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# Air Pollution Control (APC) Residues as a Potential Replacement for Lime in Fly Ash Bound Mixtures (FABM) Containing Quarry Waste Dust

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**Abstract:** This paper describes the effectiveness of a new pulverised fuel ash (PFA) activator when used in the form of fly ash bound mixture (FABM). Previous researches in this field indicated that using extra limestone quarry waste dust in Type 1 road base material considerably reduces the stiffness of the unbound mixture. To regain the loses in resilient modulus, application of ground blast-furnace slag (GBS) and blend of PFA and hydrated lime was studied on road base materials containing high level of limestone quarry waste dust. 7 and 28 day resilient modulus measurement showed that GBS was not helpful while PFA-lime binder was found to be useful in increasing the resilient modulus of the tested samples. However, to reduce the cost of utilisation, a new, cheaper activator for PFA was suggested to replace the hydrated lime. From amongst six potential PFA activators, air pollution control (APC) residues presented the highest ability in providing bound road base material due to its higher pH and lime content. 7 and 28 day resilient moduli of the samples of FABMs containing i) extra quarry waste dust, and ii) APC residues and lime as PFA activators were investigated, and compared to the resilient behaviour of typical road base and subbase aggregates. Although both activators increased the resilient modulus of dust-elevated unbound mixtures, APC residues was found to provide much higher resilient modulus and less activation time in comparison with lime, while APC residues is a type of waste.

***Key words***: *APC residues; PFA; Quarry waste dust; Resilient modulus; Road base and subbase.*

## Introduction

The extraction of aggregate from a quarry site and subsequent crushing and other processes on the material produce some unwanted fine particles. Recent investigations in the UK indicate that 106 million tonnes of limestone rock, usually crushed at quarry sites, has annually been extracted since 2002, and has produced nearly 22 million tonnes of limestone quarry dust at the end of each year [1]. All types of such materials, called "quarry waste dust", are produced from the various quarries around the UK where their total number reaches up to 1,300 quarries. Further to the UK and as examples, productions of annually 18 million tonnes of limestone dust in Greece and 30 million tonnes in Turkey have been reported [1, 2]. Latest statistics of mineral extractions in the UK [3] show that in 2006, 85% of 293 million tonnes of total mineral extraction has been directed towards the construction purposes from which 97% (around 242 million tonnes) consisted of aggregates. Therefore, accommodating waste dust into aggregate layers of roads, can reduce the stockpiles of dust, and cause economical and environmental impacts.

According to British Standards [4], fine aggregate is generally defined as the material under 4*mm* in size; however, in this research, "quarry waste dust" or "dust" is defined as under 4*mm* limestone quarry fine materials, produced in excess of the need of the quarry during the aggregate crushing process.

Stability of unbound granular mix is generally known to be affected adversely by increasing fine particles [5-12]; however, there are several evidences showing that this cannot be taken as a rigid rule, and that some factors may reverse this trend. Studies have shown that there is an optimum level for fine content at which the material shows a reduction in its strength and stability with the increase in fines [6, 8, 9, 12-15]. The maximum amounts of 12% [15] and 10% [12, 14] have been figured out as levels at which considerable reduction in material stability (softening) is expected. Fine materials in the majority of these projects have been those smaller than the number 200 sieve (75$\mu m$) while this material fills just 15% of limestone quarry waste dust (see Fig. 1). Thus, wider range of dust application in unbound aggregate systems was predicted.

A recent laboratorial study with the purpose of utilising extra dust in unbound material has reported that application of 10 to 30% extra dust in Type 1 subbase matrix reduces its resilient modulus by 30 to 40% [16]. Not only can this cause major plastic deformation and its related distresses in the structure of the road pavement, there will be further need for extra primary and expensive material for upper layers to compensate the lack of stiffness of the subbase.

An effective method to reclaim this is to change the phase of the mix system from unbound to lightly bound one [17]. Therefore, further fine material, in the form of dust, has been used while stability of the material will be kept adequate for road foundation. This will increase the sustainability within road construction, as it reduces the overburden stockpiles in quarries, and adds to the value of the material which was already considered as waste further to providing longer life span for the pavement and reducing the total thickness of the pavement. As stabilised materials are known to have higher stiffness than unbound ones do [18], thinner road surfacing structure over the lightly bound materials is required; hence,

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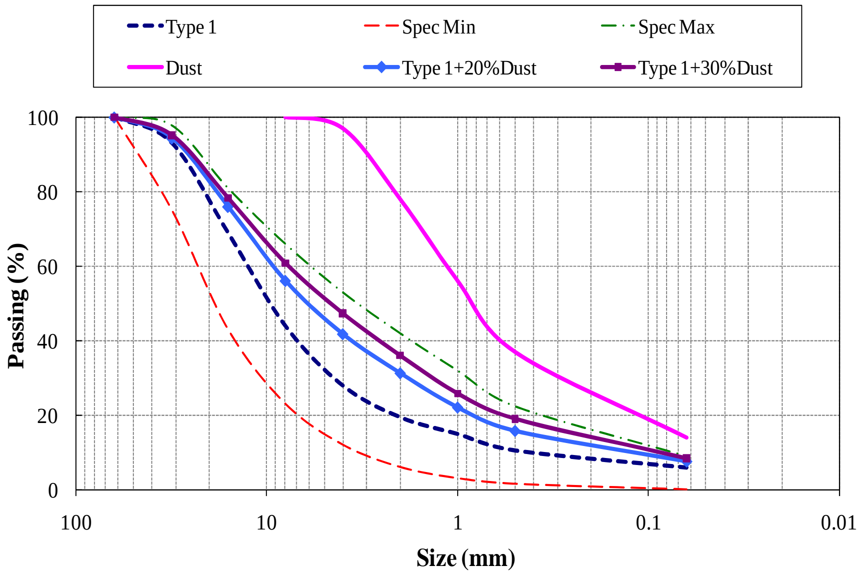

**Fig. 1.** Gradation Diagram for Specification for Highway Works (SHW) 800 Envelope and Research Unbound Mixtures.

in addition to the reduction of the problems associated to distributing fine materials [19, 20], lower cost of top layer will be another advantage of utilising lightly bound road base system.

A recent research has also found another merit in the application of high amount of fines (those smaller than 425$\mu m$) in cement-stabilised road bases which presented higher resilient behaviour or equivalent to the stabilised material with lower fines content [21]. Nonetheless, increasing 1% cement further to the optimum designed amount could negatively affect the performance of the road due to cracks generated because of extreme rigidity. The advantage with lightly bound materials is that they are highly unlikely to develop as wide cracking as the cement-based bound materials do.

Additional sustainability can be sought by using waste materials as the binding agent rather than using cement or hydrated lime which are considered as industrial products. Helping in reducing $CO_2$ emission, such approach will offer higher in performance of base layers with less cost. This paper has focused on the evaluation of some potential wastes as binders to reclaim the losses in the resilient modulus of the unbound road base materials elevated in their volume of fine.

At the first stage, applicability of granulated blast-furnace slag (GBS) and combination of pulverised fuel ash (PFA) and lime was studied as two potential binders to improve the resilient behaviour of Type 1 aggregate containing 30% extra dust. Outperformance of PFA-lime was the encouragement for further study on increasing the sustainability of the project by replacing lime with an apt waste capable of activating PFA into cementitious stage for enhancing the resilient behaviour of Type 1 material containing 20% extra dust. From amongst four wastes as lime replacement candidates, air pollution control (APC) residues material was taken for in-depth research due to its higher PFA activating ability. Performance of APC residues was studied by monitoring the gain in the stiffness of the samples containing this PFA activator in comparison with the effect of the other different stabilisers added to the control road base mix. Measuring resilient modulus of the new lightly bound material at its ages of 7 and 28 days was the guide to show the ability of APC residues in activating PFA to bond with the aggregate matrix, and improve the resilient behaviour of Type 1 aggregate containing 20% extra dust. Also, the results are clear in picturing the higher performance of PFA-APC residues as a binder in comparison to the use of the traditional PFA-lime one.

## Research Materials and Sampling

The mixes of the research were composed of aggregate and binder as two main phases of the material matrix. The aggregate phase includes Type 1 with 20% and 30% extra dust. Type 1 subbase material is a common, crushed aggregate which is used for unbound road base and subbase layers in the UK. It may be made up of primary crushed minerals, slag, or recycled materials. Type 1 envelope is governed by SHW (Specification for Highway Works), Clause 803 [22]. Type 1 mix was already checked to be in accordance with the above standards. The gradation curve of the Type 1 material used in this research, and the upper and lower borders of Type 1 aggregate envelope can be seen in Fig. 1.

Limestone quarry waste dust (dust) used in the research is the proportion of the crushed aggregate which, as excessive fine aggregate, has stayed out of Type 1 gradation. Nearly 40% of dust is smaller than 500$\mu m$ and its coarsest aggregate is smaller than 4.75$mm$ (100% dust passes sieve No. 4). Adding extra dust to Type 1 aggregate pushes the gradation curve close to the upper band of the envelope, as the percentage of fine particles has increased (Fig. 1). Type 1 and dust used in this research were both from a Tarmac limestone quarry.

For the first stage of the study and following the main purpose of the research, i.e. utilising dust in road base materials, GBS, and PFA-lime (as the binders to enhance the bearing capacity of the mixes) were added to the aggregate mix of this study with the highest amount of dust, i.e. 30%. According to the preliminary experience, 10% GBS and 5% PFA-lime at 4:1 ratio were added to the dust elevated aggregate mix within the following proportions:

- Mix 1: Type 1 limestone + 30% limestone waste dust + 4% PFA + 1% Lime.

**Table 1.** Description of the Mixes of the Research.

| Mix ID | Mix Description | Mix Water Content (OMC, %) |
|---|---|---|
| Type 1 | Type 1 Limestone Aggregate | 3.0 |
| Type 1 +20% Dust | Type 1 Limestone Aggregate + 20% Extra Limestone Quarry Waste Dust | 4.0 |
| Type 1 +30% Dust | Type 1 Limestone Aggregate + 30% Extra Limestone Quarry Waste Dust | 4.5 |
| Mix 1 | Type 1 Limestone Aggregate + 30% Extra Limestone Quarry Waste Dust + 4% PFA + 1% Lime | 6.0 |
| Mix 2 | Type 1 Limestone Aggregate + 30% Extra Limestone Quarry Waste Dust + 10% GBS | 6.0 |
| Mix 3 | Type 1 Limestone Aggregate + 20% Extra Limestone Quarry Waste Dust + 8% PFA + 2% Lime | 7.0 |
| Mix 4 | Type 1 Limestone Aggregate + 20% Extra Limestone Quarry Waste Dust + 5% PFA + 5 APC Residues | 6.6 |

- Mix 2: Type 1 limestone + 30% limestone waste dust + 10% GBS.

Dry materials were mixed with the optimum moisture content (OMC) - which was found in accordance with the guidance given by BS 1377-4:1990 [23] - for each mix to provide the highest possible dry density, ensuring that there is enough water for binder reaction. As the lime content is usually very small compared to the moisture content required for compaction of the mixture, the authors found that there is more than enough water available to hydrate the lime fully. All the compaction efforts during OMC test and sample manufacturing have been applied using the vibrating hammer.

Due to the good performance of Mix 1 in providing a lightly bound matrix, PFA-based binder was selected as the reclaiming agent for the lost resilient modulus; however, evaluating the effect of APC residues, as a selective replacement for hydrated lime, in activating PFA and providing fly ash bound mixture (FABM) matrix was the aim of the next stage of the research.

APC residues is a waste material produced from the incineration of waste in power plants, and has been defined by the Environment Agency as a mixture of fly ash, carbon, and lime - the result of a treatment process to clean the gases before they are released into the air [24]. Having been collected from an incinerator plant in the UK, it is a very fine, light grey powder which could cause problems with dust control while handling. The main properties of the material which makes it suitable to replace the role of lime in activating PFA are high lime content and pH over 12 which are two important characteristics of hydrated lime. Chemical analysis on the contents of APC residues indicate that this waste normally contains at least 25-40% lime content; however, neutralising value test on the waste material collected from the plant displayed nearly 50% lime content in APC residues. Hence, it was concluded that four portions of APC residues were required to surely activate a given amount of PFA, for the activation of which one portion of lime deemed sufficient. This was the guide to use 1:1 ratio for PFA-APC residues in the mix.

PFA of the study was provided from Rugeley Power Station which produces 200,000 tonnes of PFA per annum [25]. Currently, an increasing amount of PFA is landfilled, and the plant is looking for further outlets of PFA in the industry, as although the supply for this waste has always been exceeding the demand, recently less draw from plant, leading to bigger stockpiles, has been seen.

During stage one sample manufacturing, high volume of dust caused considerable amount of fine material (in the form of grout) to escape beneath the tamper, which reduces reliance on sample homogenity. Therefore, the amount of dust for the second stage was decreased from 30 to 20% while the amount of binder was increased for 5% so as to give the mix a better concreting opportunity. Already, it had been found that doubling the PFA-lime content of the sample not only brings no harm for sampling process, but also generates the same resilient behaviour [26]. To assess the ability of PFA-APC residues in bonding the mix matrix in comparison with that of PFA-lime, same amounts of binding agents (both 10%), though with different ratios of PFA-activator, were used in the second stage of testing. In order to keep consistency of the results, all testing, sampling, and curing procedures used for the stage one mixes were followed for the new mixes, the blends of which were as follows:

- Mix 3: Type 1 limestone + 20% limestone waste dust + 8% PFA + 2% Lime.
- Mix 4: Type 1 limestone + 20% limestone waste dust + 5% PFA + 5% APC residues.

Cylindrical triaxial samples of 150*mm* in diameter and 300*mm* high were manufactured in seven layers using vibrating hammer. Necessary studs, as bases for installing the linearly variable differential transducers (LVDTs) - to measure the vertical and radial deformations of the sample under dynamic loads of repeated load triaxial (RLT) test - were inserted in the samples at predetermined layers. After extruding the samples from the mould, they were perfectly sealed with plastic wrap to prevent any water in or out, and cured at 20±1°C. Samples were cured for 7 days before testing as a checkpoint for stabilised and lightly bound materials as stated in [18]. Some other samples were also cured for as long as 28 days as a general bound material checkpoint, and also to evaluate how the resilient moduli of the samples change in the course of time. Further investigation is undergoing to study the performance of new binder on early-life and long-term mechanical properties of Mix 4 in comparison with that of PFA-lime in Mix 3.

Table 1 summarises all the mixes used in this study with their optimum moisture at which they have been mixed and sampled for this research.

## Research Testing Regime

Lightly bound materials have an unbound behavior in their early life, and in course of time, with the extension of setting of the binding agents, they enter into a stiffer behaviour, similar to bound material, however with lower perspectives, based on which they are called “lightly bound material”. Triaxial test is known as one of comprehensive studying means for such materials, simply because it is able to reflect the behaviour of the sample under dynamic, real-like loads in both unbound and bound stages.

In addition, stabilisation has been proposed to compensate the losses in the resilient modulus of Type 1 road base material due to the introduction of extra the dust effect of which has already been studied through triaxial test. Therefore, triaxial test was used both to

**Table 2.** Stress Levels Used for Resilient Modulus Test [27].

| Stages | Confining Stress (*kPa*) | Deviator Stress (*kPa*) | |
|---|---|---|---|
| | Constant | Min | Max |
| Conditioning | 70 | 0 | 200 |
| 1 | 20 | 0 | 20 |
| 2 | 20 | 0 | 35 |
| 3 | 20 | 0 | 50 |
| 4 | 20 | 0 | 70 |
| 5 | 35 | 0 | 35 |
| 6 | 35 | 0 | 50 |
| 7 | 35 | 0 | 70 |
| 8 | 35 | 0 | 90 |
| 9 | 35 | 0 | 120 |
| 10 | 50 | 0 | 50 |
| 11 | 50 | 0 | 70 |
| 12 | 50 | 0 | 90 |
| 13 | 50 | 0 | 120 |
| 14 | 50 | 0 | 160 |
| 15 | 70 | 0 | 70 |
| 16 | 70 | 0 | 90 |
| 17 | 70 | 0 | 120 |
| 18 | 70 | 0 | 160 |
| 19 | 70 | 0 | 200 |
| 20 | 100 | 0 | 90 |
| 21 | 100 | 0 | 120 |
| 22 | 100 | 0 | 160 |
| 23 | 100 | 0 | 200 |
| 24 | 100 | 0 | 240 |
| 25 | 150 | 0 | 120 |
| 26 | 150 | 0 | 160 |
| 27 | 150 | 0 | 200 |
| 28 | 150 | 0 | 240 |
| 29 | 150 | 0 | 300 |

study the age-dependent behaviour of the stabilised mixes, and to make the results comparable to those of unbound mixes of the research.

The cylindrical samples were tested at predetermined ages of 7 and 28 days for their resilient modulus. According to BS EN 13286-7:2004 [27], 29 different sequences of dynamic load and confining pressure (100 repetitions per sequence) were applied to the samples after 10,000 repetitions (or less if the permanent deformation tends to stop increasing) of a specified deviator stress and confining pressure as conditioning stage. Table 2, based on the above standard, demonstrates the stress states to which the samples were subjected.

As resilient modulus is a stress dependent characteristic of the unbound or bound granular materials, different resilient moduli are achieved under varying stress sets of Table 2. Nevertheless, a definite stress base is required for sample behaviour comparison purposes. Numerical studies and field investigations of NCHRP 1-28A [28] have concluded that an element in typical road base or subbase layer of a flexible road pavement is likely to experience confining and deviator stresses of 34.5*kPa* (5*psi*) and 103.5*kPa* (15*psi*), respectively. The outcomes of the research done under NCHRP have been adjusted with AASHTO T-294:1992. The most similar stresses in Table 2 to the above stress values are those in stage 9 (confining pressure of 35*kPa* and deviator stress of 120*kPa*). This will be the stress set for only comparing the behaviour of all mixes in the research.

All samples were subjected to conditioning to eliminate the effect of specimen disturbance from sampling and compaction, and also to minimise the imperfect contacts between the platens and the specimen. The magnitudes of the conditioning stage during RLT test are displayed in Table 2. The stresses have been designed so that the sample remains under compaction nearly whole test long. Loads and deformations were continuously sent to a desktop computer connected into the RLT machine. Real-time resilient modulus of the sample was calculated and recorded next to the other data collected during testing.

## Test Results and Discussion

### Stage One of the Study

The purpose of this stage was to evaluate the effect of GBS and PFA-Lime in enhancing the resilient behaviour of the unbound mixes which had already lost about a third of their resilient moduli significantly due to the softening effect of the added extra dust.

The mix with the highest amount of extra dust in the preliminary study (30%) was used as the base mixture for this stage. During the whole test, the resilient moduli of Mix 1 and 2 were following an increasing trend with increase in the amount of bulk stress (the sum of stresses applied to the sample) at 7 and 28 day age of the samples (Fig. 2), showing that within the stress range of Table 2, the mixtures performed resiliently. The clearest point in this stage was the outstanding ability of PFA-lime binder in promoting the resilient modulus of the mix with considerably high volume of extra dust within 28 days. The majority of this increase seems to have taken place during week one to week four with nearly 400% further resilient modulus in comparison with that after one week. Such performance explains the high activity of PFA and lime in the mix, and the ability of this binder in combining the mix particles to enhance the sample stiffness. In contrast, Mix 2 which contained the mixture with the binder GBS did not make a big difference during those three weeks with only 8% improvement in average.

The ranges of the resilient moduli of Mix 1 at different bulk stresses indicate that the behaviour of Mix 1 has changed from unbound at 7 days to lightly bound at 28 days. This is not the case for Mix 2 whose behaviour not only remains unbound within four weeks of curing but no significant improvement has taken place during that period. Further to the above outcome, close curves of resilient moduli of 7 day samples of Mix 1 and 2 show similar resilient behaviour from these two mixes within the first week after compaction.

Fig. 3 shows 7 and 28 day resilient moduli of Mix 1 and 2 in comparison with those of ordinary and 30% dust-elevated Type 1. The resilient moduli of the mixes have been shown for a confining pressure of 35*kPa* and a deviator stress of 120*kPa*, as stated already.

In comparison to the typical base and subbase layer mix, Type 1, and that with 30% extra dust, adding the binders of total 5% PFA-lime and 10% GBS has reduced the immediate resilient moduli of the unbound mixes so that even after 7 days, still none of the two proposed activators have been able to provide as high resilient

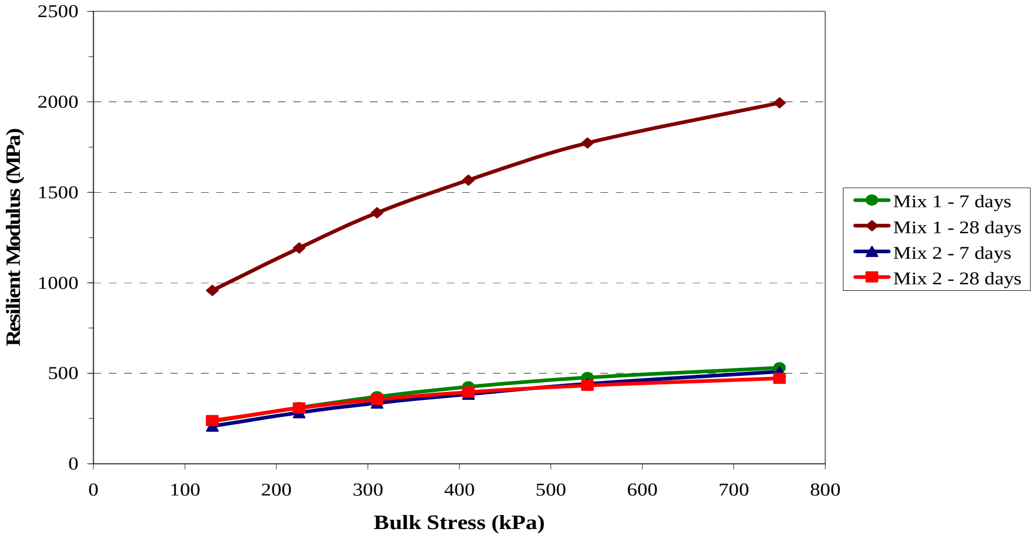

**Fig. 2.** Resilient Moduli of Mix 1 and 2 versus Bulk Stress at Their 7 and 28 Days.

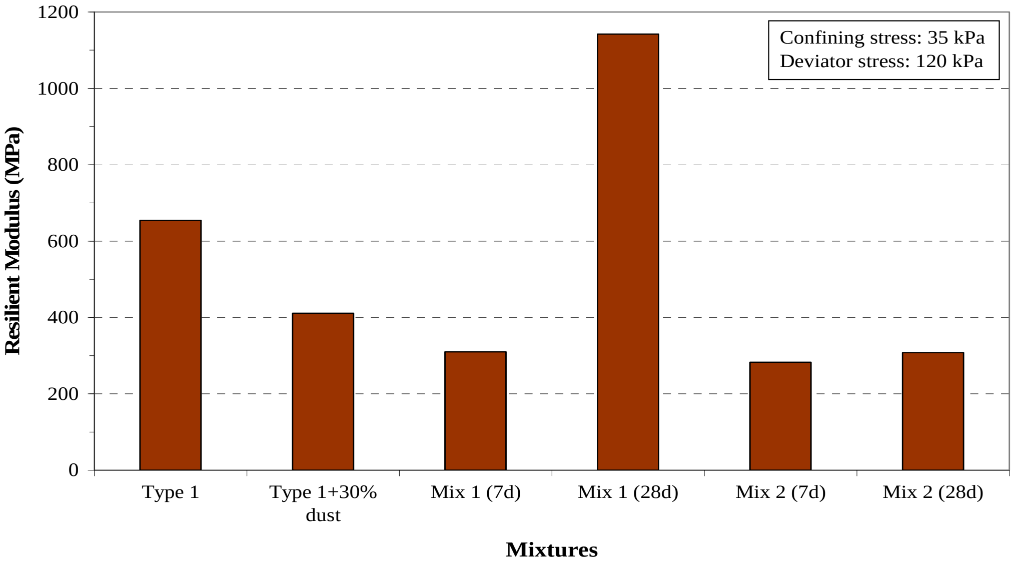

**Fig. 3.** 7 and 28 Day Resilient Moduli of Mix 1 and 2 in Comparison with Those of Ordinary and 30% Dust-Elevated Type 1.

modulus as of the Type 1 with 30% extra dust. This looks quite normal because the slow-rate binders - which are already very fine material - have replaced the primary Type 1 aggregate on which the high resilient modulus of Type 1 stands. Lesser coarse particles and increased water content have reduced the modulus further. However, PFA-lime has efficiently compensated the whole losses within 28 days whereas presence of GBS has not caused considerable improvement in resilient behaviour of Type 1 with 30% extra dust; and therefore, GBS is concluded as to be a very weak binder. Cementitious properties of 4:1 PFA-lime binder have created a lightly bound matrix which fully covered the negative effects of extra dust and managed to change the phase of the mix into a higher stiffness band.

Successful application of PFA-lime directed the research for further investigation using alternative, cheaper PFA-based binders.

## Stage Two of the Study

As described already, replacing lime with another inexpensive PFA activator was the main aim for this stage of investigation in which Type 1 limestone material with 20% extra dust was used as the base material, and the binders were made from 8:2 PFA-lime and 5:5 PFA-APC residues replacing 10% of primary Type 1 aggregate. Type 1 road base material with 30% extra waste was not used due to the difficulties in sample manufacturing, as the extra fine mortar infiltrated from the small tolerance or gap between the tamping plate and the mould.

The triaxial test results display that both binders can heal the loss in the stiffness of the samples successfully; however, Mix 4, which contains PFA and APC residues, has performed outstandingly. As seen in Fig. 4, both mixes at their 7 and 28 days have presented resilient behaviours (i.e. increase in the resilient modulus with increase in the bulk stress). The range of resilient modulus values of Mix 3 after one week suggests that the mix can be considered as an unbound road base material, whereas the behaviour of the same mix has just passed into a lightly bound system after 28 days.

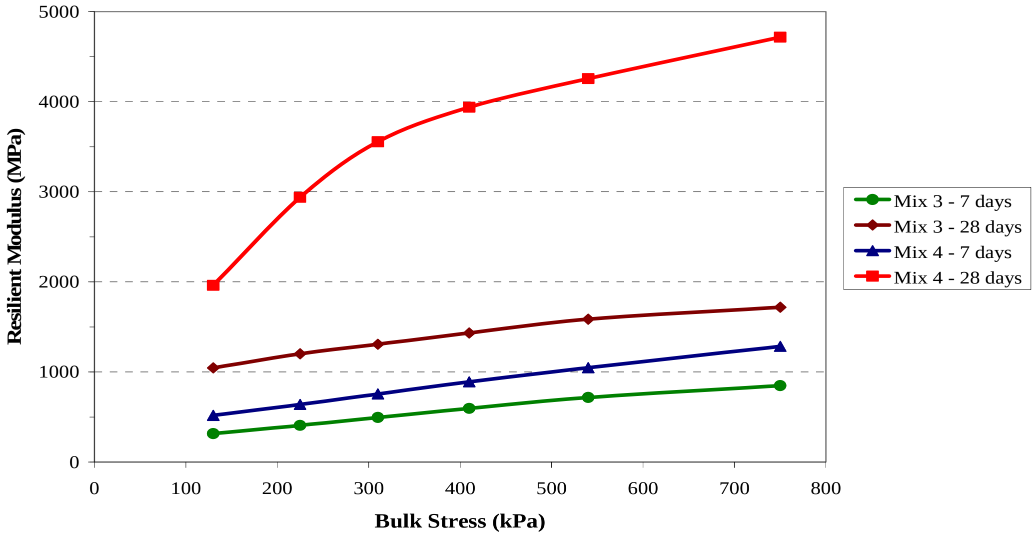

**Fig. 4.** Resilient Moduli of Mix 3 and 4 versus Bulk Stress at Their 7 and 28 Days.

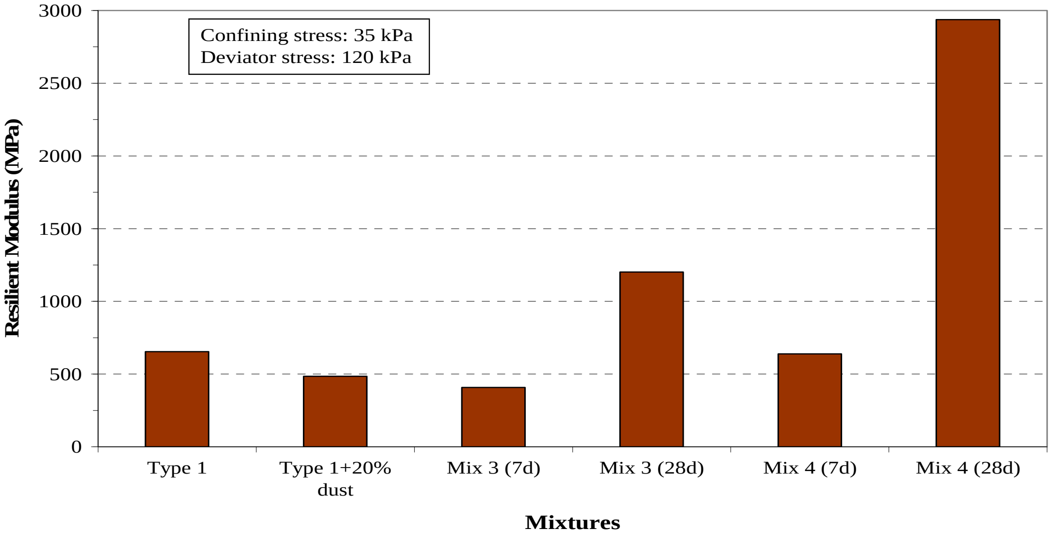

**Fig. 5.** 7 and 28 Day Resilient Moduli of Mix 3 and 4 in Comparison with Those of Ordinary and 20% Dust-Elevated Type 1.

The interesting point lays in the difference and similarity of the resilient behaviour of Mix 1 and 3 in Figs. 3 and 5. Both mixes have responded fairly identically to the stress states of triaxial test at their 28 days while weaker stiffness has been recorded for Mix 1 in comparison with that for Mix 3 after 7 days. Resilient modulus of Mix 3(7d) - which indicates the 7 day resilient modulus of Mix 3 - is 100*MPa* higher than that of Mix 1(7d). Therefore, higher waste dust content in PFA-lime based FABMs affects their short-term but not their long-term resilient behaviour. In the case of Mix 3 and 4, early-life resilient modulus of Mix 4 holds averagely 50% higher credit than that of Mix 3, indicating that APC residues material activates PFA much quicker than lime does, and thus, PFA-APC residues binder provides stronger bound matrix at the same time. This is much more visible when comparing the resilient moduli of the mixes at their 28 days.

As seen in Fig. 5, Mix 4 has performed superbly stiffer than Mix 3 has by showing that PFA-APC residues has reacted with higher rate in course of time, and consequently, Mix 4 has gained nearly 5 times higher stiffness within three weeks (between 7 day and 28 day test) while Mix 3 has just gained approximately 3 times higher resilient moduli. PFA-lime reaction within 7 days has not yet entered into its strength developing stage, and as a result, the effect of 10% primary aggregate replaced with extremely fine binder of PFA-lime is seen. During the same period of time, the ability of APC residues in activating PFA has provided a sample as stiff as Type 1 material. Just after 28 days, samples of Mix 4 have offered resilient modulus of nearly 3,000*MPa* which is over 4 times stiffer in comparison to the resilient modulus of Type 1 material; whereas Mix 3 has had improvement of less than 2 times. As the chemical reactions have taken place slowly and without creating considerable amount of heat, it is less likely to have onset cracks in the body of the hardened material which is considered as the advantage of lightly bound materials in comparison with the bound ones such as concrete.

Comparing 7 day resilient modulus of Mix 1 and 3 in Figs. 3 and 5, it can be concluded that increasing the amount of dust in the matrix of the FABMs when the binder is lime-activated PFA ends in less stability in the short-term behaviour of the FABM. In contrast, the amount of dust has not affected 28 day resilient behaviour of Mix 1 and 3 which have presented similar resilient moduli even with different amounts of dust and binder.

As an early stage outcome of the research, negative consequence of adding dust to the primary Type 1 aggregate has been recovered within the bound matrix that PFA and APC residues have provided; thus, not only 30% less primary aggregate and 20% of overburden waste dust have been suggested for road base or subbase, two other types of wastes have found a valuable stream of usage to the practice rather than being landfilled. Moreover, a stronger road foundation has been introduced, which, if fully confirmed to be used, will result in reducing the top layer thickness and extending the road life span, which both are actually the sustainability aspects of the project. Therefore, further to the environmental advantages of utilising wastes, economical benefits of utilising the new mix are predicted.

As such stiffness improvement rests on the cementitious environment that PFA and APC residues have provided due to some sort of chemical reactions, the reasoning behind the strength development of Mix 4 is currently under investigation. It is believed that studying extensive compressive, tensile, and flexural strength tests alongside with X-Ray diffraction analysis can reveal more mechanical abilities, and the reasoning for strength development. Further investigation on the short- and long-term mechanical properties of the new mixes is under process to fully identify their mechanical behaviour.

## Conclusion

The objective of the research was to provide an outlet for the overburden stockpiles of processing waste dust created during quarrying limestone aggregate. Direct usage of dust in terms of extra fine particles added to the typical road base and subbase aggregate, significantly reduced the resilient modulus of the unbound mixture.

Bound system was found effective in preventing the loss in the stability of the material which had already got softened because of introducing extra dust into the mix. While FABM was found a suitable method to compensate the losses in the road base material containing high level of waste limestone dust, GBS was not found helpful during the 28 day age of the compacted materials. PFA-lime binder provided a cementitious-like environment which unified the particles, and improved the mix stability under load so that within less than 28 days, value of resilient modulus of aggregate with 30% extra dust is higher than the resilient modulus of Type 1 material; however, a cheaper and quicker activator for PFA was preferred by the industrial sectors.

Following successful feasibility testing on APC residues, 7 and 28 day resilient modulus measurements were performed on several samples of FABMs in which APC residues and lime individually had the role of activating PFA. Both activators were found successful in reclaiming the losses in the resilient modulus of 20% dust-elevated unbound mixture. However, APC residues-containing samples presented higher resilient modulus and faster treatment due to the ability of this waste in activating PFA in comparison with what lime did. Therefore, the APC residues-activated FABM can be considered to successfully recover the negative effect of extra dust on the stability of the unbound mixes within a week by providing resilient modulus as high as that of Type 1 material.

In this project, not only has a stream for removing waste dust from the quarry sites been offered, but also another outlet for using further waste materials in road foundation can help in reducing the harm to the environment for less cost and longer high performance of roads which means sustainability.

Further investigation on the reasoning of such high strength and stiffness and also, on suitability of the new mix for road construction industry is on track.

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## References

1. Manning, D., (2004). Exploitation and Use of Quarry Fines, *Final Report of MIST Project No. MA/2/4/003, Mineral Solutions*, UK. Available from: http://www.mineralsolutions.co.uk/mist/mist2.pdf (Accessed 24 Sep 2008).
2. Galetakis, M. and Raka, S., (2004). Utilization of Limestone Dust for Artificial Stone Production: an Experimental Approach, *Journal of Mineral Engineering,* 17(2), pp. 355-357.
3. British Geological Survey, (2009). Minerals Produced in the United Kingdom, Commodity Statistics of British Geological Survey, Office of the Deputy Prime Minister, UK. Available from: http://www.bgs.ac.uk/mineralsuk/commodity/uk/home.html (Accessed 20 April 2009).
4. British Standard Institute, (2002). Aggregates for Bituminous Mixtures and Surface Treatments for Roads, Airfields and Other Trafficked Areas, *BS EN 13043*, British Standard Institute, UK.
5. Uthus, L., Hoff, I., and Horvli, I., (2005). A Study on the Influence of Water and Fines on the Deformation Properties of Unbound Aggregates, *Proceeding of the 7th International Conference on the Bearing Capacity of Roads, Railways and Airfields*, 10p, Trondheim, Norway, CD-ROM.
6. Lekarp, F., Isacsson, U., and Dawon, A., (2000). State of the Art I, Resilient Response of Unbound Aggregates, *Journal of Transportation Engineering*, 126(1), pp. 66-75.
7. Tian, P., Zaman, M.M., and Laguros, J.G., (1998). Variation of Resilient Modulus of Aggregate Base and Its Influence on Pavement Performance, *Journal of Testing and Evaluation*, 26(4), pp. 329-335.
8. Kamal, M.A., Dawson, A.R., Farouki, O.T., Hughes, D.A.B., and Sha'at, A.A., (1993). Field and Laboratory Evaluation of the Mechanical Behaviour of Unbound Granular Materials in Pavements, *Transportation Research Record*, No. 1406, pp. 88-97.
9. Kamal, M.A., Farouki, O.T., Hughes, D.A.B., and Sha'at, A.A., (1992). Performance of Unbound Road Base Material in Pavements, *Journal of Construction Maintenance and Repair*,

6(3), pp. 41-45.

10. Raad, L., Minassian, G.H., and Gartin, S., (1992). Characterization of Saturated Granular Bases under Repeated Loads, *Transportation Research Record*, No. 1369, pp. 73-82.
11. Thom, N.H. and Brown, S.F., (1987). Effect of Moisture on the Structural Performance of a Crushed-Limestone Road Base, *Transportation Research Record*, No. 1121, pp. 50-56.
12. Hicks, R.G. and Monismith, C.L., (1971). Factors Influencing the Resilient Properties of Granular Materials, *Highway Research Record*, No. 345, pp. 15-31.
13. Luzia, R.C. and Picado-Santos, L., (2004). Study of the Unbound Crushed Materials Behaviour in Road Pavements, *Proceeding of the International Conference on Cyclic Behaviour of Soils and Liquefaction Phenomena*, pp. 167-173, Bochum, Germany.
14. Babic, B., Prager, A., and Rukavina, T., (2000). Effect of Fine Particles on Some Characteristics of Granular Base Courses, *Journal of Materials and Structures*, 33(231), pp. 419-424.
15. Tutumluer, E. and Seyhan, U., (2000). Effects of Fines Content on the Anisotropic Response and Characterization of Unbound Aggregate Bases, *Proceeding of the 5th Symposium of Unbound Aggregates in Roads (UNBAR5)*, pp. 153-160, Nottingham, UK.
16. Saghafi, B. and Al Nageim, H., (2009). Resilient Modulus of Unbound Base Material Containing Extra Waste Stancombe Limestone Dust, *Proceeding of the 8th International Conference on the Bearing Capacity of Roads, Railways and Airfields,* Vol. 1, pp. 225-236, University of Illinois at Urbana-Champaign, USA.
17. Walters, C., Edwards, P., and Parry, T., (2008). The Use of Quarry Fines in Hydraulically Bound Mixtures for Construction Applications, *Guidance Document, MIRO Report*, Scott Wilson, UK. Available from: http://www.sustainableaggregates.com/docs/theme2/miro_ma_6_4_003b.pdf (Accessed 22 June 2009).
18. O'Flaherty, C.A., (2007). *Highways*, 4th Edition, Butterworth Heinemann, UK.
19. Turgut, P. and Algin, H.M., (2006). Limestone Dust and Wood Sawdust as Brick Material, *Journal of Building and Environment*, 42(9), pp. 3399-3403.
20. Felekoglu, B., (2007). Utilisation of High Volumes of Limestone Quarry Wastes in Concrete Industry (Self-Compacting Concrete Case), *Journal of Resources, Conservation & Recycling*, 51(4), pp. 770-791.
21. Ashtiani, R.S., Little, D.N., and Masad, E., (2007). Evaluation of the Impact of Fines on the Performance of Lightly Cement-Stabilized Aggregate Systems, *Transportation Research Record*, No. 2026, pp. 81-88.
22. Specification for Highway Works, (2009). Series 800: Road Pavements - Bound, Cement and Other Hydraulically Bound Mixtures, *SHW 800*, Specification for Highway Works, Manual of Contract Documents for Highway Works, The Highway Agency, UK, Available from: http://www.standardsforhighways.co.uk/ mchw/vol1/pdfs/series_0800.pdf (Accessed 01 June 2009).
23. British Standard Institute, (1990). Methods of Test for Soils for Civil Engineering Purposes - Compaction-Related Tests, *BS 1377-4*, British Standard Institute, UK.
24. Environment Agency, (2002). Air Pollution Control Residues, Environment Agency Publications, UK, Available from: http://www.environment-agency.gov.uk/hazwaste (14 March 2009).
25. Rugeley Power, (2009). Borrow Pit Application, Rugeley Power Station, UK, Available from: http://www.rugeleypower.com/ Pages/borrow%20pit.htm (Accessed 16 October 2009).
26. Saghafi, B. and Al Nageim, H., (2008). Use of High Waste Dust in Unbound and Hydraulically Bound Materials for Road Bases, *Proceeding of the 3rd Liverpool BEAN Conference*, Liverpool, UK.
27. British Standard Institute, (2004). Unbound and Hydraulically Bound Mixtures - Cyclic Load Triaxial Test for Unbound Mixtures, *BS EN 13286-7*, British Standard Institute, UK.
28. National Cooperative Highway Research Program, (2003). Harmonized Test Methods for Laboratory Determination of Resilient Modulus for Flexible Pavement Design, *NCHRP 1-28A*, National Cooperative Highway Research Program, Transportation Research Board, Washington DC, USA.