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BCURA PROJECT B62

on

Large scale semi-automated tester for rapid assessment of coal handling performance

Final report

Project start date: 01.09.02 end date: 31.08.05

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September 2005

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Executive summary

Coal blockages and handling difficulties commonly occur at the mine, during transportation and at the receiving power station. The problem was recognised in the 1960s, and the Durham Cone was devised to try to make empirical measurements of handlability by measuring the rate at which coal flows through a model hopper. This device has been in widespread use over the last 30 years, but mines have continued to have great difficulty in predicting the actual handling performance of a coal.

Under the previous BCURA Project B39, Edinburgh University produced a new interpretation of the reasons for poor coal handling at power stations, relating it to arrested flow, rather than slow flow, and arrested flow being caused by the development of cohesion in the coal. The Edinburgh team devised the new Edinburgh Cohesion Tester (ECT). It has been extensively verified in laboratory and field trials, and has been shown to discriminate very well between coals that are either just handlable or just not handlable. The BCURA Project B39 was highly successful, leading to many new understandings of the factors that affect handlability and devising methods for determining the handlability of a blend of different coals.

The ECT was devised as a simple inexpensive manually operated apparatus that could produce accurate repeatable predictions of handling performance. However, because it was to be manually operated, its size had to be restricted to dimensions that persons could operate. The chief disadvantage of such a restriction is that the full size range of coal particles (up to 50mm) could not be used in the tester, and each coal sample had to be sieved to remove larger particles before testing.

The aim of this project was therefore to overcome these difficulties by devising a larger apparatus that can deal with the full particle size range of CPP products.
The objectives were:
a) to design and construct a large industrial tester for -50mm coal blends;
b) to conduct laboratory validation tests and compare with the existing ECT;
c) to study effects of coal particle sizes on handlability; and
d) to conduct a field trial of the new large tester.

The main work carried out in this project was the design and construction of the large Automated Edinburgh Cohesion Tester (AECT). As well as basing the design on key features identified in the previous project as vital to effective measurements, several laboratory investigations were conducted to explore the effects of key design and operational factors on the tester's performance, to determine the optimal arrangement of the large semi-automated tester. These included tests on the effect of a flexible support for the sample mould, a twisting and sliding action in the mould and the aspect ratio of the sample. Significant searching and discussion took place to identify a suitable company to implement the design concept and fabricate the tester, which led to Delco Toolmakers Ltd being chosen. Their excellent and meticulous work in fabricating the tester has contributed to a successful outcome for this project, but unfortunately also led to some delay in the process.

The new AECT has a 250mm diameter sample mould which requires up to 600 kg vertical force to consolidate the coal sample. The tester is pneumatically driven and the test procedure is largely automated using a Programmable Logic Controller operated from

a display panel. One key achievement is that the prototype machine has been shown to produce highly repeatable results with a coefficient of variation of less than 5%.

After successful commissioning of the prototype tester, two field trials were conducted in late 2004 and early 2005, one at Kellingley Colliery with Eggborough Power Station and the other at Maltby Colliery with Drax Power Station. Visits were made by the Edinburgh project team to these collieries and power stations to introduce the new tester and the scientific principles behind it, and to discuss and finalise the field trials. A total of 156 cohesion tests were conducted in these two trials. Cohesion measurements were made of the coal samples taken at two half consignment load for each consignment at the collieries. The train discharging time and any handling difficulties were observed at the power stations for each consignment. The trial results showed a reasonable correlation between the train discharging time at the power station and the mean measured cohesion at the colliery. However no handling problem was encountered.

Further cohesion tests were conducted to compare the large AECT with the small original ECT and to establish the relationship between the two testers.

The successful outcome of this project has proved the major progress made in previous BCURA projects, which identified the true cause of handlability problems and their cure. These findings are now able to be exploited fully. The new tester is a larger automated tester, capable of rapid reliable coal handlability measurements. It uses a full size coal sample, eliminates tedious sieving, and gives confidence that the true coal being sold is indeed being tested.

The main conclusions of this project can therefore be summarised as follows:
1. The automated large cohesion tester (AECT) has been designed and constructed.
2. Validation tests on the AECT have been conducted and the results compared with the manual ECT.
3. Test repeatability of the new AECT on full sized coal samples has been shown to improve significantly.
4. The AECT has been designed with automated features. It is consequently very easy to operate and to measure cohesion quickly with highly repeatable results.
5. Industrial field trials were conducted successfully.

This project was sponsored by UK Coal. The provision of industrial advice and coal samples and the invaluable assistance in setting up the field trials involving two power stations are gratefully acknowledged. The field trials were also conducted in collaboration with UK Coal. The research has exploited a new technology to devise and validate a new semi-automated large tester that can be used for a rapid and accurate handling assessment of –50mm coal. Since handling problems still cause considerable loss of productivity worldwide, the outcome of this project has considerable economic value to both coal producers and coal users.

1. Introduction

A high proportion of the coal produced by a coal mine (a coal producer) is used for power generation, and one of the contractual requirements for a power station (a coal user) is that the coal must be handlable in the handling facilities at the receiving power station. When a final coal blend (also called Power Station Fuel, abbreviated as PSF) is prepared in a colliery, a quick decision is always needed to decide whether or not the prepared PSF is handlable at the power station which is intended to receive it. The correct decision is not easy without a quick and reliable measurement. A wrong decision can cause serious handling problems, such as arching at bunker outlets and can lead to additional costs for extra labour to break the arching (coal user's unwanted cost), and penalties for the coal producer.

This problem was recognised in the 1960s, and the Durham Cone was devised to make an empirical measure of handlability by measuring the rate at which coal flows through a model hopper. This device has been in widespread use over the last 30 years, but mines have continued to have significant difficulty in predicting the actual handlability performance of a coal. The Durham Cone results are not well related to the actual performance of coals at power stations.

Under the BCURA Project B39, Edinburgh University produced a new interpretation of the reasons for poor coal handling at power stations, relating it to the development of cohesion in the coal, leading to arrested flow, rather than slow flow. The Edinburgh team devised the new Edinburgh Cohesion Tester (ECT), which operates on a different principle. It has been extensively verified in laboratory and field trials, and has been shown to discriminate very well between coals that are either just handlable or just not handlable. The BCURA Project B39 was highly successful, leading to many new understandings of the factors that affect handlability and devising methods for determining the handlability of a blend of different coals.

The ECT was devised as a simple inexpensive manually-operated apparatus that could produce accurate repeatable predictions of handling performance. However, because it was to be manually operated, its size had to be restricted to dimensions that persons could operate. This meant that the coal sample dimensions had to be restricted to a cylinder of diameter around 120mm. The chief disadvantage of such a restriction is that the full size range of coal particles (up to 50mm) could not be used in the tester, and each coal sample had to be sieved to remove larger particles before testing. This feature delayed the testing process and led the users to question whether its predictions were valid for the full range of particles.

This project aims to design and construct a large semi-automated tester capable of rapid, reliable assessment of coal handlability for use at coal mines and power stations. The objectives are:

- To design and construct a larger industrial tester for −50mm coal blends;
- To conduct validation tests on the large tester, and compare with the existing smaller Cohesion Tester and observed handlability;
- To study the effects of coal particle sizes on handlability;
- To conduct a full field validation of the new semi-automated large tester.

2. Design of the large cohesion tester

2.1 General description

The primary requirement for the tester is to be large enough to measure unconfined strength of a coal of full size range (-50mm) at a consolidation stress relating bunker geometries. The experience shows that minimum mould diameter should be around 5 ~ 6 times the top size. Therefore it was decided that the internal diameter of the mould is taken to be 250mm. A maximum vertical stress of 100kPa is taken as reference stress for the design of the tester.

To get about 100kPa consolidation pressure, Edinburgh Cohesion Tester uses 120kg vertical force since it has a small internal diameter (D=127mm only). This is achievable by using a simple lever arm system and operated manually. But for the large coal tester, about 600kg vertical force is needed. This is very hard to be achieved with a reasonably sized and manual operated system.

Due to this reason, some important features of the Edinburgh Cohesion Tester need to be changed accordingly whilst keeping the same working principles. These features should include sample mould, support to the mould and a system to apply the force for sample consolidation. When these changes are made, we need to know how the unconfined compression strength may be affected. This was experimentally examined using Edinburgh Cohesion Tester and Edinburgh Powder Tester.

2.2 Key points in the specifications

- **Internal diameter of the mould**: 250mm
- **Height of the mould**: 380mm. Explanation: The sample aspect ratio is designed to be 1, so the final sample height should be 250mm. From the previous experiments, the maximum compression ratio is expected to be 30%. To achieve the final sample height, the initial sample height should be 360mm. Giving 20mm extra height will make the height of mould be 380mm.
- **Amount of coal sample**: 17kg. Explanation: The bulk density of coal varies greatly with particle size distribution and moisture contents. From the previous tests, it ranges from 700 – 900 kg/m^3. The volume of sample at initial stage is 0.02m^3, and roughly 17kg of coal sample is needed for each test. This is comparable to the Durham Cone Test.
- **Force capacity for compression**: 600kg. Explanation: the maximum compression stress is designed to be 100kPa. For the sample with internal diameter of 250mm, the maximum force required for compression is 500kg. Giving 20% overloading will bring the capacity of about 600 kg.
- **Force capacity for crushing**: 30kg. Explanation: The maximum crushing force set for Edinburgh cohesion tester is 10kg and can measure up to 9kPa unconfined compression strength. In most situations strength for a product coal is never over 5kPa under 100kPa compression stress. Using the strength of 5kPa as a limit, and for the internal diameter of 250mm mould, the maximum force required to crush a sample is 25kg. Giving 20% overloading will bring the capacity of about 30kg.

2.3 Technical requirements

The coal handling performance tests are conducted in two stages namely consolidation and loading to failure. From experience in the previous projects, the technical requirements are listed in the Table 2.1.

Table 2.1 Procedures and requirements

Procedures	Requirements
a. Specified amount of coal sample is filled into the mould in concentric and systematic manner	Easy access
b. The top surface of the sample in the mould is levelled off	Simple tool to level the surface without compression
c. Take measurement for the initial height of the sample	Accurate to 1mm
d. Apply a specified load to the sample in **force control manner;**	Specified load should be achieved quickly
e. Hold under the constant force for 1 minute	Applied force must be constant, and sample compressed from both ends
f. Take measurement for the final height of the sample	
g. Remove the mould and expose the sample	Sliding the mould without disturbing sample
h. Apply a load to the sample in **distance controlled manner** until the sample fails, and record the force and displacement of the sample	Variable loading speed to match the wide range of coals
i. Clean the tested sample and back initial stage	Quickly back to the initial set up position

2.4 Design evolution of the new tester

The sketches in Figures 2.1 to 2.8 show the sequence of operation of the proposed testing machine. The design evolution is going on.
Fig 2.1: the coal sample in the mould ready for testing.
Fig 2.2: the tooling plate has descended so that the compressing disc / load cell (red) is in contact with the test sample. We envisage that the tooling plate would stop automatically when a load is detected. The sample height could be displayed at this point if desired.
Fig 2.3: the sample under compression. The force and duration of this part of the cycle would be programmable. The sample height could be displayed after this part of the test.
Fig 2.4: the tooling plate has returned to the up position.
Fig 2.5: the test disc / load cell (blue) has traversed over the test sample.
Fig 2.6: the test disc is accelerated to just above the sample (this height is already known).
Fig 2.7: the smoothed plated tooling is withdrawn from the sample.
Fig 2.8: the unconfined sample is tested. After this the tooling plate would automatically return to its home position ready for another test.

2.5 Final version of the prototype large cohesion tester

After many extensive discussions with Delco, the design of the large coal tester was finalised, and the final version of schematic of the tester is shown in Figure 2.9.
The machine consists of:

- A guided load piston which is actuated by a 100mm bore braked cylinder;
- The position of the piston is monitored by a linear displacement transducer;
- The load piston slides within a 250mm diameter guided mould that is actuated by two smaller 40mm bore cylinders;
- Located at the top centre of the machine are 2 S-shaped beam load cells mounted in series, each is protected from overload by mechanical stops. Each load cell is

accurate to 0.025% of full load;
- The pressure in all cylinders is controlled electronically through the PLC (Programmable Logic Controller).

Each load cell has a total deflection of <0.4mm at full load and each can be overloaded by 150% without problem. If the cells are protected from being deflected by more than 0.5mm by pillars, each can measure their full load safely. This is shown in Figure 2.10.

Without the intervention of the cylinders the mould is free to move down with respect to the load piston. The mould however is not free to leave the load piston in the upward direction. In this way if the mould is pulled up the load piston will eventually tend to follow it. This is shown in Figure 2.11.

2.5.1 Operation procedures

The testing procedures are shown in Figure 2.12:

Fig.2.12a. The mould is manually filled via a chute with the sample. The mouth of the chute is approximately 1500mm above ground level and the chute is extended over and retracted from the mould manually. Access to the mould area would be via a hinged guard with a safety interlock.

Fig.2.12b The mould is pulled up by the smaller cylinders under low pressure. This in turn pulls up the load piston until the sample contacts the load cell. The position of the load piston and hence the height of the sample is noted.

Fig.2.12c The pressure in the load piston is increased in order to compress the sample. During this action the mould can be counter balanced by the small pistons so that it can float during the compression cycle.

Fig.2.12d After compression the pressure in the load piston cylinder is reduced until the force exerted on the load cells is small. The brake on the load piston cylinder is then applied and the mould is then pushed down by the small cylinders in order to leave the sample unconfined.

Fig.2.12e The brake in the load piston cylinder is then released and the low pressure in the load piston cylinder is slowly increased until the sample collapses.

A discharge chute would be fitted around the mould to catch the sample as it collapses. This would be flushed out into a suitable container at the end of each cycle. The mould and piston would also be flushed clean at the same time. All the pressures, loads and positions of the load piston are known at any point during the test sequence. Any of these can be displayed on the HMI (Human Machine Interface).

2.5.2 Advantages of the final version of the prototype

Compared with the initial version of the tester, this final prototype version has the following advantages:

- The width of the machine is greatly reduced therefore the tester becomes more compact;
- The new arrangement for the load cells for two different capacities makes it possible to shorten the testing time because there is no need to adjust the load cells any more.

3. Studies on some operational issues relating to the mould

An accurate and repeatable measurement of the unconfined strength of coal blend (a predictor of coal handling performance) relies on how coal samples are prepared. A badly prepared coal sample can reduce the repeatability of the test results, and will lead to a wrong prediction. Samples are normally prepared in a mould before a consolidation pressure is applied, and then exposed by removing the mould. The Manual Edinburgh cohesion tester has a split mould in three pieces and some springs underneath to provide a flexible support to the mould. The springs allow the mould to move down during consolidation. The sample can be exposed by removing the mould splits very easily. For the large coal tester, a whole cylindrical tube is needed because of its size. Due to this change it is necessary to quantify the effects of supporting, sliding, or twisting the mould on the shear stress between the mould and the sample and the unconfined strength.

3.1 Supporting the mould

The true stress applied to a coal sample during consolidation stage is reduced due to wall friction. This can be particularly bad if the wall surface of the mould is not smooth and the sample is tall. Reduction in consolidation pressure will result in a decrease in unconfined compression strength. In this study, Edinburgh Powder tester was used with Maltby Coal C8 at a consolidation stress of 62.5kPa. When all other factors are kept the same such as coal sample preparation, filling method, consolidation time and final sample height, the maximum force required to slide the mould and the failure force were measured at "with support" and "without support" conditions.

For the "with support" condition, the mould was supported from the bottom edge rigidly during the consolidation period. The mould was then pushed downwards using a jack system with a load cell, and maximum force required to slide the mould was measured. The height of the coal sample was measured before a failure test was performed.

For the "without support" test condition, the mould was supported initially during the filling and first 30% of full consolidation pressure. Then the support to the mould was withdrawn before further load was applied to achieve a full consolidation pressure. Thus the coal sample was compressed from both ends.

Table 3.1 Effect of supporting to the mould

Test	**With support**		**Without support**	
No	Shear Stress	Unconfined Strength	Shear Stress	Unconfined Strength
	kPa	kPa	kPa	kPa
1	0.56	3.35	0.76	3.95
2	0.57	3.35	0.95	4.10
3	0.59	3.65	0.85	4.40
4	0.59	3.45	0.84	4.00
5	0.60	3.50	0.93	4.35
Mean	0.58	3.46	0.86	4.16
STDEV	0.014	0.124	0.076	0.204
CoV	2.45%	3.60%	8.75%	4.91%
Effect of removing the mould support				
	Wall shear stress increased by:			**48%**
	Unconfined strength increased by:			**20%**

Five tests were performed at the consolidation pressure of 62.5kPa and the results are summarised in the Table 3.1 above. The results show that by withdrawing the support to the mould, the wall shear stress increased by 48% and unconfined compression strength of coal samples increased by more 20%.

3.2 Twisting

As indicated in the Table 3.1 above, large shear stresses at the mould internal surfaces can be generated when a coal is consolidated under a large pressure. This study aims to find out if a twisting action applied to the mould can reduce the shear stress. It was believed that twisting could break up the link between the coal particles and the mould internal surface, therefore the force required to slide the mould may be reduced. Furthermore twisting may also help with consolidation by redistribution of the coal particles and may help to make a good coal sample.

Tests were conducted with Edinburgh Powder Tester. When all other parameters were kept the same, tests were performed at “twisting” and “no twisting” conditions. Maltby C8 was used at the consolidation pressure of 62.5kPa. The mould was twisted four full rounds manually during the consolidation period. The mould was not supported and twisting action was carefully applied to the mould. Efforts were made to ensure that no vertical load was induced to the mould during the twisting action.

Five tests were conducted for each test condition and the results were shown in Table 3.2. It shows that twisting action did not reduce the shear stress between the sample and the mould. In quite opposite direction, it caused 60% increase in shear stress, and over 20% of increase in unconfined compression strength.

Table 3.2 Effect of twisting the mould

Test	**With twist**		**Without twist**	
No	Shear Stress	Unconfined Strength	Shear Stress	Unconfined Strength
	kPa	kPa	kPa	kPa
1	1.59	5.25	0.76	3.95
2	1.13	4.90	0.95	4.10
3	1.34	5.30	0.85	4.40
4	1.51	4.80	0.84	4.00
5	1.35	5.10	0.93	4.35
Mean	1.38	5.07	0.86	4.16
STDEV	0.176	0.217	0.076	0.204
CoV	12.76%	4.28%	8.75%	4.91%
Effect of twisting the mould				
	Wall shear stress increased by:			**60%**
	Unconfined strength increased by:			**21%**

During the tests, it was observed that only relative motion is between sample bottom surface and the bottom platen. The whole sample rotated with the twisting action. There was no relative motion between the sample top surface and the plunger (through which the load was applied), and no relative motion between the sample and mould internal surface. From further analytical calculation, it can be shown that the sliding between the sample and the mould internal surfaces can only occur if the wall frictional angle is less that 15^{o} (very smooth wall) and the sample aspect ratio (H/D) of less than 0.65 (very short coal sample). Thus no twisting action will be introduced in the new tester.

3.3 Sliding

If the mould is a whole cylindrical tube, it must be forced to slide so that the coal sample can be exposed. To slide the mould down will generate some shear stress on the surfaces of the sample and will induce a vertical stress of about 5% - 15% as it was suggested in the previous tests. This study examined how the unconfined compression strength is affected by this additional vertical stress induced from the shear stress at the wall.

Edinburgh Cohesion Tester was used because it has a split mould and can perform "sliding" as well as "no sliding" tests. All other parameters were kept the same in this series of experiment. The mould was initially supported with rigid metal block during the stage of filling and first 20kPa of consolidation pressure. The support was withdrawn before another 42kPa consolidation pressure was applied. One minute consolidation time was used throughout the test series. For "no sliding" tests, the split mould was removed to expose the sample and then failure test was performed, as in the existing Edinburgh Cohesion Tester. For the "Sliding" tests, the jack system was used to push the mould down for about +20mm and maximum force required to slide the mould was measured. We then removed the mould split before performing a failure test, and maximum failure force was measured.

The results are shown in the Table 3.3 below. At a full consolidation pressure of 62 kPa, a vertical stress of 9.11 kPa was induced in the coal sample which accounts for about 14.5% of the full load. However very little increase in the unconfined strength is observed.

Table 3.3 Effect of sliding the mould

Test	**With no sliding**	**with sliding**	
No	Unconfined Strength	Shear Stress	Unconfined Strength
	KPa	kPa	kPa
1	3.54	1.37	3.61
2	3.55	1.37	3.84
3	3.62	1.33	3.67
4	3.48	1.44	3.62
5	3.61	1.37	3.74
Mean	3.56	1.38	3.70
STDEV	0.054	0.042	0.095
CoV	1.52%	3.04%	2.58%
Vertical stress induced kPa:			**9.1**
Relative vertical stress increase:			**15%**
Relative unconfined stress increase:			**4%**

3.4 Remarks

The large coal tester must use a whole tube, instead of split mould, to prepare a coal sample, and sliding the mould somehow is necessary in order to expose the sample for failure tests. Theoretically twisting the mould before the mould is forced to slide can reduce the shear stress if the wall friction is small and the sample is short. But the results here show opposite effect: shear stress increased dramatically and so did the unconfined strength. Therefore twisting action is left out of the design for the tester.

By introducing a sliding action to withdraw the mould, a significant amount of additional vertical shear stress is induced in the coal sample, but because it is only a fraction of the consolidation stress level generating the expanded yield surface, it has minimum effect on the unconfined compression strength. Therefore this simpler method of mould removal will in cooperated in the design procedure.

The support to the mould must be withdrawn during consolidation in order to ensure that the frictional effect of mould wall surfaces could be minimized. This is considered to be very important, therefore will be implemented in the design procedure.

4. Wall friction tests

A mould for holding the coal sample is an important part of the tester because it will affect the repeatability and reliability of the test results. There are two key questions to be addressed:

(a) How should the mould be operated during the testing and how would the mould operations affect the test results. This issue was studied very careful and the results were presented in the first progress report.

(b) What type of internal surface should the mould have? This is important because wall friction reduces the actual stress applied to the coal sample during consolidation, and the consolidation stress has an ultimate effect on the unconfined strength of the coal. This is particular true when the coal of full sizes is tested because wall friction is closely associated with contacts between wall surfaces and coal particles of different sizes. It was also revealed that the surface that looks or feels smooth may not necessarily produce a low friction because it depends upon both the surface type and the particle properties. The low wall frictional coefficient is what we are looking for.

4.1 Experiment

Two types of wall material samples were provided by Delco Toolmakers Ltd namely untreated mild steel and nedox plated mild steel. Both were tested with Maltby C8 coal and the results were compared with those of Mylar that was used in Edinburgh Cohesion Tester. Both metal plates have the same dimensions of 205 x 75 x 8 mm (Length x Width x Thickness). The C8 was chosen because it was tested many times in previous projects and it has a well defined the Stress-Moisture-Cohesion function, and a typical SMC curve for C8 is shown in Figure 4.1.

The Jenike shear cell (Figure 4.2, IChE, 1989) is a standard tester to determine wall frictional properties and was used in the test series. The shear ring has a diameter of 65mm. A normal force V is applied to the coal sample in the ring through the bracket on the cover to achieve a maximum normal stress of 25kPa. According to the standard testing procedure this load is reduced in 5 steps, with each shearing approximately 1mm distance. The shearing force S between the coal sample and the wall material on the shear plane is measured using a load cell at the known normal stress. The displacement is also measured using a LVDT transducer. Both measurements were taken using a data logger linked to a PC.

In each test, the shear ring was carefully positioned on the top of the plate of a wall surface, and then carefully filled with the coal sample. After levelling the surface of the coal, a shear lid was placed on the top and a normal load was applied before the shearing was initiated. A constant shearing speed of 1.5mm per minute was used throughout the tests. The test results show how the shear stress between with the coal and the wall surface varied with shear displacement at different normal stress.

Maltby C8 was tested at two moisture levels: at about 3.0% (w/b) representing the dry coal and at about 10% (w/b) representing the coal at peak stress in SMC function curve. Dry coal samples were tested first on three types of the wall surfaces: untreated mild steel, nedox plated mild steel and Mylar sheet. The moisture of coal particles were then increased to the wet state (~10% w/b) by spreading the precise amount of water into the sample and mixed thoroughly by hand. The sample was then sealed in a plastic bag and kept overnight before conducting the wall friction tests. This process will ensure the uniformity of the water added in the sample. Each test was repeated three times which would verify the repeatability of the results.

4.2 Results and discussion

The results for the dry coal on three wall materials are shown in Figures 4.3 to 4.9. The initial data obtained at the first place is that represented by the curve of the shear stress and displacement (Fig.4.3 showing a typical curve of shear stress vs. displacement). The shear stresses at the first 1mm displacement were seen as very scattered, and according the standard procedure for the tester, these reading should be ignored. Along with further shearing, the scatter reduced significantly. The results for the three tests repeated quite well especially in the low normal stress levels.

To find out the wall frictional coefficient, the curves for shear stress vs. normal stress have to be established. These curves are shown in Figures 4.4 to 4.6 for the dry coals, and Figures 4.7 to 4.9 for wet coals. The average wall friction angles calculated from the results are summarised in Table 4.1.

Table 4.1 Friction angles between different wall materials and the coal

Wall material	Dry Coal (deg)	Wet Coal (deg)
Untreated mild steel	19.0	18.8
Nedox plated mild steel	14.4	11.8
Mylar	18.2	13.6

It is observed that the frictional coefficient between wet coal and all three wall plates are lower than that between the dry coal and the plates. However the magnitude of the reduction depends upon the type of wall material. The friction angle reduces more, by the introduction of water, for the nedox plated mild steel and Mylar than for the untreated mild steel wall.

For the coal samples at both moisture levels, Nedox treated wall has the lowest wall friction angle. This is an interesting finding as the Mylar surface looks and feels by hand a much smoother surface than that of Nedox treated plate. Based on the test results, Nedox treated mild steel is chosen for the sample mould of the prototype tester.

5. Manufacturing the cohesion tester and initial trial

The aim of the project is to produce a larger version of cohesion tester based on the same principle of Edinburgh Cohesion Tester to deal with coals with full particle sizes (up to 50mm). To do this, the size of the mould to produce coal sample must be large enough which ultimately leads to a very large normal force needed to achieve required consolidation stresses. Automated system is the best option to keep the tester relatively compact and to reduce the need for the operator to handle weights.

The test consists of two stages: consolidation and loading to failure. To make a good repeatable test, coals are required to be compressed at a specified consolidation stress for certain amount of time. Using compressed air with suitable control can apply a required force on coal sample very quickly and therefore is ideal for this application. However using the same system in the second part of test – loading sample to failure can cause some problems.

In the second stage of the test, the coal sample is crushed to failure by a constantly moving plunger so that the whole behaviour of loading can be captured. But the above system has led to a very sudden and unsmooth crushing action. This was later modified by using an electric motor installed on the top of the machine to ensure that a constant loading speed can be achieved during the process of loading to failure.

5.1 Automated Edinburgh Cohesion Tester

Automated Edinburgh cohesion tester is shown in Figure 5.1. The machine is wholly sealed with metal and polycarbonate sheets for safety purposes. A filling chute is attached to the side of machine (Figure 5.2) and can be tilted for filling around a pivot on the top edge.

A programmable control unit is fixed in the front of machine (Figure 5.3). All actions are programmed in the control including the main settings such as consolidation stress, holding time and so on. Using the touch screen feature of the unit, all settings can be easily changed.

When the mould is filled and settings accepted, sample is consolidated under required stress at required time, and then sample is exposed and ready for crushing (Figure 5.4). A motor is fixed on the top of the machine used for driving the plunger in a constant speed to crush the coal sample to failure. This works very well for our specification. After the sample is failed, the full results including sample initial filling height, compressed height, compression stress and unconfined compression will be displayed on the screen.

5.2. Initial trial tests

During the visit to Delco, some initial trial tests were conducted on Edinburgh coal TC8 aiming to test if the machine works well in principle. The coal was taken from Edinburgh right down to Plymouth and tested at "as received moisture" for repeatability. The coal was filled into the chute first, and then the chute was tilted so that the coal particles were sliding into the mould through the outlet of the chute. For this test a filling hopper was not used as it was not ready yet. Using the filling hopper should guarantee the uniform distribution of the coal particle across the whole section of the mould.

The coal in the mould was consolidated at a stress of 80kPa and held for one minute. Crushing test was then performed and unconfined strength of the coal was measured. Five tests were performed on the same conditions for the same coal sample and the results are shown in Figure 5.5.

It was found that the machine was very easy to use though the chute needed to be filled manually first. The coefficient of variation over five tests is less than 5% proving that the main part of the machine works very well.

To check how well the machine responses to the change at either low or high stress level, another set of tests were done at 30kPa, 50kPa and100kPa stress levels at the same moisture level. Each test was repeated twice and the average of two tests was used in the report. The results are shown in Figure 5.6. The unconfined strength increases, as is expected, with the increase of the consolidation stress.

6. Industrial trails on Automated Edinburgh Cohesion Tester (AECT)

The timing and conduct of the industrial trials naturally depend on the operational constraints of UK Coal and the associated power stations. As a window of opportunity has arisen for a field trial to be conducted before December 2004, it was decided that the laboratory testing programme be delayed to exploit this opportunity.

The first industrial trial on the Automated Edinburgh Cohesion Tester (AECT) was conducted at Kellingley Colliery and Eggborough Power Station, from 9th to 19th of November 2004. The second trial was conducted at Maltby Colliery and Drax Power Station from 17th Jan to 1st Feb 2005. Two separate visits were made by the Edinburgh project team to these collieries and power stations before the start of the trial in order to introduce the new tester and the scientific principles behind it, and to discuss and finalise the field trial.

The previous trials showed that cohesion varies significantly for each train consignment, and handlability of the coal in each consignment can be monitored using cohesion measurements taken on four quarter loads of each consignment. However this practice has not been possible this time because the mould with an increased diameter needed much more coal for each sample and the current CPP sampling practice cannot easily meet the requirement. It was finally decided to test two samples collected for each half of the consignment.

All tests were performed using a consolidation stress of 100 kPa for one minute. For each sample two tests were performed first, and a third one was done if the difference between the first two measured values is larger than 10%. The other relevant measurements such as moisture content and ash content were also recorded in the data sheet.

The trial was arranged in such a way that cohesion measurements were taken at the colliery and handling behaviour of each trainload was observed at the power station. Specially designed data sheet for colliery and pro-forma report for power stations were prepared and all information was properly recorded.

6.1. Field trial at Kellingley Colliery and Eggborough Power Station

Prior to the trial, some handling problems have been reported at Eggborough Power Station at the location when the coal passed through the Moxey conveying system. A brief description is given below.

6.1.1 Moxey – a multifunctional belt conveyor

Moxey is a multi-functional belt conveyor whose name originates from the name of a company that made the machine. In the power station, Moxey takes the coal from the receiving bunker to stockpile when the received coal is more than that needed by the plant. It also picks up the coal from stockpile and takes it back to the system. The machine can change position very easily to meet the needs and therefore is very versatile.

When Moxey takes coal from the stockpile back to the system, the coal is first taken up by a belt conveyor, and then dropped into a bigger hopper (Figure 6.1). Immediately below the hopper, there is a small section of the inclined hopper (Figure 6.2) where the blockage problems were observed. It was said that the purpose of using the inclined hopper is to reduce the direct impact of the falling coal particles on the belt conveyor below which takes the coal back to the system. Structurally there is no connection between these two hoppers. The big hopper is supported by the Moxey machine's main frame, and the inclined hopper is supported from the ground. The top opening diameter of the inclined hopper is bigger than the outlet of the bigger hopper, therefore there is a big gap (Figure 6.3) which is used as an access to break the coal blockage using a metal stick.

The exact geometries of the inclined hopper are impossible to measure on site. From observation and pictures (Figures 6.2 and 6.4), the sketch of the hopper is shown in Figure 6.5. It shows that the downside of inclined hopper has an angle of less than 20º (Figure 6.5) to the horizontal. This may not be steep enough for reliable gravity flow and may be the primary cause for blockage problems for sticky coals.

6.1.2 Key results for Kellingley-Eggborough trial

During this trial, a total of 9 trainloads were arranged from Kellingley Colliery to Eggborough Power Station. For the first two days, only consignment samples were tested but for the rest of the trial period, 2 samples were collected for the first and second half time during coal preparation and unconfined compression strength of these samples were measured using AECT in Kellingley.

At Eggborough Power Station, observations on both receiving bunker and the Moxey machine were made during the discharging of each consignment. Total discharging time together with cohesion measurements and other information were summarised in Table 1.

During the whole trial, no arching or other handling problem was observed in any part of the system in the power station. Therefore the following discussion will focus on the variability of the coal handlability, and relationship between measured cohesion in colliery and observed discharging time in the power station.

6.1.3 Variability of the coal handlability

Table 1 shows all the cohesion measurements taken on all the samples. The variation of the cohesion values between the repeat tests of each sample was small for the majority of the samples. This indicates good repeatability of the tester.

All measured cohesion values were plotted in Figure 6.6. It shows in general that the cohesion in the coal varied significantly over the period of trial. The variation of cohesion for each consignment is demonstrated in Figure 6.7 in which the mean cohesion for each sample is plotted. Mean cohesion for the first half sample is different from that for the second half sample (up to more than 90% for 18th of November train). Overall mean cohesion value for each trainload is taken as an average of cohesion values for the two samples and is shown in Figure 6.8. It varies from 3kPa for trainload of 10th November to over 7kPa for that of 18th November.

6.1.4 Discharging time

Discharging time vs overall mean cohesion for each trainload is shown in Figure 6.9. There is a trend of increasing discharging time as the measured cohesion increased, which is what would be expected. The best fit correlation between the cohesion σ_u and the train discharge time T_d (min), is given by $T_d = 2\sigma_u + 35$.

Table 1 Cohesion measurements and observation during discharging

Date	Sample	Test No	Measured cohesion	Sample height	Moisture content	Ash	Mean cohesion	STDEV	CoV	Overall Mean	Total discharge time
			kPa	mm	%	%	kPa			kPa	min
09/11/2004	Consigment	1	5.12	252.6			5.11	0.12	2%	5.11	40
		2	5.22	251.7							
		3	4.98	245.5	12.8	14.6					
10/11/2004	Consigment	1	3.1	269.6			3.09	0.01	0%	3.09	40
		2	3.08	258.2	12.1	15.4					
11/11/2004	1st half	1	5.26	244.8			5.66	0.35	6%	4.97	40
		2	5.91	264.5							
		3	5.82	266.7							
	2nd half	1	4.16	257.3			4.28	0.17	4%		
		2	4.4	262.4							
12/11/2004	1st half	1	3.08	273.6			3.51	0.37	11%	3.59	45
		2	3.67	264.2							
		3	3.77	254							
	2nd half	1	3.68				3.67	0.05	1%		
		2	3.62								
		3	3.71								
15/11/2004	1st half	1	4.18	269.8			4.24	0.08	2%	5.19	50
		2	4.29	267.4	11.4						
	2nd half	1	6.29	256.3			6.14	0.23	4%		
		2	5.88	257.6							
		3	6.26	253.4	11	16.3					
16/11/2004	1st half	1	4.69	269.3			4.79	0.10	2%	4.85	45
		2	4.8	273.7							
		3	4.89	268.2	12.1						
	2nd half	1	5	269.2			4.91	0.13	3%		
		2	4.82	272.1	12	14.3					
17/11/2004	1st half	1	4.47	274.6			4.65	0.19	4%	5.14	41
		2	4.65	276.4							
		3	4.84	269.7							
	2nd half	1	4.43	265.7			5.63	1.79	32%		
		2	7.69	263.3							
		3	4.76	280.1	11.2	16					
18/11/2004	1st half	1	7.62	266.4			9.43	1.93	20%	7.22	49
		2	9.2	274.1							
		3	11.46	265.4	11.4	13.3					
	2nd half	1	5.06	255.7			5.02	0.06	1%		
		2	4.97	253.1	11.6	13.8					
19/11/2004	1st half	1	5.03	248.2			4.95	0.11	2%	4.15	40
		2	4.87	248.5	10.9						
	2nd half	1	4.54	262.3			3.35	1.05	31%		
		2	2.57	264.2							
		3	2.95	263.5	11.2	14.7					

6.2. Field trial at Maltby Colliery and Drax Power Station

Industrial trial on Edinburgh Cohesion Tester (ECT) was conducted five years ago at Maltby colliery (with West Burton Power Station at the time). Because it was a very successful trial, Maltby Colliery decided after the trial to replace Durham Cone with ECT and have been using the ECT for daily quality control.

During this trial, a total of 27 trainloads were delivered and a total of 53 samples were tested. The only anomaly was that a second sample collected for the second half of Batch No. 7924 on 25 of January was not tested because of the machine breakdown.

One problem was that the consolidation stress of 100kPa could not always be maintained accurately during consolidation. The maximum consolidation stress recorded for each test is shown in Figure 6.10, which shows a maximum value of up to 110kPa. This did not happen for the first trial at Kellingley-Eggborough. Some further work is needed to improve the control unit of the machine to achieve a more stable consolidation stress level.

6.2.1 Variability of the coal handlability

Cohesion value for each test and the mean cohesion value for each half consignment are all shown in Figure 6.11 for all batches tested. For each batch of consignment, measured cohesions are different between the first and second half samples. For some batches, it varies only a little e.g. for batch No 7936 the mean cohesion value for the first half sample was 3.36kPa and for the second half sample was 3.20kPa. For some batches, it varied more e.g. for batch No 7911: 5.97kPa for the first half and 3.02kPa for the second half.

The mean measured cohesion for each consignment is plotted in Figure 6.12. This shows the variability of handlability for Maltby coal. The mean cohesion varied significantly between consignments, ranging from a low value of 3 kPa to a high value of over 7 kPa. This again reflects the natural variability in coal and the inherent complexity with coal handlability.

6.2.2 Comparison of cohesion measured by ECT and AECT

In this Maltby trial, each sample collected was also tested using the manual Edinburgh Cohesion Tester (ECT) under the same condition. A comparison can thus be made between the ECT and the AECT measurements. The results are shown in Figure 6.13. The cohesion measured using the ECT is significantly smaller than that using the AECT. This is as expected because:

(a) the sample aspect ratio (sample height to diameter ratio) for the ECT is ~1.6 but for the AECT, it is only ~1. A shorter sample increases the influence of end constraint and will produce a bigger cohesion value;
(b) the mould diameter is bigger for the AECT which makes the packing of coal particles easier, particularly when particle sizes are large;
(c) AECT has automation to deal with the testing procedure including mould removal whereas for the ECT, the mould has to be removed manually which may disturb the delicate sample and weaken it.

6.2.3 Discharging time

The recorded discharging time is plotted against the mean measured cohesion using the AECT in Figure 6.14 for each trainload. Discharging time is again seen to increase with increasing cohesion. There is a reasonable correlation between the cohesion σ_u and the train discharge time T_d (min), given by $T_d = 2\sigma_u + 26$.

During the trial, no handling problem was observed at Drax Power Station, as expected. The bunker used in Drax was relatively new with steep walls and smooth internal surfaces. This is in contrast with the much poorer condition of the bunker at West Burton Power Station at the time when the first original trial on ECT was conducted several years ago. At that last Maltby-West Burton trial, the marginal cohesion value for West Burton was about 2.8kPa using the ECT, as demonstrated by the fact that the trainloads which had cohesion values larger than 2.8kPa were all reported to cause bunker blockage problems at the receiving end.

In the current trial, the mean cohesion values measured by ECT are all smaller than 2.8kPa. Coals with such low cohesion values are thus not expected to have any handling problem at Drax.

7. Validation tests

Intensive laboratory experiments have been conducted to valid the automated cohesion tester. Edinburgh coal N with full size ranges (up to 50mm) was selected through out the test series because there is a large sum in stock. An electric cement mixer was used to get the uniformity of the sample before carry out any test. The total moisture contents of the coal sample were measured using one of the soil laboratory ovens.

7.1 Repeatability and comparison with the ECT

Eight independent tests were done using both ECT and AECT at both 42kPa and 62kPa consolidation pressures at 1 minute. The results are shown in Figures 7.1 and 7.2. As for the results at 42kPa, the unconfined compression strength of the coal from both testers is found to be very repeatable, but the standard deviation for the automated tester is much smaller than that for the manual tester. This shows that the repeatability of the large tester for the full size range coals is improved. When the consolidation stress was increased to 62kPa, the unconfined compression strength is found to be increased slightly with the number of tests. It is due to that repeatedly using the same sample may break the coal particles into fines which would make the sample stronger hence the cohesion increased.

It was noticed that the automated cohesion tester measures higher unconfined compression strength than the manual cohesion tester for the exact same samples and it is expected. This is because the manual tester has a significant friction on the sample mould which reduces the vertical stress to compress the sample. But for the automated tester, the internal surface of the mould has been specially treated with permanent lubrication to reduce the friction. In addition, the sample aspect ratio of H/D is aimed to be 1 (1.6 for the manual tester).

7.2 Effects of consolidation pressure

The same source coal was used with the both testers to investigate the effect of consolidation pressure. The results are shown in Figure 7.3. The unconfined compression strength is found to be increased almost linearly with the consolidation stress with in the tested ranges. This is the same trends as those obtained previously for the other coals using manual cohesion tester. This indicates that bigger bunker or the same bunker but filling more coals may experience handling problems.

7.3 Effects of sample heights

During the industrial trials, one of the questions to be asked is how much sample should be filled in the mould and how it would affect the final measurements. To clarify the question, different amount of coals (the same coal N) was tested at 50 and 100kPa consolidation stresses. The results are given in Figure 7.4.

When the sample height is ranged from 245mm to 320mm, the unconfined compression strength is found not changed. This is because the AECY has a build-in function for sample height correction. The program in the machine has automatically converted the measured value into cohesion using sample aspect ratio of 1.

8. Conclusions

This project has led to the following major conclusions:

6. The automated large cohesion tester (AECT) has been designed and constructed.
7. Validation tests on the AECT have been conducted and the results compared with the manual ECT.
8. Test repeatability of the new AECT on full sized coal samples has been shown to improve significantly.
9. The AECT has been designed with automated features. It is consequently very easy to operate and to measure cohesion quickly with highly repeatable results.
10. Industrial field trials were conducted successfully.

In addition, investigations within this project have also shown that:

1. The shear stress between the mould wall and the sample during consolidation is significantly affected by whether or not the mould is supported, which in turn significantly affects the measured unconfined compression strength. This further demonstrated the significant effect of wall friction. In order to eliminate this effect, the mould should be allowed to move freely at both ends during the consolidation;
2. Twisting actions effectively increased the consolidation of the coal, but did not shear at the interface between the coal sample and the mould. It was therefore not used in the tester;
3. Sliding the mould down could induce a significant vertical stress (accounting for ~15% of full consolidation pressure in this study), but since this is applied when the sample is already over-consolidated, it does not affect the unconfined compression strength significantly.
4. The Mylar wall looks and feels smoothest by hand, but it did not produce the lowest wall friction coefficient.
5. The sample mould is a key part of the tester, and the friction coefficient between its internal surface and the coal particles should be as low as is possible. Nedox treated mild steel wall has been shown to give the lowest wall friction angle for the coal samples at two moisture levels tested, and therefore was chosen for the mould;
6. A significant variation in coal handlability often occurs even within a single consignment.
7. The time taken to unload a train is sensitive to blockages occurring in the most cohesive part of the consignment: this part must therefore be identified, and a mean value for the whole consignment is not very meaningful unless the consignment is rather homogeneous.
8. Testing of coal handlability must therefore be made of several parts of each trainload.
9. Where the coal handlability does not vary greatly within the consignment, the measured cohesion gives a good indication of the time it is likely to take to unload the train;

10. There is a reasonable statistical correlation between the cohesion σ_u and the train discharge time T_d;
11. The empirical relationships between measured cohesion and train unloading times were found to be T_d (min) = $2\sigma_u + 35$ for the first trial in Kellingley/Eggborough, and T_d (min) = $2\sigma_u + 26$ for the second trial at Maltby/Drax.
12. These show the strong influence of cohesion on coal handlability in real practical handling situations.

9. Proposed work for a subsequent program

This project has produced a novel industrial tester that has been validated in two field trials and shown to produce highly repeatable and reliable measurements of the handling characteristics of a wide range of coals. The high level of automation introduced in the testing procedure has made the tester very easy to operate. It requires only a limited amount of further development to become an on-line monitoring device for coal handlability. The project team at the University of Edinburgh is very keen to proceed to develop this on-line handlability monitor in collaboration with an industrial partner to exploit all the knowledge that has been gained over the last decade in a series of projects funded by BCURA. The team believes that this would then be the world leading system for monitoring coal handlability, with great advantages of being on-line, rapid and closely related to the true performance of coals in materials handling systems. It would represent a major advance in handlability measurement for the coal industry throughout the world.

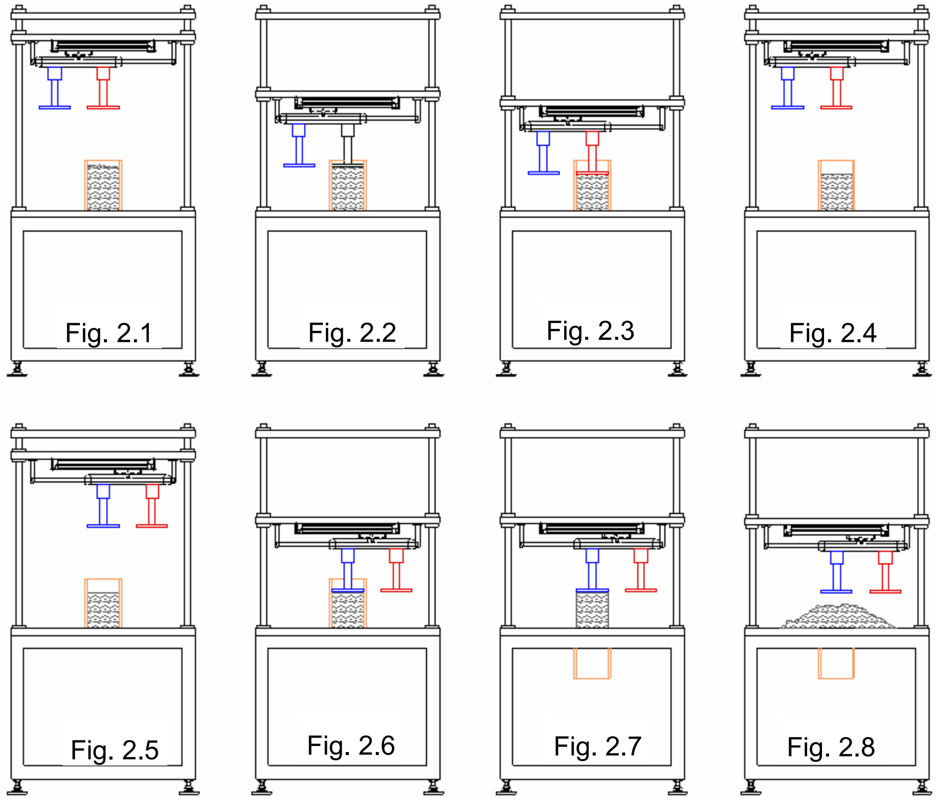
10 Publications arising from the project

1. Zhong, Z., Ooi, J.Y. and Rotter, J.M. (2004) *"Predicting the handleability of a coal blend and optimising the blending process"*, 5th European Conference: Coal research and its application, 6-8th Sep. 2004
2. Zhong, Z., Ooi, J.Y. and Rotter, J.M. (2004) *"Practical assessment of coal handleability - overview"*, 5th European Conference: Coal research and its application, 6-8th Sep. 2004
3. Zhong, Z., Ooi, J.Y. and Rotter, J.M. (2004) "Predicting the handlability of a coal blend from measurements on the source coals", Fuel, 1-8, 2005

11 References

1. Ooi, J.Y., Rotter, J.M., Lahlouh, E.H. and Zhong, Z. (1998) "Blind Trial on Coals for Rapid Handling Assessment", Proc., 6th Int. Conf. Bulk Matls Stor, Handling and Transptn, IEAust, Sept., pp 73-78.
2. Zhong, Z., Ooi, J.Y. and Rotter, J.M. (2001) "Edinburgh Powder Tester – Development and preliminary results", First progress report, Sept. 2001, University of Edinburgh.
3. Ooi, J.Y. , Rotter J.M. and Zhong, Z (2001) "Enhancing handlability through coal blending multi-parameter optimisation", Final report for BCURA Project B39b, November 2001,University of Edinburgh
4. IChE (1989) Standard shear testing technique for particulate solids using the Jenike shear cell. IChE/EFChE joint publication, IChE, England.

Figures



Figures 2.1 to 2.8 Schematic of large coal tester

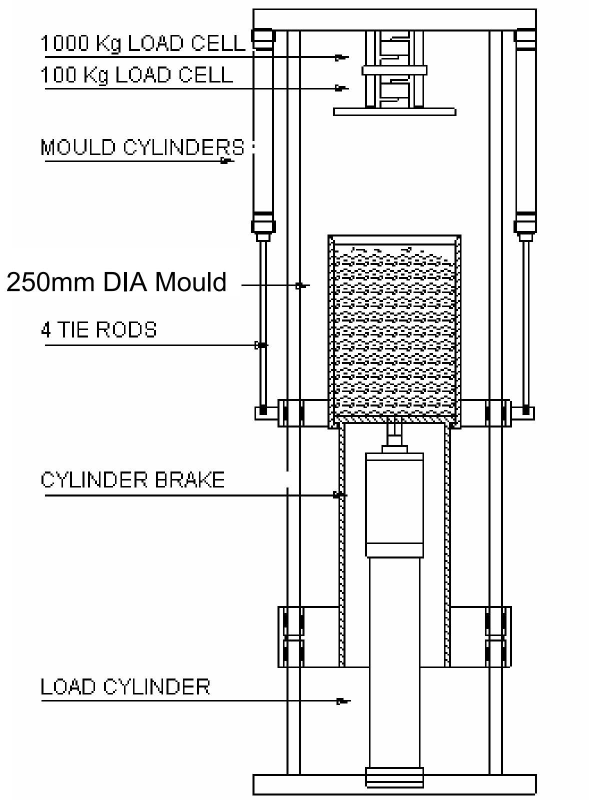


Figure 2.9 Final version of schematic of the coal tester

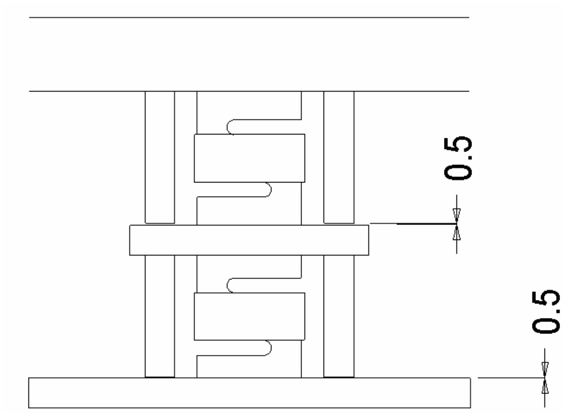


Figure 2.10 Arrangement for loadcells

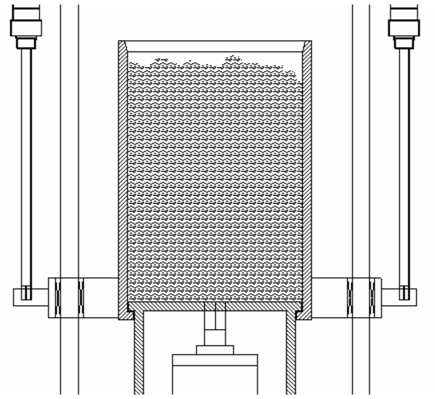


Figure 2.11 Relative movement of the mould

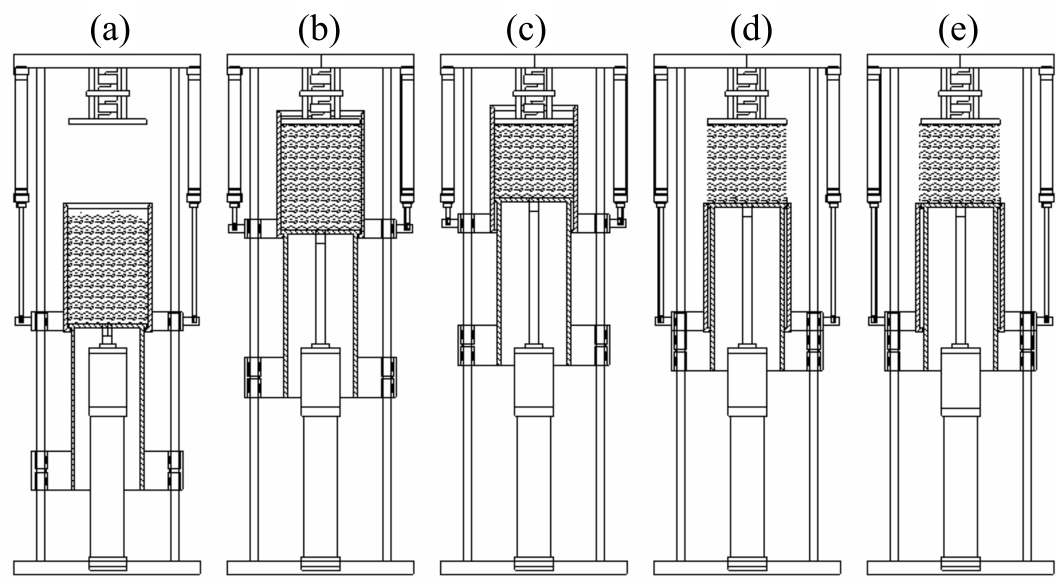


Figure 2.12 Testing procedure

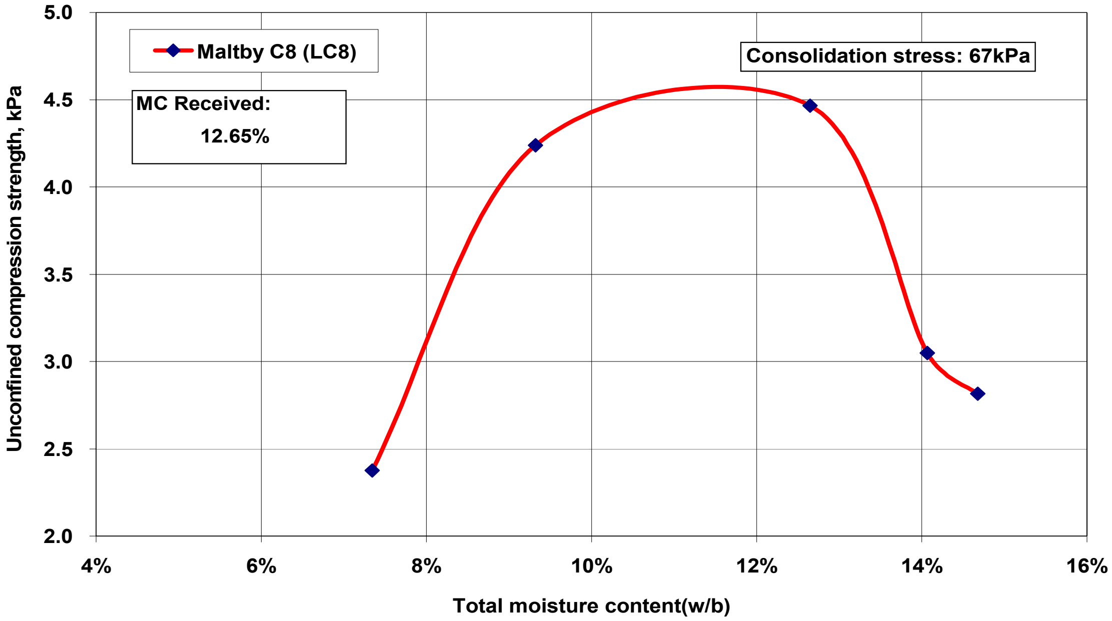


Figure 4.1 Stress-Moisture-Cohesion Function of Maltby C8

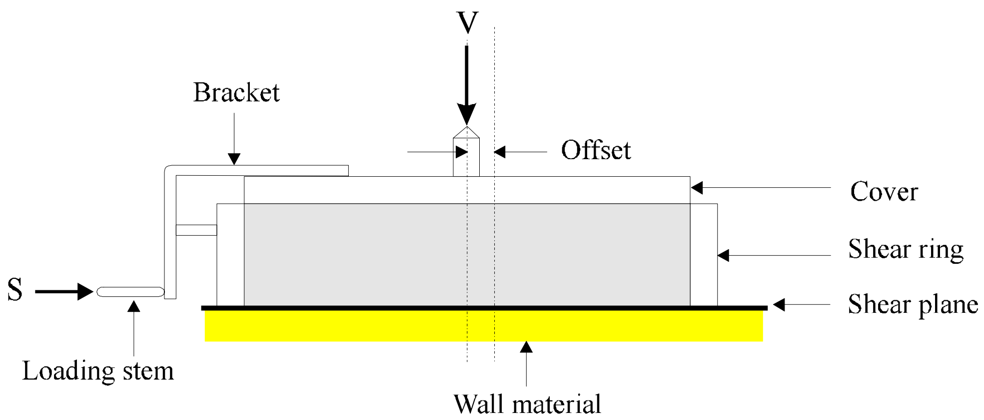


Figure 4.2 Jenike shear cell for wall friction test

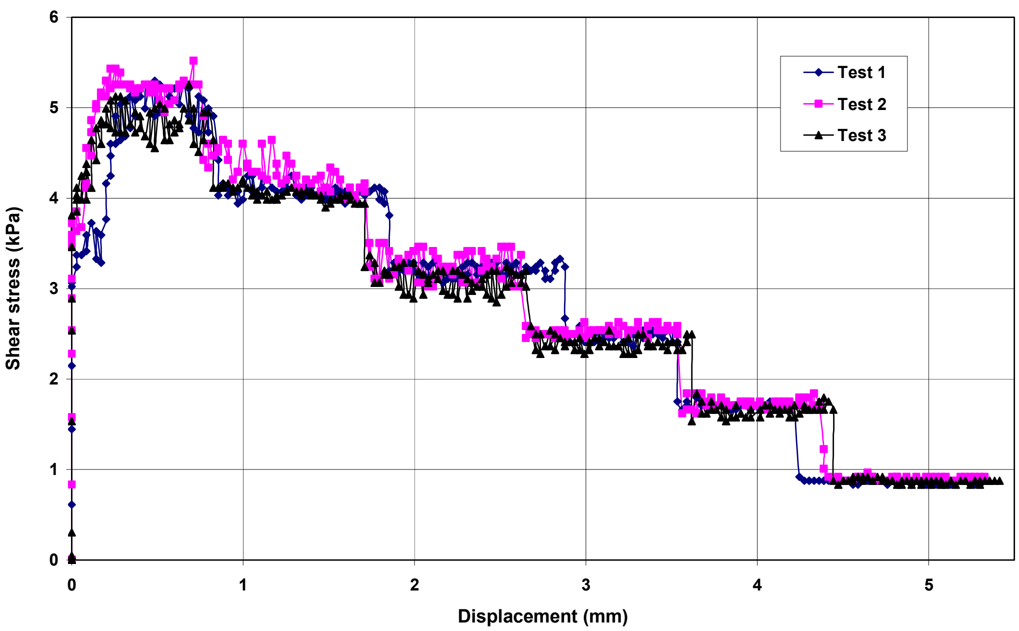


Figure 4.3 Shear stress vs. displacement for the dry coal on nedox treated wall

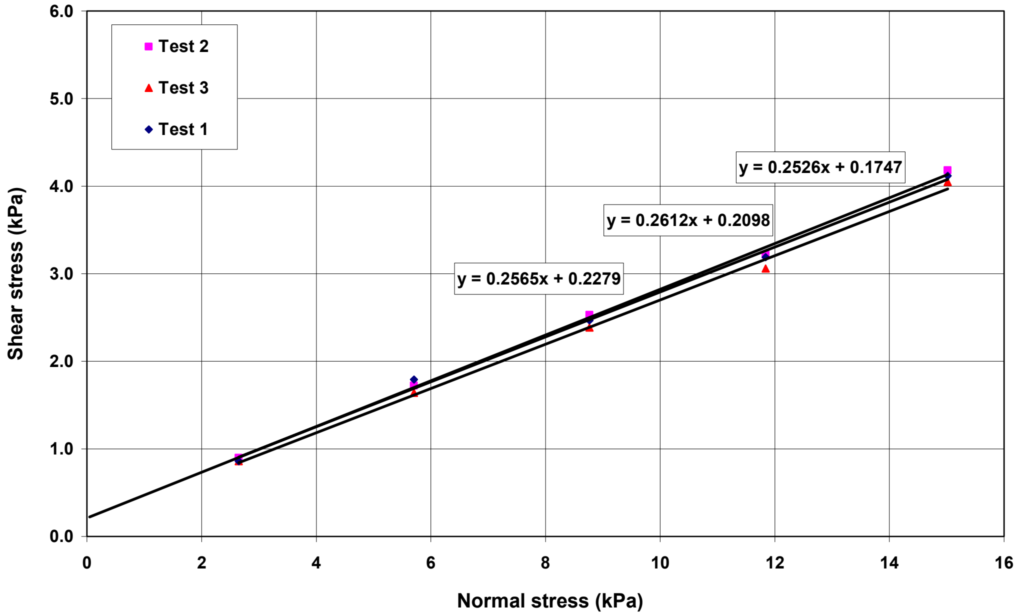


Figure 4.4 Shear stress vs. normal stress for dry coal on nedox treated wall

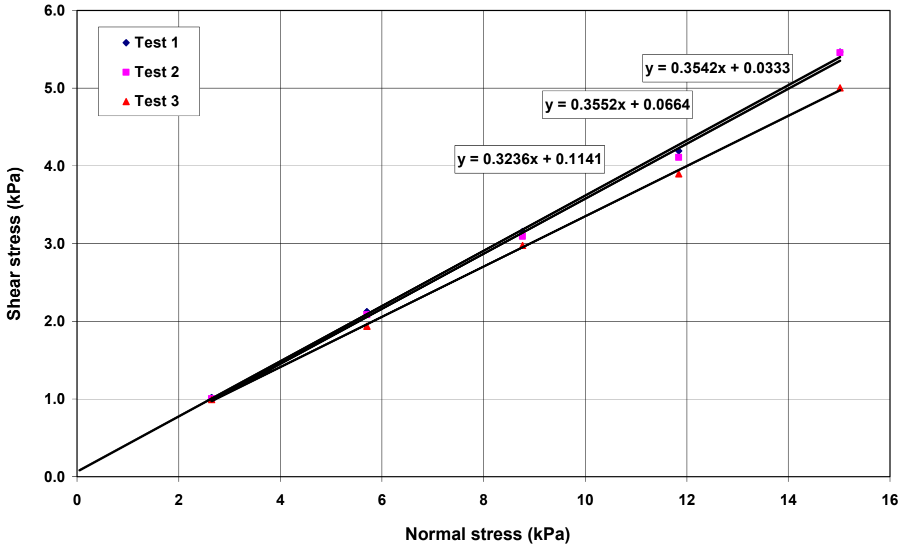


Figure 4.5 Shear stress vs. normal stress for dry coal on mild steel wall

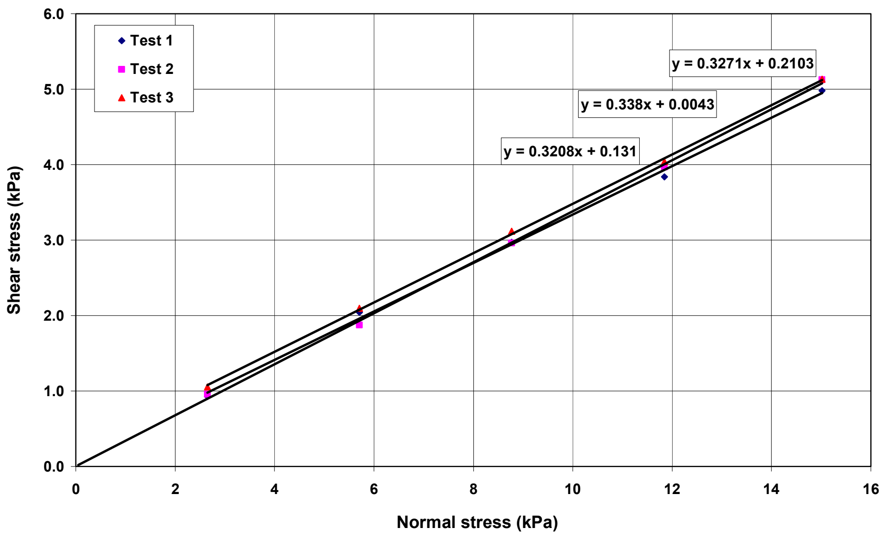


Figure 4.6 Shear stress vs. normal stress for dry coal on Mylar wall

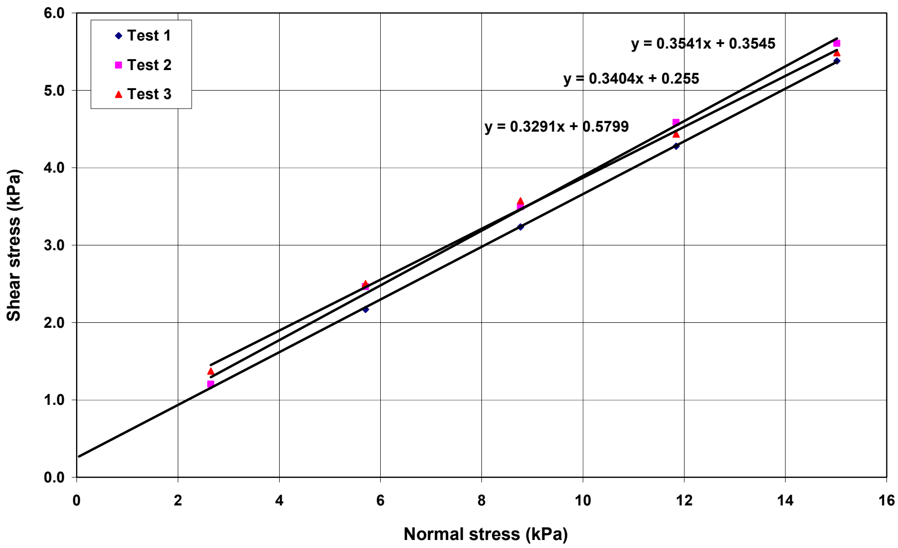


Figure 4.7 Shear stress vs. normal stress for wet coal on mild steel wall

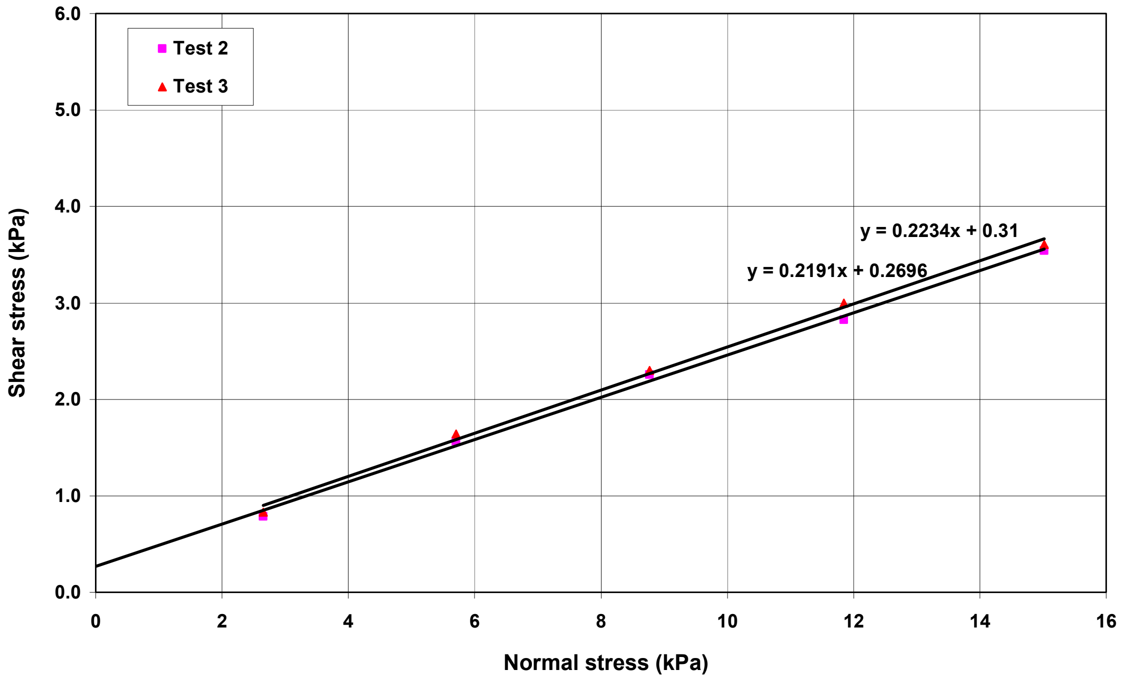


Figure 4.8 Shear stress vs. normal stress for wet coal on nedox treated wall

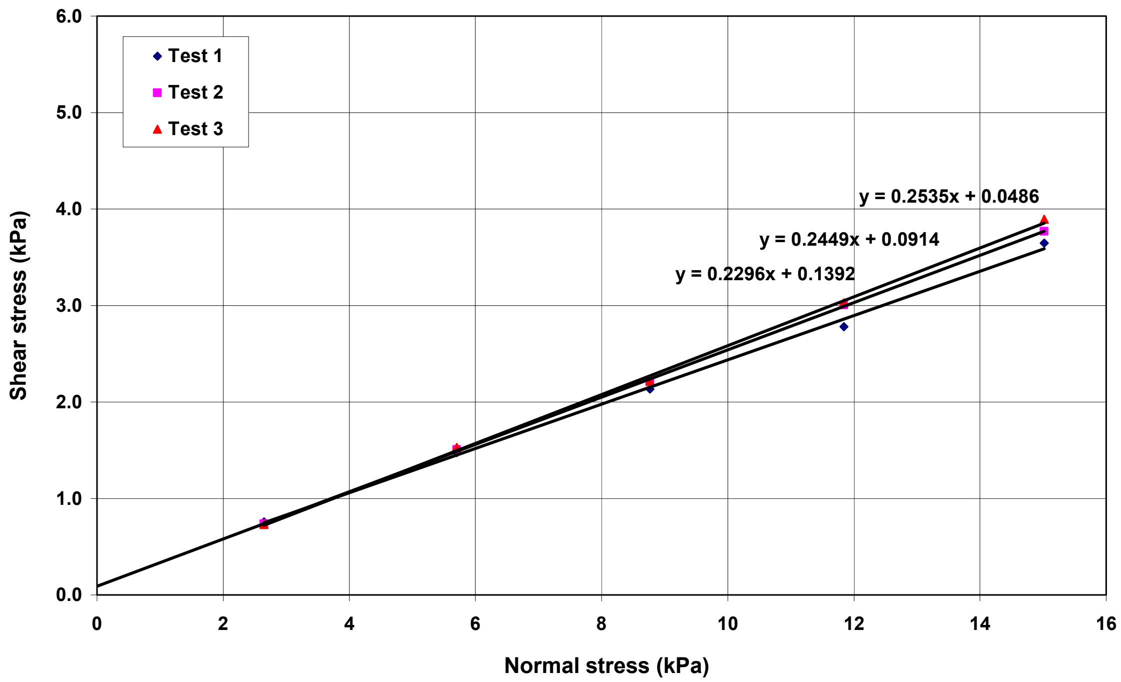


Figure 4.9 Shear stress vs. normal stress for wet coal on Mylar wall

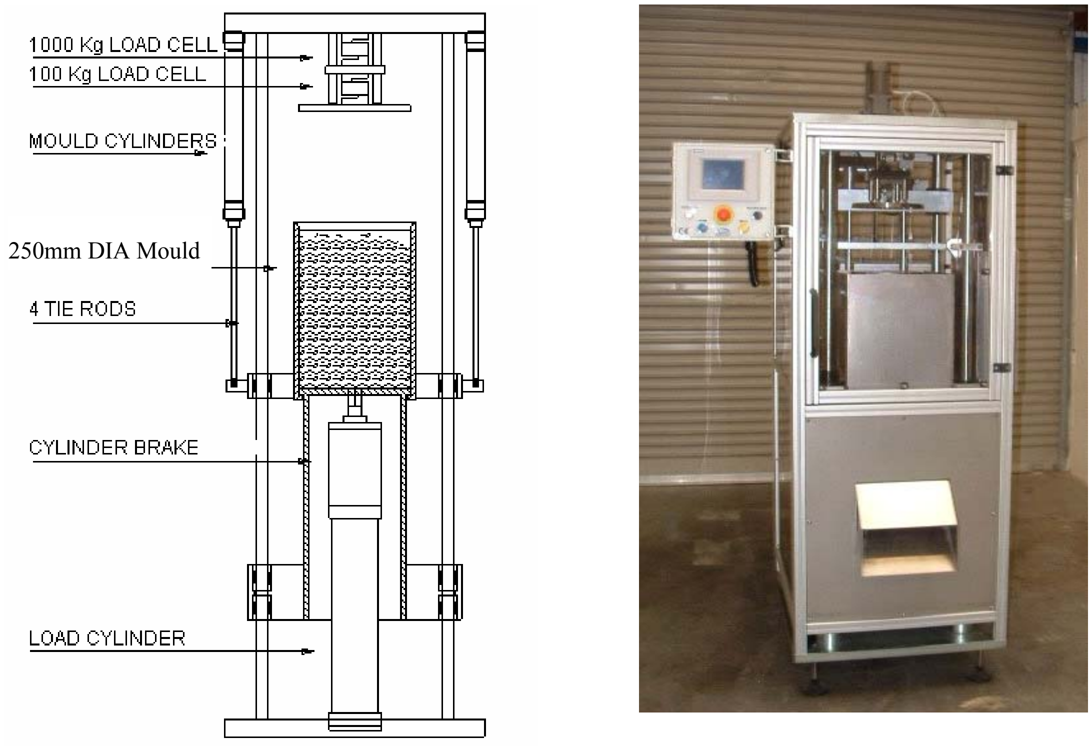


Figure 5.1 Edinburgh automated Cohesion Tester

Figure 5.2 Filling chute attached to the side of machine

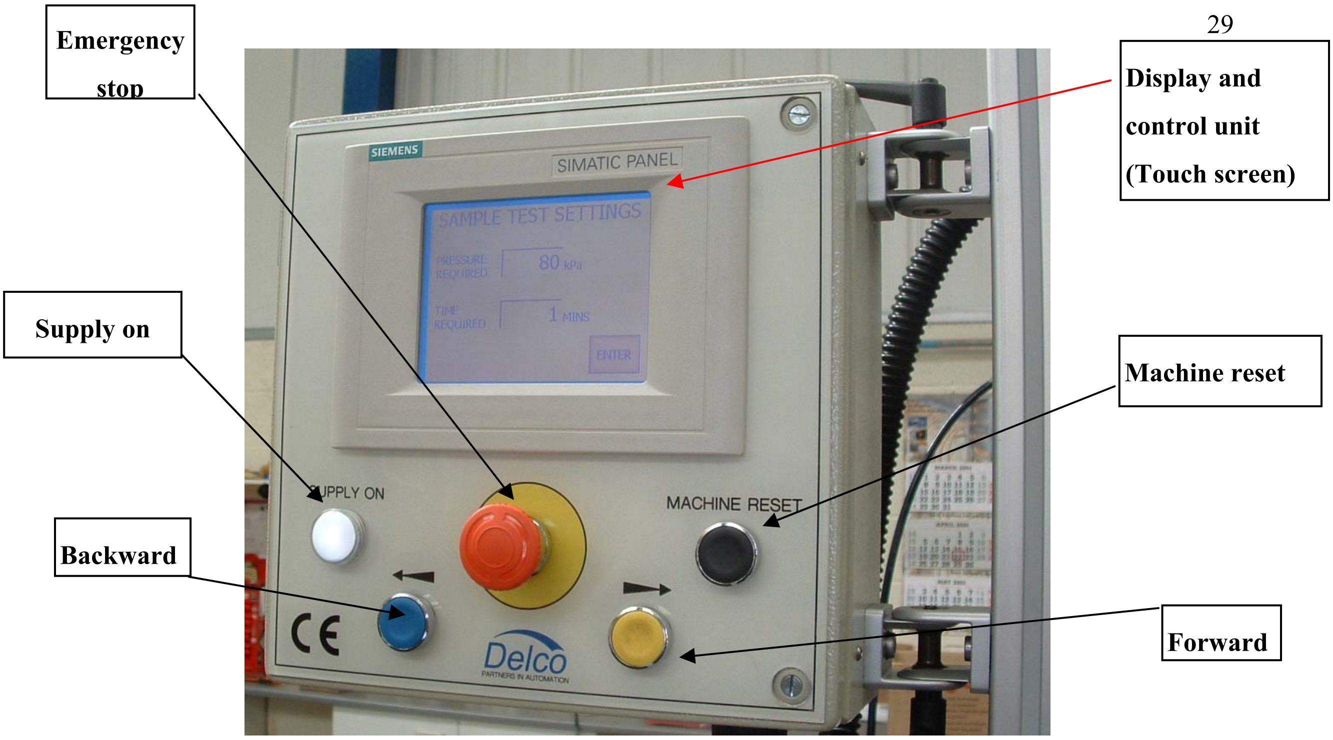
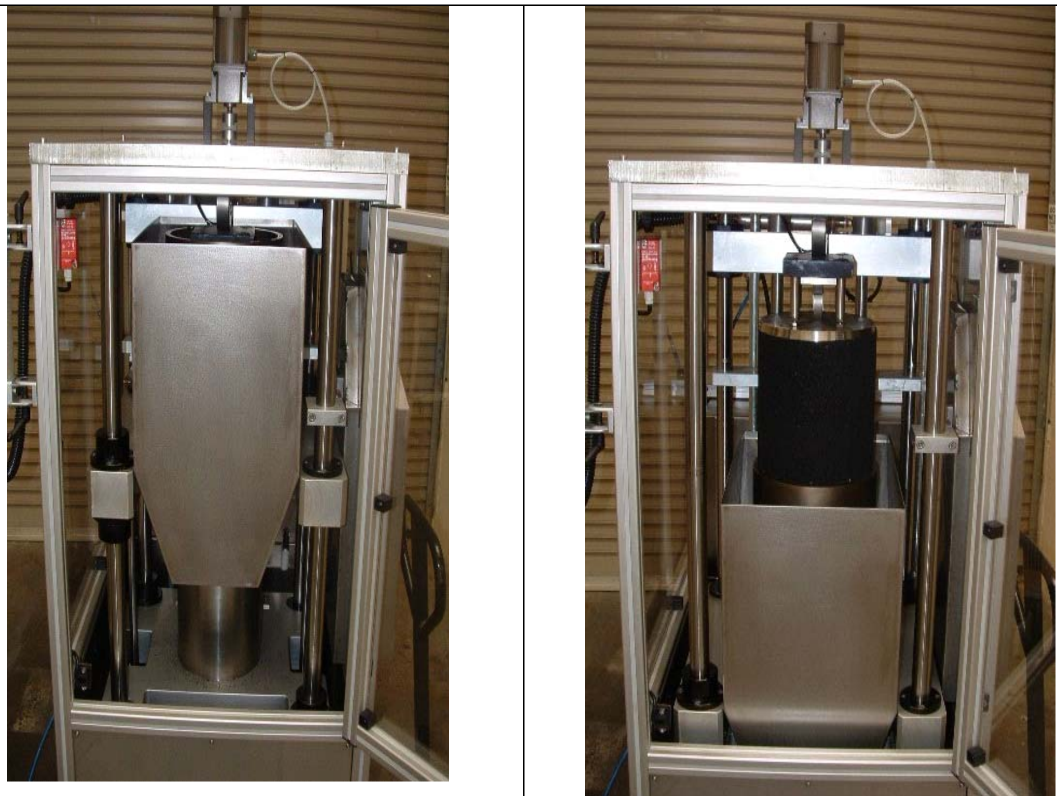


Figure 5.3 Programmable control unit



(a) Consolidation	(b) Loading to failure

Figure 5.4 Main stages of cohesion test

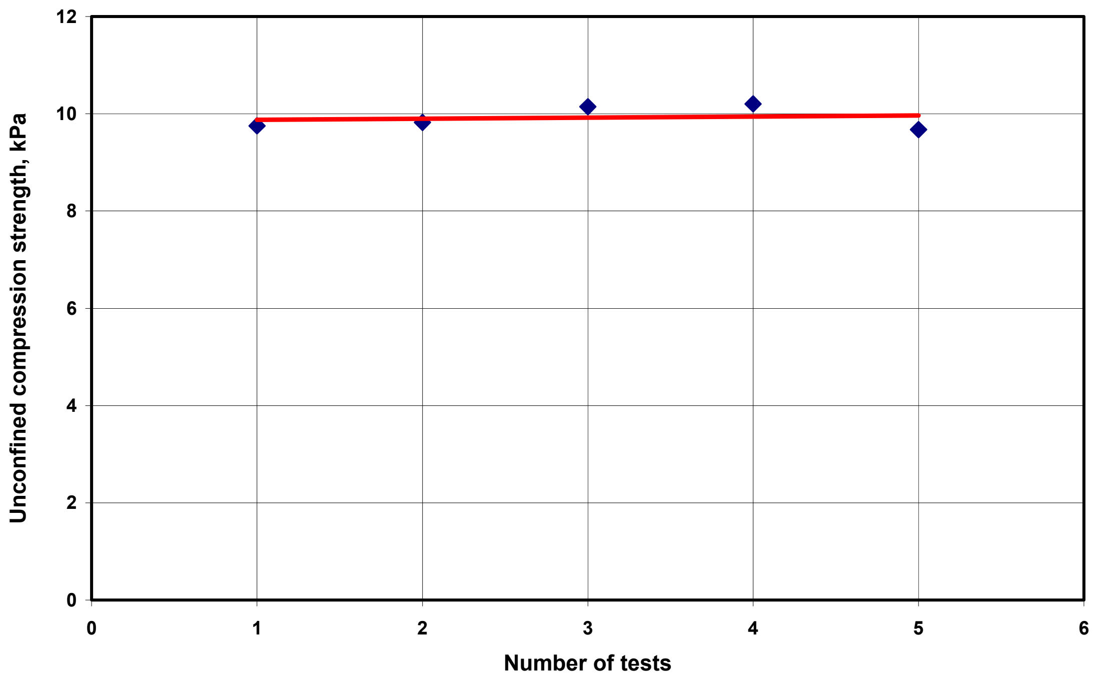


Figure 5.5 Repeatability of the Edinburgh automated cohesion tester

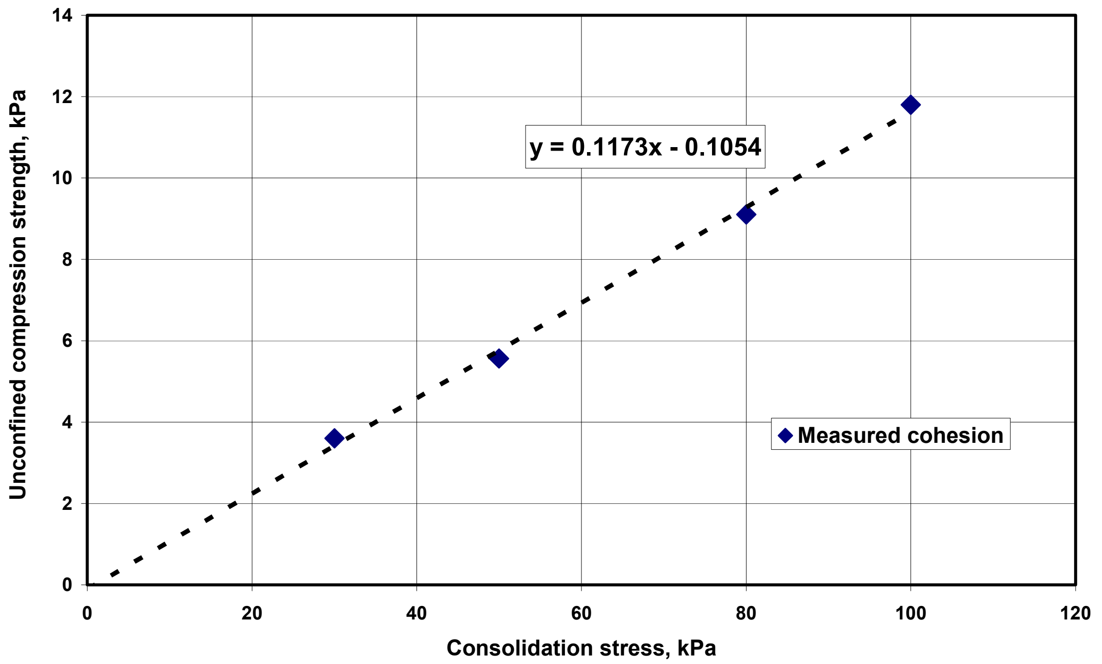


Figure 5.6 Effect of consolidation stresses on handlability

Figure 6.1 General view of the hopper in the Moxey

Figure 6.2 Vertical and inclined hoppers

Figure 6.3 Gap between the two hoppers

Figure 6.4 Shape of the inclined hopper

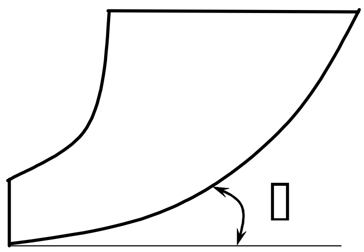


Figure 6.5 Slope of the inclined hopper

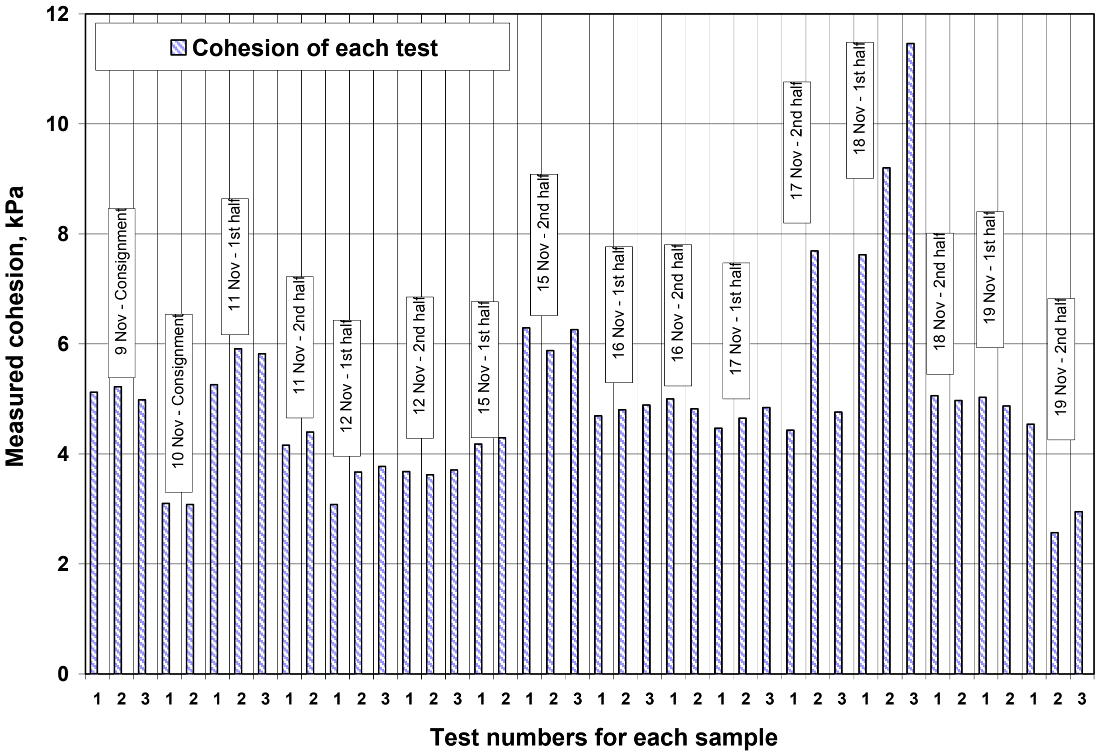


Figure 6.6 Measured cohesion during the trial period

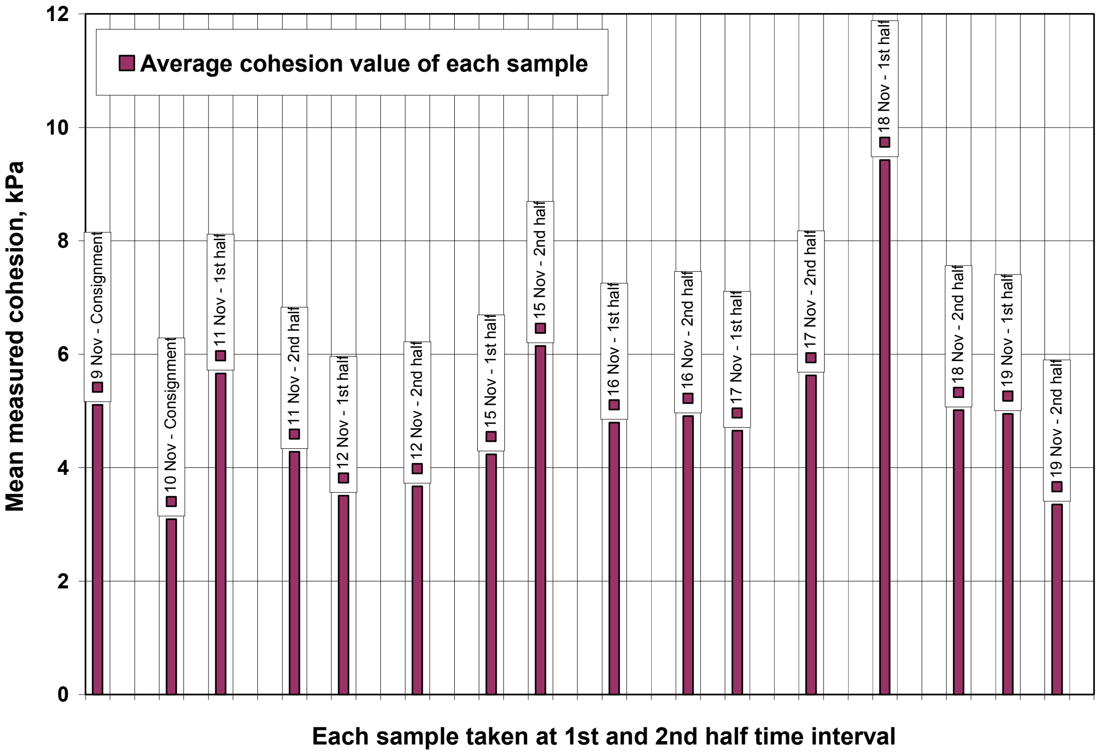


Figure 6.7 Cohesion variation for each consignment

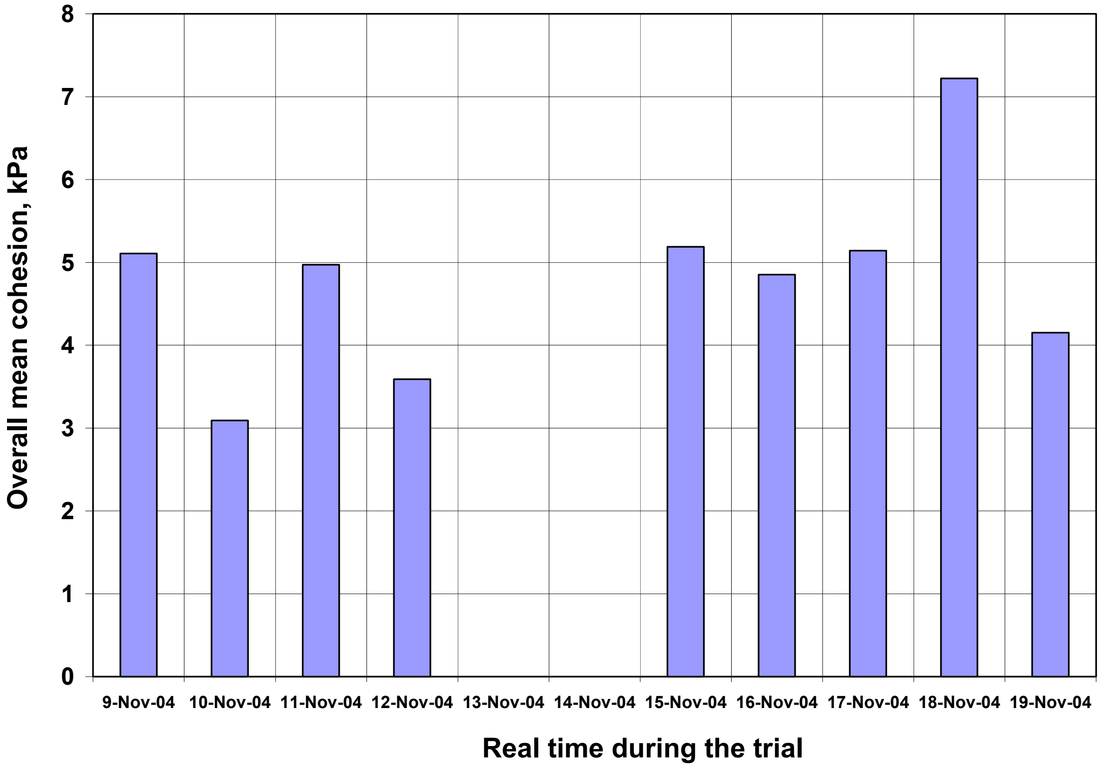


Figure 6.8 Handlability variation during the trial period

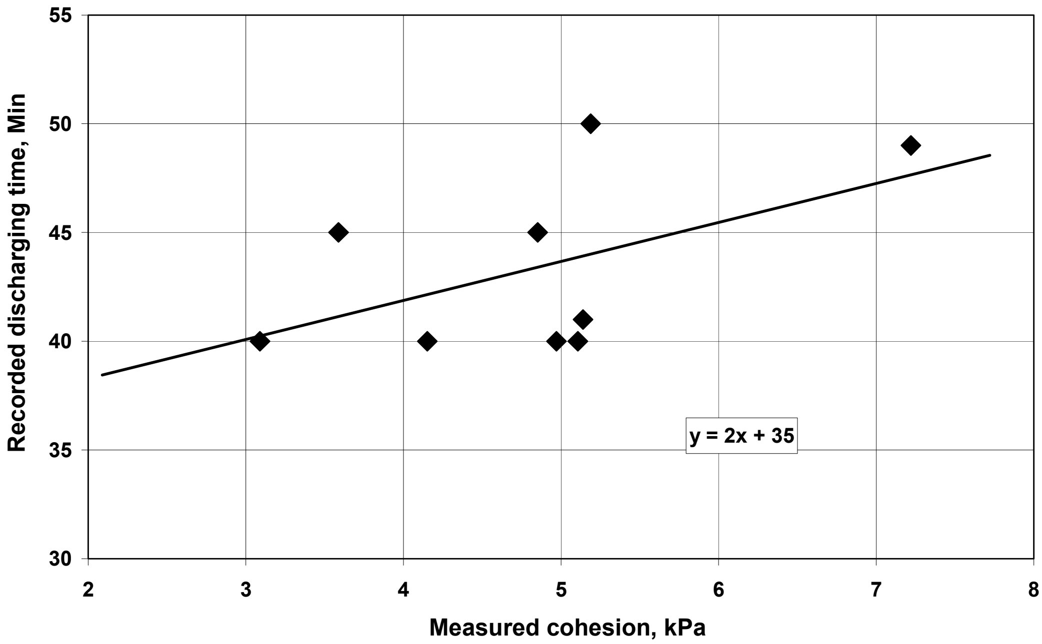
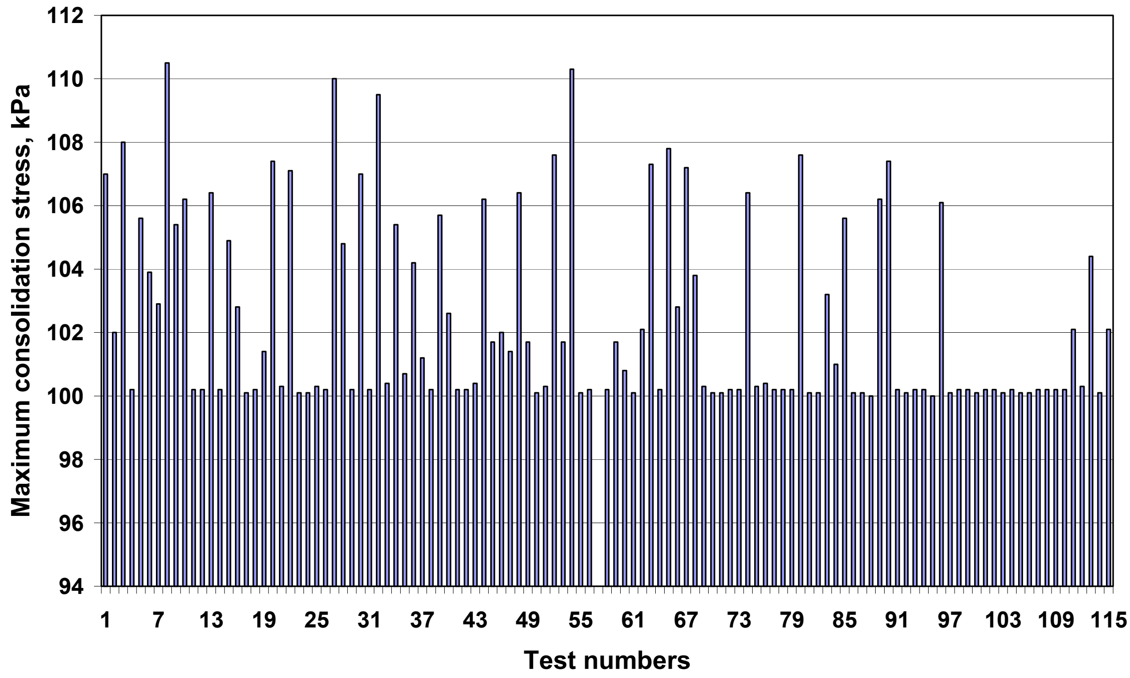


Figure 6.9 Discharging time vs mean cohesion of the consignment



*[*The gap in the figure is due to a missing data point because of machine break down]*

Figure 6.10 Variation of consolidation stress

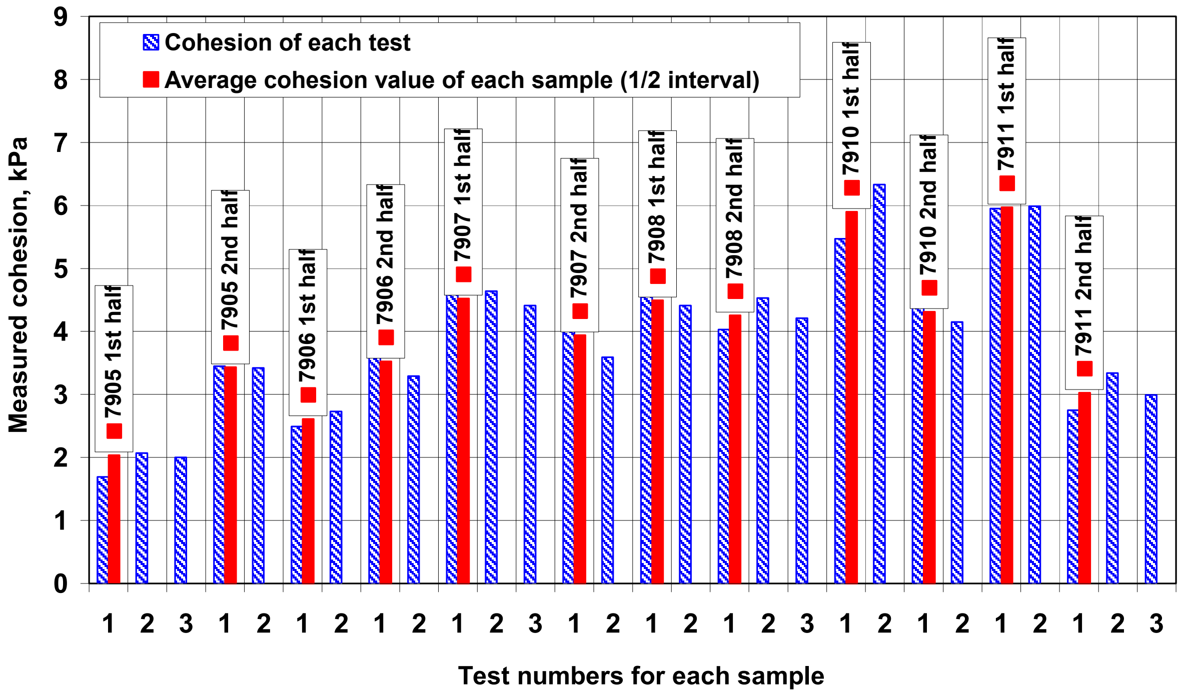


Figure 6.11a Variation of measured cohesion

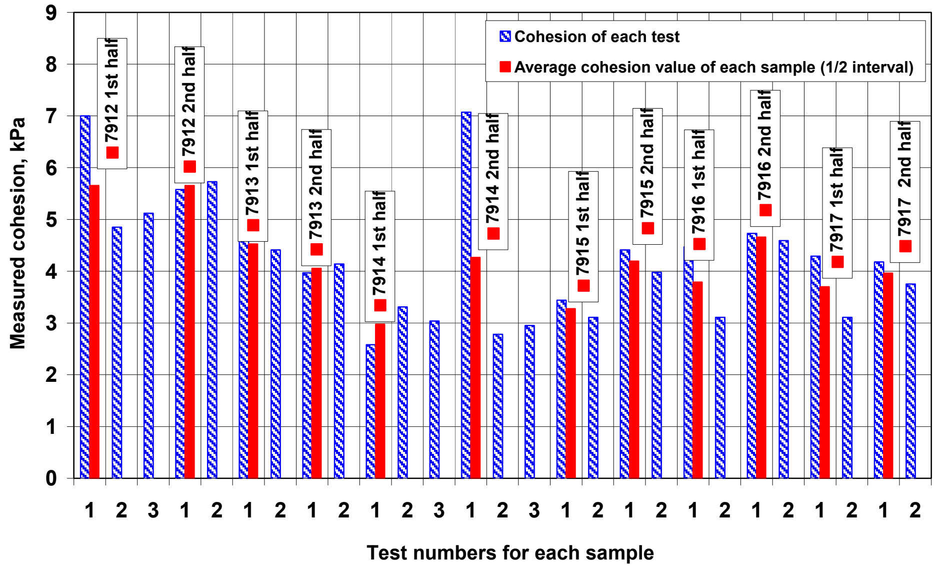


Figure 6.11b Variation of measured cohesion

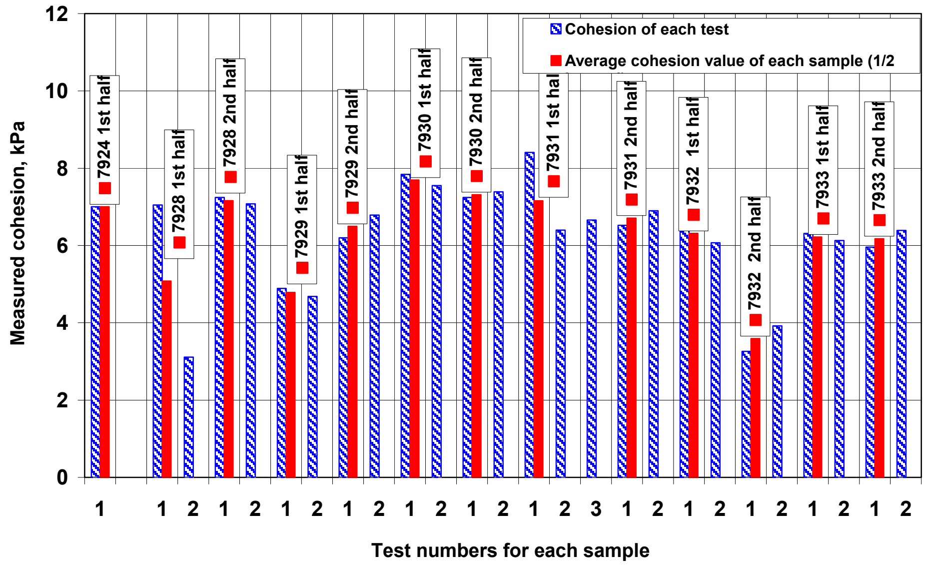


Figure 6.11c Variation of measured cohesion

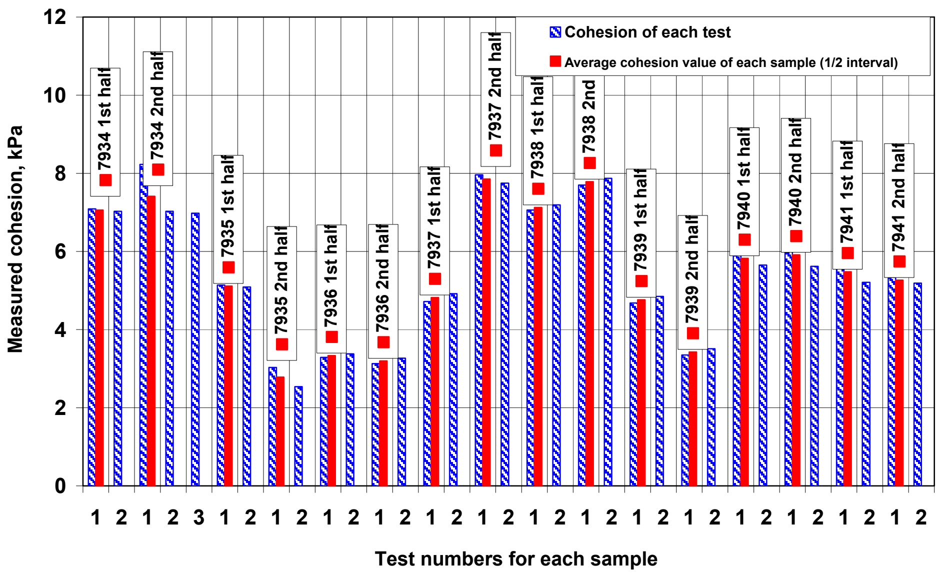


Figure 6.11d Variation of measured cohesion

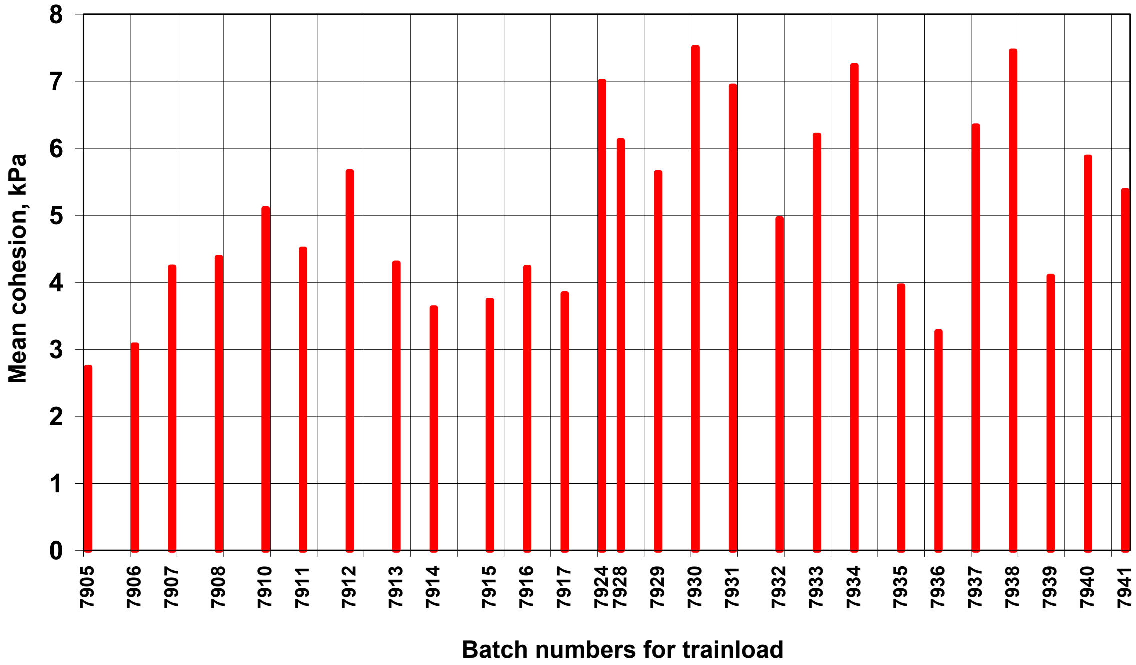


Figure 6.12 Variation of handlability of Maltby coal during the trial

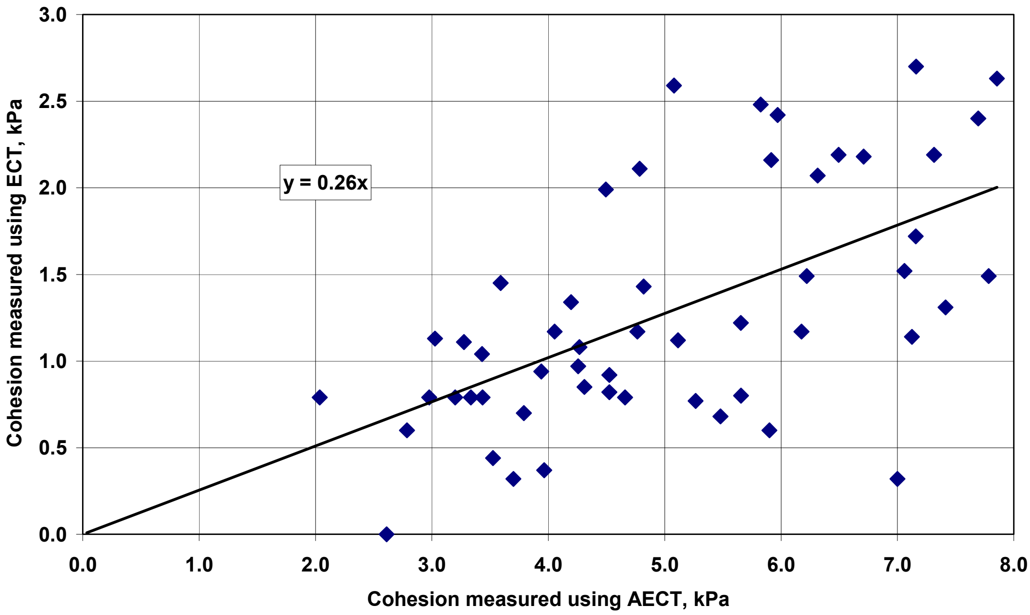


Figure 6.13 Comparison of cohesion values measured by ECT and AECT

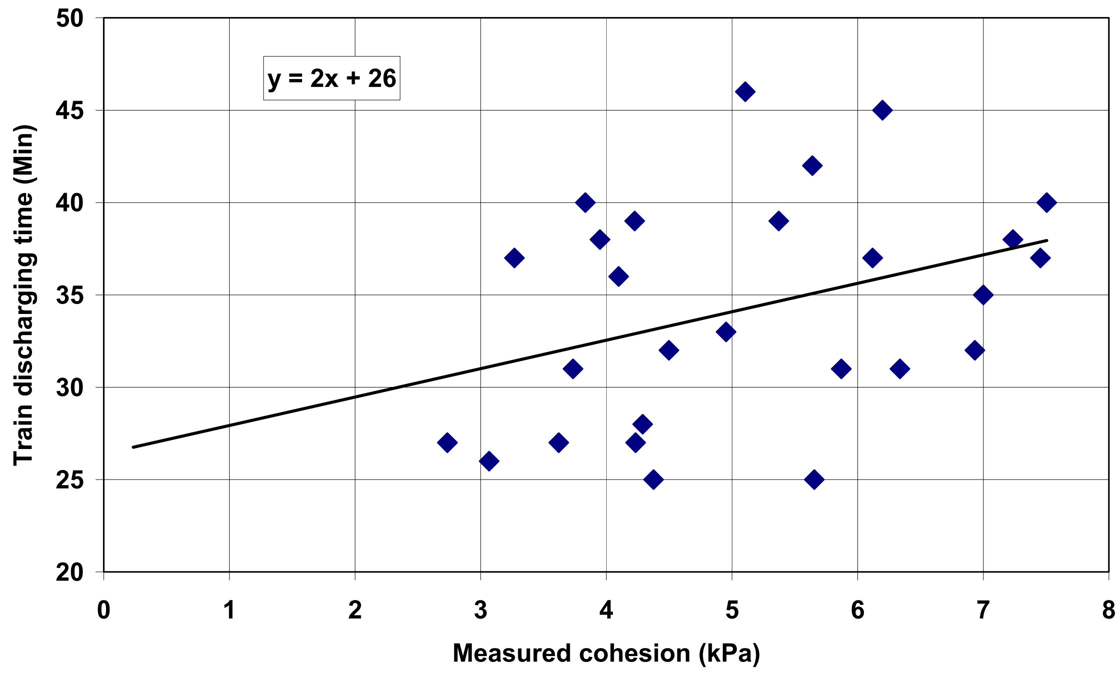


Figure 6.14 Train discharging time vs cohesion measured using AECT

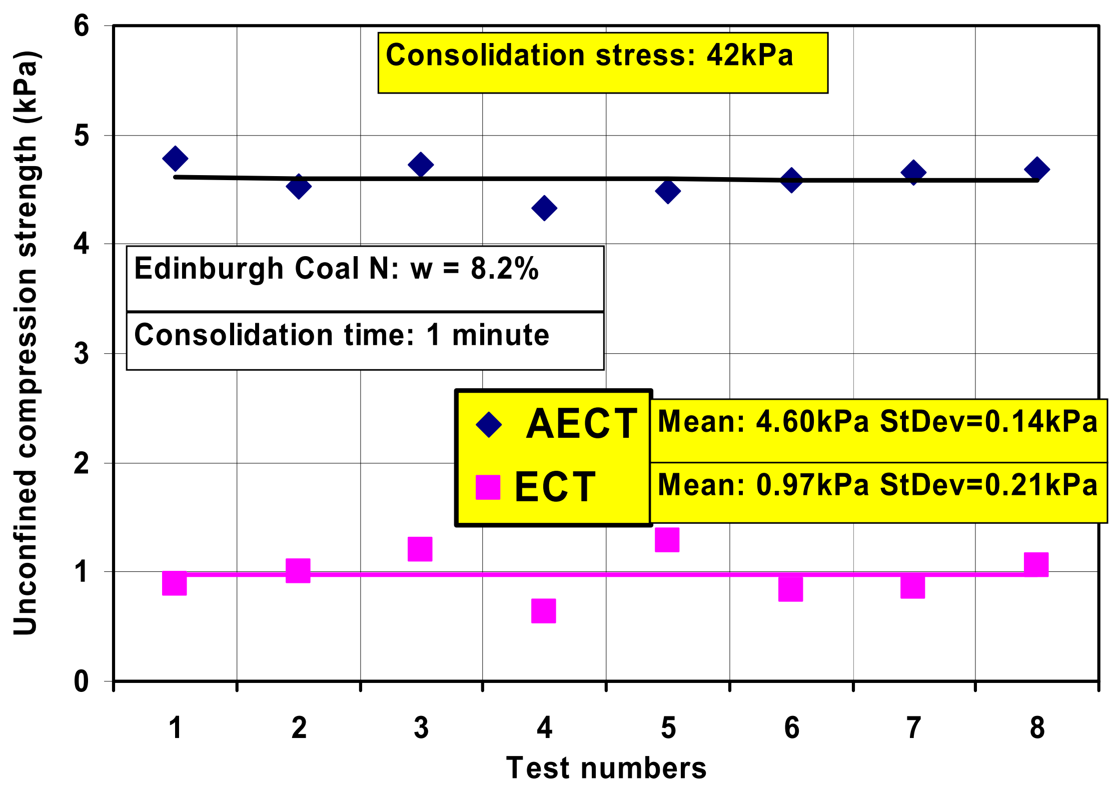


Figure 7.1 Repeatability for full size range at 42kPa

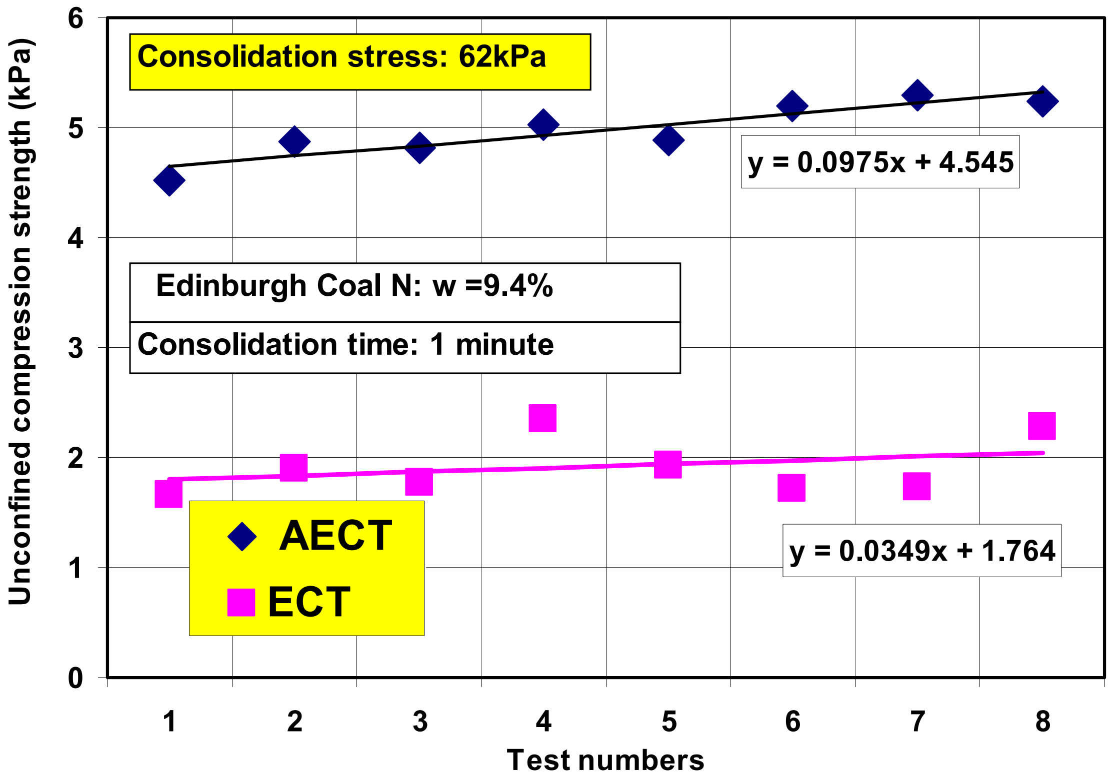


Figure 7.2 Repeatability for full size range at 62kPa

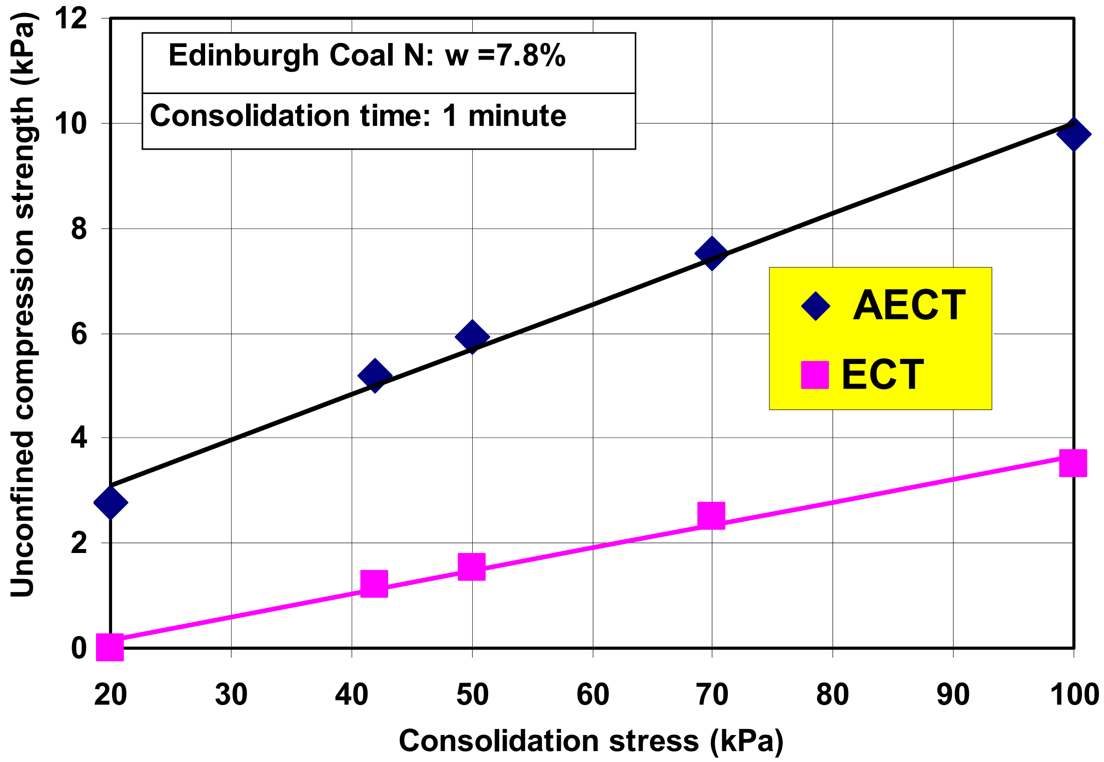


Figure 7.3 Effect of consolidation stress

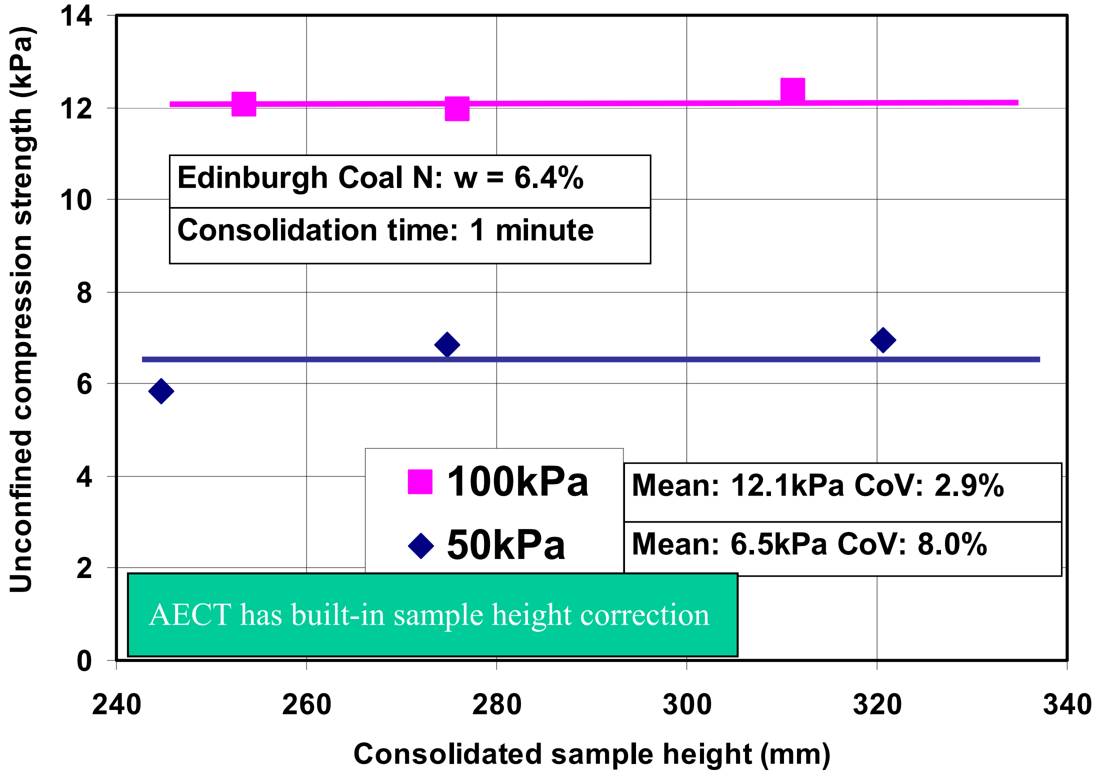


Figure 7.4 Effect of sample height