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Full Length Research Paper

Frictional resistance of coal dust fouled uniformly graded aggregates

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Large deposits of coal over vast expanse of lands attract mining companies, power stations and petrochemical companies and thus the development of coal towns with rail and road networks. High traffic volume of large quantities of coal across coal cities often result in the gradual accumulation of fine coal dust particles on road pavements, rail ballast and sleepers. The effect of coal dust on the Direct Shear Friction Angles (DSFA), Direct Shear Interface Friction Angles (DSIFA) and Direct Shear Modulus (DSM) of uniformly graded gravel aggregate were investigated. The results show that at increased coal content, the DSFA of the gravel tends to the DSFA of the coal. The rate of decrease of DSFA was dependent on the moisture content of the coal fouled gravel. The DSIFA was higher than the DSFA at any degree of coal fouling. The DSM at small displacement was more sensitive to changes in moisture content of the fouled gravel than friction angles and is thus a better indicator of coal fouling effect.

Key words: Angle of friction, gravels, direct shear strength, interface shear strength.

INTRODUCTION

Mining and Agriculture are the major employment sector in Mpumalanga, providing jobs and contributing to over one fifth of Mpumalanga's Gross Geographic Product (GGP) (Thys, 2003). Extensive coal beds are situated in the western and south western part of the Province and sustain most of the large coal-fired power stations situated on the highveld between the towns of Witbank, Standerton, Piet Retief and Carolina, as well as the petrochemical plants in the area. The Witbank coalfield lies between Bethal and Springs in Gauteng Province, while the southern highveld coalfield lies between Secunda and Standerton and the eastern highveld coalfield lies between Ermelo and Volksrust (Thys, 2003).

The high density of coal mining activities has resulted in gradual accumulation of very fine dust particles in roads and railways in the semi arid province. The accumulation was primarily enhanced by the static electric properties of dry fine particle**.** Fine soil particles i.e. dust accumulation in arid and semi arid regions can enhance the occurrence of hydraulic scouring in roads as asphalt is scoured or removed through the action of water and traffic as well as reduced asphalt binder film thickness.

The surface texture of aggregates has significant impact on the adhesive properties of road aggregates. The adhesive strength is derived from cohesion in the binder and interlocking properties of the aggregates. The interlocking properties of aggregates depend on angularity, flatness and elongation. Aggregate interlocking and interfacial properties of aggregate – binder matrix are dependent on the wetting characteristics and contact angle at the interface, and these properties can be significantly altered by fine dust particles fouling. A typical case is the road rehabilitation program embarked in 2007 by Eskom (South Africa Power Parastatal) to improve and maintain the various coal haulage routes keeping the power generating heart in Mpumalanga alive. Havenga Road is one of such major roadway links between the Mpumalanga coal fields and the recently recommissioned Camden Power Station situated South East of Ermelo next to the N2 en route to Piet Retief. While the obvious cause appear to be high daily traffic of heavy axle loads, the effect of soil dust and coal fine deposits of road failure have not been fully investigated (Rottcha, 2011).

Railway foundation engineers often describe good quality ballasts as broken pieces of mainly igneous and sedimentary rocks of average particle size range of 25 to 60 mm, over which the railway tracks are laid. They are angular shaped rocks of high toughness and hardness, high resistance to weathering, minimum fouling from aggregate breakdown, of rough surfaces and minimum hairline cracks. A combination of shape properties that is, roundness, sphericity and flakiness index in conjunction with toughness and hardness in relation to abrasion and damping properties are important criteria for the selection of large aggregates as ballasts (Tutumluer et al., 2009).

The sub angular particle structure with predominant sharp corners enhance ballast-ballast and ballast-sleeper interlocking, which in turn ensures efficient transfer of train load, rail foundation stability and proper vertical and horizontal alignment of rail track. Train induced cyclic loads result in degradation of ballast and generation of fine particles. The filling of the open graded ballast with fine materials (fouling) is known to affect morphological properties, static strength of ballast and the life span of rail and sleepers as these properties depend on the interlocking ability of the ballast. In South Africa, more than 50% of the total power generated for industrial and domestic use is derived from coal. Rail is a common means of coal transportation and the associated problems are the gradually deposition of fine coal particles on rail ballast materials.

Conventional methods employed to determine the most economical time to clean or replace polluted and degraded ballast entail visual evaluation for evidence of fouling, pumping and ponding at ditches and shoulders, as well as ballast sampling and testing for fouling by laboratory sieve analyses of the bulk aggregate particle.

Series of tests on the effect of iron oxide coating on the mobilized frictional angle of Saldanha residual granitic sands and rough concrete interface revealed that when the iron oxide coating is increased in rough textured particles, a decrease in mobilized friction angle was indicated due to shift in the failure plane from the interface to the soil. The study of the effect of wetting on the interlocking properties of aggregate - coal mixture in unbound matrix will facilitate the prediction of the service performance of railways foundation aggregates, because of the tendency of coal to exhibit significant decrease in strength in the wet state.

A number of investigations on the static and dynamic properties of ballasts and the effect of geofabric on rate of ballast degradation rates are well documented (Gentzis, 2007). Studies on the geotechnical properties of coal in relation to engineering applications are also detailed (Indraratna et al., 2006; Jasinge, 2009), but specific attention to wetting effects on stability of stabilized access coal roads have not been investigated in detail. The effects of coal dust fouling on ballast interlocking properties have not been investigated in detail. Some of the challenges are that the inherent structural and physico chemical variability of coal are dependent on a lot of environmental factors and geology, but mainly because of the size of testing device that is required to test ballast materials ballast (Marto et al., 2009, Tutumluer et al., 2009). The aim of the work is to study the effect of fine coal particles on the interlocking strength of uniformly graded gravel in direct shear. The objectives are to indentify and recommend physical and mechanical indicators that may better inform ballast screening and cleaning methods for fouled highways, and evalute the effect of coal fines on the performance of road and railways especially during the rainy seasons.

MATERIALS AND TEST METHODS

The coal materials were collected from an open cast coal mine close to Nelspruit, in Mpumalanga Province, South Africa. The as dug particle size distribution of the coal is shown in Figure 2. The coal material was oven dried at temperature of 60˚C to constant mass over three days, grounded to fine particles and sieved through the 0.075 mm mesh and sealed in airproof bags. The coal material could not be oven dried at 100˚C because the organic structure of the coal is distructured and contain small quantities of ash. The particle size curve of the residual granitic filler soil that is commonly used for road construction is shown in Figure 2.

The determination of physical properties was guided by TMH, (1996) and TRH 4, (1994). The soil material used for the strength properties tests were gravel fractions held between the 9.52 to 12.5 mm meshes.

The maximum density of the aggregate was determined by the use of dead weights on the samples placed on a vibrating table. The maximum densities and optimum moisture content of the dust fouled aggregates were determined by ASSTHO compaction method. Two major sets of specimens were investigated; specimens that were compacted to 90% maximum dry density and OMC, and dry specimens that were compacted to 90% maximum dry density. An initial concern was the non uniform distribution of dry coal dust within the gravel for specimens with low degree of fouling (Kim et al., 2005). However visual observation after compaction revealed uniform distribution of coal particles at the mid section. It was also decided to average the results of three tests.

Direct shear test

The soil material used for the direct shear and interface tests were washed gravelly fractions of 9.52 to 12.5 mm diameter range. The direct shear properties of mixtures of coal and the granitic stones were studied in a 150 mm square shear box apparatus shown in Figure 1. The device was mounted on the expanded track rail of the conventional 100 mm square box. The specimens were compacted to height of 60 mm and sheared at a strain rate of 0.5 mm/min. Although the selected strain rate does not simulate the field condition of interest, it does not allow for the build up of excess pore pressure within the specimen. Different percentages of coal fines per dry mass of the aggregates were tested, at OMC and in dry state over a range of normal stress from 100 to 300 kPa.

Direct shear interface test

Concrete blocks made from aggregate particles of diameter range from 9.82 to 12.5 mm were used as interface material in the lower half of the shear box. The lower half of the shear box was 30 mm. The concrete blocks were roughly tapered from between 29.0 and

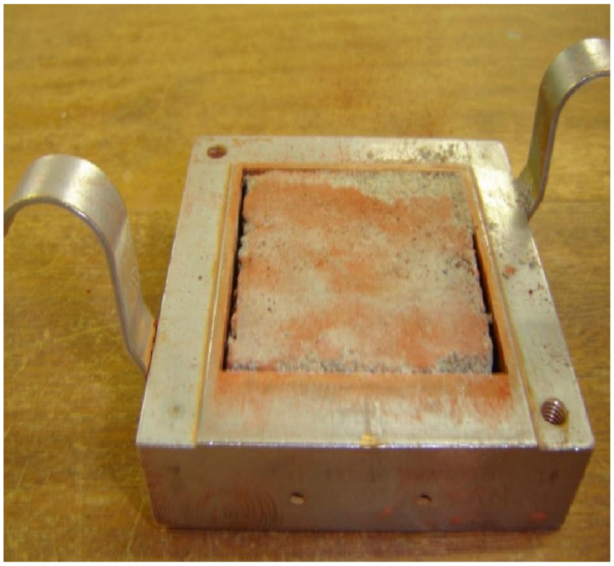

Figure 1. Interface blocks in the lower half of the shear box.

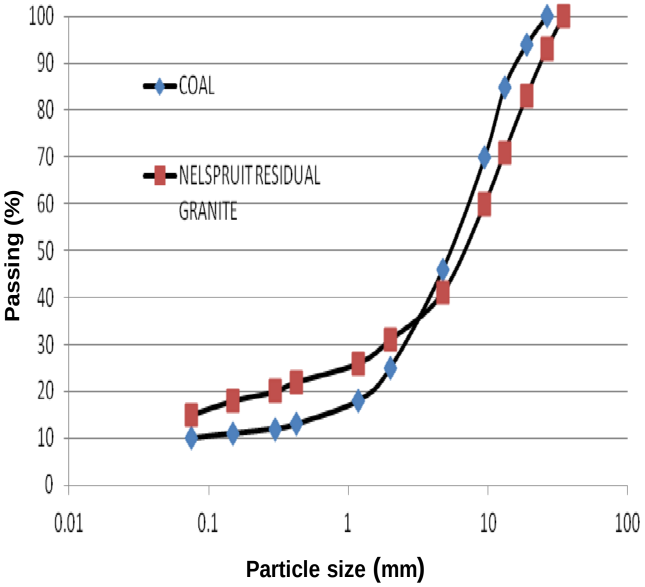

Figure 2. Particle size curves of Mpumalanga coal and Nelspruit granitic gravel.

29.5 mm height to 30 mm height along the direction of shear displacement, in order not to restrict the relative horizontal movement of the two halves of the shear box at one end and to enhanced concrete interface – soil contact at the other end. The fouled aggregates were compacted into the upper half of the box.

The series of tests conducted are:

Series 1: Direct shear test on dry gravel and coal fines at different moisture contents
Series 2: Direct Shear test on Gravel mixed with increasing percentage of coal fines at 90% dry densities and optimum moisture contents
Series 3: Direct Shear test on Gravel mixed with increasing percentage of dry coal fines at 90% maximum dry densities.
Series 4: Interface Direct Shear test on Gravel mixed with increasing percentage of Coal fines at the 95% dry densities and optimum moisture content.

RESULTS AND DISCUSSION

Physical properties

The major compounds identified by XRD in the coal samples are silicon oxide, copper aluminium sulphate, benzene, Iron arsenide sulphate, Aluminium silicate (Rottcha, 2011). The presence of arsenides sulphate and benzene makes the coal an environmentally toxic material (Karim et al., 1997; Kim et al., 2006).

The particle size constitution of the as dug coal were gravel size = 75%, sand size = 15%; Fines = 10%. Only the fine particle that is, passing the 0.075 mm sieve were used for this study. The liquid limit of the fresh coal was 43% and the plastic limit was 13%. The specific gravity was 1.45. The maximum dry density of the coal is 1356 kg/m^3 and the optimum moisture content was 17%. The maximum dry density of the 9.8 to 12.5 mm diameter granites was 1570 kg/m^3.

The particle sized curves of the granite aggregate and the coal were presented Figure 2. The particle size distribution are gravel size = 68%, sand size = 32%; Fines = 15%. The fractions held between the 9.52 and 12.5 mm diameter sieves were used for this study. The granite is an important source of ballasts for railway foundations and coarse aggregate for road construction. The effect of fine coal particles on the compaction properties of the uniform gravel is shown in Figure 3. A slight increase in optimum moisture content and a decrease in maximum dry density and dry unit weight are indicated. The marginal change in the density is due to the low specific gravity of the coal material.

Direct shear strength of coal fines and gravel aggregates

The effect of moisture content on the direct shear strength parameters of coal fines and gravel aggregates were investigated. The coal fines were compacted at the dry density and moisture content ranges from dry state of the OMC. The stress and deformation curves of compacted coal fines are shown in Figure 4. The stress strain curves are elasto plastic and minimal strain hardening behaviour that is typical of soft soil material. The coal fines exhibit shear induced compressive deformation that is proportional to the magnitude of applied normal stress. The coal fines that were tested at lower moisture content indicated stress strain curves with weak trend of strain softening behaviour that decreased with increasing normal stress and exhibited marginal contraction that increased with increase in the applied normal stress. The direct shear envelopes of the coal fines and gravel

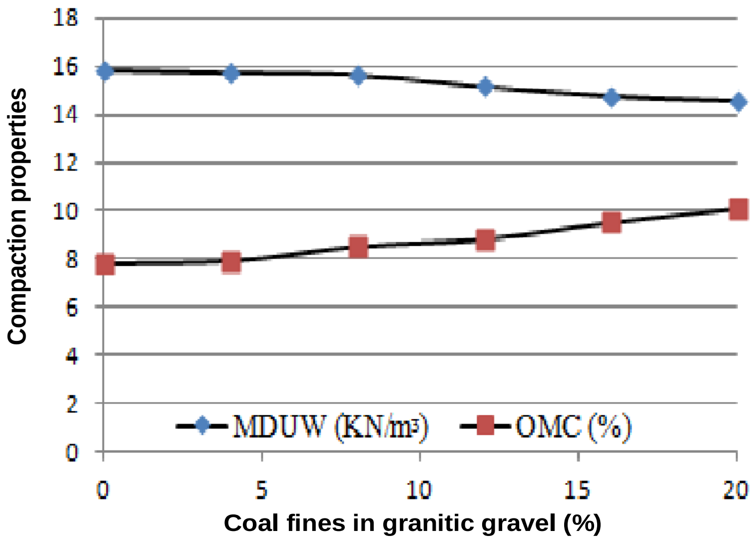

Figure 3. Maximum dry unit weight and optimum moisture content of coal fouled gravel.

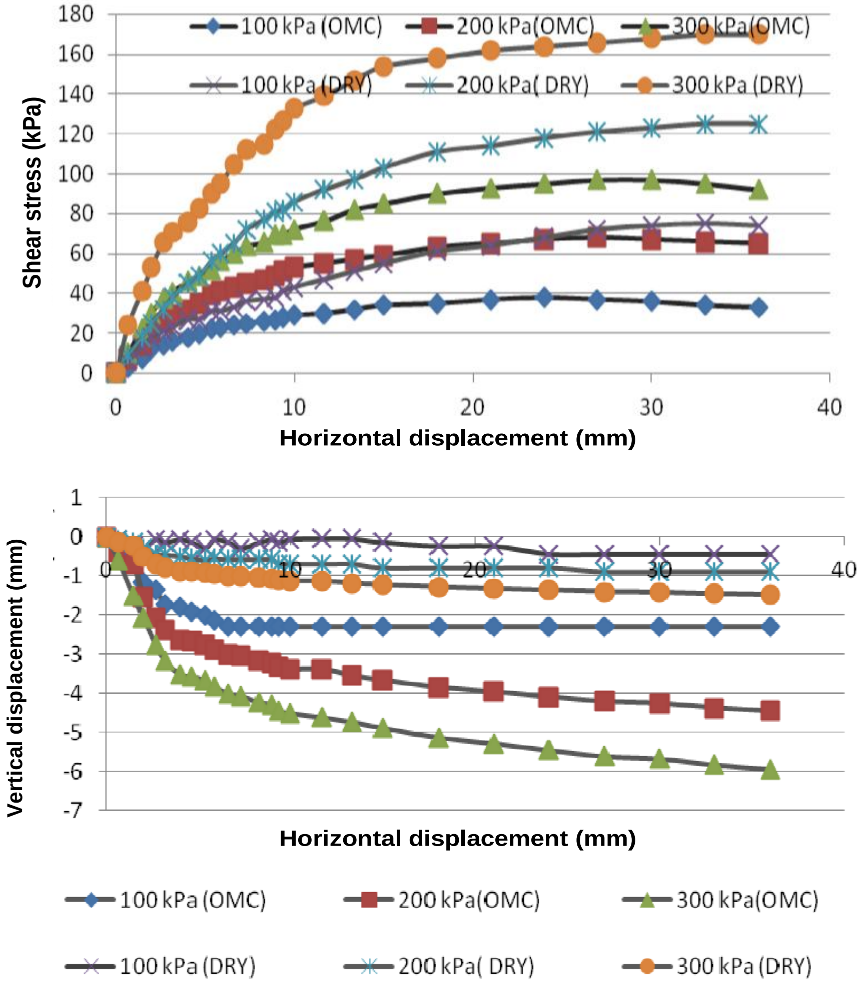

Figure 4. Direct shear stress and deformation curves of coal fouled gravel at diffrent normal stresses.

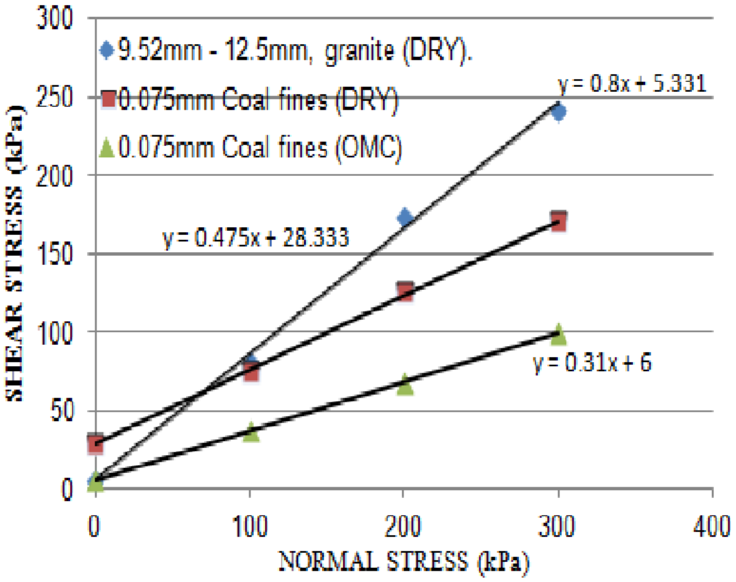

Figure 5. Direct shear strength envelopes of gravel and coal at OMC and dry state.

Table 1. Friction angles of gravel and coal fouled gravel.

Coal dust (%)	Granite - Coal (Dry)	Granite - Coal (OMC)	Coal (OMC)	Interface granite - Coal (OMC)
0	46	46	17	57
4	44	37	17	48
8	36	31	17	43
12	30	25	17	38
16	25	22	17	34
20	23	20	17	32

aggregates are shown in Figure 5. The direct shear strength envelope showed that the gravel aggregate has a frictional angle of 46˚. A decrease in moisture content of the coal fines from 19% to the dry state resulted in increase in friction angle from 17 to 27°. The friction angles of gravel and coal fouled gravel was presented in Table 1.

Effect of dry coal fines on gravel

Series of tests were conducted on compacted mixtures of dry coal fines and gravel. The stress mobilized by the granitic material due to increasing normal stress from 100 to 300 kPa in direct shear is shown in Figure 6. The maximum shear stress increased with increase in normal stress. For the degree of fouling investigated, no defined maximum peak stress ratio was indicated. At 4% coal fouling, the stress strain behaviour is general strain hardening elasto plastic response at high normal stress, however there is evidence of yielding and straining hardening at lower normal stress of 100 kPa. At 20% fouling the stress strain response is straining hardening response. The stress ratio at 4% fouling tends to a constant value at large imposed horizontal displacement. Increased degree of fouling resulted in decreased mobilized stress ratio for the range of normal stress applied. The effect of increase in the amount of coal fines on the angle of friction of the granitic stones are shown in Figure 7. As the percentage of dry coal fines increases to 20%, the angle of friction of the granitic stones tends towards the angle of friction of the coal fines at the optimum moisture content, implying that the granite – granite intergranular friction is significantly reduced and but not completely eliminated by the dry coal fines.

Detailed tests on the change in strength parameters due to increase in moisture content of the coal fines reported by Tutumluer et al. (2009) indicated significant decrease in friction angle.

The stability of compacted aggregates is a function of friction and deformation. The direct shear induced vertical strain, showed dilatancy at 4% fouling and minimal

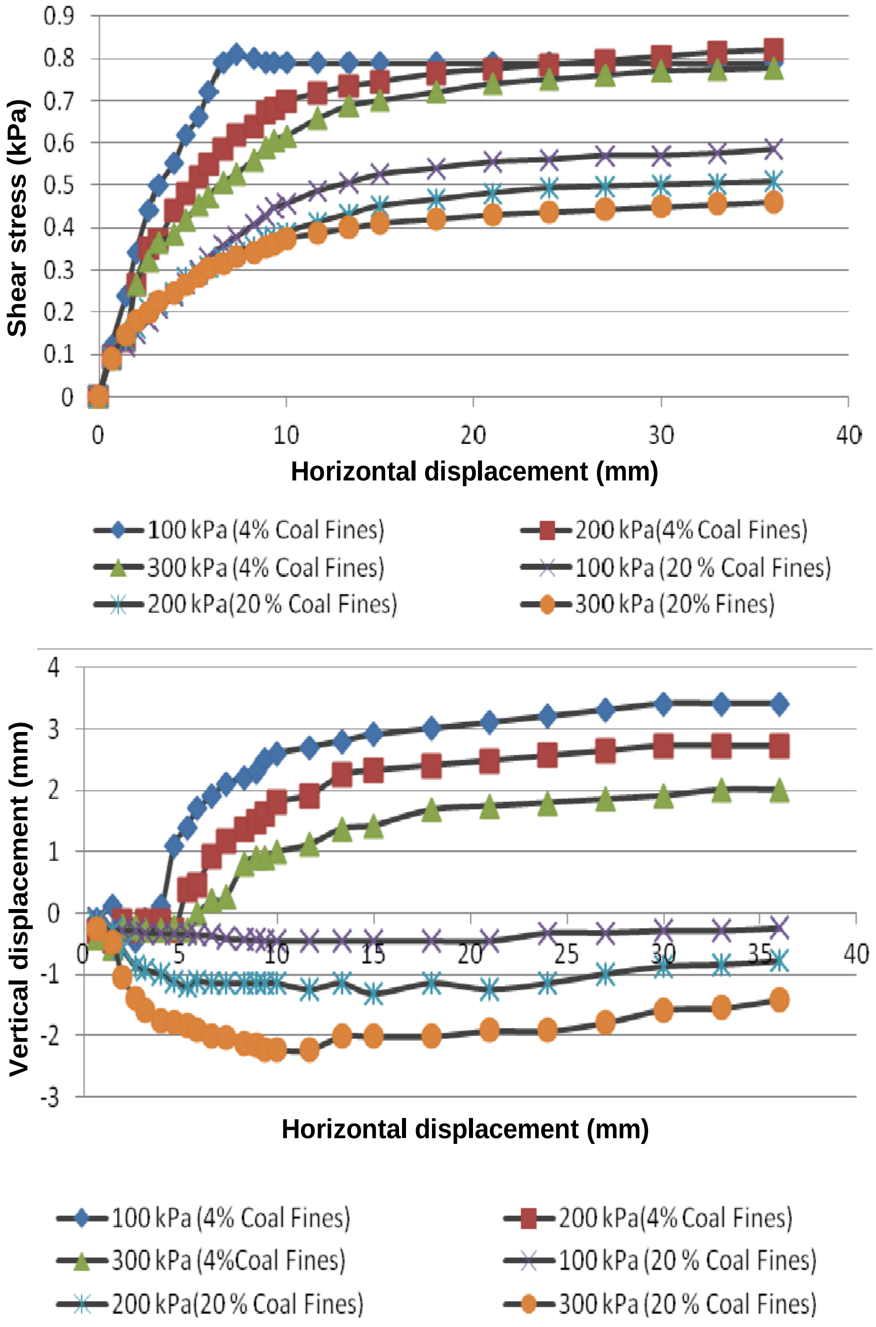

Figure 6. Stress and deformation curves of dry coal fouled gravel.

vertical compressive strain with a maximum value of (2/60) at 20% fouling, thus direct shear interlocking stability was not significantly impaired when the particles are dry.

Effect of coal fines at OMC on gravel

The effect of mixture of coal fines and gravel that were compacted at omc on stress strain behaviour and friction angles was also investigated. The stress strain behaviour and stress ratio mobilized by the fouled gravel material due to applied normal stress of 100 to 300 kPa in direct shear was shown in Figure 8. For the degree of fouling investigated, no defined maximum peak stress ratio was indicated. At 4% coal fouling, the stress strain behaviour is general strain hardening elasto plastic response at high normal stress, however unlike the dry coal dust; there is no evidence of yielding at lower normal stress of 100 kPa. At 20% fouling the stress strain response is also a

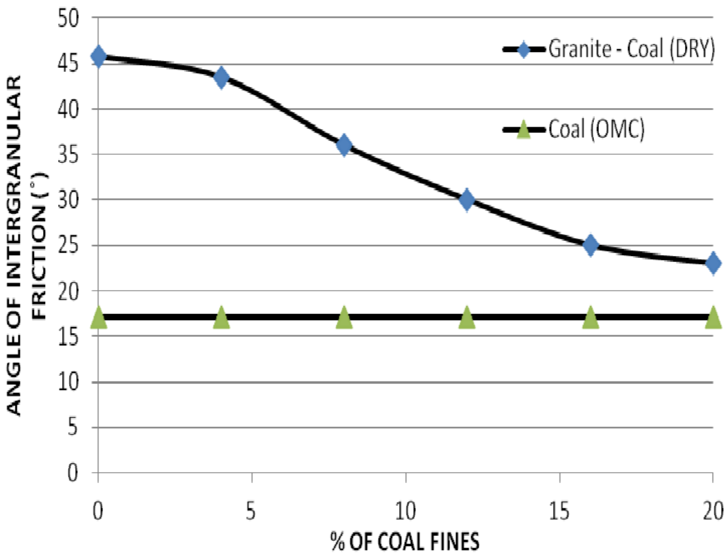

Figure 7. Friction angles of dry coal fouled gravel.

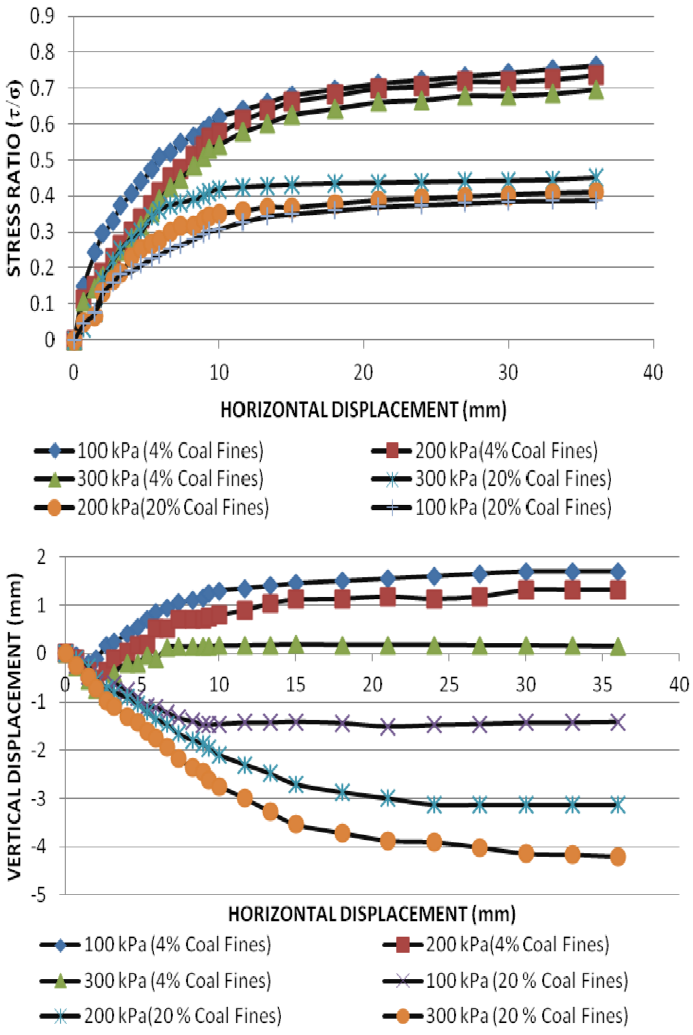

Figure 8. Stress and deformation curves of coal fouled gravel at OMC.

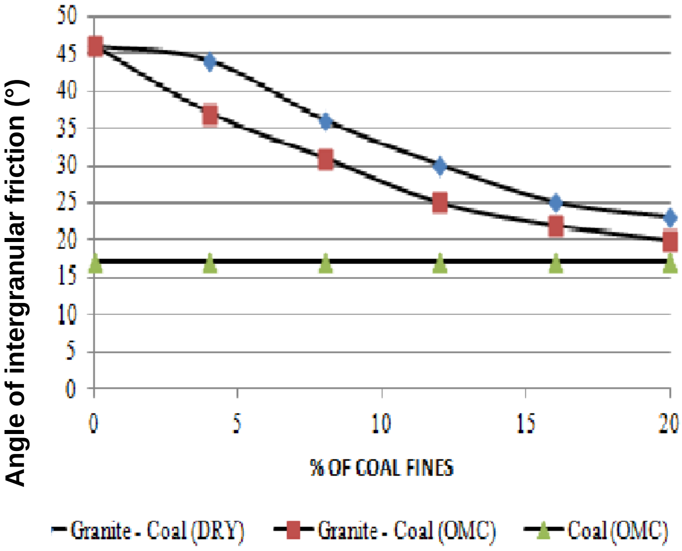

Figure 9. Angle of intergranular friction of coal fouled gravel at OMC.

straining hardening response. The stress ratio at 4 and 20% fouling tends to a constant value at large imposed horizontal displacement. Increased degree of fouling resulted in decreased mobilized stress ratio for the range of normal stress applied. The effect of increase in the amount of coal fines on the angle of friction of the granitic stones was shown in Figure 9. As the percentage of wet coal fines increases to 20%, the angle of friction of the granitic stones decreased towards the angle of friction of the coal fines at the optimum moisture content, implying that the granite–granite intergranular friction is significantly reduced and almost completely eliminated by the wet coal fines.

Dilatant direct shear induced vertical strain was indicated by 4% degree of fouling and significant vertical compressive strain with a maximum value of (4/60) at 20% fouling, which is twofold the value indicated by the dry mix. Thus the direct shear interlocking stability can be significantly impaired due to significantly reduced friction angle and increased direct shear induced compressive vertical strain.

Interface shear strength at OMC

The effect of different constitutions of gravel and coal fines that were compacted at OMC on the interface direct shear stress and deformation behaviour in shown in Figure 10. At low degree of fouling strain hardening response with well defined peak stress ratio as well as shear induced dilatant volume change was indicated for the normal stresses applied. At 20% degree of fouling, a weakly defined peak followed by strain hardening behaviour was indicated. This behaviour is similar to the stress strain response of 4% fouled aggregate in dry state.For samples compacted at OMC, the shear induced compression of 20% degree of fouling due to interface shear was lower than the value due to direct shear. The DSIFA of the clean aggregate was 57˚, the DSFA was 46˚. Figure 11 shows that for the range of following upto 20%, the mobilized DFISA was higher than the mobilized DSFA. A general trend of decrease in interface friction angle with increase in coal fines at OMC was exhibited. In particular, a reduction of DSIFA from 57˚ to 32˚ due to increased in degree of fouling by 20% was indicated.

At the maximum degree of fouling, the DSIFA was significantly greater than that of coal at OMC. Also the shear induced vertical compression was almost half the value indicated by coal fines at OMC. Thus although the interface friction angle and vertical compression were reduced by 20% coal fouling, the direct shear particle – interface interlocking stability was not significantly impaired at 20% of fouling.

Direct shear modulus at 0.03 horizontal strains

The shear modulus is based on stress in the direction of induced strain. The observed vertical strain in the shear box is in the orthogonal direction to the direction of direct shear displacement. Thus shear modulus cannot be determined. However at small displacement of 5 mm in a 150 mm length sample or 0.033 horizontal strain, when $\tan\varphi = \sin\varphi$, coincidence of stress and strain can be assumed (Wroth and Wood, 1982; Das and Yudhbir, 2005) and thus direct shear modulus, can be determined.

Table 2 and Figure 12 showed the direct shear modulus at 0.033% horizontal strain for the range of applied normal stress used. The slopes of the lines indicate that both the modulus of coal fines at OMC and

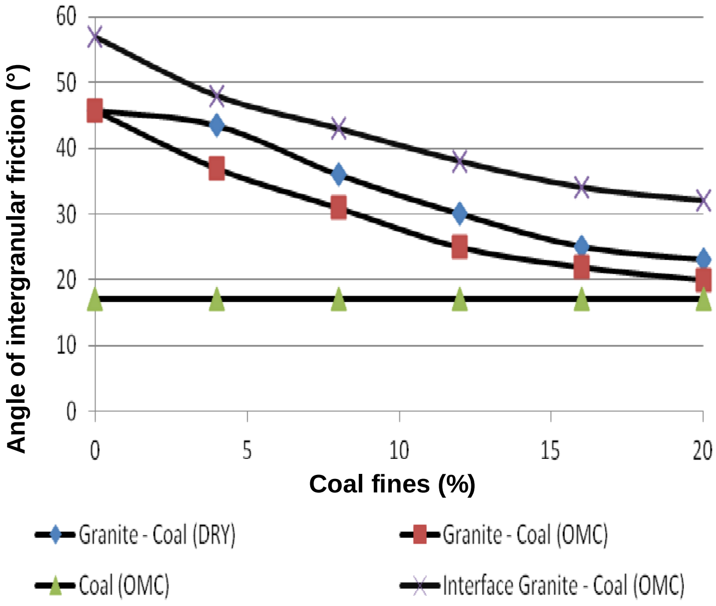

Figure 11. Intergranular and interface angles of friction of coal fouled gravel.

Table 2. Direct shear modulus of gravel and coal fines fouled gravel at strain of 0.033.

Coal dust (%)	Gravel + Coal (Dry)	Gravel + Coal (OMC)	Coal fines (OMC)
0	2788	2788	660
4	1980	1020	660
8	1678	998	660
12	1534	964	660
16	1489	941	660
20	1410	900	660

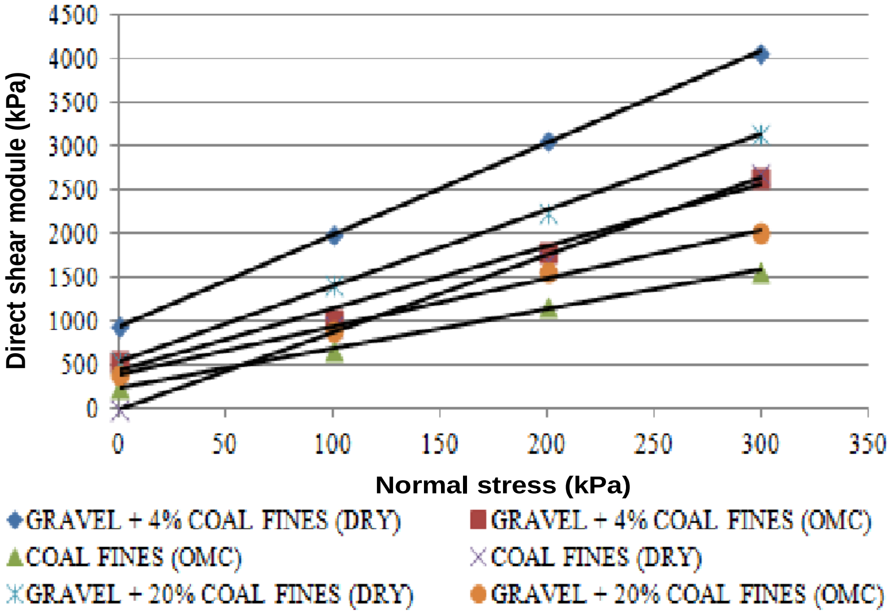

Figure 12. Direct shear modulus envelope of gravel and coal fines fouled gravel.

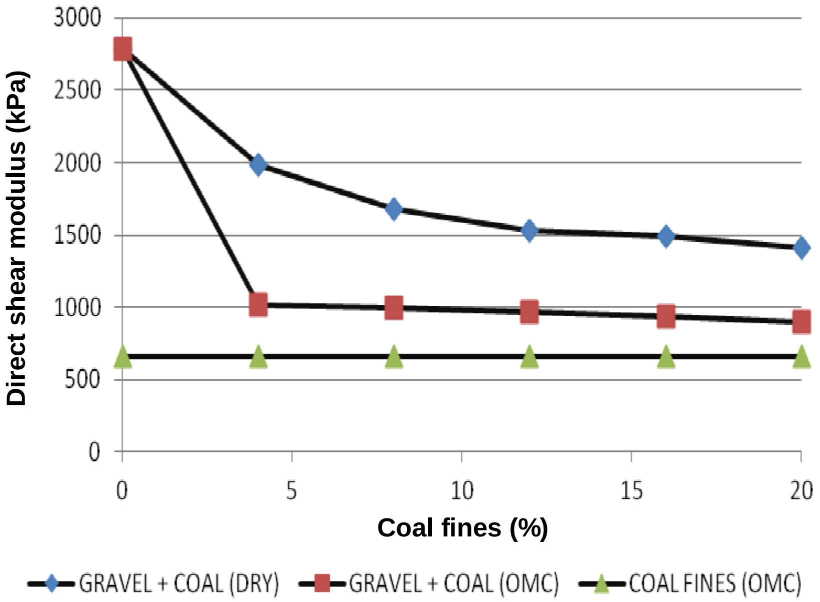

Figure 13. Direct shear modulus of gravel and coal fines fouled gravel.

20% fouled coal at OMC are sensitive to increase in applied normal stress.

The change in direct shear modulus with increasing degree of fouling was shown in Figure 13. An increase of 50% in modulus due to decrease in moisture content was indicated at 20% fouling. This is more than the 10% increase in friction angle due to decrease in moisture content. Thus the direct shear modulus (DSM) was a more sensitive indicator of degree of fouling than direct shear friction angle (DSFA).

Conclusions

Coal drives the bulk of sub Saharan economy. Rail transportation over large distances in semi arid climate distributes fine particles of coal on rail foundations. Road transportation of coal by trucks is also common. The effect of increasing amount of fine coal dust on the shear strength parameters of Nelspruit granitic gravel investigated in a medium size direct shear apparatus show that the stress strain behaviour of the fouled granitic material can be strain hardening or weak strain softening elasto plastic response depending on sample moisture content and magnitude of applied normal stresses.

The effect of fouling on direct shear particle - particle interlocking stability depended on the moisture content of the coal. In the dry state, the friction angle decreased while the vertical strain increased slightly with increase in fines, thus direct shear interlocking stability was not significantly decreased when the particles are dry. In the wet state, reduced stress ratio and increased shear induced vertical compressive strain resulted in significantly decreased direct shear particle–interface interlocking stability.

The direct shear modulus (DSM) of coal fouled aggregates was found to be more sensitive to wetting and changes in degree of fouling than direct shear friction angle (DSFA). It is thus a better indicator of wetting induced changes in strength and deformation of coal fouled aggregates.

The stability of bound and unbound granular materials is governed by friction angles, shear modulus and shear induced strain.

Aggregate interlocking and interfacial properties of aggregate – binder matrix are dependent on the wetting characteristics and contact angle at the interface. These properties depend of intergranular friction angle and shear induced strain and could be significantly altered by fine dust particles fouling.

The 9.52 to 12.52 mm diameter aggregates are smaller than the typical ballasts of 25 to 65 mm average particle diameter. Thus a degree of fouling greater than 20% would be required to reduce the interlocking of real ballast to the minimum. The overall implications of the result of this study is that there is a high likelihood of the stability of ballasts being significantly impaired in wet seasons due to increased degree of coal dust fouling and therefore more stringent screening should be recommended during the rainy seasons. The main aim of this research was to provide basic testing programs that can better inform the methodology of screening fouled aggregates and frequency of cleaning fouled aggregates. A 20% coal dust fouling can threaten the stability of ballasts especially in rainy seasons and air based cleaning should be implemented at frequency that can ensure that dust accumulation up to 20% fouling never occurs in service. Significant reduction in friction angle and direct shear modulus were found to be good indicators, however direct shear modulus was found to be a better moisture content sensor for coal fouled aggregates.

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