (OH)_2\ ((SO_4)_x(H_2O)n)$	-
Potassium Aluminum Silicate Oxide	$K\ Al\ Si_3\ O_8$	-
Magnesium Aluminum Silicate	$Al_{0.5}\ Mg_{0.25}\ Si_{0.5}\ O_2$	-

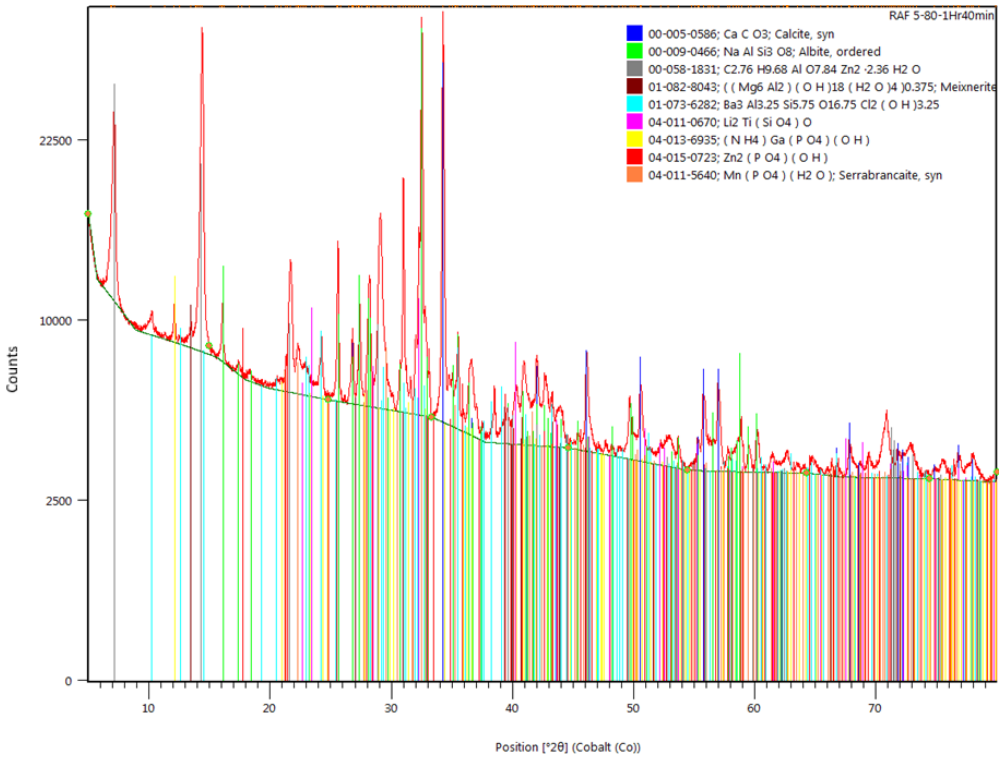

Figure 1: Mineralogical composition of RAF

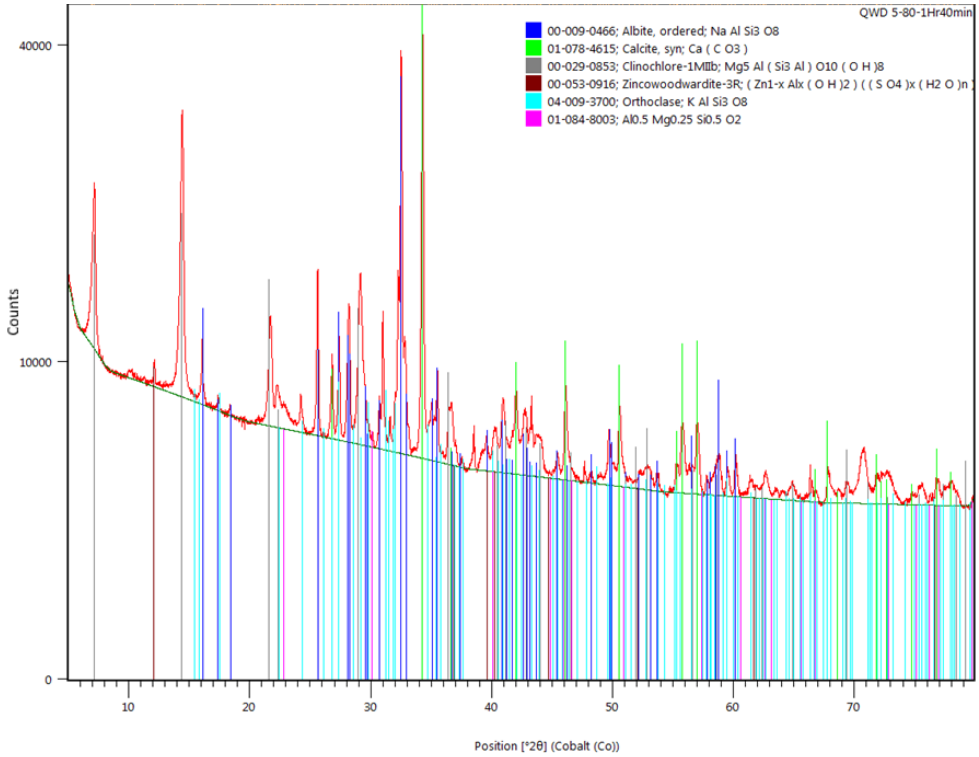

Figure 2: Mineralogical composition of QWD

2.3 Chemical Oxides of Raw Materials

Table 2 shows the chemical composition of the raw materials used in the research. The results of the X-ray fluorescence tests showed the two major oxides (CaO and SO_3) present in the PG. It can be seen that the RAF and QWD contain more of SiO_2 and moderate levels of CaO, Fe_2O_3 and Al_2O_3. The GGBS on the other hand has high-to-moderate levels of calcium oxide (CaO) and silicon dioxide (SiO_2).

Table 2: Chemical oxide composition of raw materials

Oxides	PG (%)	RAF (%)	QWD (%)	GGBS (%)
SiO_2	0.96	35.00	34.00	33.23
TiO_2	0.03	1.60	1.80	1.09
Al_2O_3	0.31	12.00	12.00	13.14
Fe_2O_3	0.27	12.00	12.00	0.52
MnO	0.00	0.42	0.41	0.33
MgO	0.13	6.40	5.30	8.92
CaO	40.00	12.00	14.00	39.76
Na_2O	0.02	1.90	2.60	0.21
K_2O	0.09	1.20	0.87	0.45
P_2O_5	0.02	0.47	0.56	-
SO_3	52.00	1.30	0.99	1.12

2.4 Physical properties

Analysis to determine the physical properties of the raw materials used in this paper was carried out using a Malvern Mastersize 2000 equipment and the outputs created by the Malvern Laser Granulometer with an accuracy of +/-1%. Figures 3 and 4 show the particle size distributions of Groups 2 and 9 with the blends PG/RAF/GGBS and PG/QWD/GGBS, respectively. The particles for the two blends range approximately between 0.3 to 1500 microns and their 50^{th} (D50) and 90^{th} (D90) percentiles as shown in Table 3.

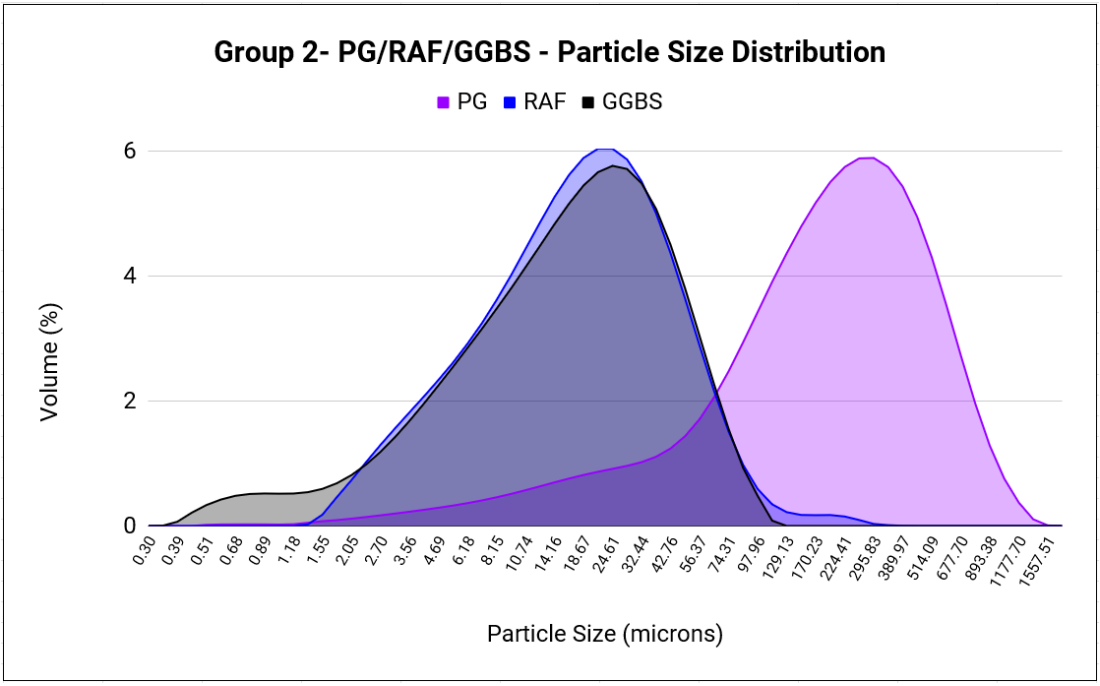

Figure 3: Particle size distribution of Group 2

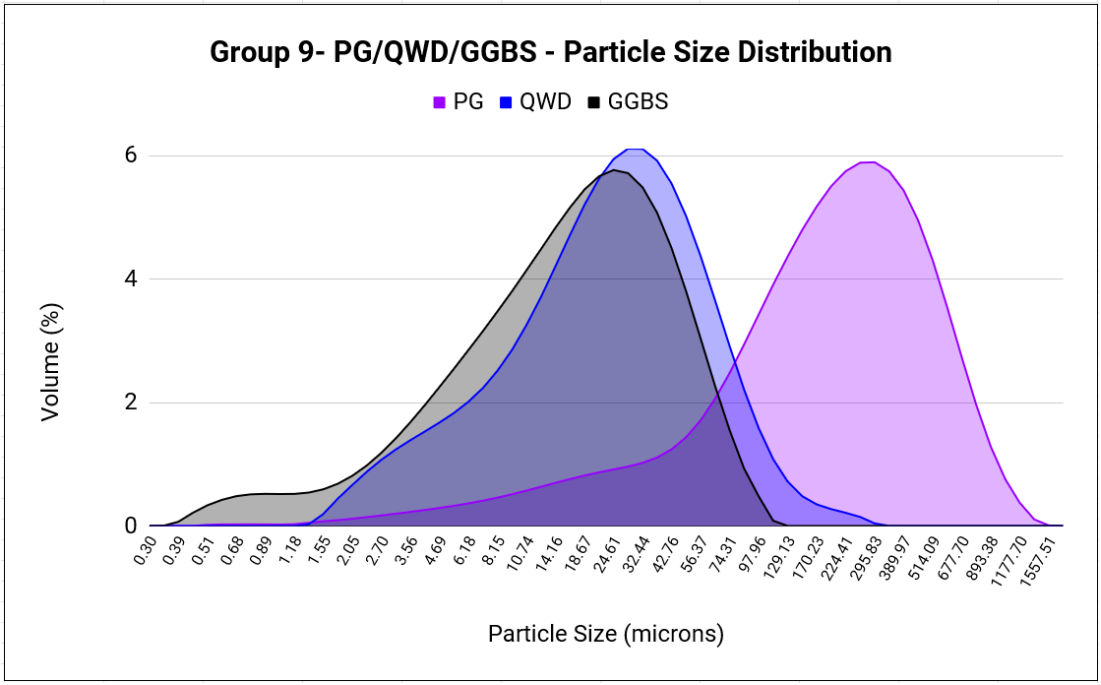

Figure 4: Particle size distribution of Group 9

Table 3: 50th and 90th percentiles of materials

	PG	RAF	QWD	GGBS
D50	202.54	18.18	24.41	17.3
D90	564.93	51.42	69.23	49.27

3 Methodology

The methodology used in this research study is shown in Figure 5.

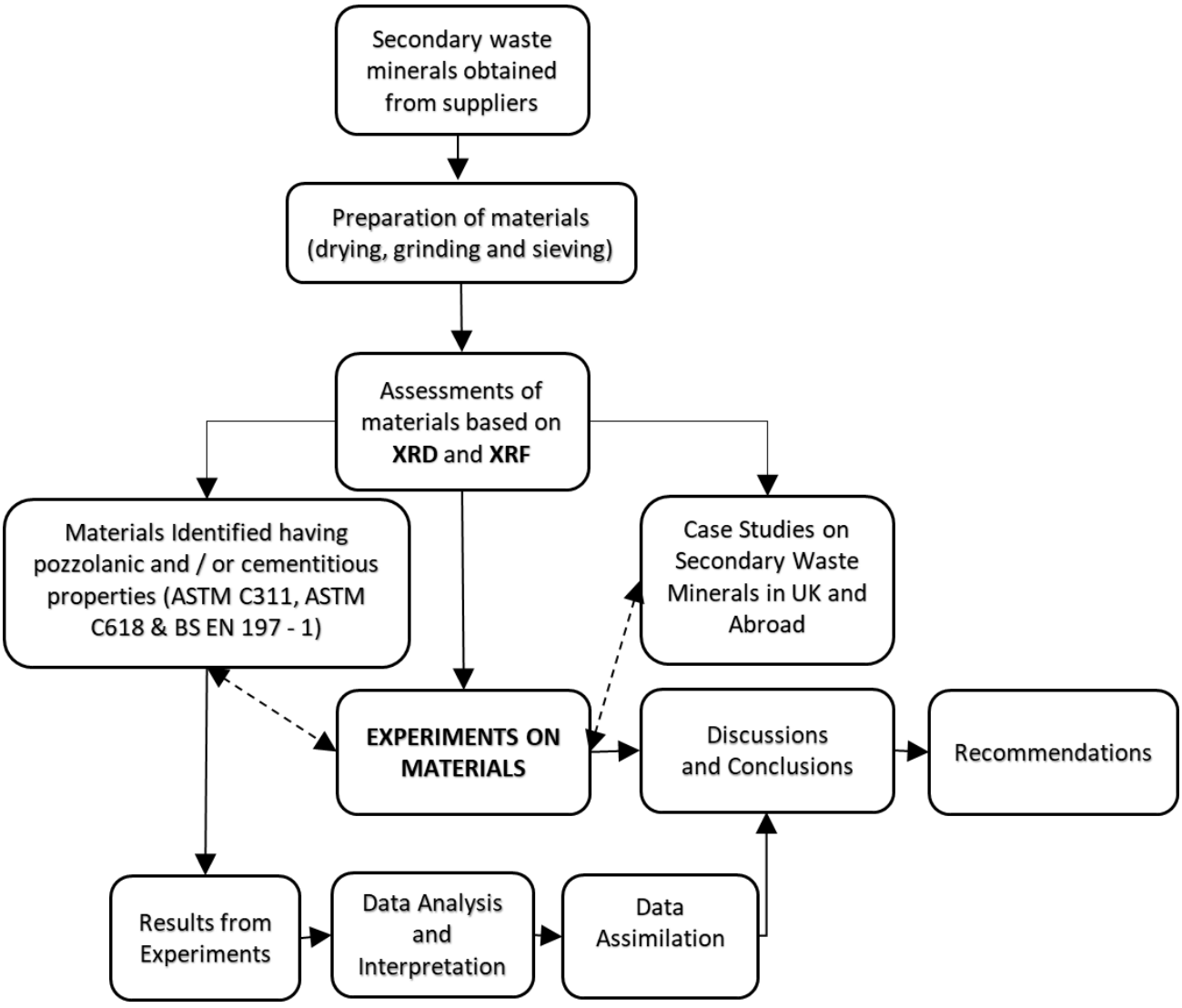

Figure 5: Methodology overview

3.1 Preparation of Materials

The RAF, QWD and GGBS were delivered dry with particle size less than 600 microns. No further treatments were needed, therefore, preparations for these materials were not required. Unlike the PG, they were broken down into sizable pieces of approximately 600mm by 500mm. The plasterboards were further broken down into smaller pieces and were ground to remove the paper backing. The grinding exercise was done by using different sieve sizes to fully de-contaminate the plasterboard gypsum of paper. After all the paper backing had been completely removed, it was further ground to a fine powder passing through a 600 microns sieve.

3.2 Materials Suitability

Experiments to determine secondary waste minerals suitability were conducted using X-RD and X-RF tests. Raw minerals identified to have pozzolanic and / or cementitious properties were further explored in the study. Materials with no pozzolanic or cementitious properties can be used as coarse or fine aggregates if they are considered to have satisfactory mechanical properties, which is resistant to crushing.

3.3 Design of Experiment

A statistical mixture design programme – Minitab 18, was used for the Design of Experiment (DoE) for Groups 2 and 9. Extreme Vertices Design (EVD) method was used to set the boundaries of the components in each group for the designs. The mix designs have the following vertices constraints:

$$0 \leq X_i \leq 1 \qquad \text{[Eq. 1]}$$

Where X_i represents the proportion of component i. EVD was chosen for this experimental study because of the provisions of the upper and lower bounds used in the ternary combinations, it allows precision in the design, provides better estimates, maximises variance and generates plots for all three components in the model. This allows for good coverage and the design points adequately cover the design space. The unique design space on EVD allows points to be placed not only at the centroid, midpoints and axial points, but also at the extreme vertices of the region. EVD satisfies the formulation in having constraints that ensure correct specifications. Also, it satisfies the formulation that optimises the response for certain reactions; and more importantly it satisfies the formulation on how the different samples used in the ternary groups affect a response.

Limbachiya, Ganjian and Claisse (2015) mentioned how the statistical programme (Minitab 18) generated the vertices of constrained design space (Lower Limit < Material < Upper Limit) and then calculated the centroid point up to the specified degree using Piepel's CONAEV algorithm. Reviewing literatures, Ganjian et al.

(2008) and Singh, Tripathy and Ranjith (2008) provided an indication of effective replacement levels of the materials. One of the objectives of this study was to maximise and compare the use of the two quarry by-products (RAF and QWD); the upper and lower limit boundaries used for PG, RAF/QWD and GGBS were 20%-80%-60% and 0%-20%-0% by weight respectively. In other words, the constraints for both Groups 2 and 9 were the same. Due to the high content of materials used in some of the components, the combination of binary and ternary mixes was produced in the designs. Table 4 and [Figs. 6,7] show the mix proportions required in each mix and the simplex design plots.

Table 4: Mix design proportions for Group 2 and 9

Components (% wt)	Mix Design												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
PG	20	10	10	5	20	15	20	0	15	0	0	5	10
RAF/QWD	20	80	55	47.5	50	37.5	80	80	67.5	40	60	67.5	30
GGBS	60	10	35	47.5	30	47.5	0	20	17.5	60	40	27.5	60

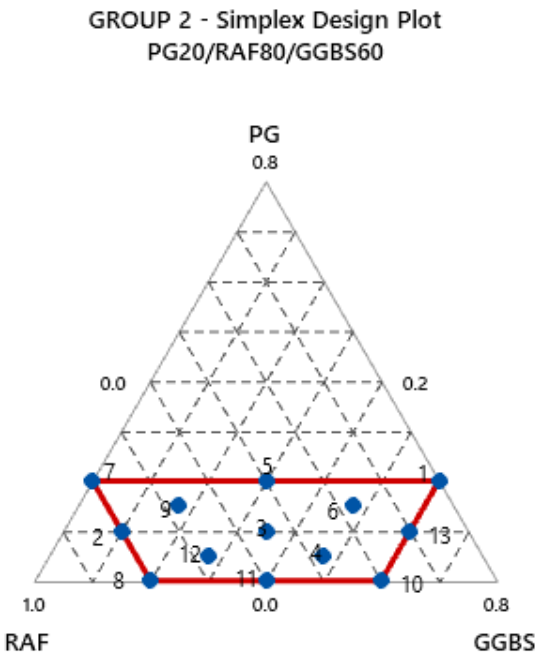

Figure 6: Group 2 simplex design plot

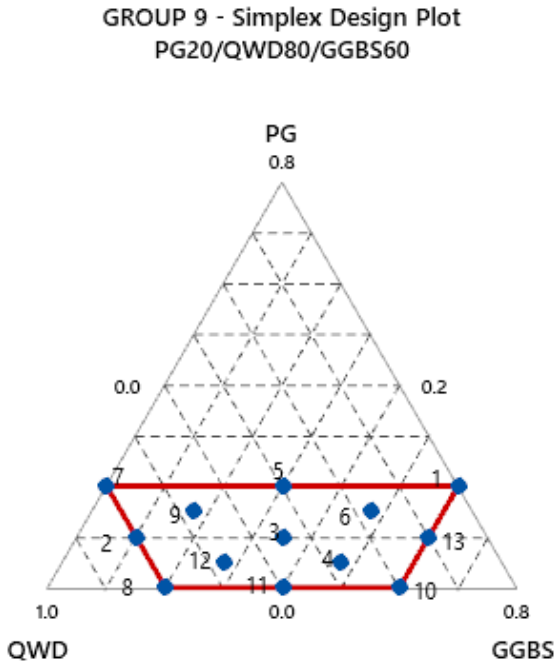

Figure 7: Group 9 simplex design plot

3.4 Fabrication

The research conducted in this study was to develop a hydraulically bound cementitious material for applications in road(base), foundation and sub-grade in pavement construction. Hydraulically bound material is a mixture that hardens by hydraulic and / or pozzolanic, sulphatic and / or carbonic reaction, which usually has a workability to suit compaction by rolling and which is generally used in bases, sub-bases and capping layers (EN, B. 2003). The pastes analysed in this study were also semi-dry form and the cubes made were solely compacted to simulate real life applications in construction sites.

The mixing of the materials took approximately 6 minutes. After the materials were weighed, water was intermittently slowly added at 1 and 3 minutes of mixing. The pastes were cast in 50 mm cube moulds [Fig. 8]. The sample was pre-compacted with a square tamping rod (25 mm x 25 mm x 300 mm) in three layers of 90g per cube at 25 strokes per layer. The sample was further compacted using hydraulic machine. The hydraulic pressure was set at 90 KN for a gang of three prepared 50 mm moulds. A constant rate of loading at 5 KN/s was applied to the samples. The hydraulic compaction of 30 KN per cube pressure used in this study is in line with the requirements set out Series 800 (2020). This is whereby either a vibrating or pneumatic-tyres roller with a wheel loading of not less than 30 KN followed by at least eight passes is used to compact hydraulically bound mixtures. The pressure of 90KN was applied to the samples for 2 minutes before it was released.

The 50 mm semi-dry specimens were easy to handle, and therefore, casting was carried out immediately after the specimens had been hydraulically pressed without a shock or vibration. The specimens were later cured in transparent sealed propagators [Fig. 9] at 20°C +/- 2°C with a relative humidity of between 95 – 98%.

Figure 8: Gang of three 50 mm cube moulds being prepared for use

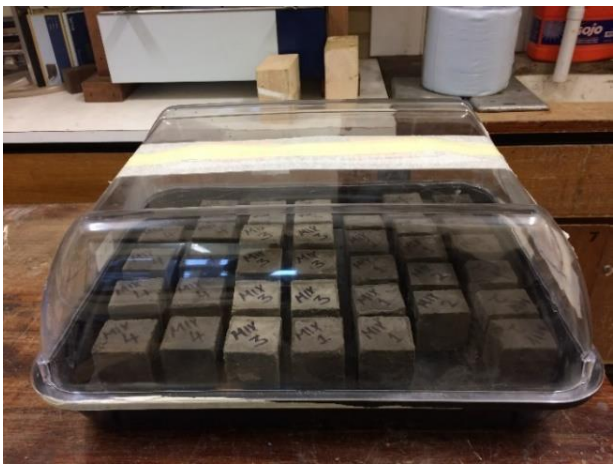

Figure 9: 50 mm Specimens being cured in a sealed propagator

4 Experiments

Selected Mixes 1, 4, 6 and 13 with the same proportions of the different materials in Group 2 (PG/RAF/GGBS) and Group 9 (PG/QWD/GGBS) have been used to evaluate the effect of RAF and QWD in mixes containing PG and GGBS at 7, 14, 28, 90 and 180 days, because they were the top four mixes identified in both groups. The effect of RAF and QWD have been based on the optimum liquid / solid ratios at 28 days and 90 days to achieve the strongest mechanical performance of the mixes.

4.1 Compressive Strength

The contour plots for Groups 2 and 9 at 28 days using 15% and 17% liquid/solid ratio are shown in Figures 10 and 11. Mix 4, with the proportions of 5%PG, 47.5%RAF and 47.5%GGBS attained highest compressive strength at 27.02MPa for Group 2. Group 9 on the other hand attained the highest strength at 30.23MPa with the proportions of 10%PG, 30%QWD and 60%GGBS on Mix 13. It can be seen that the highest strength on both systems provided very close results even though their mix proportions are different. Comparison of 7 and 28 days test results for the top four mixes on both groups revealed that all the mixes showed a significant increase in strength development as the specimen ages.

Bonferroni's method (Bland and Altman 1995) stated that a Probability Value (p-value) for any term of a mixture design should be no greater than 0.05 to ensure 95% of the associated response to the related term (s) to be true. In other words, the 95% confidence level and the p-value threshold of <0.05 helped to decide whether to reject the null hypothesis or not. Eq. 2 was used to calculate the predicted values of Groups 2 and 9 at 28 days compressive strength. Predictors with low p-values are likely to be significant to the model as they are directly related to changes in the response variables.

$$Y_{ijk} = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 \quad \text{[Eq. 2]}$$

Where Y_{ijk} represents the response for the i^{th} proportion of the component 1 (X_1), the j^{th} proportion of component 2 (X_2) and the k^{th} proportion of component 3 (X_3). Therefore, using Groups 2 and 9 with the components PG, RAF/QWD and GGBS:

$Y_{PG,RAF/QWD,GGBS}$ represents the response when (X_1) = PG, (X_2) = RAF/QWD and (X_3) = GGBS. X_1, X_2 and X_3 are the variables and represent the response in each mix design and β_1, β_2 and β_3 are the coefficient of the terms which are constant. The equations [Eq. 3-4] that predicted the compressive strength (CS) and produced the contour plots [Fig. 10-11] for Groups 2 and 9 were:

CS = -821.884(PG)-11.9009(RAF)-11.2269(GGBS)+1059.19

*(PG*RAF)+1203.40(PG*GGBS)+79.2780(RAF*GGBS)* [Eq. 3]

$$CS = -633.958(PG)-7.30408(QWD)+18.8068(GGBS)+807.383$$
$$(PG*QWD)+911.116(PG*GGBS)+19.1738(QWD*GGBS) \quad \text{[Eq. 4]}$$

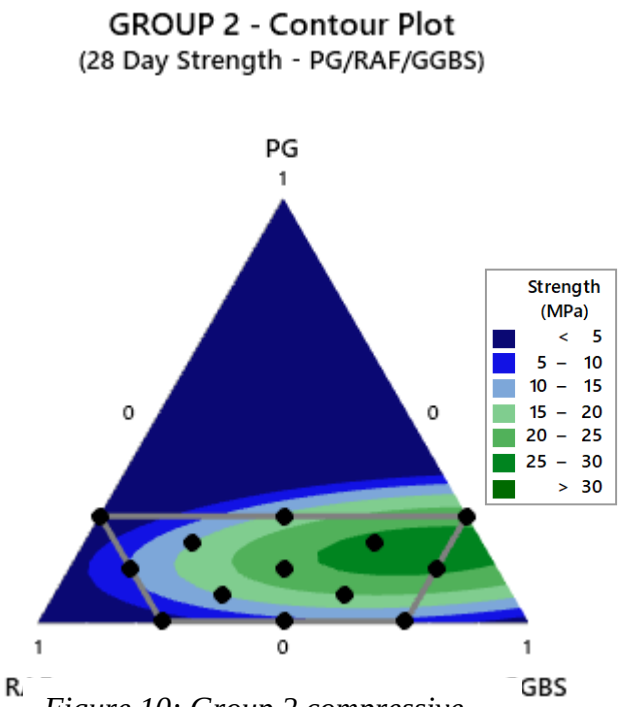

Figure 10: Group 2 compressive strength contour plot

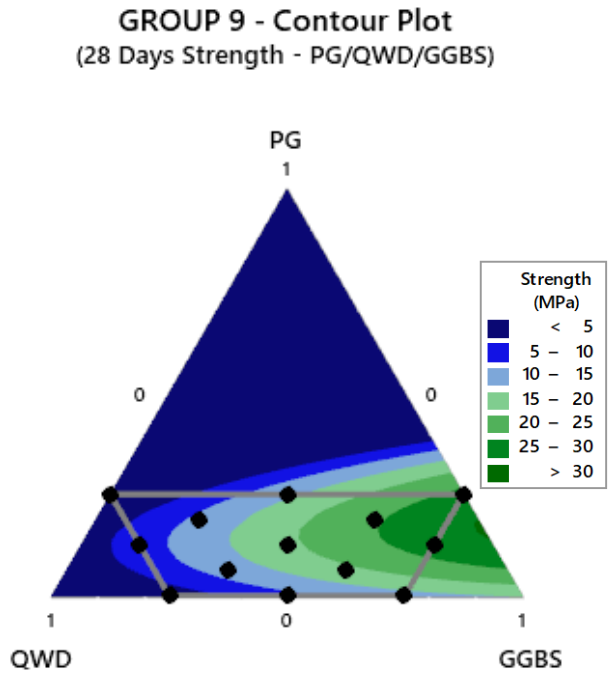

Figure 11: Group 9 compressive strength contour plot

4.2 Resistance to Freezing and Thawing

Laboratory tests to determine resistance to freezing and thawing of the hydraulically bound mixtures were carried out in accordance with CEN/TS 13286 (2014). The freeze-thaw cycle of the two mixes (Mix 1 of Group 2 and Mix 13 of Group 9) commenced at a stage which was a significant proportion of their ultimate strength i.e. 90 days of age. Longer age curing of 91 days was required for the two mixes as they were slow setting and hardening mixtures. The optimum liquid/solid ratio for Groups 2 and 9 was 17%.

Two sets of six specimens were used in the experiment for each mix. On completion of curing for the first set 'A' (R_A), the specimens were placed in an environmental chamber and subjected to ten freeze-thaw cycles. Each freeze-thaw cycle lasted 24 hours with a starting temperature of 20°C, to -1°C in two and half hours, maintained cool at -1°C for four hours, reduced to -17.5°C in three hours, maintained cool at -17.5°C for six hours and warmed again to 20°C in eight and half hours. The relative humidity of the cabinet was set at 100%. After completion of the tenth freeze-thaw cycle, specimens 'A' were returned for 1 day curing to ensure complete thawing. The

compressive strengths of set ‘A’ and the control set ’B’ (R_B) were measured and the mean value of the strength for each set compared.

4.3 High Pressure Flow Test

This experimental work was similar to the one adopted by Ganjian, et al. (2004); Ganjian, et al. (2006), where a modified Hoek cell was used to measure the permeability of the hydraulic paste in preventing the flow of fluid around the sides of the sample. Figure 12 shows the schematic layout of the test. Methods of compaction of the samples was like that used for the compressive strength tests on the hydraulic cube pastes to achieve better density. The moisture contents were based on the ultimate strengths. A gang of three 50mm cylindrical moulds was used to produce cylindrical shaped specimens with 55mm diameter and at least 50mm in length.

After the specimen had been installed in the triaxial cell and bolts on the external framework tightened, an oil pressure of up to 40 bars was applied. Flow around the specimen was prevented by maintaining the high pressure of hydraulic oil inside the flexible membrane. The pressure was maintained with the ramp pump by adjusting the weight on the balance unit. The water pressure valve was set at 30 bars, 10 atmospheres lower than the oil pressure. The permeability of the specimen was based on measuring the time it took to collect 25 ml of water passing through the Hoek cell.

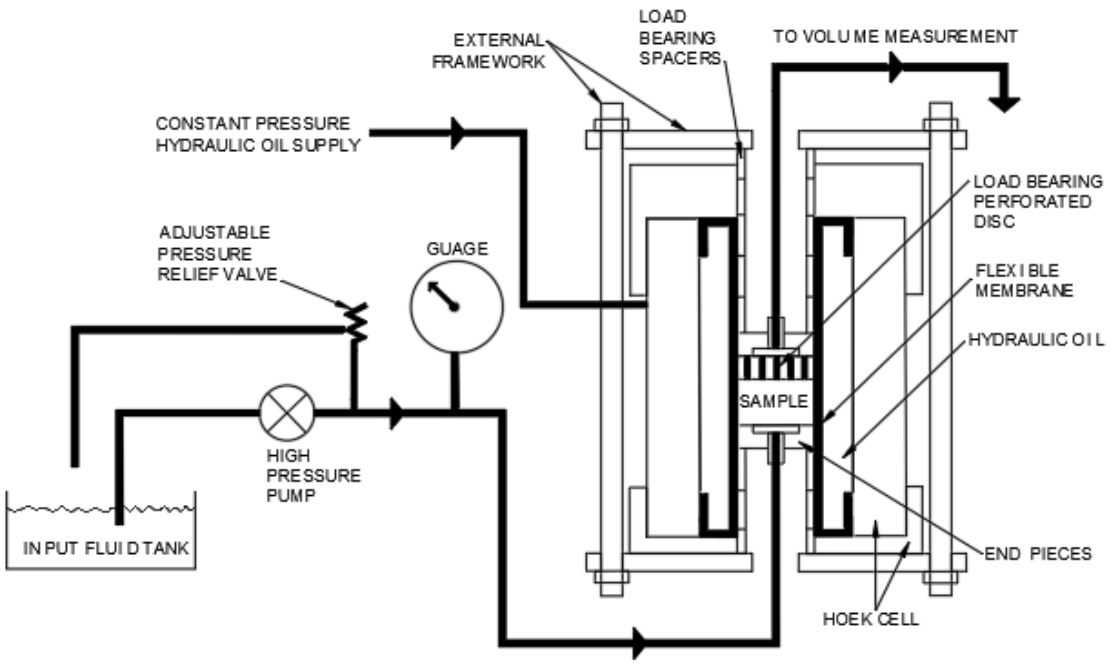

Figure 12: High pressure flow test

5 Results and Discussions

5.1 The Effect of RAF and QWD in Mixes Containing PG and GGBS

The effect of RAF and QWD have been based on the optimum liquid/solid ratios at 90 days to achieve the strongest mechanical performance of the mixes. The optimum ratio of 17% was used for both systems. Figure 13 shows comparison of RAF and QWD in the selected mixes containing PG and GGBS.

Analysis of the results show that the presence of QWD when compared to RAF in the pastes containing PG and GGBS does not cause a decrease in short, medium or long-term strength development. In general, both the QWD and RAF in the two different groups behaved similarly with regard to strength development. However, it was recognised that there was a notable difference in the early strength development on some of the selected mixes with QWD. The percentage by mass of the major chemical oxides (SiO_2 + Fe_2O_3 + Al_2O_3) for both the RAF and QWD are similar. The main difference between the RAF and QWD is that one is a natural pozzolan and the other is an artificial pozzolan (also referred to as natural calcined pozzolan).

Even though both materials are pozzolans and conform with requirements set out in ASTM C311 (2013), the activity index is over 75% of the controlled mix at 28 days. They are also in line with the requirements set out in EN, B. (2011) whereby it consists predominantly of reactive silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3). The content of the reactive silicon dioxide (SiO_2) shall be not less than 25% by mass. ASTM C618 (2003) stipulates that for a material to be pozzolanic, it should meet the requirement content of pozzolanic oxides (SiO_2 + Fe_2O_3 + Al_2O_3) of more than 65 – 70%. The XRF analysis of the RAF carried out on two separate batches received over a two year period (2017 and 2018) showed the samples to be approximately 65 and 59%, respectively. On the other hand, analysis on the QWD showed the pozzolanic oxides content to be approximately 60%. As the percentage by mass of the major oxides are similar in both the RAF and QWD, the decrease in the short-term strength development in mixes containing RAF may have been the results of both mineralogical properties and / or the minor chemical oxides present in the sample.

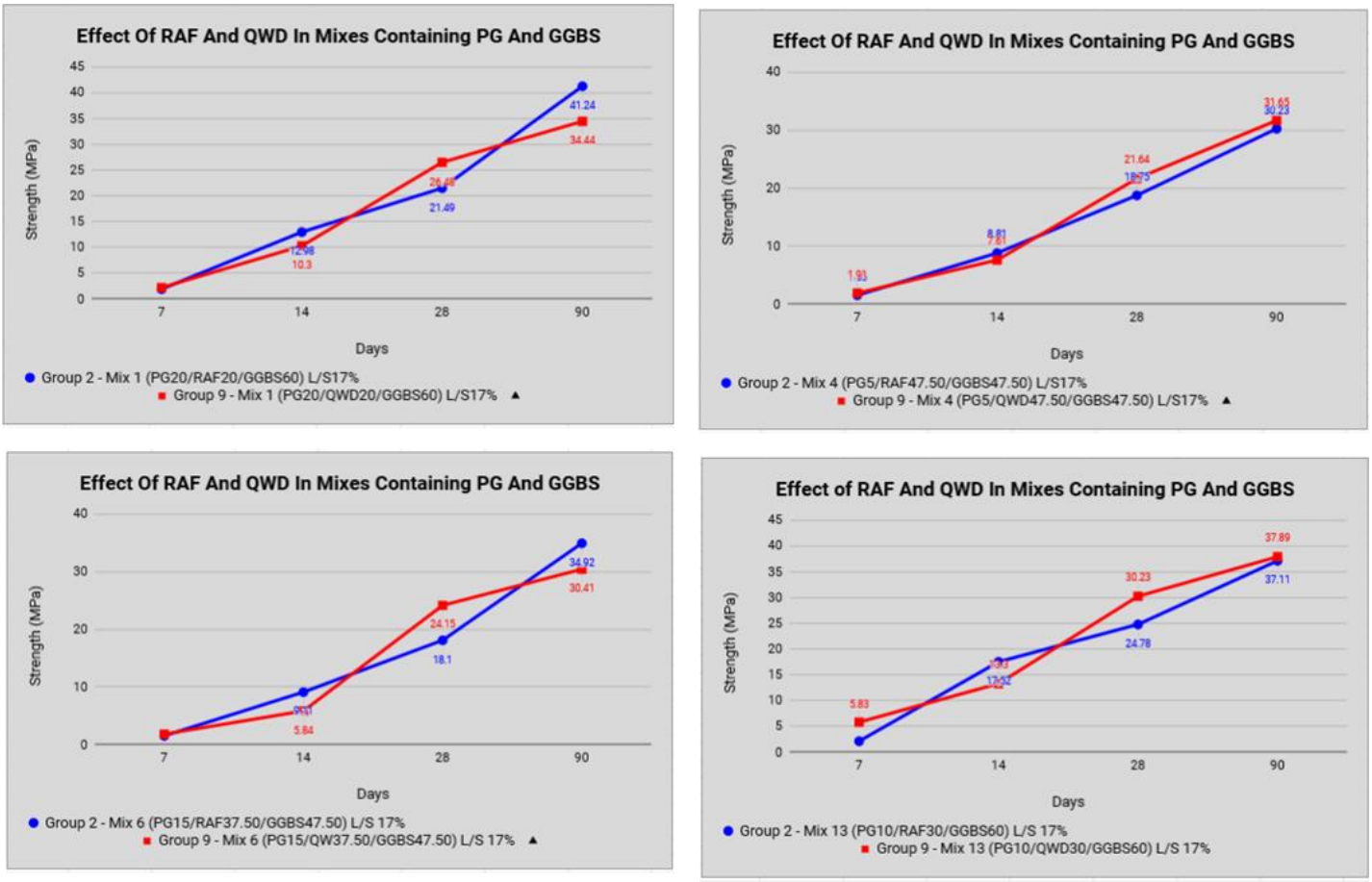

Figure 13: Comparison on the effects of RAF and QWD on selected mixes containing PG and GGBS

5.2 Strength Development of Hydraulic Pastes

Compressive strength results of selected mixes on Groups 2 and 9 for 7, 14, 28, 90 and 180 days have been presented in Table 5. Looking at the trends of this research study's findings, one can hypothesise that the short and long-term strength development of the hydraulic paste containing GGBS are in agreement with reports carried out by Hogan and Meusel (1981); Roy (1982). Their report found that the strength development was slow during the early stages of hydration for concrete containing 40 – 60% GGBS as cement replacement. In a separate study carried out by Khatib and Hibbert (2005), they reported similar findings that the presence of GGBS is highly beneficial between 40 and 60% replacement. They acknowledged a reduced strength during the first 28 days. After 28 days and up to 90 days, they concluded the strength increases with the presence of GGBS of up to 60%.

Table 5: Strength development of selected mixes on Group 2 and 9

Group	Mix Design Reference	Strength at Days (MPa)					L/S Ratio
		7	14	28	90	180	
2	**Mix 1 - PG20/RAF20/GGBS60**	2	13	21	41	41	0.17
	Mix 4 - PG5/RAF47.50/GGBS47.50	2	9	19	30	38	0.17
	Mix 6 - PG15/RAF37.50/GGBS47.50	2	9	18	35	36	0.17
	Mix 13 - PG10/RAF30/GGBS60	2	18	25	37	39	0.17
9	Mix 1 - PG20/QWD20/GGBS60	2	10	26	34	37	0.17
	Mix 4 - PG5/QWD47.50/GGBS47.50	2	8	22	32	40	0.17
	Mix 6 - PG15/QWD37.50/GGBS47.50	2	6	24	30	33	0.17
	Mix 13 - PG10/QWD30/GGBS60	6	13	30	38	41	0.17

A study carried out by Siddique (2014) on the utilisation of iron and steel industry by-product (GGBS) in concrete concluded that the use of GGBS does not only accelerate the hydration process, an amount of between 40 – 60% increases the compressive strength, split tensile strength and flexural strength of concrete.

Generally, industrial by-products, including those used in this research study, are not conventional materials and, therefore, not expected to behave exactly like traditional materials. Industrial by-products of this sort are highly acceptable for their ultimate strength (80- 90%) to be achieved at 90 days of curing. Multiple samples were tested for compressive strength on the top two mixes (Group 2 Mix 1 - PG20/RAF20/GGBS60 and Group 9 Mix 13 - PG10/QWD30/GGBS60). Three replicates of the mixes were checked for consistency over a three year period. The standard deviation of the samples tested are shown in Table 6 and Figure 14. The standard deviation for the top two mixes is different. The data set for Mix 1 of Group 2 showed the most variability. Mix 13 of Group 9 on the other hand showed tighter results. Figure 15 shows the percentage of strength development of the top two mixes in both systems.

Table 6: *Compressive strength of replicate samples at 90 days*

	90 Days Compressive Strength (MPa)			Mean	Standard Deviation	Standard Error
	Test 1	Test 2	Test 3			
Group 2 Mix 1 (PG20/RAF20/GGBS60)	41.24	37.52	38.99	39.25	1.87	1.08
Group 9 Mix 13 (PG10/QWD30/GGBS60)	37.89	37.41	36.87	37.39	0.51	0.29

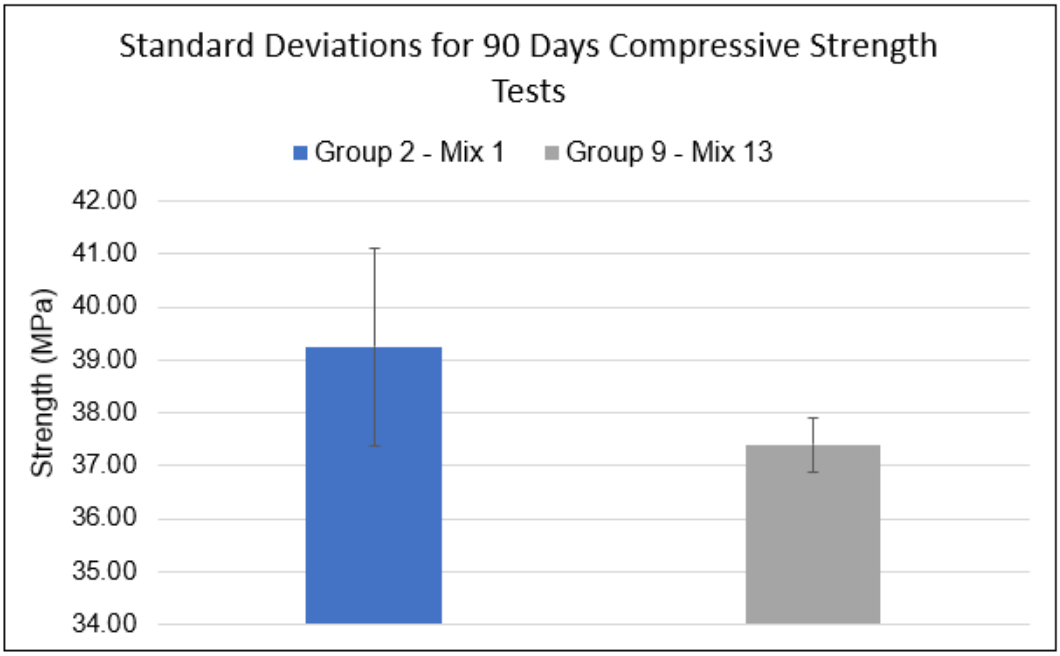

Figure 14: *Standard deviation of replicate samples at 90 days*

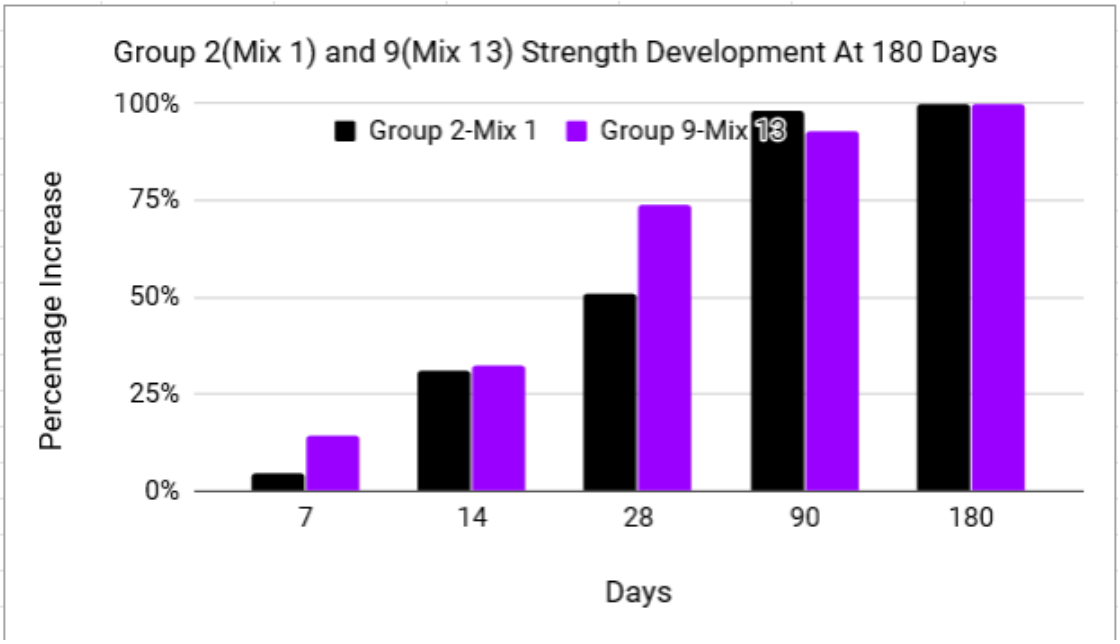

Figure 15: Percentage of strength development of Mix 1(Group 2) and Mix 13(Group 9)

Given the novelty of this research study and the introduction of new industrial by-products to fully replace cement, a direct comparison of the strength gained as the specimen ages on the preferred mixtures cannot be made to similar materials as most research concentrate on partial cement replacement. However, a review carried out by Suresh and Nagaraju (2015) concluded that a 50% by weight of GGBS concrete will typically achieve approximately 45 to 55% of its 28 days strength at seven days, with a gain of about 20% from 28 to 90 days. Unlike Suresh and Nagaraju's (2015) findings, the top two mixes in this research had 60% by weight of GGBS. Approximately, 50 to 65% of strength was gained at 28 days and over 90% of strength achieved at 90 days. Strength gained for Mix 1 of Group 2 was about 50% and that of Mix 13 of Group 9 was about 20% from 28 to 90 days.

5.3 Resistance to Freezing and Thawing Results

After the specimens were examined having gone through the tenth freeze-thaw cycle, they showed no damage of scaling and cracking. The lack of scaling and cracking may have been the presence of smaller particle size in the components. It was assumed that the smaller particle size present improved the packing. This improved packing may have provided better matrix, served as fillers and increased compaction of the components to eliminate air voids.

Review of research work by Mangulkar and Jamkar (2013) showed particle packing models are based on the concept that voids between larger particles would be filled by smaller particles, thereby reducing the volume of voids or increasing the packing density. In other words, one of the major effects of particle packing theory is its minimisation of voids or maximisation of the packing density of the components.

Sarkkinen, Kujala and Gehör (2019) applied the same experimental standard CEN/TS 13286 (2014) used in this research study to compare alkali activated composite and ordinary Portland cement as stabilisation agents. Their results indicate that there was no damage in the specimens due to the freeze-thaw cycles because the compressive strength and density increased after the 10 cycles. The increase in strength and density was likely caused by an increase in binder products formed due to extra moisture and high temperatures during the warmer cycle period.

The results of the two mixes (Table 7) showed a loss in strength below the strength for the control specimens. Mix 13 of Group 9, with the proportions 10%PG, 30%QWD and 60%GGBS, had retained ratio greater than 98% when compared to Mix 1 (20%PG, 20%RAF and 60%GGBS) of Group 2 with retained ratio of approximately 93%. Hamoush et al. (2011) concluded in their research work on freezing and thawing durability of very high strength concrete that a good freeze - thaw resistance should be a durability factor greater than 85% to avoid freeze/thaw damage.

Table 7: Resistance to freezing and thawing on Mixes 1(Group 2) and 13(Group 9)

Mix	SET 'A'		SET 'B'		Durability Factor R_A/R_B (%)
	91d (MPa)	Density Kg/m3	91d (MPa)	Density Kg/m3	
Mix 1 (PG20/RAF20/GGBS60)	36.43	1895	38.99	1930	93.43
Mix 13 (PG10/QWD30/GGBS60)	36.75	1963	37.41	1980	98.23

5.4 High Pressure Flow Test Results

The surface skin of concrete is the first line of defence against the ingress of aggressive agents such as chlorides, sulphates and carbon dioxide. For this reason, there is an increasing awareness of its importance for durability of concrete (Claisse, Peter A., Ganjian and Adham 2003). Results of the flow test showed that Mix 13 of Group 9 had lower coefficient of permeability of 5.283E-10 compared to Mix 1 of Group 2 (2.40E-09). Mix 13 had a slightly lower coefficient of permeability to Mix 1. The high permeability for the two mixes generally may have been the absence of aggregates in the constituents. Ganjian, et al. (2006) stated the properties of an ideal barrier system should have a low permeability of not less than 10^{-9} m/s in the UK.

5.5 Innovations of Research Work

Unlike the research studies carried out by Raghavendra et al. (2016) and Lizarazo-Marriaga et al. (2011) mentioned in the literature review of this paper, this research can fill the knowledge gap by fully replacing cement with two quarry by-products (RAF and QWD) in combination with PG and GGBS in road (base) and foundation. Other contribution to knowledge includes:

- the reduced percentage of liquid – by-product – ratio used in the two groups discussed in this paper (varied from 15 – 17%). The principles of compaction to obtain optimum density of the pastes was innovative. This method to produce a maximum density of a mixture, does not utilise the conventional concept of minimising the water – to – cement ratio to maximise a cement paste or concrete strength. Unlike the conventional method, the best compaction gives the best strength. The best compaction occurs at the most wet mix that will support the hydraulic pressure machine, in both lab and site environment operating of the vibrating roller; and

- the design of experiment and analysis of the results were carried out using a statistical software package – Minitab18. The software has predictive capability that can be compared to the actual results obtained with high degree of accuracy. The software also allows precision in the design, provides

better estimates, maximises variance and generates plots for all three components in the model.

5.6 Discussions

There are two key factors that influenced the strength of the optimum mixes at 90 days on Group 2 Mix 1 (PG20/RAF20/GGBS60) and Group 9 Mix 13 (PG10/QWD30/GGBS60): i) the constituent of the mix itself in regards to the proportions of the different materials present; and ii) the percentage of the liquid / solid ratios used in the mixture

It can be said that the dominant factor of calcium sulphate - $CaSO_4$ ($CaO + SO_3$) in the PG materials, calcium silicate – $CaSiO_3$ ($CaO + SiO_2$) in the GGBS and the pozzolanic activity ($SiO_2 + Fe_2O_3 + Al_2O_3$) present in the RAF and QWD heavily influenced the performance of the cement paste at both early and late age strengths.

It is also highly likely that the mineralogical properties of the RAF and QWD may have had a great influence on the strength development of the optimum mixes. Both materials consist predominantly of reactive silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3).

The PG, RAF, QWD and GGBS used in this research study met the conformity criteria for common cement in terms of compositions and specifications (EN, B. 2011).

Another factor that may have influenced the mechanical performance of Groups 2 and 9 was the physical properties of the materials in the components. The particles for the two blends range approximately between 0.3 to 1500 microns. Ganjian, Eshmaiel, Claisse and Sadeghi-Pouya (2007) report that pozzolanic materials with a finer particle size results in faster hydration and reduced setting time of the binder. This is due to the higher surface area and electric charges induced on the surface of the particles during the grinding process.

6 Conclusions

The compressive strength obtained for the selected mixes have potential to be used not only in highway pavement projects, but in a wider civil engineering, architecture and building construction applications. Experimental results show that different liquid / solid ratios in the mixture can achieve different compressive strength at specified age.

In general, all the mixes had increased compressive strength as the specimens age, this may be due to the high volume of pozzolan present in the components. The dominant pozzolans in Group 2 Mix 1 (PG20/RAF20/GGBS60) and Group 9 Mix 13 (PG10/QWD30/GGBS60) with compressive strengths of 41.24 MPa and 37.89 MPa respectively at ultimate strength, may have been one of the major contributory factors to their success coupled with chemical / physical properties of the materials and the correct liquid / solid ratio of 17%.

Even though the two top mixes had high permeability, they were not susceptible to the freeze-thaw experiment. In fact, it had no negative effect on the long-term durability of the specimens in terms of the freeze-thaw exercise carried out in the study.

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