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New Activator used in Fly Ash Bound Mixtures (FABM) and High Dust Base and Subbase Materials

Behrooz Saghafi[1], Hassan Al Nageim[1], Shaun Friel[1], Nizar Ghazireh[2]

[1] *School of Built Environment, Liverpool John Moores University, Liverpool, L3 3AF, UK. E-mail: <b.saghafi@2007.ljmu.ac.uk>, <h.k.alnageim@ljmu.ac.uk>, <shaunf@iol.ie>.*

[2] *Tarmac Quarry Materials Ltd, Millfields Road, Ettingshall, Wolverhampton WV4 6JP, UK. E-mail: <nizar.ghazireh@tarmac.co.uk>.*

ABSTRACT

Preliminary laboratorial investigation on using extra dust (up to 30%) within the typical unbound subbase material at different moisture contents resulted in a loss of about one third in the sample resilient modulus in comparison with that of the typical Type 1 material. To compensate the stiffness loss, a blend of PFA-lime was found as a successful incorporator to the unbound matrix to improve the resilient modulus. However, due to the high cost of hydrated lime, a cheaper alternative activator was required. This research has focussed on evaluating the suitability of air pollution control (APC) residue in activating PFA in the road base and subbase material. The results showed that using APC residues as an activator for PFA produces an acceptable slightly bound system with an impressive enhancement in short-term resilient modulus and adequate compressive strength for use in road base and subbase layers in comparison with PFA-lime bound ones.

INTRODUCTION

With the government and various worldwide environmental organisations continuing to increase pressure on the cement and aggregate industries to reduce CO_2 emissions, and reduce the extraction of naturally occurring aggregates, new and innovative solutions are constantly being sought to provide replacement materials which can be substituted for the primary aggregates. According to the statistics published by DEFRA, there was 335 million tonnes of waste produced in the UK in 2004. The majority of this waste was generated in the construction and demolition (32%), and in the mining and quarrying industries (29%) [DEFRA 2004].

Quarry waste dust, in the form of fine aggregates, is a waste produced during rock extraction and rock-to-aggregate process. Due to worldwide usage of aggregates, the consequential problems of this process are considered globally. Statistics show that UK has kept using limestone both constantly and as the most consumed construction-aimed mineral [Hetherington et al. 2008]. Circa 95 million tonnes per year of limestone extraction has been recorded during six years since 2001. This has annually left about 21 million tonnes of limestone quarry waste dust, which is as much as a quarter of its primary aggregate production.

Current construction outlets for the fines include mainly unbound mixtures (base and subbase, capping and fill) and bound applications such as asphalt and concrete. Synthetic and lightweight aggregate, bricks and blocks, and artificial tiles and stones are other construction uses of fines. Agricultural, horticultural, and leisure (gardening, model making and craft materials) applications are grouped as non-construction uses of fines [Wright et al. 2009; Terzi & Karashin 2007; Felekoglu 2007; Turgut & Algin 2006; Galetakis & Raka 2004; Manning 2004; Bosilikov 2003]. "*The conventional uses for fines are predominantly in the construction industry, and demand depends strongly on road building and other construction activity*", Manning [2004] claims in MIST project report. For many reasons including sustainability, high quality of raw primary material in comparison to secondary, and opportunities to reduce extraction of sand and gravel, industry wants to consume the fines, but some obstacles like aggregate tax on fines, transportation costs, and customer ignorance and prejudice have not let the fines to find their true market.

Literature in the filed of soil mechanics has got records of negative effects of extra fine material in aggregate systems [O'Flaherty 2007; Uthus et al. 2005; Lekarp et al. 2000; Tian et al. 1998; Kamal et al. 1993, 1992; Raad et al. 1992; Thom & Brown 1987; Hicks & Monismith 1971]; nevertheless, some other researchers have conditioned the behaviour, making it dependent to the type of aggregate, its shape, gradation, moisture content, testing methods, etc. While an increase of 10% in fine material has been reported to be positive, another research believes adding more fines will not end in weaker performance as long as good drainage is provided [Luzia & Picado-Santos 2004; Babic et al. 2000; Boudali & Roberts 1998; Lekarp et al. 2000; Kamal et al. 1993, 1992; Hicks & Monismith 1971].

From the practical point of view, commercialisation of quarry waste dust needs further information and more focused hints to encourage the construction industry to consider quarry waste dust as a merit material. Following recent investigations [Tarmac Ltd. and Associates 2007; Manning 2004] on the potential outlets for accommodating limestone quarry waste dust in road unbound layer, utilisation of quarry waste dust in Type 1 material was investigated, and a lose of about one third in resilient modulus, regardless of the amount of added dust in the range of 10% to 30% was observed. Also, it was found out that the amount of moisture content in the frame of ±2% of optimum value does not affect the resilient modulus greatly [Saghafi and Al Nageim 2009]. In order to claim this loss back, development of further co-operation between the fine and coarse particles, known as "stabilisation", was targeted.

Different stabilisation methods have been advised to improve mechanical properties of soil/ aggregate materials [O'Flaherty 2007]. Fly ash bound mixture (FABM), as a slightly bound mixture, is mainly constituted of fly ash activated with a small percentage of lime or cement plus enough water to cause a pozzolanic reaction which enables the fly ash to harden and improve stiffness and strength.

Following nearly half a century of the usage of fly ash in the UK, particularly in construction industry [Sear 2004], its usage in road construction has been of interest. PFA (pulverised fuel ash) stabilized base and subbase layers, which are proportioned mixtures of PFA, aggregate and an activator (cement or lime), have been found to produce a strong and durable pavement foundation for both flexible and rigid pavements. Fly ash bound mixtures were first used in the UK in 1997 for the reconstruction of a section of the A52 Stoke-on-Trent to Ashbourne road in Staffordshire [Sear 2008]. After 10 years of service, evaluation of the deflection of the pavement with road base of 15% binder agent (3% lime and 12% PFA) and 85% local material showed a fairly fixed stiffness of the pavement during nine years [Kennedy 2008].

Following the successful image of PFA-lime in stabilising soil material, this binder was proposed for being used in the mixes with high amount of dust which have already lost stiffness due to the increase in their fine portion. The early investigation showed that the mixture of PFA and lime is able to bind the aggregates within the sample [Saghafi & Al Nageim 2008]. The idea of utilising quarry waste dust in PFA-lime-bound mixes is still costly due to the use of hydrated lime, which is an expensive industrial product, and may disqualify the project from financial point of view. Thus, a replacement for lime, which can in any way activate PFA, sounds necessary and problem solving. Russell and colleagues [2005] have tried the effectiveness of spent mushroom compost ash (SMCA) in activating the PFA in the presence of cement. SMCA speeded up the reaction of PFA in the cementitious environment.

From among six types of wastes whose producers claimed their high alkalinity and good amount of free calcium elements, APC (Air Pollution Control) residues passed the preliminary tests, and presented better strength development on the small cubes of paste made from PFA and the wastes. Therefore, further investigation on the suitability of this waste for reclaiming the lost stiffness has been under study. Information presented in this paper is from the successful performance of APC residues as an activator of PFA in terms of mechanical properties.

According to the producer of APC residues, currently, this waste is only land-filled, and no further usage of this material is on the table while huge amount of this waste is being produced. Therefore, every even tiny application of this material in a suitable way which reduces the volume of landfill is highly appreciated by the waste producer.

MATERIALS

The soil material used in this research was a mix of limestone Type 1 aggregate and its quarry dust ranging in 0 to 4 mm. The other phase of the mix, which acts as the time-dependent binding agent, is pulverised fuel ash (PFA) and its activators, in this case, lime and APC Residues.

Type 1 base and subbase material (Type 1)

As a common gradation used for unbound subbase layers in the UK, Type 1 subbase material is an unbound mixture made from crushed aggregates, including virgin materials, slag or recycled aggregates, and may contain up to 10% by mass of natural sand passing the 4 mm sieve. The properties and characterisation of Type 1 is governed by SHW 800 (Specification for Highway Works), Clause 803. As the aggregate supporter of the research, Tarmac Quarry Materials Ltd. follows the national standards in produncing aggregates. Fig. 1 shows the SHW envelope for Type 1 and the grading of the Type 1 aggregate used in this research.

Quarry waste dust (dust)

BS EN 13043:2002 draws the border between coarse and fine aggregates. Fine aggregate for construction purposes, including concrete, is the portion of the material passing the 4 mm sieve; however, this changes to the 2 mm sieve when the target application of fine aggregate is asphalt. In this research, ‘dust’ or ‘quarry dust’ is defined as 0/4 mm limestone quarry waste dust, implying to the limestone fine aggregates produced in excess to the need of the quarry production within the aggregate crushing process. The gradation diagram of dust has been illustrated in Fig. 1.

Pulverised fuel ash (PFA)

As a type of fly ash, it is a waste material produced in power stations as a result of burning coal in order to generate electricity. The coal is burnt in a furnace at a temperature of 1500±200°C. As a result of such extreme temperature the material undergoes various chemical and physical changes, and the exact nature of these changes are dependent on the nature of the coal being burnt, temperature and how long the material is kept inside the furnace. PFA is extremely fine material whose particles are 70% smaller than 90 microns. The PFA used in this research contained Silicates and Aluminates [UKQAA Technical Datasheet 9 2008].

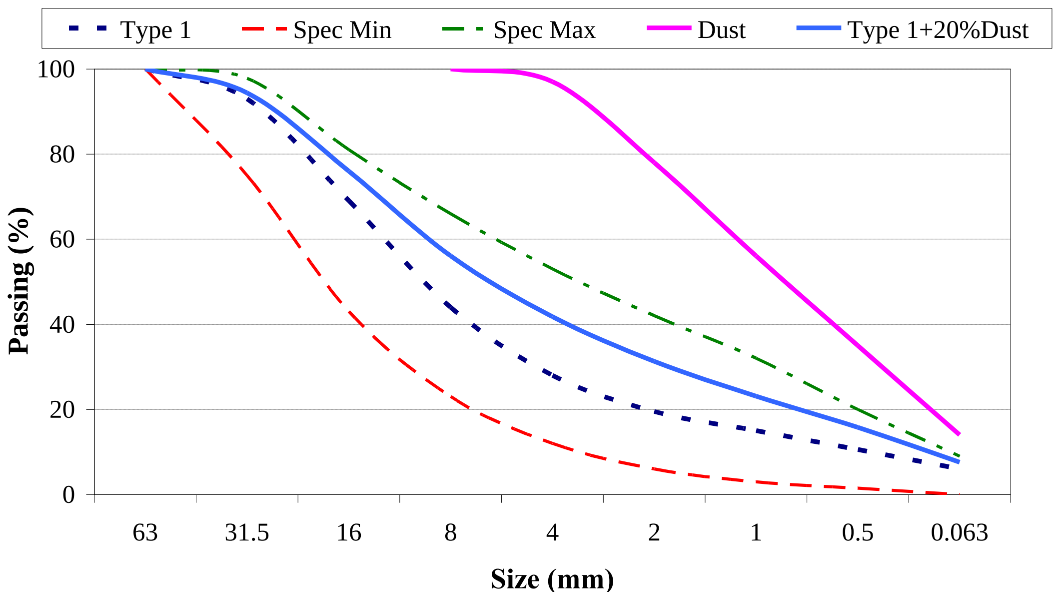

Fig. 1. Grading Diagram for Aggregate Materials and Type 1 Envelope

Hydrated lime (lime)

Fine, white dry powder, hydrated lime (also termed as hydraulic lime) is the type of lime which is used for construction purposes including stabilisation of earth material in road structure or improving asphalt quality for surfacing. [Brennan and O'Flaherty 2007]. With the formula of $Ca(OH)_2$, hydrated lime (calcium hydroxide) is not a complex, and is simply produced with watering quick lime (CaO). As a strongly alkaline material, it possesses pH over 12. Its only mineral which contributes in bounding and creating ettringite is the element of calcium (Ca) which presents as an ion of Ca^{2+} when it is dissolved into the water. The other ion (OH^-) provides the alkalinity of the mix.

Air Pollution Control (APC) Residues

It is a waste material produced from the incineration of waste, 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 [Environment Agency 2002].

Having been collected from an incinerator plant in the south of the UK, it is a fine powder-like material, and is grey to white in colour, containing small black particles of activated carbon. Due to the fineness of the material, this can cause problems with dust control while handling [APC Datasheet 2008]. The main properties of the material which make it suitable to replace the role of lime in activating PFA are high lime content (25% to 40%) and pH over 12. Therefore, in the presence of water, calcium ion will be released in a high alkaline environment which provides necessary elements for PFA to react.

TESTING PROCEDURE

Before determining the optimum moisture content (OMC) of the mix, PFA-APC ratio should have been figured out. 4:1 PFA-lime was the proportion approved by UKQAA where lime is consisted of more than 90% calcium hydroxide. Data sheet of APC Residues had reported the calcium hydroxide content of this waste for around 25% to 40%. Comparing to lime, it was concluded that nearly four portions of APC Residues is required to activate the same amount of PFA for the activation of which one portion of lime deemed sufficient. This fact was supported by neutralising value test done on APC and was the guide to use 1:1 PFA-APC in the mix which requires 5% PFA and 5% APC for a mix having 10% binder.

- PFA-Lime: 70% Type 1 limestone + 20% limestone dust + 8% PFA + 2% lime
- PFA-APC: 70% Type 1 limestone + 20% limestone dust + 5% PFA + 5% APC residues

Previous study [Saghafi and Al Nageim 2008] had shown that the 28 day resilient behaviours of the samples containing 5% (4:1) and 11% (9:2) PFA-lime are similar. In order to provide high use of waste material, it was decided to use 10% binder in the final mix, i.e. 90% aggregate (containing 70% primary Type 1 and 20% waste dust) plus 10% slow-rate binder, 8% PFA and 2% lime for the control mix and 5% PFA and 5% APC for the study mix.

OMC was the design water of the mixes. OMC of both mixes was determined in compliance with BS 1377-4:1990, using a vibrating hammer, as it was to be the compaction method for the samples. The materials used for this purpose were all oven-dried apart from the APC, as it would make some reactions if it was left in the oven. Dry Type 1 and dust were mixed together in the mixer preceding the grout of the PFA-based binder of each mix was added to the aggregate mix. A part of the water designed for each mix was used to make the grout and the rest of that was used to partially moisten the aggregates. This was to make sure that whole the fine binding agent has received enough water. Mixed material was left over night fully sealed to let the moisture migrate into the final mix.

In order to record the strength development of the new mixtures, resilient modulus and compressive strength were to be tested at different ages of the samples: 3, 7, 14 and 28 days. Resilient modulus is the same as elastic modulus for pavement design purposes, and is one of very important mechanical behaviour parameters of pavement materials which are not totally elastic and may have permanent deformation under some, even small, load applications. Elastic modulus based on the recoverable strain under repeated load is called the resilient modulus [Huang 2004]. Actually, a material’s resilient modulus is an estimate of its modulus of elasticity. While the modulus of elasticity is defined as stress over the correspondent strain for slowly applied load, resilient modulus is stress divided by strain for rapidly applied loads which in reality happens for an element in pavement structure [Huang 2004].

Unconfined compressive strength (UCS) test was carried out using a 2000 kN test machine which could apply slow-rate, strain-controlled loading on the cubes. The sizes of the cubes were measured prior to testing to see if shrinkage has happened and to find the area on which the load was applied. It is noted that no shrinkage was observed.

Cubic samples for UCS test and cylindrical samples for resilient modulus measurement were cast. The 150 mm cubes were manufactured in five layers to balance between the compaction power and the layer numbers. Then, they were off-moulded and left secured and fully sealed so that all the reactions are done using the moisture induced into the mix. At the determined ages, mentioned above, the samples were carefully unpackaged for UCS test. The compressive strength was determined in accordance with Clause 4.2.7 of BS 1924-2:1990 by crushing the cube specimens in a compression machine, and calculating the compressive strength from the crushing force and cross-sectional area of the cubes.

Cylindrical samples for the repeated-load triaxial (RLT) test were manufactured in seven layers. The cylinders of 150 mm in diameter and 300 mm in height were equipped with nine studs inserted into the samples at necessary layers before the compaction of that layer was done. The studs were the base for radial and vertical linearly variable differential transducers (LVDTs). After sampling the samples were confined with proper pipes and were fully sealed.

The cylindrical samples were tested at the above mentioned ages for their resilient modulus. According to BS EN 13286-7:2004, 29 different sequences of axial load and confining pressure (100 repetitions per sequence) after 10,000 repetition (or less if the permanent deformation tends to stop increasing) of a specified deviator stress and confining pressure as conditioning stage were applied to the samples. All samples were subjected to conditioning to eliminate the effect of specimen disturbance from sampling, and to minimize the imperfect contacts between platens and the specimen. Table 1 shows the types and amounts of stresses applied. The resilient modulus under compaction was the aim of this research. Loads and deformations, as the resultants of load application, were continuously being sent to the computer plugged into the RLT machine, and the resilient moduli of the samples were calculated and recorded next to the other collected data.

Table 1. Stresses Levels Used for Resilient Modulus Test

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

TEST RESULTS AND DISCUSSION

The results obtained for the samples of PFA-APC have been compared to those of PFA-Lime to evaluate the performance of the samples containing new mix in comparison with a previously experiences mix of PFA-Lime. In order to observe the development of strength and stiffness under both confined and unconfined loading regimes and to provide a wider image of the performance of new FABMs under real stresses both compressive strength and resilient modulus tests were performed. It is noted that although the RLT test was known as a non-destructive test on the cylindrical samples, separate samples were manufactured for studying the behaviour of the samples at each testing age so that testing procedure and deformation would not interrupt bondage process of in the samples.

The results of crushing cubes, illustrated in Fig. 2, show a more favourable outcome for PFA-APC mix, implying that better binding reaction has been developed in the new mix. It can be clearly seen that both mixes have gained strength in course of time; however, the rate of PFA-APC mix has been higher than that of the PFA-Lime one.
While the growth of strength in both mixes looks having a uniform progress with age, the results for PFA-Lime mix have encountered a drop in compressive strength at the age of 14 days. The explanation for this occurrence could be that such performance has been caused by the sudden drop in the temperature of the lab hall where the samples were cured at lab temperature. The reasoning is well reinforced when looking to the resilient moduli of the samples of PFA-Lime mix where the same resilient modulus as of the 7 day samples has been recorded for the 14 day samples. It is noted that recent preliminary investigations of the research team have clarified the dependency of the behaviour of FABMs to temperature of their surrounding environment. More accurate study on the effect of temperature on the sample strength development is one of the topics for the next step of the research.

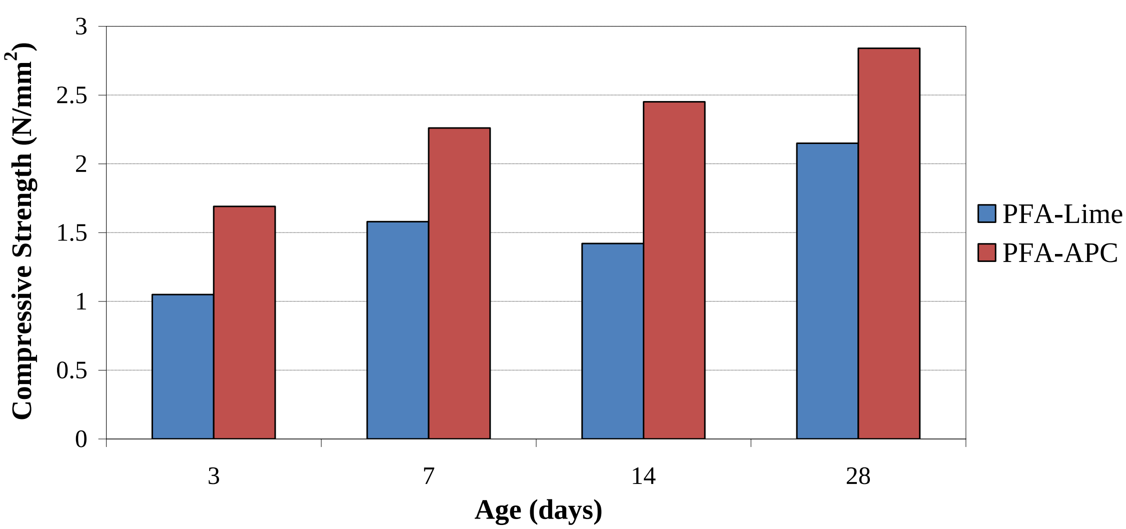

Fig. 2. Compressive Strength Values for PFA-Lime and PFA-APC Samples

PFA-APC mix is almost 40% stronger than PFA-Lime one at 3 days, and 30% stronger at 7 days. Although the former mix looks stronger than the latter at the age of 14 days, the excellence of the new mix can not be figured out until the test at this age is repeated. The 28 day UCS test results show that almost 25% higher strength has been obtained when the PFA has been activated by APC residues. These results show that the APC residues have reacted more effectively with the PFA than the lime has as a well-known activator for PFA. In addition, the reaction initiates with higher pace for PFA and APC rather than PFA and lime (at the proportions used in this research), as 3 day results declare. Therefore, PFA-APC would be a more favourable material to use for the contractors, as it would allow the base layer to be trafficked earlier. That whether or not the mixes containing PFA-APC and PFA-Lime will reach to the same strength in their long-term life is the next step of study in the agenda of the research.

As resilient modulus is a stress dependent parameter, several values have been recorded for every mix at different confining and deviator stresses, meaning that each mix can be corresponded to a range of resilient moduli which show the resilient properties of the sample as a function of applied stresses. Nonetheless, only one value, as a representative of the sample resilient behaviour, is required for comparison purposes. Furthermore, pavement design methods need a single value of the resilient modulus of each layer in the pavement thickness selection process when the design process is in its early stages. Therefore, the representative stress state acting upon each layer must be either known or assumed. The stress state that can stand as the actual stress when an element is under real traffic load would be the best to pick out.

The results from a recent highly qualified research [NCHRP 1-28A 2003] recommend using a deviator stress (σ_d) of 103.5 kPa (15 psi) and a confining pressure (σ_c) of 34.5 kPa (5 psi) for calculating the design resilient modulus of subbase or base course within triaxial test results. The outcomes of research done under NCHRP have been adjusted with the last stage of the second confining pressure set (stage 6) in AASHTO T-294:1992. The most similar stage of stresses recommended by BS EN to stage 6 of AASHTO is stage 9 in Table 1 (confining pressure of 35 kPa and deviator stress of 120 kPa). Upon this base, the triaxial test results of the 9th stage have been selected for comparing resilient behaviours of the mixes.

Fig. 3 compares the resilient moduli of the samples at different ages under the above stresses. The PFA-APC samples have predominantly outperformed with higher resilient moduli in comparison with the PFA-Lime ones. Increase in stiffness has taken place for both mixes as a result of activating PFA; however, similar to the cubes, it has had higher rate for the samples of PFA-APC. Using FABM has been a successful treatment for stabilising the negative effect of adding extra limestone dust which resulted in reducing one third of the resilient modulus of Type 1 material. Not only has the loss in resilient modulus been reclaimed, higher road earth layer quality which will end in higher life span for road has been achieved.

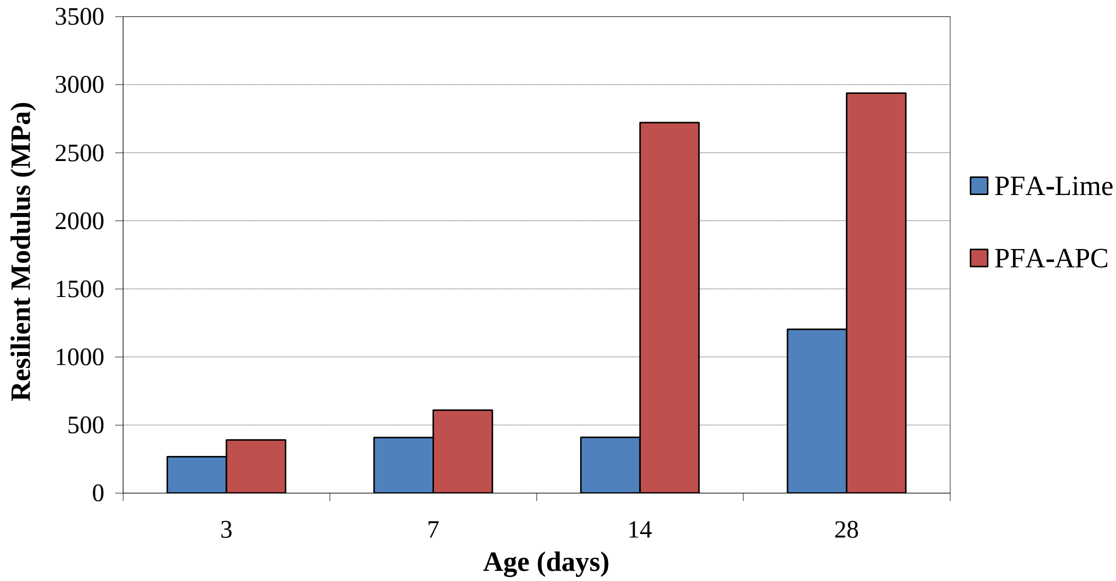

Fig. 3. Resilient Modulus Values for PFA-Lime and PFA-APC Samples

Triaxial test on the unbound samples of Type 1 containing 20% extra limestone dust measured a resilient modulus of about 400 MPa under the same stress state [Saghafi and Al Nageim 2009]. The same test has recorded the identical value of resilient modulus for 3 day PFA-APC samples while the latter contain 10% less primary aggregates replaced with fine waste materials. Just within a week, the samples of PFA-APC have fully recovered the loss in resilient modulus of Type 1 material with 20% extra dust, and provided resilient modulus of over 600 MPa which is actually as high as the value measured for Type 1 samples. Furthermore, within a month a resilient modulus five times as high as that of performed by unbound Type 1 material was achieved. This opens the gates for the utilisation of waste limestone quarry dust even with a greener approach due to the usage higher amount of wastes.

Due the problem of lab hall temperature drop which was already explained, the resilient modulus for the PFA-Lime samples of 14 day age has been exactly as high as that of 7 day age. The interesting point is that in the case of cubes the 14 day strength was less than the 7 day one, but, in the case of cylinders, they are equal. It is believed that the reason lays in the packaging of the samples. Cylindrical samples are confined with the membrane, pipes and fully sealed bag while the cubes are only covered with fully sealed bags. It seems that the multilayer packaging of cylinders has kept the heat for the sample longer than the one-layer plastic packaging of the cubes.
Another draw from the resilient modulus of PFA-APC samples relates to their sudden growth in stiffness in the period of 7 to 14 days while such a sharp raise is not seen for the UCS test results. Although further investigation is necessary, it is hypothesized that the behaviour of PFA-APC samples changes its phase from unbound-like behaviour to a slightly bound one during 14 days after compaction.

The reasoning behind the strength development of PFA-APC within road base and subbase material is under study as well. Although not very strong, it is not still known that if the strength has been the outcome of the PFA and APC residues reaction or that extremely fine powder of limestone dust have contributed in developing strength. It is believed that studying extensive compressive strength test alongside with X-ray diffraction analysis can reveal the binder constituents.

CONCLUSION

The research undertaken was to create an outlet for utilisation of the stockpiles of limestone quarry waste dust; however, due to the immediate loss of about one third in the resilient properties of the unbound samples containing 10% to 30% extra dust, stabilising the material reached to the top of the research agenda. Preliminary testing implied the capability of FABMs in reducing such negative effect up to an acceptable level; nonetheless, construction-related issues in terms of time dependency of FABMs, and also, economical and environmental aspects could render the project since lime or cement was a constituent of an ordinary FABM. Therefore, another PFA activator as a replacement for lime/ cement deemed to be helpful. APC residues material as an end-waste of a recycling plant in the UK was chosen as a potential candidate for such a purpose. Any successful usage of this waste can create a new outlet for it (which is currently being land-filled) as well as waste quarry dust.

Compressive strength and resilient modulus tests were performed on the samples having APC residues and lime as the PFA activators to make FABM system for reclaiming the loss in the stiffness and strength of the aggregates containing extra waste dust. Test results showed that PFA-APC residues is a successful solution for the primary problem of utilisation of quarry waste dust towards using less virgin aggregates and more sustainable road base and subbase material. According to the research outcomes, new APC residues-activated FABM mix can fully reclaim the whole loss in resilient modulus within one week of the material compaction. Although lime could activate PFA, its reaction rate is slower, further to its higher cost in comparison with fairly free APC residues. Additionally, FABMs gain far higher stability and strength as a result of ongoing binding ability which will further reinforce the performance of the road.

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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