Investigations into the effect of discontinuities on the strength of coal pillars

by G.S. Esterhuizen*

Synopsis

The major proportion of South African coal is extracted by the bord-and-pillar mining method which requires that the overlying strata be supported by pillars of coal. The stability of the pillars is a major safety concern. One of the factors which affects the strength of coal pillars is the intensity and nature of discontinuities in the coal seams. Current design methods for pillars assume that all the coal seams have equal strength and are equally disturbed by natural discontinuities, resulting in over-designed pillars in some cases and potentially unstable pillars in others. Research was carried out to determine the nature of discontinuities in coal seams and to assess their potential effect on pillar strength. It was found that large variations exist in the intensity of discontinuities in the different coal seams being mined. In addition, numerical model studies showed that the discontinuities could significantly reduce pillar strength if the width-to-height ratio of the pillars is small, but the effect decreases as the width-to-height ratio increases.

Introduction

Coal produced from underground mines in South Africa is mainly extracted by the bord-and-pillar method in which the overburden is supported by coal pillars. The stability of these pillars is a major safety concern, since failure of the pillars could result in the collapse of several square kilometres of a mine. The dimensions of the pillars should therefore be selected so that they are strong enough to ensure the long-term stability of the mine workings. In South Africa pillars are designed using equations which were developed by Salamon and Munro[1,2]. The equations were empirically derived by studying both collapsed and stable pillars. The equations are based on the average strength of coal in South African coal mines. A safety factor of 1,6 is used to accommodate variations in the strength of coal seams in the various mines of South Africa. The design equations have served the coal mining industry for over the past 28 years. However, a number of collapses of bord-and-pillar workings did occur using the design equations, fortunately without catastrophic consequences. It was concluded that the coal seams in certain areas were considerably weaker than the average[2] and it is known that coal seams in other areas were considerably stronger than assumed for the pillar design equation. The consequence is that pillars may be under designed in some mines and over designed in others.

A research project was supported by the Safety in Mines Research Advisory Committee (SIMRAC) to reassess pillar design methods so that site specific design of pillars could be carried out, with the objective being to allow rock engineers to identify weak coal seams and modify the pillar design accordingly. The results reported in this paper concentrate on the effect of discontinuities on pillar strength, which is only one aspect being considered in the project on pillar design. Note that in this paper the coal seam strength is considered to be the strength of approximately 1 cubic metre of coal, determined in such a manner that the effect of cleats and other discontinuities are accounted for and is distinct from coal pillar strength which depends on the seam strength and a number of other factors.

Discontinuities in coal seams

Joint mapping by scan line techniques was initially carried out to obtain data on the nature of discontinuities in coal. It soon became apparent that standard mapping techniques were not suitable for coal seams. The first problem arose due to the large number of minor discontinuities in coal, referred to as cleats. Major discontinuities were also present but may be spaced 30 m to 50 m apart, and may be missed by a typical scan line survey. Standard joint mapping techniques were clearly inadequate to account for the different types of discontinuities and the large variation in frequencies.

Types of discontinuities in coal

The initial observations of discontinuities in coal showed that a different approach was

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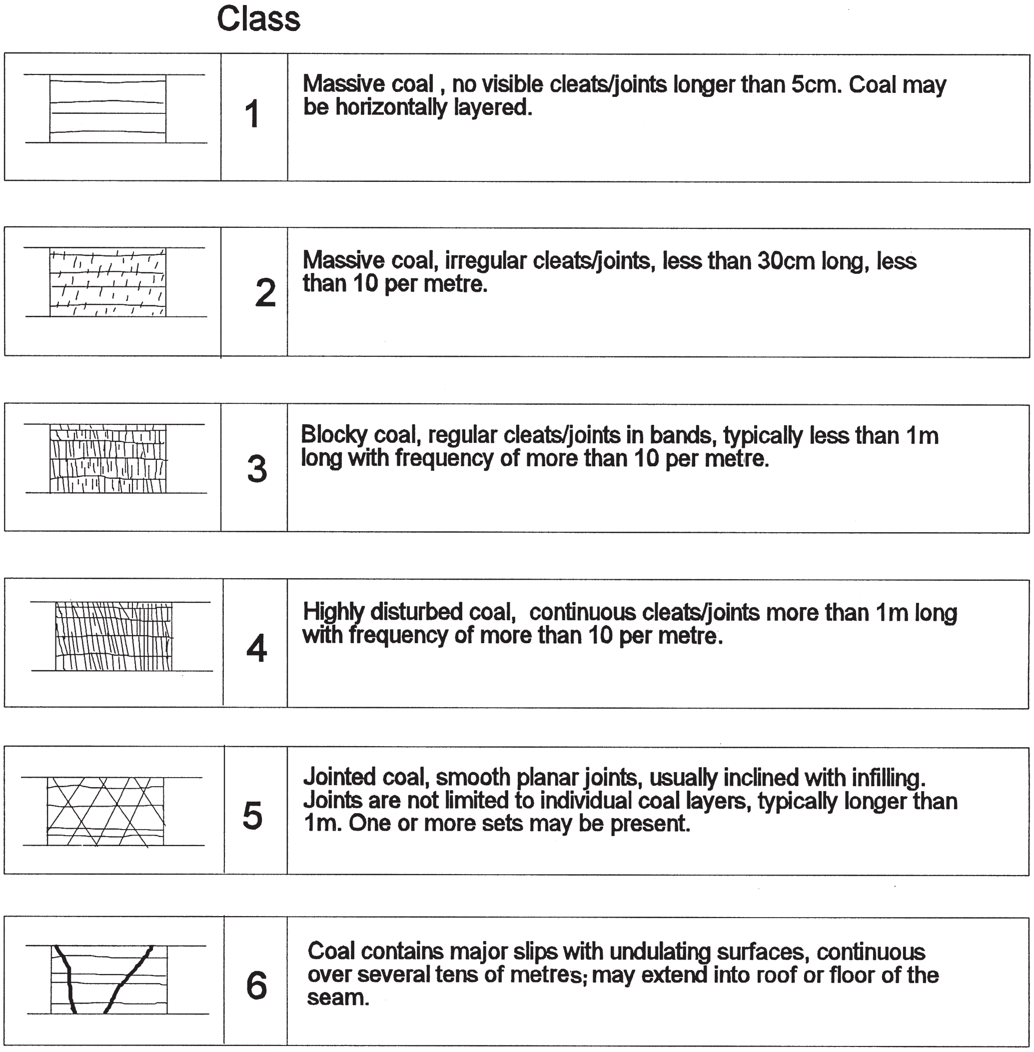
required to map discontinuities, which would accommodate the large variation in type and frequency of discontinuities. An advantage in coal mine workings is that one usually has access to all four sides of a coal pillar, allowing a good estimate to be made of the true spacing of discontinuities. A mapping technique was developed in which three categories of discontinuities were recorded, each being mapped separately, as follows.

1. Minor discontinuities, usually referred to as cleats. Cleats may be considered to be part of the structure of the 'intact material' of coal. Cleats exist on a microscopic scale but may be up to 1m long. Cleats were observed to be vertical and usually occur in two orthogonal sets, with one of the sets being better developed than the other. Cleats are often infilled with calcite or clay minerals and are straight and planar.
2. Joints, which are similar to joints in rock. These discontinuities may dip at any inclination and usually extend from the roof to the floor of the coal seam, but rarely extend into the surrounding strata. Joints are continuous over several metres on strike and are typically straight and planar with minor infilling. Many of the coal seams mapped were observed to contain no joints at all. However, seams containing joints would often have several sets of joints, which are expected to result in a low coal mass strength.
3. Major discontinuities which extend over several tens of metres in the strike direction. These discontinuities are often referred to as 'slips' in mining terminology and are responsible for many roof falls, since they often extend into the roof strata. Slips may be wavy and undulating with weak infilling up to several centimetres thick. Slips are seldom found in specific sets, but are randomly distributed in orientation, and are not necessarily sympathetic to other jointing in the coal seams.
4. Well-developed layering effects. Coal is often well bedded, and the layers may be considered to be an additional set of joints.

Experience showed that seams could be readily classified into one of six classes or combinations of classes, depending on the cleats, joints or slips present in the coal. A visual classification of seams into classes is presented in Figure 1. The first four classes are related to the cleats in the coal and are used to describe the coal structure. Class 5 describes coal containing joints whilst class 6 describes coal with major



Class	
1	Massive coal , no visible cleats/joints longer than 5cm. Coal may be horizontally layered.
2	Massive coal, irregular cleats/joints, less than 30cm long, less than 10 per metre.
3	Blocky coal, regular cleats/joints in bands, typically less than 1m long with frequency of more than 10 per metre.
4	Highly disturbed coal, continuous cleats/joints more than 1m long with frequency of more than 10 per metre.
5	Jointed coal, smooth planar joints, usually inclined with infilling. Joints are not limited to individual coal layers, typically longer than 1m. One or more sets may be present.
6	Coal contains major slips with undulating surfaces, continuous over several tens of metres; may extend into roof or floor of the seam.

Figure 1—Description of discontinuity classes in coal seams

slips. Most coal seams are combinations of the classes. For example, a seam may be described as class 3–5–0 which indicates that it contains cleats with jointing but no slips. The visual classification has been found useful for discussing and comparing coal seams without carrying out formal classifications of the seams.

Examples of discontinuities in coal seams

The types and frequencies of discontinuities in different coal seams were found to vary considerably. Coal seams varied from massive unjointed coal to highly jointed coal with numerous cleats. It was clear that it could not be assumed that all coal seams have a uniform strength. An example of the variation in the type and frequency of discontinuities at three sites in different coal seams were as follows:

Site 1 is in the Witbank coal field where most of the coal is mined in South Africa. The seam lies at a depth of 120 m and has been extensively supported by pillars.

Site 2 is in the Vereeniging coal field, where it is suspected that the coal is considerably weaker than the average South African coal[3]. The coal seam contains no visible cleats and no jointing, but has a relatively high intensity of major slips.

Site 3 is also located in the Witbank area, but on a different mine than site 1, where highly jointed coal is being mined. The coal contains numerous joints which would have a dominating effect on the strength of coal pillars.

The data from the sites indicated that there was a large variation in the intensity of the discontinuities, and consequently, a large variation could be expected in the strength of the different coal seams. Using the discontinuity classes from Figure 1, case 1 could be described as Class 2–5–6, case 2 is Class 0–0–6 and case 3 is Class 3–5–6.

Rock mass classification of coal seams

Rock mass classification techniques have become popular in rock engineering because they allow experience from one site to be correlated with other sites. A useful addition to rock mass classification techniques has been the estimation of rock mass strength from classification data. The Hoek-Brown criterion[4] may be used to estimate rock mass uniaxial compressive strength (UCS_m) as follows:

$$UCS_m = \sigma_c \cdot \sqrt{s}$$

where σ_c is the uniaxial compressive strength of a 50 mm diameter intact rock sample tested under laboratory conditions and s is a parameter which depends on the condition of the rock mass. The value of s may be estimated by applying the equation of Serafim and Perreira[5]:

$$s = \exp\left(\frac{GSI \pm 100}{9}\right)$$

GSI is the Geological Strength Index[6], which ranges from 100 for intact rock to 10 for extremely poor rock masses. The GSI value is determined from the rock mass classification of Bieniawski[7], assuming the rock mass is dry and without making any adjustments for excavation orientation.

The GSI was determined for the coal seams in the three sites presented earlier. Cleats were considered to be part of the coal structure and it was assumed that their effect would be included in the strength of intact samples of the coal σ_c. Slips and joints were considered in the rating of the seams.

For the purpose of applying the rock mass rating, it was assumed that the strength of intact samples was equal in all the cases so that only the effect of discontinuities would be reflected in the variation of the rock mass rating. A value of 40 MPa was assumed for the uniaxial compressive strength of the intact coal. Since the rock quality designation (RQD) was not available for the seams, the equation of Priest and Hudson[8] was used to estimate the theoretical RQD (TRQD) in each case:

$$TRQD = 100e^{\pm\lambda t}(1 + \lambda t)$$

where λ is the frequency of the joints (joints per metre) and t is the threshold length for determining the RQD, which is equal to 10 cm.

Table I presents the values and ratings for the different categories of the Bieniawski classification system for each of the sites. The resulting ratings were used to determine the rock mass strength using the equations above.

The results in Table II show that the presence of joints could account for a considerable variation in the strength of coal pillars. The coal mass at site 1 is shown to be 3,6 times stronger than the coal mass at site 3. Although the rock mass rating system used to obtain Table II is not particularly suited to coal, the results show the importance of jointing on coal seam strength. Improved methods of estimating the large-scale strength of the coal could therefore be developed using the jointing data.

Pillar shape and discontinuity effects on pillar strength

The effect of jointing on the strength of pillars could be accounted for by simply reducing the calculated strength of a

Table I

Rating values for Bieniawski's classification

Site	UCS (MPa)	RQD	Discontinuity spacing	Discontinuity condition	Ground water	Total rating out of 100
1	40	99	1 m	Rough-curved	Dry	
Ratings:	4	20	23	20	10	77
2	40	100	4 m	Soft gouge	Dry	
Ratings:	4	20	30	4	10	68
3	40	90	20 cm	Infill < 1 mm	Dry	
Ratings:	4	18	10	12	10	54

Table II

Rock mass rating and predicted rock mass strength for three sites

Site	Rock mass rating out of 100	s-value in Hoek & Brown equation	Calculated UCS of rock mass (MPa)
1	77	0.0776	11.14
2	86	0.0286	6.76
3	54	0.0060	3.11

pillar by an amount equal to the reduction in the seam strength predicted by classification methods. This would, however, reduce the strength of all pillars by an equal amount, regardless of the width-to-height ratio. Intuitively it seems inappropriate to apply a constant reduction in strength to pillars of different width-to-height ratios. For example, jointing is not likely to affect a pillar with a width-to-height ratio of 4:1 as severely as it would affect a pillar with a width-to-height ratio of 1:1. Numerical models were used to investigate the effects of jointing on pillars with different width-to-height ratios.

Modelling method and model calibration

A numerical modelling method was required which could model the presence of joints as well as the deformation and failure of the coal material. The distinct element program UDEC[9] was selected. The program is able to model elastic and plastic deformation of an assembly of blocks in two dimensions. Strain-softening behaviour of the pillar material may be modelled. The joint interfaces between blocks are modelled as Coulomb surfaces.

The modelling method and input parameters were first calibrated against the measured behaviour of coal pillars tested *in-situ* by Wagner[10]. These pillars were square with a width-to-height ratio of 2,0. Although the program can only model two-dimensional rib pillars, the model was first calibrated to result in the same peak strength and post peak behaviour as measured by Wagner[10]. This was achieved by using realistic cohesion and frictional properties for the coal and interfaces and modifying the strain-softening parameters. Once satisfactory strain-softening parameters had been obtained, the model cohesion was modified to result in the same strength as predicted for a rib pillar with a width-to-height ratio of 2,0 using the Salamon and Munro[1] equation for pillar strength. The equivalent width of a rib pillar was used as proposed by Wagner[2]. The validity of the input parameters was tested by modelling pillars with width-to-height ratios of 1,0 up to 8,0 and their peak strength determined and plotted against the predicted strength for rib pillars according to the Salamon equation and squat pillar equation[11], using the equivalent width method. The results are shown in Figure 2. It can be seen that except for width-to-height ratios of less than 3,0 the model predicts peak strength values which are similar to those based on the empirical strength equations.

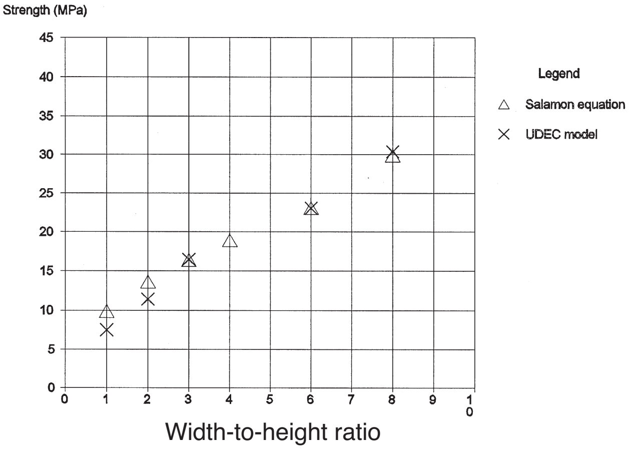


Figure 2—Comparision between model strength and strength based on empirical design equations

Model results for jointed pillars with different width-to-height ratios

Models were set up to evaluate the effect of joints spaced 0,5m apart on the strength of pillars with width-to-height ratios of 2, 3, 6, and 8. The joints were modelled at dips of between 90 and zero degrees. The peak strength for each model was determined and is shown in Figure 3. It can be seen that joints with a dip of 45° have the greatest effect on pillar strength, but as the width-to-height ratio increases, the effect of the jointing decreases, as summarised in Table III. This implies that pillars with large width-to-height ratios are less sensitive to the presence of joints. Inspection of the results showed that shear occurs along joints only in the outer portion of a pillar, up to a depth approximately equal to the height of the pillar. Most of the shear along joints was found to occur at the roof and floor contacts of the pillar.

The effect of varying the joint orientation between 75° and 45° on the stress-strain behaviour of modelled pillars is

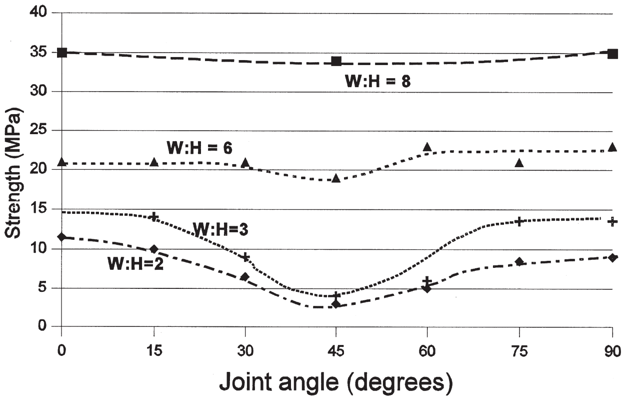


Figure 3—Effect of joint inclination on pillar strength determined from numerical models

Table III

Strength reduction due to joints dipping at 45°

Width-to-height ratio of pillar	Reduction in strength, %
2	77
3	64
6	17
8	3

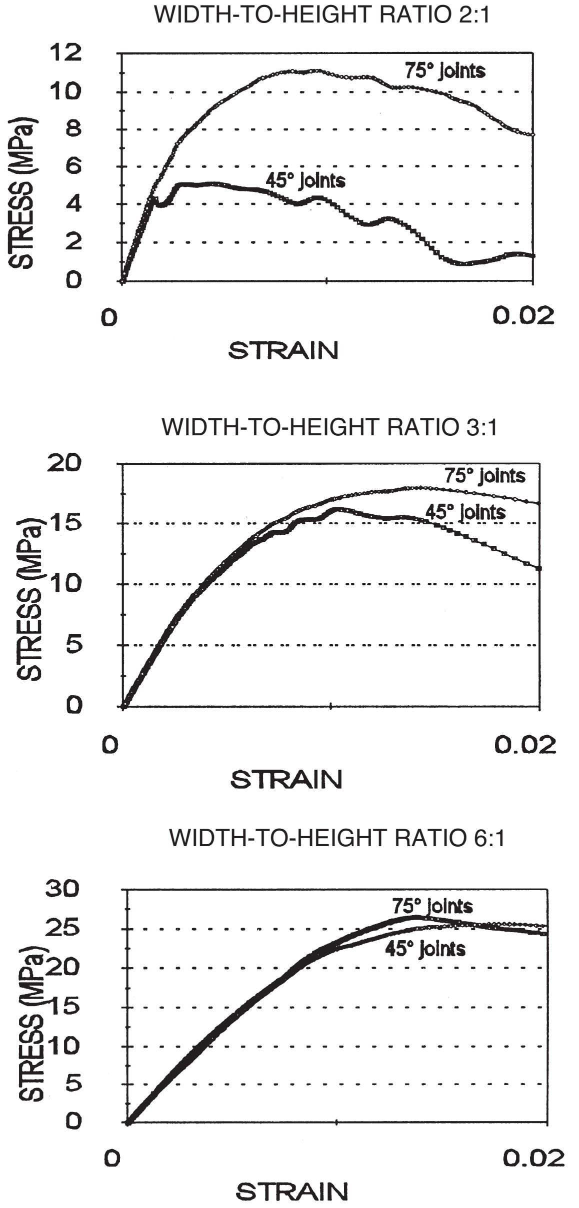


Figure 4—Stress-strain behaviour of modelled pillars, showing effect of 45 degree and 75 degree joints on pillar strength

shown in Figure 4. It is clear from these results that the sensitivity of modelled pillars to joint orientation decreases with width-to-height ratios. The pillar with a width-to-height ratio of 2:1 shows a large decrease in strength owing to the 45° joints, whilst the strength of the 6:1 pillar is hardly affected, whether the joints dip at 45° or 75°.

The model results illustrate that it would be erroneous to simply assume that the strength of a pillar is reduced by the same amount as the reduction in coal seam strength. The reduction in pillar strength depends on the shape (width-to-height ratio) of the pillar.

Conclusions

The research described in this paper showed that discontinuities in coal could be classified into three main types, based on their continuity. The types are:

- minor cleats which form part of the coal structure
- joints and bedding, similar to jointing in rock
- major discontinuities (slips) which may be continuous over several tens of metres.

The intensity of discontinuities in coal seams in South Africa varies from massive unjointed coal to highly jointed coal. Standard rock classification techniques predict that variations in the intensity of discontinuities are likely to result in large variations in the strength of coal seams.

Numerical model studies showed that the reduction in the strength of coal pillars due to the presence of jointing is not constant for all width-to-height ratios, but the effect of jointing becomes less pronounced as the width-to-height ratio increases.

The research shows that accounting for the variation in discontinuities in coal seams will result in improved pillar design methods.

Acknowledgements

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References

1. Salamon, M.D.G. and Munro, A.H. A study of the strength of coal pillars. *Jnl South African Inst. Min. & Metall,* 1967. Vol. 67, pp. 56–67.
2. Wagner, H. Pillar design in coal mines, *Jnl South African Inst. Min & Metall,* 1980. Vol. 80, pp. 37–45.
3. Van der Merwe, J.N. Revised strength factor for coal in the Vaal basin, *Jnl South African Inst. Min. & Metall,* 1993. Vol. 93, pp. 71–77.
4. Hoek, E. and Brown, E.T. *Underground excavations in rock,* 1980. London: Inst. Mining and Metall.
5. Serafim, J.L. and Perreira, J.P. Consideration of the geomechanics classification of Bieniawski. *Proc. Int. Symp. Engng Geol. and Underground Construction,* 1983. Lisbon, Portugal. pp. 1133–1144.
6. Hoek, E., Kaiser P.K., and Bawden W.F. *Support of underground excavations in hard rock,* 1995. Rotterdam, A.A. Balkema. pp. 89–98.
7. Bieniawski, Z.T. Rock mass classification in rock engineering. *Exploration for rock engineering,* 1976. Z.T. Bieniawski (ed.), 1: Rotterdam, A.A. Balkema. pp. 97–106.
8. Priest, S.D. and Hudson, J.A. Discontinuity spacings in rock. *Int. J. Rock Mechanics & Min. Sci.* 1976. 13, pp. 135–148.
9. Itasca Consulting Group. *User's manual UDEC,* 1992. V1.8. Minnesota.
10. Wagner, H. Determination of the complete load-deformation characteristics of coal pillars. *Safety in Mines Research Proc. of the 21st Int. Conf. Sydney.* 1974.
11. Madden, B.J. Squat pillar design in South African collieries. *Symp. Advances in rock mechanics in underground coal mining,* 1989. SA National Group on Rock Mechanics. pp. 83–90.

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University of Pretoria . . .

Engineering lecturers foundation on which ECSA builds*

The Engineering students of the University of Pretoria are making a huge contribution to the activities of the Engineering Council of South Africa (ECSA). This is apparent from the large amount of academics of this Faculty who are serving on various councils.

The Dean of the Engineering Faculty, Professor Jan Malherbe, is a member of the ECSA council and is ex officio member of the Committee of Deans.

Professor Uys Grimsehl, head of the Department of Chemical Engineering is serving on the ECSA council, is chairman of the Professional Advisory Committee for Professional Engineers, is a member of the Accreditation Committee for University Programmes and is a member of the Registration Committee: Professional Engineers.

Professor Archie Rohde, head of the Department of Civil Engineering is a member of the ECSA council, chairman of the Professional Advisory Committee for Civil Engineering, a member of the Registration Committee: Professional Engineers and a member of the Qualification and Examination Committee for Professional Engineers.

The head of the department of Materials Science and Metallurgical Engineering, Professor Roelf Sandenbergh serves on the ECSA council, is chairman of the Professional Advisory Committee for Metallurgical Engineering and is a member of the Central Advisory Committee.

The Director of the Institute for Technological Innovation, Professor Calie Pistorius, serves as committee member on the evaluation committees for electrical and electronic engineering.

Professor Wilhelm Leuschner, head of the Department of Electrical and Electronic Engineering, serves on ECSA's Professional Advisory Committee for Electrical Engineering.

Professor Jasper Steyn, head of the Department of Mechanical and Aeronautical Engineering, is a member of the Professional Advisory Committee for Mechanical Engineering. Professor Stephan Heyns of the same department, is a member of the Professional Advisory Committee for Aeronautical Engineering. He is also an alternate member of the ECSA council.

The head of the Department of Industrial and Systems Engineering, Professor Schalk Claasen, serves on ECSA's Professional Advisory Committee for Industrial Engineering. Professor Paul Kruger, also from the Department of Industrial Engineering is an alternative member (representative of the SA Institute for Industrial Engineering) of the ECSA council.

The head of the Department of Agricultural and Food Engineering, Professor Rennie du Plessis, serves on ECSA's Professional Advisory Committee for Agricultural Engineering.

Mr Essie Esterhuizen from the Department of Mining Engineering serves on the Professional Advisory Committee for Mining Engineering.

Various members of the Faculty act as ECSA examiners and participate in determining the academic status of foreign universities.

Brilliant young academic receives President's Award from FRD*

Professor Chris Pistorius (30), Professor in the Department of Materials Science and Metallurgical Engineering at the University of Pretoria, has recently received the coveted President's Award from the Foundation for Research Development (FRD).

The President's Award is awarded annually by the FRD to a few outstanding young researchers. Academics who wish to qualify for the President's Award should be younger than 35 years, already have a doctorate and should be regarded as a future leader in their particular field, both nationally and internationally.

Researchers are appraised through a process of national and international evaluation. The President's Awards are conferred in the fields of Science, Engineering and Technology.

At present there are only 23 holders of the President's Awards in the country, among whom are Professor Calie Pistorius, currently Director of the Institute for Technological Innovation at the University of Pretoria and Dr Rachel Carter of the Department of Physics at the University of Pretoria.

The President's Award is valid for five years and entails not only international recognition as an outstanding researcher, but also financial support from the FRD.

Engineering student wins national SAIEI competition*

Mr Cobus van Eeden, a final-year student in Electronic Engineering at the University of Pretoria in 1996 was named the national winner of the National Project Competition of the South African Institute of Electrical Engineers.

Almost all final-year students in Electrical and Electronic Engineering in the country, representing six different universities, entered the competition. Mr van Eeden was elected the overall winner among 10 finalists. Mr Cristoph Niewoudt acted as Mr van Eeden's tutor.

Mr van Eeden's project entailed the assembly of a prototype of face verification system. The system uses a video camera linked to a personal computer. When the candidate appears in front of the screen, a photo of the person is taken and compared by the camera with a preassembled database of faces. The face with the best resemblance is then identified and displayed within five seconds. Of 35 faces tested, all were recognised correctly. The unique software developed for the project, enables correct identification even when the person tries to disguise himself or herself for instance by using a beard or glasses or by making funny faces. This system is ideal for use in access control systems or automatic teller machines where people's identities need to be ascertained quickly and accurately. ◆

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